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National Geodetic Infrastructure – Status Today and Future Requirements: The Example of Norway

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About this document

Purpose and scope

This document is based on the final report for the project *National Geodetic Infrastructure - Status Today And Future Requirements.* The goal of this project was to assess the adequacy of current geodetic infrastructure in Norway for the provision of the observations and products required by a wide range of users, and, if necessary, to recommend steps that would ensure that the infrastructure meets likely future requirements.

The advent of the space-geodetic techniques and the rapid improvement and growth of communication techniques and capacities have started a revolution in the field of applied and global geodesy. Therefore, it is timely to assess thoroughly the user requirements for the geodetic observations and products and compare them to what is currently available to meet those requirements in order to identify potential present or future gaps.

Several countries have carried out or are in the process of carrying out similar studies. Examples are the Geodetic Institute of Sweden, which has produced a report "RefStrat - strategier för referanssystem och referansnät". In Canada, the independent consulting company BearingPoint carried out an indepth study of the requirements for the national geodetic infrastructure including comparative studies in five countries. Representatives of this company also visited Norway and interviewed members of the Norwegian Mapping Authority.

The work in the project was carried out in three main steps, namely

(1) **Consolidation**: Review of User Requirements (UR) for the geodetic observables and products as well as characterization of the temporal and spatial variability of the geodetic observables and derived products;

(2) **Specification**: Specification of a geodetic observing system on global, regional and national level;

(3) **Recommendation**: Assessment of existing infrastructure, cost-benefit analysis, and recommendations for the future, with particular emphasis on those infrastructure gaps in greatest need of closure.

This report summarizes the results of the project. In particular, it provides

(i) a comprehensive overview of the URs for geodetic observations and products as derived from a broad range of societal benefit areas and scientific requirements;

(ii) an account of the temporal and spatial variability of the three fundamental geodetic quantities, which are the shape of the Earth (geometry), the gravitational field of the Earth (potential), and the Earth's rotation (dynamics);

(iii) the system specifications in terms of functional requirements, spatial network geometry, and products to be delivered;

(iv) an assessment of the existing geodetic infrastructure on global and regional level as well as the national level in Norway;

(v) a cost-benefit analysis, and

(vi) the identification of infrastructural gaps and priorities to close or mitigate them.

The report provides a comprehensive overview over requirements for geodetic observations, products and services on national as well as global level and, based on these, general considerations for the design of the global and national geodetic observing system. Thus, the material presented in the report is applicable not only to the specific situation in Norway but rather consistitutes a generic basis for the design of national and global geodetic infrastructure.

In many countries, the national geodetic authority is involved in or associated with in time and frequency transfer, and geodetic infrastructure is used for these purposes. However, this report does not address the application of space-geodetic infrastructure for time and frequency transfer. Considering that the basic measurements in space geodesy are time measurements, this may appear as a deficit of the report. However, the geodetic infrastructure in Norway is not used for time and frequency applications, and, therefore, this aspect is considered out of scope for this report.

Abstract

Executive Summary

The mission of the Norwegian Geodetic Institute: The Geodetic Institute of the *Norwegian Mapping Authority* (NMA) has the responsibility for the determination and maintenance of the national geodetic reference frame. Geodetic reference frames are the basis for all georeferencing and positioning in a modern society and have to meet the requirements of a wide range of users for the determination of position and height. For mapping, land surveying and navigation on land, on sea, and in air as well as the planning in the society, a geodetic reference is of similar importance as the roads and railroads are for national transport and schools for education. Similarly, the geodetic reference frame and the infrastructure required to maintain this frame on a dynamic Earth can be compared to the foundation of a house.

The benefits of the global and national geodetic infrastructure are enormous: A national geodetic reference frame is indispensable in a modern society and its benefits are truly tremendous. The *Norwegian National Geodetic Infrastructure* (NNGI) and the *Norwegian Geodetic Reference Frame* (NGRF) are in line with their roles in one of the technologically and socially most advanced societies:

- The NGRF is the backbone of a wide range of economic activities and contributes substantially to the *Gross Value Added* (GVA[1]).
- The NNGI allows the exploitation of the space-geodetic technologies for a wide range of practical and scientific applications.
- The NNGI integrates the Norwegian reference frame into the European one and links it to the global geodetic reference frame.
- The NGRF allows the interrelation of all geo-referenced databases and resources in the same frame and thus facilitates full interoperability of geo-related databases and services.
- The NNGI supports the participation of Norwegian companies and research institutes in international projects and developments, particular in the field of technology development.
- The NNGI and NGRF support the governmental priorities and international activities, such as sustainable development, climate change, the *Integrated Global Observing Strategy* (IGOS), the *Global Earth Observation System of Systems* (GEOSS), the *Intergovernmental Panel on Climate Change* (IPCC), and the *United Nations* (UN).
- The NNGI strongly supports Norwegian participation in important global programs aiming at a better understanding of the Earth system, its climate, global geodynamics, geohazards, etc, and the mitigation of impacts of natural and anthropogenic hazards on society.

Over many years, the international scientific community has managed in major cooperation efforts facilitated by the *International Association of Geodesy* (IAG) and based on contributions of institutions and individuals in many countries to develop and maintain a global infrastructure that provides the observational basis for the determination of a highly accurate reference frame as well as operational products that give reliable and easy access to positions in this frame. Today, this frame and the underlying system are crucial for applications in many economic and scientific fields, and they are taken for granted, almost as a natural part of the societal infrastructure freely available to everybody.

The reference frame together with high-speed communication and advanced data processing enables modern societies to operate very cost-efficiently and hence create a basis for higher standards of living. A study in Canada estimates that uses of the geodetic reference frame contribute 6% to 9% of the GVA or, in other words, support activities in various economic sectors which impact from 6% to 9% of the GVA to the Canadian economy. Considering the economical structure in Canada and Norway, a similar or even higher fraction is likely for Norway. Therefore, an insufficient development of the NNGI and the NGRF can have serious consequences for the national economy.

Geodesy in transition: Geodesy is in a transition (if not a revolution) of methods brought about by the advent of space-geodetic techniques and the combination of these with rapidly improving communication technologies and capacities. The development in

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[1] The GVA is an economic indicator similar to the *Gross Domestic Product* (GDP), with the relation being GVA = GDP - taxes on products + subsidies on products. Here, GDP is the total value of final goods and services produced within a country's borders in a year.

computer technology, data communication, satellite-based positioning and navigation creates many new opportunities and increases the demand for geographical information technologies from a wide range of users and applications. Cooperation between countries, integration, globalization, and increasing international transport demand uniform geodetic reference frames as a basis. This poses new requirements for a national geodetic reference frame.

A uniform geodetic reference frame within Norway and across its borders is prerequisite for effective support to many of the existing and emerging applications. To be able to support the full economic exploitation of the advantages modern satellite-based positioning can offer, a geodetic reference frame must be accurate, homogeneous in space and time, and easy to access and use.

Moreover, geodesy increasingly gains importance in the frame of Earth observation as the provider of both the global reference frame and observations of the Earth's geometry, gravity field, and rotation. Global Earth observation needs to be built upon national infrastructure in many countries, with the national geodetic infrastructure having a central role in the global monitoring system.

In this situation of rapidly emerging new technologies and applications and a transition to new methodologies, it is timely to consider the requirements for national geodetic infrastructure. One focus of this report is on the geodetic reference frame in Norway and on the status of the geodetic infrastructure required to maintain the reference frame. Another focus is on the geodetic infrastructure required for comprehensive Earth observations as requested by the World Summit on Sustainable Development and in the progress of the implementation of the GEOSS through the *Group on Earth Observation* (GEO).

Present geodetic reference frame: The present geodetic reference frame in Norway consists of separate horizontal and vertical reference frames:

- The horizontal reference frame is a realization of the *European Terrestrial Reference System* (ETRS) and is denoted as EUREF89. The main network of points is the Stamnett, which is densified by local networks called Landsnett.
- The vertical reference frame is a leveling network with the heights given in NN1954, that is, heights as they were in 1954.

These two frames are suited for relative positioning.

Currently, most positioning is carried out relative to local geodetic markers with known coordinates. With relative positioning, it is possible to determine coordinates that can be kept fixed within certain accuracy limits over a long time, depending on how stable a given area is. However, relative positioning requires parallel measurements in both the new points for which coordinates are to be determined and one or more reference points. Relative positioning does not allow full exploitation of the potential of the space geodetic techniques.

Towards exploitation of the full economic potential of new technologies: The space-geodetic techniques, in particular the *Global Navigation Satellite Systems* (GNSS), allow for the first time the determination of coordinates in a global, geocentric reference frame with high accuracy and independent of nearby reference points. This method facilitates the determination of precise point coordinates at any location where no direct use is made of the geodetic infrastructure on the Earth's surface. This *precise point positioning* method uses the satellite orbits instead to gain access to reference frame.

In order to transform coordinates determined in a global, geocentric reference frame to the national horizontal and vertical reference frames as well as to meet the growing accuracy demands of users, two new elements had to be added to the national reference frames over the last ten years, namely

- a velocity model which describes how coordinates change over time (in particular, a land uplift model for the vertical component);
- a height reference surface, which connects ellipsoidal (geometric) heights from GNSS to the heights in the national height reference frame.

There is considerable economic advantage in point positioning compared to relative positioning. Therefore, we expect that in the near future precise point positioning will be used for a large fraction of all positioning. Already today, the existing GNSS, in particular GPS, can be used to determine with high accuracy new coordinates almost anywhere on the globe, depending only on the visibility of a fraction of the sky with a sufficient number of satellites. Together with an accurate geoid model, precise point positioning can be used to determine point heights anywhere with GNSS. In the open ocean, precise point positioning enables hydrographic surveys and the mapping of the ocean bottom with unprecedented accuracy, and it facilitates the monitoring of changes due to, for example, extraction of oil and gas in marine areas.

However, post-processed satellite orbits are currently required to obtain highest accuracy in precise point positioning. We envisage a future when these highly accurate orbits are available in near real-time, potentially broadcast by the GNSS satellites as part of their *Signal in Space* (SiS).

The reference frame for precise point positioning is given through the satellite orbits and clocks and the Earth rotation parameters. The satellite orbits and clocks are today monitored by a global network of reference stations established in a major international cooperation effort under the auspices of the *International GNSS Service* (IGS) of the IAG, and they are given in a global reference frame. All points on the Earth's surface are in constant, though slow, motion with respect to the global reference frame and the satellite orbits. Motion in Norway is mainly due to plate tectonics (mainly horizontal) and post-glacial deformation (mainly vertical). In order to utilize the space-geodetic techniques for the determination of coordinates in the NGRF, it is necessary to monitor Norway's motion in relation to the satellite orbits that provide access to the global geodetic reference frame. Moreover, an accurate geoid model is required in order to fully exploit the economic advantages of precise point positioning for height determination. The Geodetic Institute of NMA is implementing the permanent geodetic infrastructure required for the necessary, future-oriented monitoring of the variations and changes in geopotential.

International cooperation for a global reference frame and Earth observation: Modern national geodetic reference frames and services that give access to these frames would not be possible without a highly accurate global reference frame. This frame is provided by the *International Terrestrial Reference Frame* (ITRF), which is a realization of the *International Terrestrial Reference System* (ITRS). The ITRS is a conventional coordinate system including all conventions for the orientation of the axis, physical constants, models, and processes to be used in the realization. The ITRF is a set of globally distributed points for which coordinates and (currently constant) velocities are given. The *International Earth Rotations and Reference Systems Service* (IERS) of the IAG and the *International Astronomical Union* (IAU) is responsible for the definition of ITRS and the determination and maintenance of ITRS.

The ITRF is determined on the basis of several independent space-geodetic techniques, including *Very Long Baseline Interferometry* (VLBI), *Satellite Laser Ranging* (SLR), GNSS, and *Doppler Orbitography by Radiopositioning Integrated on Satellites* (DORIS). For each of these techniques, a technique-specific IAG Service maintains a global network of tracking stations (based on the best efforts of many contributors), which provides the observations required for reference determination. Each of these techniques has unique advantages and disadvantages, and only the combination of the techniques guarantees an accurate and stable reference frame. The most important elements for the determination and maintenance of a global reference frame are the so-called fundamental stations, which have at least three of the independent techniques co-located (including in addition to the space-geodetic techniques also absolute and relative gravity observations and tide gauges, where possible). Globally, there are currently only about 25 fundamental stations, and due to its particular location, the Ny-Ålesund observatory is a rather central one of them.

The emerging *Global Geodetic Observing System* (GGOS), which IAG is setting up as the unifying umbrella for the IAG services, is expected to link the geodetic services into the global Earth observation systems and to provide a more consistent service to the users. In particular, GGOS aims to ensure that the geodetic products and tools respond to the increasingly more demanding user requirements.

GPS and, in the near future, more generally, GNSS has developed into the most widely applied technique for positioning (and navigation). The dramatic development of GPS over the last ten years towards a highly accurate and economically very efficient technology for positioning has been facilitated globally by the work of the IGS and regionally the *European Reference Frame* (EUREF). The Geodetic Institute contributes several permanent GPS stations to these international networks, which are used to determine the ITRF. The national densification of the global and regional networks allow the determination of transformations between the time-dependent ITRF and the national, fixed user reference frame (i.e., in Norway EUREF89).

The *European Combined Geodetic Network* (ECGN) is intended to be the regional implementation of GGOS in Europe, which is coordinated in the frame of EUREF. In Scandinavia, the cooperation of the national geodetic authorities and geodetic institutes has led to the proposal for a *Nordic Geodetic Observing System* (NGOS) with the goal of providing geodetic infrastructure that serves the needs of scientific and nonscientific users in the Nordic countries as well as a component of GGOS.

Towards a modern geodetic reference frame: A modern geodetic reference frame supporting precise point positioning consists of

- a highly accurate, global geodetic reference frame based on a sufficient number of multi-technique tracking stations (e.g., ITRF);
- a service providing satellite orbits and clocks as well as Earth rotation parameters of high quality and long-term consistency in the global reference frame;
- a national or regional three-dimensional reference frame with coordinates fixed to a common epoch (e.g., EUREF89);
- a highly accurate geoid model;
- a velocity model and transformations between the time-dependent global reference frame and the fixed national reference frame.

Nationally, the classical geodetic reference frame is focused on relative positioning, and this frame is in its final phase of establishment. The new monitoring part required for the maintenance of the global reference frame and the satellite orbit and clock service, the determination of the transformation between global and national reference frames, and the construction of the required geoid model, is under development. The Geodetic Institute has made significant steps towards the full implementation of the necessary infrastructure, but if this development is not continued, the geodetic infrastructure is likely to be insufficient to meet the increasing user requirements in terms of accuracy and access to the reference frame in the near future.

In particular, the national geodetic services that give access to the reference frame are not developed sufficiently and do not facilitate the exploitation of the full economic potential of the space-geodetic techniques on a national level. This includes access to transformations between ITRF and the national EUREF89, as well as a user-oriented service for the determination of coordinates in EUREF89 based on precise point positioning.

National contributions to global and regional programs are necessary: International cooperation and national contributions are mandatory for the maintenance and further development of the global reference frame, which is particularly expected through the establishment of GGOS. GGOS is based on national contributions provided according to best effort of the relevant institutions. Without nations contributing sufficiently, there would be no GGOS and no ITRF.

Considerable research and development are required over the next decade in order to improve particularly consistency and long-term stability of the ITRF. The Geodetic Institute is contributing to these international activities, and, for a modern, knowledge-based and open society, it is highly recommended that these contributions be continued at the same or a higher level. Participation in international geodetic research helps to ensure that the national infrastructure and products are of appropriate quality to meet the user requirements, and that the outputs of the global system are available for national interests.

The geodetic infrastructure is increasingly used for Earth observations purposes and supports research in the field of Earth sciences, in particular, global change and climate-related research. The NNGI contributes to the global observing systems established under the *United Nation's Framework Convention on Climate Change* (UNFCCC). The further development of the NNGI should aim to maintain and eventually increase its contribution to the global observing systems.

The Geodetic Institute contributes in several areas to international programs in geodesy and Earth observations. The fundamental station in Ny-Ålesund contributes to the *International VLBI Service* (IVS), the IGS, the *Global Sea Level Observing System* (GLOSS), the *European Sea Level Service* (ESEAS), the *International DORIS Service* (IDS), and the IERS. Data from the GPS sites in Ny Ålesund and Tromsø are delivered to IGS on a daily basis, but a station in southern Norway is lacking (e.g., Trysil and/or Tregde). Four permanent GPS sites contribute their data to EUREF. Four tide gauges are co-located with nearby permanent GPS stations and deliver the data to ESEAS and GLOSS.

Products are contributed in the frame of the *Global Geophysical Fluid Center* (GGFC) of the IERS, where the Geodetic Institute hosts the web site of the *Special Bureau for Loading* and routinely produces a number of products for the global space-geodetic community that help to improve the ITRF and precise point positioning. For the ESEAS, the Geodetic Institute hosts the *Central Bureau* and the main part of the ESEAS web site, giving access to the European sea-level database. These high-level contributions, which require considerable research and development, have an important benefit for Norway in terms of developing and maintaining excellence in the field, which allows participation in internationally funded research projects.

International organizations such as GLOSS, IVS and IGS have indicated that, considering the specific geographical location and extent of Norway and the areas administrated by Norway, a greater contribution to the global geodetic infrastructure would be appropriate. The Reference Document for the Ten Year Implementation Plan for GEOSS emphasizes the cost-benefit principle, according to which countries having a large benefit from the global observation networks should contribute with infrastructure not only in their own territory but also outside. Norway, which extends far into the Arctic region and has considerable offshore activities, is such a country having a high benefit from the global cooperation. Therefore, an effort should be made to close at least the significant gaps in the NNGI within the Norwegian territory including the areas administered by Norway, such as Jan Mayen, Bjørnøya, and Drowningen Maud land. Permanent GNSS tracking stations and modern tide gauges in these locations would close crucial spatial gaps in the global networks. Moreover, data availability with low latency or in real time is increasingly important, and the NNGI should therefore aim at low latency data provision where appropriate.

Contributions to the development of geodetic techniques: The Geodetic Institute has contributed over the past to the development of new and the improvement of existing space-geodetic techniques. In particular, the Geodetic Institute has contributed to Galileo, the upcoming European GNSS. The engagement of the Geodetic Institute in research directed towards improved technologies on the one hand helps to ensure that these technologies are developed for the best benefit of the users, in particular those in high latitude regions, and on the other hand ensures that the expertise of the Geodetic Institute is leading edge and appropriate for the maintenance of a NGRF that would meet the future requirements of its users.

National center of excellence in geodesy: Geodesy is developing into a field that, for maximum societal benefit now and in the future, requires a high level of expertise in theoretical geodesy and the use of the space-geodetic techniques for determination and maintenance of the reference frame, positioning, and monitoring. This includes a deep understanding of the dynamical processes in the Earth system, which affect the three fundamental geodetic quantities and, consequently, any reference frame and positioning. The technical development and the increasing user requirements in terms of availability, accuracy and long-term stability of positioning puts a high demand on top-level expertise in the field, which currently is not satisfied on national, regional, and global levels.

Considering the fundamental role of the reference frame and positioning for a large part of the economic activities in a modern society, there is a strong need for a center of excellence that can support a wide range of users in getting appropriate access to the reference frame and full benefit from the technological development in geodetic techniques. One key contribution of such a center would be a service that allows easy access to highly accurate positions in the NGRF.

In Norway, the Geodetic Institute is in fact the national center of excellence in geodesy. This role is visible in the considerable contribution to the science of geodesy on national, regional, and international levels. The Geodetic Institute should maintain and strengthen this position and continue to participate in national and international research projects. Increased cooperation with universities on national and international levels is important in this context.

Internally, the Geodetic Institute has available all of the main elements that are required for the user oriented service mentioned above. However, the actual service that provides access to the reference frame and allows for precise point positioning with high accuracy for nonexpert users is not established.

Infrastructure for geodetic monitoring: The NNGI currently consists of a nested set of networks, with the fundamental station in Ny-Ålesund on the top, and the network of local markers for geometry

(Landsnett), height (leveling network) and geopotential (relative gravimetry) on the bottom. Considering the extent of the Norwegian territory and the situation in the neighboring countries, a second fundamental station in the southern half of Norway is considered necessary, with Trysil being the most promising candidate. Moreover, the national permanent GNSS network, which today has nearly 50 stations, though mainly in concentrated in southern Norway, has large geographical gaps. Highest priority should be given to the closing of the gaps in northern Norway. The densification of the monitoring network through the episodic 4-D points is consider appropriate with 60 to 100 points being re-observed every three to five years.

The infrastructure for gravimetry (absolute, relative, and continuous observations) needs overall revision and implementation in a consistent conceptual frame.

The current tide gauge network along the coasts of the mainland is mostly of high quality, but there are several major gaps in other geographical regions such as Jan Mayen, the high Arctic (Svalbard and Bjørnøya), and Antarctica. In these remote areas, the co-location of modern tide gauges with GNSS receivers would constitute a very relevant contribution to the global sea-level observing system and the IGS tracking network.

In cooperation with other national institutions, the geodetic infrastructure needs to be developed for commercial and nongeodetic applications in order to utilize national infrastructure optimally. Examples are the co-location of stations with other monitoring sites, the low-latency suport of surveying, the meteorological application of GNSS, and time transfer.

Recommendations for the further development of the infrastructure and its applications: For the immediate future, a set of recommendations can be distilled that, if implemented, would improve the current situation significantly:

- Utilize Ny Ålesund's unique location for a cost-efficient network on the Northern Hemisphere and develop the observatory to one of the required 30 to 40 fundamental stations in the world as Norway's central contribution to the fundamental part of the global reference frame.
- Equip the Trysil station with satellite laser ranging equipment and continuous gravity observations and thus develop this site into a fundamental station for the height reference in southern Norway and Scandinavia.
- Improve the knowledge about local variations in the strain and velocity field on land by improving the network of permanent GNSS stations by, among others, utilizing the permanent stations for real time services and ensuring that these stations meet the geodetic requirements.
- Improve the knowledge of the open ocean areas by establishing permanent GNSS and ESEAS-type of stations, with Jan Mayen and Bjørnøja being primary locations, and provide the data to relevant global observing systems.
- Improve efficiency in data collection in particular in the open ocean areas by, among others, establishing better cooperation with the Coast Guard and the operators of arctic stations.

Consequences of an insufficient development of the current activities: The present monitoring activities of the Geodetic Institute are nearly at an appropriate level to ensure today and in the near future a NGRF satisfying the requirements of most users. However, considerable work is required to improve the geoid model in order to allow the determination of accurate heights in the NGRF with GNSS, particularly on the basis of precise point positioning. There is also some room for improvements, in particular in the network of fundamental stations and permanent GNSS tracking stations both for the contribution to ITRF and in the national network. If these spatial gaps are not closed or if the present infrastructure is reduced, the transition to precise point positioning would be delayed or impossible to achieve, particularly for the emerging applications with high accuracy requirements. The contribution of Norway to the global reference frame would be insufficient with noticeable effects on the accuracy of the ITRF particularly at high latitudes. Norway would still be able to benefit substantially from using the ITRF and space-geodetic techniques for major economic activities (in particular, offshore), but without returning appropriate support to the international community maintaining the ITRF. Norway, with potentially very large impact of climate change, would also be able to benefit from the global effort in Earth observation, but again without a substantial contribution. Moreover, the NGRF and the NNGI would fall behind the development in other comparable European countries. Norway would therefore not have the same potential for more efficiency in positioning, monitoring, and process control that other European countries aim to utilize in the near future. Among other consequences, this would reduce the lifetime of the present NGRF and induce considerable costs for updating the NGRF in the near future. Thus, not closing the present gaps in the geodetic infrastructure (including those in the available expertise) or even reducing the level of activities, almost certainly will lead to considerable societal and economic costs.

The societal prospects of space geodesy: The technological development facilitated through the new space-geodetic techniques for navigation and positioning will bring new and difficult challenges and continuously increasing requirements in terms of accessibility, accuracy and long-term stability of the geodetic products. Therefore, the geodetic institution in a modern society has to be a center of excellence not only in the classical fields of geodesy but also in Earth system dynamics.

The rapid development towards satellite-based and particularly precise point positioning enables a wide range of position-related applications. The new geodetic technologies will lead to tremendous changes not only in all areas of traffic and transport, but also for application in process control (e.g., precise farming, construction, mining, resource management), monitoring of infrastructure (e.g., offshore platforms, reservoirs dams, bridges), surveying and mapping (including offshore), and Earth observation. Geodetic techniques are crucial in the assessment of geohazards and anthropogenic hazards, and they will play a pivotal role in early warning systems for natural and anthropogenic hazards and disasters. The result of these changes will be increased security, a better use of resources, and progress towards sustainable development.

The Geodetic Institute has to be the national center of excellence in geodesy in order to live up to its responsibility for a national geodetic infrastructure and a national geodetic reference frame able to meet the user requirements now and in the future.

1 Introduction

1.1 Objectives of the study

The Norwegian Mapping Authority has the mission to provide a geodetic reference frame that meets the requirements of a wide range of users in a modern society with specific needs in terms of positioning, monitoring, and navigation. Moreover, the national geodetic infrastructure maintained by the Mapping Authority is to contribute to international Earth observation programs in the frame of the country's international obligations and commitments.

Traditionally, geodesy has served society with the provision of a reference frame for a wide range of practical applications ranging from regional to global navigation on land, the sea, and in the air, over building of roads, bridges, tunnels, and railroads, to the determination of reliable boundaries of real estate property. Many scientific applications depend on detailed knowledge of the Earth's shape, its gravity field and rotation, and in the past, geodesy has with ever-increasing accuracy provided the necessary observations, products and information. The fairly recent advent of space-geodetic techniques has brought about a rapid development in global geodesy, particularly during the last decade. Today, the techniques facilitate the measurement of changes in the geometry of the Earth's surface with accuracy of millimeters over distances of several 1000 km. Moreover, the *Global Navigation Satellite Systems* (GNSS) provide access to a global reference frame with an accuracy in precise point positioning of down to 1 cm.

On the user side, this technological development has stimulated new applications demanding even better accuracy and, even more so, better access to geodetically determined positions. On local to regional scales, applications such as land surveying, monitoring of infrastructure, prevention and mitigation of impacts of environmental hazards, and numerous technical applications require today nearly instantaneous access to geodetic positions in a reliable reference frame with centimeter accuracy or better. Already today, the economic benefit of the geodetic reference frame is enormous. A recent study in Canada (Williams et al., 2005) estimated that uses of the geodetic reference frame contribute 6% to 9% of the *Gross Value Added* (GVA). Considering the distribution of economic activities in Canada and Norway, a similar or even higher fraction can be expected in Norway. And this fraction is very likely going to increase in the future: In particular, the emerging combination of broadband communication, georeferenced databases, and easily accessible accurate positioning can be expected to facilitate many new applications and services that will transform the society and lead to an increasing dependency on the geodetic foundation, that is, the geodetic reference frame including easy access to this frame in the form of accurate positions (fig. 1).

The biggest challenge for geodesy, however, may arise from the recent development in global Earth observation. Stimulated by the international quest for sustainable development and the resulting demand for information on the state and the trends in the Earth system (GEO, 2005a), the need for comprehensive Earth observations is acknowledged in the extensive programs of the United Nations, the European Union, and the international community, which culminated in the establishment of the *Group on Earth Observations* (GEO) at the *Earth Observation Summit III* (EOS-III) on 16 February 2005 in Brussels, Belgium (see Section 2.1). GEO has the task to implement the *Global Earth Observing System of Systems* (GEOSS), with the vision for this system "*to realize a future wherein decisions and actions for the benefit of humankind are informed by coordinated, comprehensive and sustained Earth observations and information*" (GEO, 2005a).

The fundamental geodetic quantities are the shape of the Earth, the Earth's gravitational field, and the Earth's rotation. Geodesy determines these quantities and observes their changes in time and space. Setting up the *User Requirements* (UR) for observations and products related to all three geodetic quantities is an important step towards a specification of a national geodetic infrastructure required to ensure a sufficient reference frame for both scientific and nonscientific applications as well as to contribute realistically to international programs and activities directed towards global Earth observation. The key societal benefit areas of Earth observations as identified by the *Earth Observation Summit II* (EOS-II, see Section 3.3) are a reasonable starting point for the determination of the URs. Based on these URs and the resulting system specifications, an assessment of the global as well as national infrastructure in Norway can be carried out.

The main objective of the report is to specify the observational infrastructure required both on global, regional and national level in order to meet the URs. Particular emphasis is on meeting the requirements of users on a national level. A further focus is on

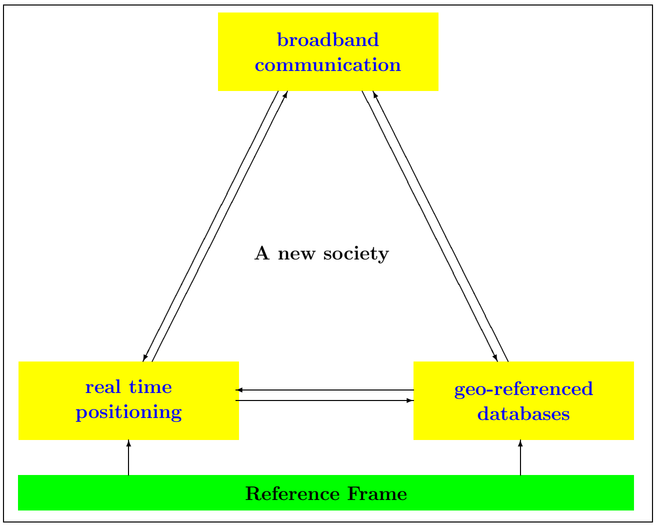

Figure 1: The geodetic reference frame as the foundation of emerging services.

It is expected that the combination of broadband communication with georeferenced databases and accurate positioning in real time will have an enormous influence on many areas in society, including but not limited to transport, surveying, navigation, mobility, security, environment, outdoor activities, science, and Earth observation. It is of fundamental importance that all databases and positioning can be related to the same underlying reference frame and that this frame be maintained with sufficient accuracy.

the Norwegian contribution to European and global programs for Earth observations. Of particular importance is the global infrastructure required for the *Global Geodetic Observing System* (GGOS, see Section 2.3), which is currently implemented by the *International Association of Geodesy* (IAG). IAG developed the idea of GGOS (originally named *Integrated Global Geodetic Observing System*, IGGOS, see e.g., Rummel et al., 2002) over the last eight years, in response to the increasing requirements from users in scientific and nonscientific fields. Therefore, it is also a goal to identify the main Norwegian contributions to GGOS and the infrastructure required to ensure this contribution.

A deep understanding of the complex Earth system is a basis for the development of strategies for a sustainable management of the planet and the protection and preservation of its environment and climate for future generations. Considering the particular geographical location of Norway with its proximity to the North Atlantic and Arctic Oceans and the entailing vulnerability to severe impacts of changes in the ocean circulation and the climate, it is obvious that Norway will benefit greatly from the ongoing global efforts in Earth observation. Consequently, it is assumed here that Norway, as a partner in the global community, will provide its share of Earth observation and contribute relevant infrastructure in and outside of Norway (as is demonstrated by the recent Norwegian effort to support a hazard warning system for the Indian Ocean). GEO (2005b) has emphasized the importance of a cost-benefit sharing mechanism, under which countries having demonstrated benefit through global Earth observations should support infrastructure in regions outside their territory, particularly if the local governments are unable to provide the necessary resources. Therefore, the present report also identifies serious gaps in the geodetic Earth observation systems that do not directly fall into the region and responsibility of Norway.

Within the context of the rapid development, which on the technical side provides new capabilities and on the users' side poses new requirements, it is timely to thoroughly examine the users' needs as well as the characteristics of the geodetic quantities to be observed. In a subsequent step, these URs and the characteristics of the observables can be used to design a geodetic observing system that would ensure that the users' needs are met today as well as in the near future. These system specifications provide a solid basis for the assessment of the actually available infrastructure, the identification of gaps, and recommendations on which of these gaps should be addressed.

1.2 Definition of the problem and approach

Driven by the rapid development of new space-geodetic techniques leading to a transition, if not a revolution, in the geodetic methods and capability, and to a wide range of new applications having specific requirements for geodetic observations and products, the national geodetic infrastructure in most of the more developed countries has gone through an equally rapid development in the last decade. In combination, these national efforts have led to a dramatic change in the global geodetic infrastructure.

But is this infrastructure on global, regional, and national level appropriate in order to produce the observations and products required to meet the wide range of user requirements now and in the near future? And if the answer is no, what are the steps to be taken that would lead to a noticeable benefit? These are the two questions to be answered here.

The approach used to answering these questions

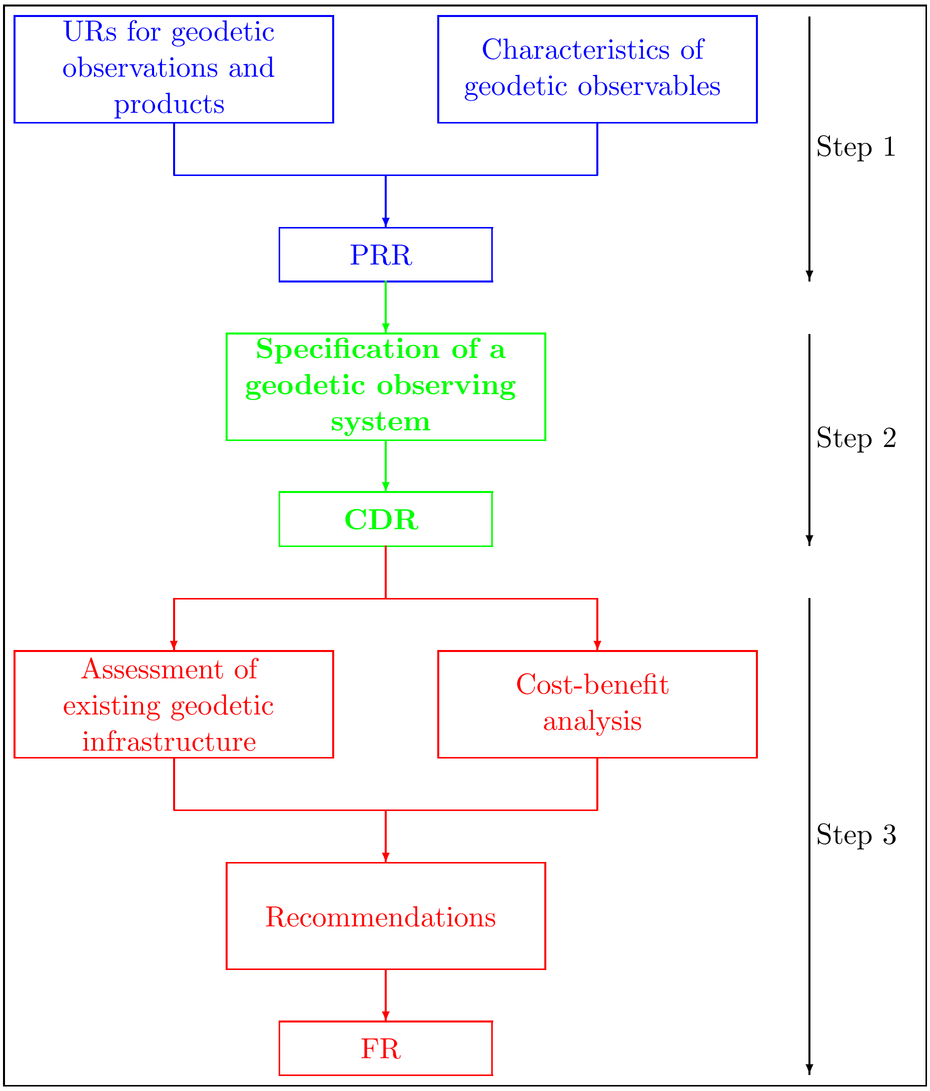

Figure 2: Overall study logic.

PRR is the Preliminary Requirement Review, CDR the Critical Design Review, and FR the Final Review.

was based on three main steps (fig. 2):

- **Consolidation:** The first step had two goals (1) to set up URs for geodetic observations and products (in particular, a geodetic reference frame), both on a global level in the context of Earth observations and on regional and national levels for a wide range of scientific and nonscientific applications, and (2) to describe the temporal and spatial characteristics in changes of the three fundamental geodetic quantities and to relate these characteristics to the presently available observational techniques. Focus was on the review of existing documentation concerning URs and the description of the characteristics of the fundamental geodetic observables. This phase concluded with the *Preliminary Requirements Review* (PRR).

- **System specification:** The second step had the goal to specify a geodetic observing system in terms of its functions and infrastructure on national level, taking into account the required global and regional components, which would be able to meet most of the URs. The end point of this step was a *Critical Design Review* (CDR).

- **Recommendations:** The third step had the goal to provide recommendations for specific actions to maintain and, where necessary, to improve the national component of the geodetic observing system and its service for national, regional and global users. These recommendations were derived on the basis of an comparison of the system specification to the actually available geodetic infrastructure and the products currently made available to the users, as well as the determination of a cost-benefit relation for the maintenance and, if necessary, improvements of the geodetic observing system. This step was concluded in the *Final Review* (FR), where the main focus was on these recommendations.

The two questions posed above cannot be answered without a detailed knowledge of the URs for the wide range of existing and emerging applications that require access to positions or knowledge about the state and trends in the Earth system. The study of the URs for geodetic observations and products has to address three key areas, namely

- **Earth observation for sustainable development**, which includes a global component that allows the derivation of information on all spatial scales from global to local and from short time scales of warnings for extreme events and disasters to long-term predictions to ensure sustainable development;
- **scientific applications** that study the Earth system on all spatial and temporal scales; and
- **nonscientific applications** including surveying on land and in the ocean, mapping of the Earth's surface, steering of processes, monitoring of infrastructure and environmental parameters, and navigation.

In order to elucidate the background for the description of the URs more, in the following we comment of these three key areas in more detail.

The goal of Earth observations can be pictured as a contribution to the global 'cockpit' of the Earth system, a cockpit with the necessary instruments that provide the information required by the 'pilots', that is the politicians, governments, and decision makers in general, in order to keep the spaceship Earth on a sustainable course. In this context, sufficient information concerning the state and the trends in the Earth system are required as a basis for decision-making. In many cases, these observations require a global, highly accurate reference frame, and the requirements for such a frame are increasingly more demanding. Moreover, maintaining a global reference frame on a dynamic Earth with the accuracy and stability required for many applications is a demanding task, which can only be solved based on a consistent set of observations of all three fundamental geodetic quantities.

In the frame of the *ad hoc* GEO and the *Global Monitoring for Environment and Security* (GMES) program of the European Commission, the URs for observations in many fields have been compiled in various documents. However, none of these documents provides a comprehensive overview of the requirements for observations of the three fundamental geodetic quantities and the main products derived from these.

Many scientific applications require access to a highly accurate and long-term stable reference frame in order to monitor changes in the Earth system parameters or to position sensors. Moreover, understanding the dynamics of the Earth as expressed in its rotation, the mass transport in the Earth system as evidenced by changes in the Earth's gravity field and its shape, as well as processes in the solid Earth as documented by deformations of the solid Earth's surface, requires highly accurate observations of the fundamental geodetic variables. After three decades and an increase in accuracy of more than three orders of magnitude (Chao, 2003), the space-geodetic techniques are able to observe the integrated mass transport in the Earth system as well as the dynamics of the system and the kinematics of the surface with unprecedented accuracy. Therefore, the integration of GGOS into GEOSS is timely and of crucial importance for scientific progress. The integration of the geodetic observations into an integrated database serving science will help to facilitate the improvement of a comprehensive Earth system model (fig. 3). Not least, such an integrated system approach is required for contributions of Earth sciences to achieving sustainable development (Rotman, 1998).

In servicing society, geodesy contributes to the efficiency of society, which is a prerequisite for a sustainable development. The increasing societal demand for highly accurate positions also puts more demanding requirements on the national geodetic infrastructure used to maintain a national or regional reference frame for positions. In particular, it is often required to relate one positions to another over time (monitoring and process control), which puts high demands on the temporal stability of the reference frame. Better tools and an improved methodology for access to the reference frame are also needed. However, no comprehensive overview of the URs taking into account the societal and technological development over the last few years appears to exist.

A key geodetic contribution to all the areas mentioned above is an accurate, long-term stable, and easily accessible reference frame as a backbone for all positioning. Once more, it is emphasized that such

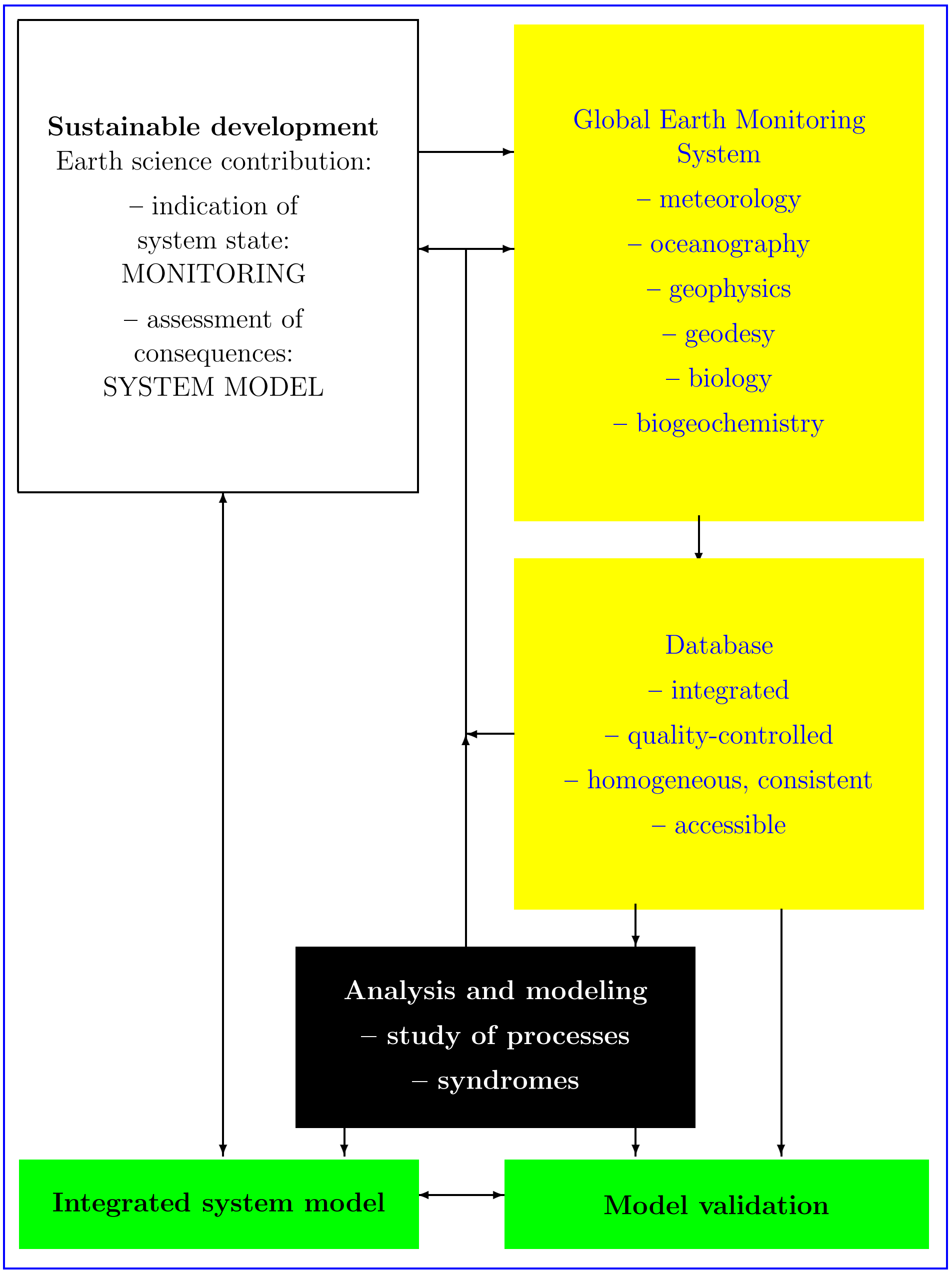

Figure 3: Integrated view on Earth observation and modeling for sustainable development.
Sustainable development requires input from Earth sciences both with respect to the state of the Earth system and the assessment of impacts. Crucial components required to provide this input are a global Earth monitoring system, and an integrated database of the observations. The latter serves science for studies of processes and syndroms (e.g., Schellnhuber et al., 1997; Schellnhuber, 1998) as well as for validation of models.

a reference frame can only be maintained and made available through an observing system such as the GGOS.

It also needs to be pointed out that the space-geodetic infrastructure has other, nongeodetic applications. In particular, GNSS ground station networks can be used to sound the atmosphere and ionosphere and to derive *Integrated Precipitable Water*

Vapor Content (IPWV) and *Total Electron Content* (TEC), respectively, from the observations. The former is relevant for numerical weather prediction and climate monitoring (e.g., Elgered et al., 2005), while the latter is of importance for navigation and communication. In order to exploit the infrastructure optimally, we will also consider the URs for these potential collateral products of the geodetic infrastructure.

Space-geodetic infrastructure, in particular GNSS, is also utilized for time and frequency transfer. In fact, the basic measurements in space geodesy are time measurements. Nevertheless, this report does not address these applications, as they are not relevant for the specific case of the national geodetic infrastructure, for which no time and frequency-related applications are envisaged.

1.3 Organization of this report

In the next section, we first give a general overview of the substantial contribution of geodesy to Earth observation and societal activities in general. This section also describes the background in Earth observation and briefly reviews the relevant development in geodesy over the last two decades with focus on the introduction of GGOS. Section 3 then addresses on the requirements for these contributions from a user's point of view. The URs for a wide range of applications are specified in terms of required quantities, accuracy, latency, and temporal and spatial resolution. The URs are grouped according to the three key areas identified above, namely Earth observation, scientific applications, and nonscientific applications. Applications range from maintenance of a reference frame as a general utility, land surveying, process control, monitoring of infrastructure, georeferenced databases, determination of natural and anthropogenic hazards to monitoring of mass transport and the dynamics of the Earth system, including the water cycle, atmospheric dynamics and sea level variations. For that, a number of existing documents including but not limited to the relevant documents produced in the frame of IAG, the *Integrated Global Observing Strategy* (IGOS), the *Three Global Observing Systems* (G3OS), GMES, GEO, *International Earth Rotation and Reference Systems Service* (IERS), GGOS, and *Nordic Geodetic Commission* (NKG) have been reviewed.

Section 4 is devoted to the description of the characteristics of the three fundamental geodetic quantities. Focus is on the temporal and spatial variations, the magnitudes, and the status with respect to modeling these variations.

Based on the URs and the knowledge of the characteristics of the geodetic quantities, specifications for a global geodetic observing system and the national geodetic infrastructure meeting the accuracy, latency and resolution requirements are derived in Sections 5 and 6, respectively. The specifications are given in terms of functional requirements, spatial network geometry, and products to be delivered. In Section 7 the system specifications are used to assess the existing geodetic infrastructure on global and regional level as well as the national level in Norway.

The cost-benefit analysis reported in Section 8 forms the basis for the identification of serious gaps in the NNGI and the products made available. The main conclusions are summarized in Section 9 before we in Section 10 give specific recommendations and priorities for the further development of the NNGI and NGRF.

2 Earth observations and geodesy

2.1 Recent developments in Earth observation

Sufficient monitoring of the Earth system is one of the cornerstones required to ensure sustainable development (see fig. 3 on page 18). The last two decades have seen the emergence of many global or regional programs and activities directed towards monitoring of the environment. However, until very recently, monitoring the Earth system was strongly subdivided and organized according to disciplines and subsystems. A major disadvantage of this lack of integration was the nearly complete absence of the integrated data sets required for the study of system processes. Consequently, science programmes or projects aiming at a better understanding of system processes were, and currently often still are, forced to build up such integrated databases first.

Currently, the monitoring system is still characterized by a number of sub-networks with spatial and temporal heterogeneities and with a lack of coordination and cooperation across disciplinary boundaries. The ground-based component consists of meteorological, hydrological, oceanographic, geophysical, geodetic and chemical networks, with the number of operational stations varying in time. Additionally, a significant amount of data is collected in campaign-type measurements at varying time intervals and locations. All of these sub-networks produce data sets which are inhomogeneous due to spatial and temporal heterogeneities in the station distribution, and due to variations in the observation procedures including the sensors and recording equipment. Problems due to these inhomogeneities are exemplified in Ellsaesser et al. (1986) using the station temperature observations at land and sea sites. For a sustainable monitoring, the problem of long-term homogeneity is a crucial one.

Over the last two decades, a strong spaceborne component has been introduced into the monitoring. The nearly complete coverage of most of the remote-sensing satellites has greatly improved monitoring and opened new doors to the understanding of system processes. However, in terms of sustainable monitoring, the limited life time of the satellites and sensors, and the high costs of most of the missions, are severe limitations likely to introduce temporal heterogeneities into the data sets. Spaceborne sensors require a long planning phase. The high risk during launch easily can introduce significant gaps if a launch turns out to be unsuccessful, like the recent launch of CryoSat. In many cases, only single sensors exist, and the danger of processing errors and misinterpretation is high (for two recent examples see Nerem et al., 1997; Dickey et al., 2002, with the former demonstrating an error in TOPEX/Poseidon processing, and the latter a misinterpretation of LAGEOS-derived changes in the Earth's gravity field).

Major early milestones towards more integration of the observing systems were the definition of the IGOS, and the establishment of the G3OS in the context of the *United Nations Framework Convention on Climate Change* (UNFCCC). Initially, IGOS was of particular importance within Earth monitoring based on remote sensing (see, e.g., Williams & Townshend, 1998), and it was developed in the framework of the G3OS (see, e.g., Dahl, 1998). The drivers for IGOS are the scale of the issues (global climate change, sustainable development) to be addressed, the cost of space components for remote sensing of the Earth environment, the logistics especially for *in-situ* data, and the need for data integration from multiple sources for products of use to decision makers, science, and society at large. For key variables of the Earth system, IGOS attempts to provide long-term continuity, adequate data archives, accessibility, consistency of data records, and the ancillary data required for data quality assessment. IGOS provides the framework for a coherent response of the monitoring system to the integrated user requirements. Under IGOS, an operational system guaranteeing the long-term continuity of observations to support scientific research can be achieved. IGOS intends to build upon existing strategies for international observation programs, focusing on the identification of areas where the existing systems can be improved, where duplication of observations can be reduced and gaps in observations and data sets can be identified. Moreover, IGOS facilitates improved high-level product developments and capacity building in developing countries. Thus, if effectively implemented, IGOS appears to be the strategy for providing the observational basis for a future Earth information system. A key issue identified in IGOS is the need to transform many observational activities from a research state into operational monitoring.

In 1998 the further development and implementation of IGOS was put into the frame of the *Integrated Global Observing Strategy Partnership* (IGOS-P) (see, e.g., Smith, 1998, for the early development of IGOS-P). IGOS-P is a partnership of organizations that are concerned with global environmental change issues. IGOS-P links research, long-term monitoring, and operational programs. IGOS-P seeks to provide a comprehensive framework to harmonize the common interests of the major space-based and *in situ* systems for global observations of the Earth. Its aim is to provide an over-arching strategy for conducting observations relating to climate and atmosphere, oceans and coasts, the land surface and the Earth's interior. The Partners, through IGOS, build upon the strategies of existing international global observing programs, and upon current achievements, in seeking to improve observing capacity and deliver observations in a cost-effective and timely fashion.

Main efforts are directed to those areas where satisfactory international arrangements and structures do not currently exist. The goal of IGOS-P is a small number of so-called Themes with strong linkages to critical societal issues. The process of Themes selection is based on an assessment of the relevant scientific and operational priorities for overcoming deficiencies in information, as well as the analysis of the state of development of relevant existing and planned observing systems. Currently a number of Themes exist or are in the planning with most of them depending heavily on geodetic observations and products (see Section 3.4 on page 31).

In the frame of the G3OS, a number of global and regional subsystems have been established over the last decade. Relevant examples are the *Global Sea Level Observing System* (GLOSS) as a parameter-focused component (see IOC, 1997) of the *Global Ocean Observing System* (GOOS). GOOS is implemented through regional initiatives, such as Euro-GOOS, which develop their own specific operational and scientific agendas (see, e.g., Prandle & Flemming, 1998). Another example of a parameter-oriented, regional service is the *European Sea Level Service* (ESEAS), which aims at an integrated observing system for local and regional sea level and associated sea level hazards (see, e.g., Plag, 2002).

The last few years have seen a rapid programmatic development in Earth observations on global scale, which partly was stimulated by activities in Europe. There, the GMES initiative was launched in May 1998 and adopted by ESA and the EU Councils in June and November 2001, respectively. The overall aim of GMES is to support Europe's goals regarding sustainable development and global governance by providing timely and quality data, information and knowledge (Commission & ESA, 2003).

Following up the recommendations of the Johannesburg conference, EOS-I was held in Washington, DC, in July 2003. This summit initiated an unprecedented global effort towards coordination of global Earth observation. Through its declaration (see Annex 1 in GEO, 2005b), EOS-I established the *ad hoc* GEO with the task to draft a 10-year Implementation Plan for the GEOSS. Subsequently, this *ad hoc* GEO met six times, and, supported by several Subgroups, drafted the requested plan (GEO, 2005a) together with a reference document containing many details of the vision for GEOSS (GEO, 2005b). The work of GEO was guided by the Framework document adopted by EOS-II in Tokyo in April 2004 (see Annex 2 in GEO, 2005b, for the full text). This Framework document identifies nine major societal benefit areas of Earth observations and in that strongly underlines the importance of coordinated global Earth observations. The Implementation Plan was adopted by EOS-III, which took place in February 2005 in Brussels. It is noted here that by then, the membership in the *ad hoc* GEO had grown over the less than two years of its existence from initially about 30 countries to more than 60 countries, and the number continues to grow.

The presence is dominated (and so will be the next few years) by the first steps towards an implementation of GEOSS. IAG is involved in this process in order to ensure that the geodetic observing system is developed consistently with the needs and progress of GEOSS for a maximum benefit.

Summarizing the broad current consensus, we can state that comprehensive monitoring of the Earth system is a crucial prerequisite for sustainable development. The monitoring system needs to be established within the research community and transformed into operational activities. The necessary properties of a sustainable monitoring include long-term stability, homogeneity in time, multi-parameter sites, global coverage and participation, and integrated observation and data sets.

2.2 Contribution of geodesy to Earth observation and other societal areas

The three fundamental geodetic quantities are the shape of the Earth, the gravitational field of the Earth, and the rotation of the Earth. Today, all of these quantities are observed with space-geodetic techniques using a combination of spaceborne and airborne sensors and *in situ* networks. The internationally coordinated geodetic observations result in a global terrestrial reference frame (fig. 4), which is determined and monitored on the basis of observations provided continuously by the global station networks (see Section 7.2.1 on page 77 for a description of these networks). This well-defined, long-term stable, highly accurate and easily accessible reference frame is the basis for all precise positioning on and near the Earth's surface. It is the indispensable foundation for all sustainable Earth observations, *in situ*, as well as airborne and spaceborne.

With the three main geodetic quantities, geodesy precisely observes and consistently monitors the mass movements in the Earth system and the associated dynamics by

- observing and providing the geometric shape of the Earth's surface (solid Earth, ice, and oceans), globally and regionally, as well as its horizontal and vertical temporal variations at time scales from rapid to secular;
- monitoring the variations of the Earth rotation as an indicator of all angular momentum exchange inside, on or above the Earth, as well as of the interaction between the Earth and the Sun and Moon;
- exploring the Earth's gravity field, both the sta-

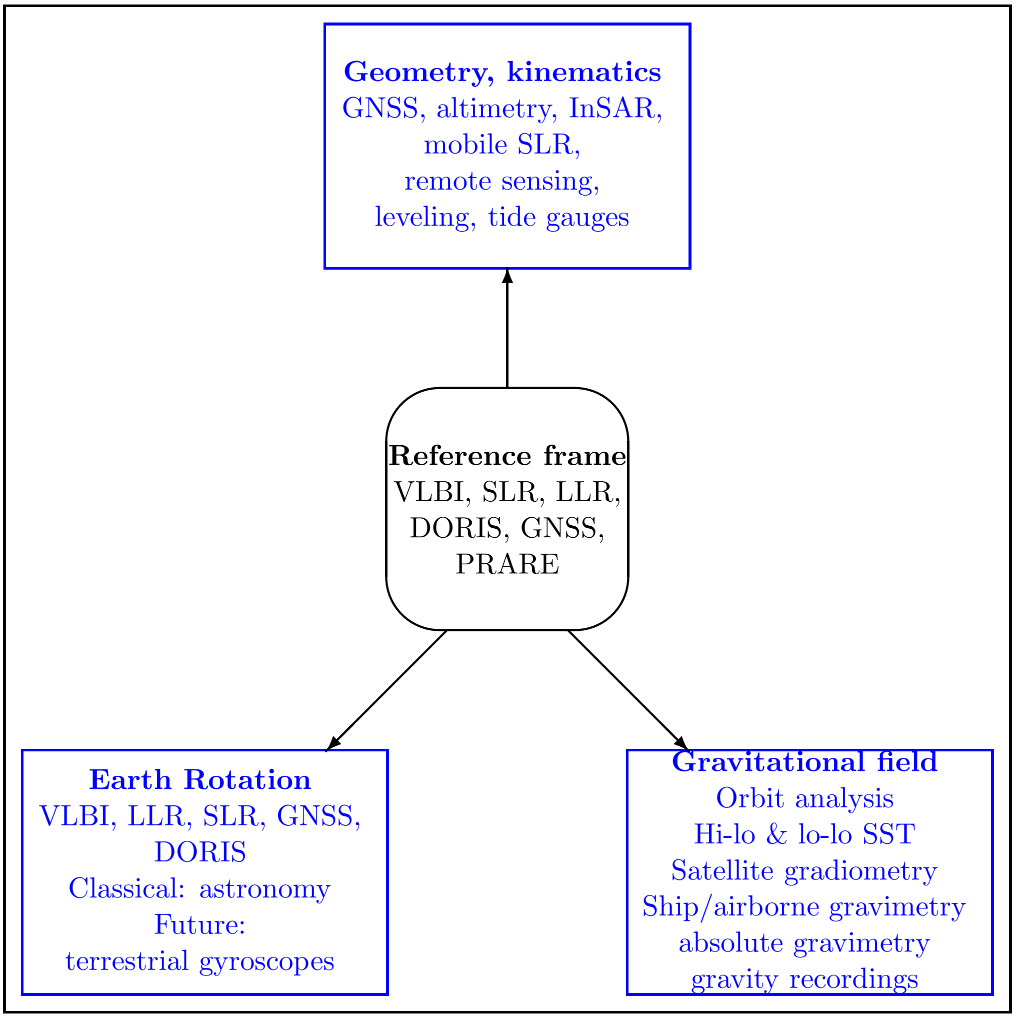

Figure 4: The three pillars of geodesy.

The fundamental geodetic quantities, which define the three pillars of geodesy, are the Earth's shape, gravitational field, and rotation. These quantities and their changes are all intimately related to global terrestrial and celestial reference frames. Today, the space-geodetic techniques are crucial in the determination and monitoring of these quantities and the reference frames. GGOS will integrate all the observational techniques and provide the indicated observations as well as the basis to determine the reference frame with high accuracy, spatial resolution and temporal stability. Modified from Rummel (2000). For an explanation of the acronyms, see the list in Appendix C on page 111.

tionary field and the time variable fields due to changes of mass distribution in the Earth system as a whole including the solid Earth, liquid core, atmosphere, oceans, hydrosphere, cryosphere;

- monitoring the atmosphere, oceans, and cryosphere with space geodetic remote sensing techniques.

In summary, geodesy provides a unique frame for the monitoring, understanding and prognosis of the Earth system as a whole. Modern space-geodetic techniques are inherently strong on global to regional scales and thus constitute an important complement to traditional *in situ* observation systems.

Over the last one and a half decades, the global geodetic networks have provided an increasingly detailed picture of the kinematics of the Earth surface and the temporal variation in the Earth shape. Among others, the observations have been used to determine improved models of the secular horizontal velocity field (e.g., Kreemer & Holt, 2001; Kierulf et al., 2002; Kreemer et al., 2003), to derive seasonal variations in the terrestrial hydrosphere (e.g., Blewitt et al., 2001; Davis et al., 2004), to study seasonal loading (e.g., Dong et al., 2002), to determine surface mass movement (e.g., Wu et al., 2003; Kusche & Schrama, 2005; Wu et al., 2006), and to improve the modeling of the seasonal term in polar motion (Tamisiea et al., 2002; Gross et al., 2004).

The innovative sensor technologies used in the current and planned gravity field missions *Challenging Minisatellite Payload* (CHAMP), *Gravity Recovery and Climate Experiment* (GRACE) and *Gravity field and steady-state Ocean Circulation Explorer* (GOCE) are already contributing to a substantial improvement of the Earth gravity field recovery (e.g., Reigber et al., 2003; Tapley et al., 2004b). In parallel, the altimetry missions, originally with missions such as TOPEX/Poseidon and continuing with ENVISAT, Jason-1, GFO, and ICESat, continue to observe the surface of the ocean and ice sheets with a spatial and temporal sampling sufficient for the determination of the temporal variability with high resolution. Moreover, the envisaged Galileo will add another system to the already now highly accurate GNSS. The integration of all the satellite missions with the existing space-geodetic techniques for the determination of changes in the Earth's shape creates new opportunities to determine and study the mass transport in the Earth system in a globally consistent way.

In addition to the geodetic quantities, the space-geodetic infrastructure is also capable of providing collateral information such as soundings of the atmosphere and ionosphere with the electromagnetic waves of the GNSS. These observations allow, for eaxmple, the determination of the IPWV of the atmosphere and the TEC of the ionosphere, respectively.

Over the last decade, IAG has established a system of services (see Section 7.2.1 on page 77 for an overview), which provide a number of products to a wide range of scientific and nonscientific users. These services have established considerable observing infrastructure, comprising global ground-based networks of observing sites, dedicated satellite missions, data and analysis centers and web sites giving access to the products. Organizationally, these geodetic services are based solely on the voluntary contributions of institutes in many countries, which contribute based on their needs for, and their desire to assure, the collective output.

The relevance of the contribution of geodesy to Earth observations in general is obvious and the fundamental contribution of geodesy is widely acknowledged (e.g., Solomon & The Solid Earth Science Working Group, 2002; Lawford & the Water Theme Team, 2004; Marsh & the Geohazards Theme Team, 2004; GEO, 2005a,b). Moreover, from the list of requirements for geodetic observations and products extracted from the GEO documents (in particular GEO, 2005b, table 2 in Section 3.3), it is clear that geodesy will be a major contributor to GEOSS. This may lead to the impression that geodesy's contribution is already available to and trivial to understand for the Earth sciences community. However, this impression would be wrong.

The establishment of GGOS is an appropriate response to the emerging broad range of scientific and practical requirements with respect to geodesy. By establishing a coherent geodetic observing systems, the user requirements can be met in a consistent and efficient way. This system will provide on a global scale the spatial and temporal changes of the shape and gravitational field of the Earth, as well as the temporal variations of the Earth's rotation (fig. 4). Moreover, the system will provide the observations to determine and maintain a terrestrial reference frame with higher accuracy and much improved temporal stability. On the basis of the observations provided by GGOS, it will be possible to determine mass movements in the atmosphere, the ocean, and the terrestrial hydrosphere as well as in the Earth's interior.

2.3 The Global Geodetic Observing System (GGOS)

GGOS was established through the decision of the IAG Executive Committee at the 23rd IUGG General Assembly, 2003 in Sapporo, Japan. This decision was supported through an IUGG Resolution of the same assembly (see Appendix B.3). The Executive Committee of IAG at its meetings in August 2005 in Cairns, Australia, decided to transform the initial project into a permanent observing system.

2.3.1 Goals, structure and external links of GGOS

The GGOS as proposed by Rummel (2000) and further developed by Rummel et al. (2002) and Beutler et al. (2003) "*aims at maintaining the stability of and providing the ready access to the existing time series of geometric and gravimetric reference frames by ensuring the generation of uninterrupted time series of state-of-the-art global observations related to the three pillars of geodesy.*"

This system will provide global geodetic observations and, more importantly, a consistent set of well defined products derived thereof, with the spatial and temporal resolution required by the entire community of Earth sciences. In particular, GGOS will facilitate the determination and maintenance of a terrestrial reference frame with higher accuracy and much improved temporal stability. Thus, GGOS can be considered as the metrological basis for Earth sciences. On the basis of the observations provided by GGOS, it will be possible to determine mass movements in the atmosphere, the ocean, and the terrestrial hydrosphere as well as in the Earth's interior. In its capability to provide information on the dynamics of the solid Earth and its fluid envelop on all relevant spatial and temporal scales, GGOS is an unique contribution to the Earth monitoring system. However, only a holistic, geodesy-driven approach to the entire Earth system and its dynamics will ensure that geodesy will contribute in an optimum way to Earth sciences in the wider sense.

GGOS aims at integrating the different levels of the geodetic observing systems from ground-based stations as level (1), Low Earth Observing satellites as well as gravity and altimetry missions as level (2), and navigation satellite systems as Level (3), to quasars as level (4) into one consistent system (fig. 5) and at analyzing and interpreting the observations in a consistent Earth system frame. The way to achieve this goal is long and will require considerable developments, both in observational capabilities and physical modeling, including theoretical developments. In particular, the transition from a mainly research-based and science-driven system to an operational, more user-driven system will deserve special attention.

The accuracy level targeted by GGOS, in response to user requirements, for the three fundamental geodetic quantities (and their mutual consistency level) is 10^{-9} or better. At this level of accuracy, a big variety of mechanical interactions between the different Earth system components are relevant and need to be treated consistently. In this respect, modern geodesy requires a system approach to the dynamics of the Earth and involves expertise from all Earth sciences in the analysis and interpretation of the geodetic observations. Partly, this development is brought about by requirements articulated in the Earth observation community. However, since this community is not necessarily aware of what is needed in terms of geodetic observations and products, it also needs stimulation and outreach from GGOS itself.

The internal structure of GGOS is based on the IAG Commissions and a dedicated GGOS Science Panel as the advisory component, the IAG Services as the components responsible for observations and analysis, and GGOS Working Groups for the specific development of GGOS (fig. 6A). Regionally, GGOS will be implemented through regional subsystems, of which some are already under implementation (fig. 6B).

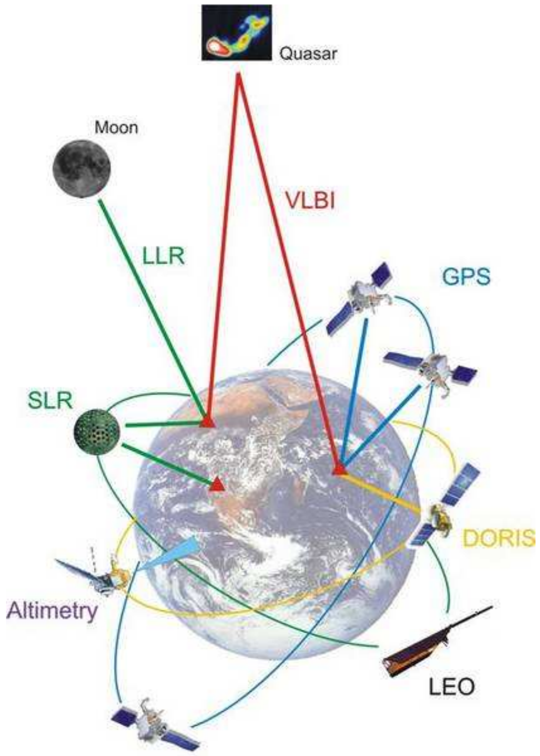

Figure 5: Space components of GGOS.
GGOS will integrate the space-based geodetic infrastructure with global ground-based networks into a consistent global observing system. From http://www.ggos.org. Courtesy by M. Rothacher.

Internally, GGOS will facilitate steps towards fully consistent data processing, which will improve the quality and accuracy of the products made available to internal and external users. Moreover, GGOS will advocate standardization of the products and ensure that the interface giving access to products is fully interoperable with the other systems contributing to GEOSS.

Externally, GGOS is the unique interface of the observing systems maintained by IAG, that provides geodetic observations and products to GEOSS and other users outside of IAG (fig. 6B). IAG is a Participating Organization in GEO, and IAG has delegated the contribution to GEO to GGOS. GGOS is a contributing system of GEOSS. Thus, organizationally, GGOS links GEOSS and other users on the one side and the IAG Services on the other side.

In May 2006, GGOS was accepted as a member in IGOS-P. A proposal for an IGOS-P Theme addressing the dynamics of the Earth system is in preparation (see below). The membership of GGOS

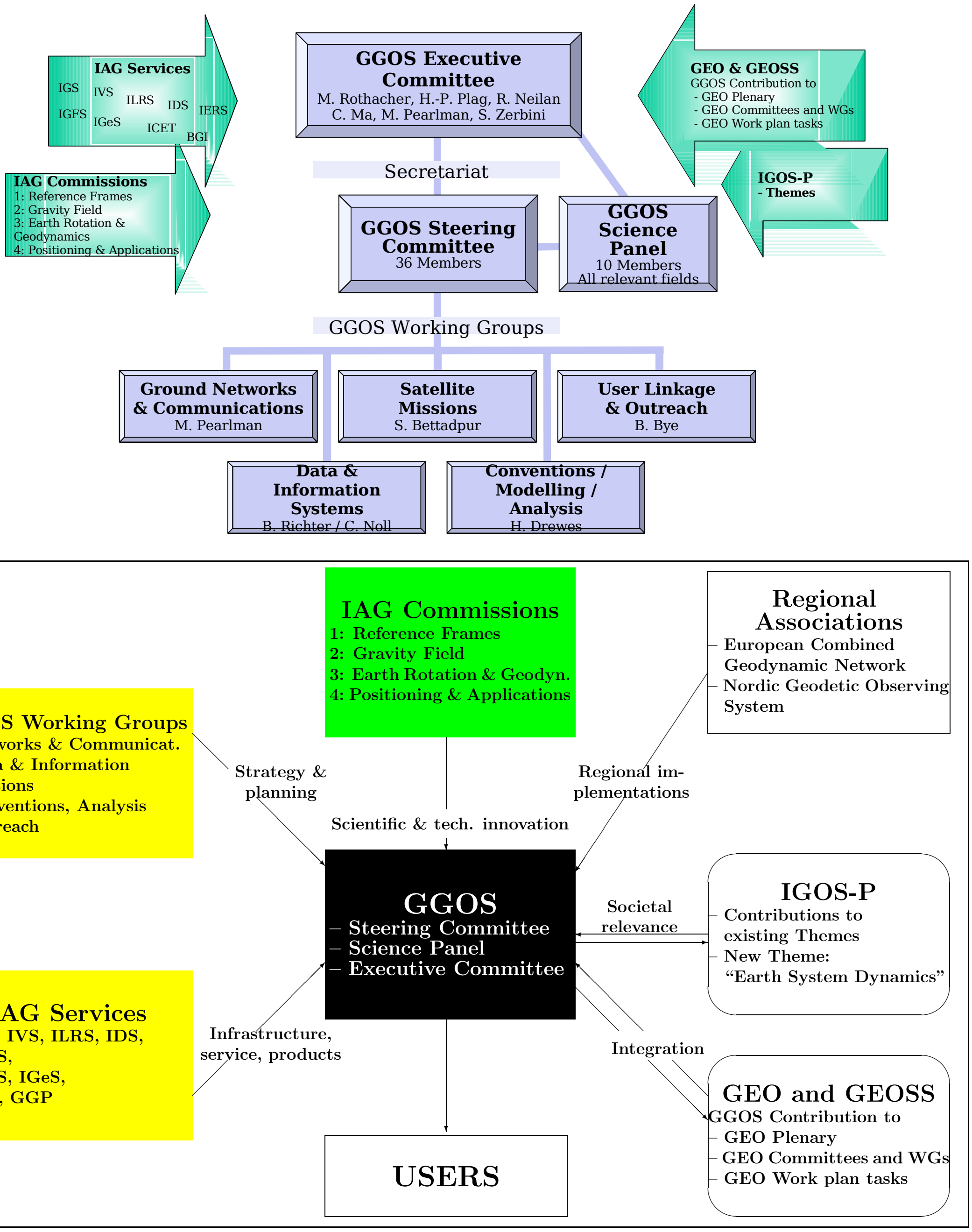

Figure 6: Overview of internal organization of GGOS and its links to external programs. *A (upper diagram): The internal structure of GGOS is based on existing IAG Services and Commissions as well as newly established GGOS Working Groups. B (lower diagram): Externally, GGOS is contributing to IGOS-P and GEOSS.*

in IGOS-P supports the development of GGOS in line with the IGOS and, together with the association to GEO, facilitate a proper linkage between GGOS and other existing and developing Earth observation systems. Moreover, steps are being taken to associate GGOS with an appropriate UN agency.

The implementation of GGOS as a global system will depend on support from the regions. Therefore, emerging regional implementations will be important for GGOS and need to be appropriately integrated.

Considering the development in IAG towards the GGOS, the *European Reference Frame* (EUREF) group has initiated the *European Combined Geodetic Network* (ECGN), which aims to ensure a European network of high-level stations, combining space-geodetic and gravimetric techniques at carefully selected stations. A call for station proposals was issued in 2003 and resulted in nominations for stations in most of the European countries (see http://www.bkg.bund.de/ecgn/ for more information).

The NKG established in 2002 a Task Force with the mission to prepare the concept for the regional implementation of GGOS in the Nordic countries. This group suggested the establishment of a *Nordic Geodetic Observing System* (NGOS) as described in the reference document by Poutanen et al. (2004). NGOS aims to integrate the existing geodetic infrastructure in the Nordic countries into a homogeneous system serving both scientific and nonscientific users and providing an interface for the contribution of this subregion to GGOS, as well as the regional implementation of GGOS.

2.3.2 The science challenge for GGOS

The scientific basis for GGOS is summarized in Rummel (2000), Rummel et al. (2005), and Drewes (2006). In order to foster the implementation of GGOS and to further detail the scientific basis for GGOS, as well as to strengthen its linkage to existing and new Earth observing systems, such as GEOSS, the IAG has taken a first step to propose a specific IGOS-P Theme addressing the dynamics of the Earth system from a focus on mass movements. In order to understand the necessity for such an 'Earth System Dynamics' Theme, it is important to summarize the current status and the planned development of GGOS.

Based on the continuous monitoring and analyzing activities of the relevant IAG services, that is, the *International VLBI Service* (IVS), the *International Laser Ranging Service* (ILRS), and the *International GNSS Service* (IGS) using the space geodetic techniques *Very Long Baseline Interferometry* (VLBI), *Satellite Laser Ranging* (SLR)/*Lunar Laser Rasnging* (LLR), and GNSS, respectively, and thanks to the IERS, which analyzes the products of the technique-specific services, the *mean* terrestrial and celestial reference frame today both are accurate close to the 10^{-9}-level. This essentially implies (sub-)cm and (sub-)0.1 mas accuracies, respectively. With these established reference frames it is possible to derive the Earth rotation parameters (precession, nutation, length of day, UT1-UTC, polar motion) on the same accuracy level. The two reference frames and the time series of Earth rotation parameters can and should now be made mutually consistent on the 10^{-9}-level. However, the mentioned accuracies and consistency only can be claimed in a mean sense for the terrestrial system (mean site coordinates and velocities), while user requirements increasingly require this accuracy in an instantaneous sense.

Based on more than thirty years of SLR/LLR and mainly based on the dedicated gravity missions CHAMP, GRACE, GOCE, accuracy in gravity is approaching the 10^{-9}-level (with a spatial resolution of 50-100 km, half wavelength) or is expected to reach this level within the next few years, as well. This accuracy implies a 1-cm accuracy for the global geoid. However, this accuracy requires the availability of the above mentioned geometrical reference frames for the determination of the orbits of the low-orbiting spacecrafts. Here, the instantaneous accuracy determined by the knowledge and modeling of short-period variations of station coordinates and gravity field (including ocean and atmosphere contributions) is the limiting factor.

From the above, it can be concluded that the generation and maintenance of the geometrical and gravitational reference frames on an accuracy- and mutual consistency-level of 10^{-9} with a temporal resolution down to the sub-daily domain will be *the* challenge for GGOS. Having this in mind, an IGOS-P 'Earth System Dynamics' Theme appears to be the appropriate tool to develop the necessary scientific and operational frame for addressing this challenge. From a GGOS point of view, it is the objective of the suggested 'Earth System Dynamics' Theme to provide the science basis for the implementation of GGOS and to ensure that GGOS can be fully integrated in the frame of IGOS. Moreover, through interaction of such a Theme and/or the GGOS with the other IGOS-P Themes, particularly the Ocean, Global Water Cycle, Geohazards, and Coastal Themes, the full exploitation of the geodetic contribution to all other global observation systems will be facilitated. Most importantly, the Theme will ensure that GGOS meets the user requirements both from the other IGOS-P Themes and the nine societal benefit areas identified by the EOS-II.

The need for such a theme is mutual, both from the IAG/GGOS side as well as from the user side. As pointed out above, on the one hand, GGOS will not be able to exploit the full potential of the observations without taking a comprehensive system approach considering all mechanical interactions between the different system components. Thus, without considering Earth system dynamics in a consistent frame, GGOS will not be able to serve the users appropriately. On the other hand, existing and planned IGOS-P Themes such as the Geohazard, Water, Ocean, Cryosphere and Coastal Zone themes, will benefit considerably from a better monitoring of mass transport in the Earth system, particularly on global to regional scales. The accuracy and long-term stability of the reference frame resulting from observations provided by GGOS is crucial for most of the observing systems implemented through the existing or planned Themes. Long-term stability of the reference frame on the level required to monitor, for example, sea level and changes in ice sheets requires to take into account the Earth system dynamics fully. Monitoring displacements of the Earth surface on local to regional and global scale is crucial for understanding and mitigating the impact of geohazards. Most of the societal benefit areas of GEO depend also on improved knowledge of mass transport in the Earth system. Consequently, most of these areas identify a need for geodetic observations. Moreover, most observing systems will depend heavily on having access to a stable reference frame. GEOSS focuses on long-term, georeferenced databases, and for these, the stability of the reference frame is crucial, too.

3 Review of User Requirements

3.1 Introduction

Geodesy is in a rather peculiar situation with respect to users and their requirements. In many cases, users are not aware of their needs with respect to geodetic observations and products. They are often not aware of the fact that they are using tools that would not be possible or less practical without geodesy providing crucial input.

For Earth observations, a similar, though less pronounced, situation is found. Scientists involved in studies of the Earth system are mostly fully aware of their needs with respect to Earth observation. However, users further down the line of information production display less awareness with respect to their requirements, and the end users in decision making normally show little awareness of the requirements for Earth observations (table 1). For GGOS and the geodetic contribution to Earth observation, this reduction of explicit understanding of the requirements with distance from the observation system itself is even more pronounced.

GEO advocates an strongly user-driven approach to the implementation of GEOSS (see GEO, 2005b). However, a science-driven approach may be necessary for some components, particularly those with a service function for other components. This applies in particular to GGOS, which provides the reference frame as the foundation for all Earth observations. Assuming a general need for comprehensive monitoring of the Earth system (as postulated, for example, in the IGOS, see IGOS-P, 1999), we can take a science-driven approach to an observing system that will accomplish this.

Comprehensive monitoring of the Earth system is a prerequiste for understanding the Earth system processes and thus, ultimately for achieving sustainable development. During the last three decades, the need for global monitoring of the Earth has been recognized in particular by the United Nations in setting up the Earth Watch program and initiating global observing systems (see, e.g., Plag, 2000, for a summary).

In parallel, the last three decades have seen an increase in accuracy of the space-geodetic techniques of more than three orders of magnitude (Chao, 2003). Today, these techniques provide a global reference frame of unprecedented accuracy and stability as well as highly accurate observations of crucial quantities related to changes in the Earth's geometry, rotation and gravitational field. However, Plag (2000) pointed out that the emerging observing systems neither include a geodetic component nor are they directly connected to the extensive global geodetic observing networks established over the last decade. Thus, until very recently, the fundamental role of geodesy as the backbone for all Earth observations was not formally recognized in the existing systems. The recent discussion in the frame of the *ad hoc* GEO has changed the situation and led to a broad acknowledgement of the fundamental importance of a sufficiently accurate terrestrial reference frame and geodetic observations for Earth observations.

The Subgroup *User Requirements and Outreach* of the *ad hoc* GEO discussed the URs for Earth observations, and a number of UR studies were stimulated, mainly on national level. Generally, the goal of these studies was to identify the extent to which Earth observations are required for societal applications. As an examples of such studies, we report here on the extensive inquiry carried out in Canada. This study, which was based on user surveys, revealed a clear need for Earth observations across a broad range of societal areas, but the results were complex and hard to interpret in terms of quantitative requirements (Béchard, 2005, personal commun.).

Table 1: User requirements for Earth observations and GGOS products.

Modified from G. Foley, personal communication.

General Products and applications	*Geodetic Contribution*	*User groups*
		URs generally well documented
Earth observations, Earth system models	Reference frame and observations	Earth system scientists and modelers
Data-to-information archiving & services	IAG Services, GGOS	Earth system service providers
Decision support tool development	Provision of information, often through others	Environmental process modelers & researchers
Decision making	Not aware of requirements	Policy makers & environmental managers
Assessments of benefits	Often not aware of geodesy	Public officials, advocacy groups and the public
		Less able to document needs

Similarly, the Reference Document to the GEOSS Implementation Plan (GEO, 2005b) provides a high-level overview of the URs in the nine societal benefit areas (see Section 3.3 below) identified by the EOS-II (see Annex 2 in GEO, 2005b). It is important to point out that, in most areas, the requirements include geodetic observations (see table 2 on page 30).

Increasingly, access to highly accurate geodetic positions is demanded for many scientific and nonscientific applications. This is equivalent to requiring access to an unique, technique-independent reference frame decontaminated for short-term fluctuations due to global Earth system processes. Providing instantaneous access to highly accurate single point positions in such a unique, global, long-term stable reference frame would considerably ease present applications and support many new applications, particularly if combined with the rapidly developing communication tools and geo-databases.

GNSS techniques like the *Global Positioning System* (GPS) and the coming Galileo are, in principle, able to provide such point positions relative to a unique, global reference frame anywhere without simultaneous measurements at or proximity to local reference points. However, only the combination of the space-geodetic techniques into an integrated system monitoring the Earth surface kinematics, rotational perturbations and gravity field changes will eventually enable the realization of the reference frame with sufficient accuracy and long-term stability as the backbone for an Earth monitoring system. This GGOS will also provide the observations to describe the surface velocity field well enough to fully exploit the potential efficiency of precise point positioning and to meet the requirements of most of the emerging applications.

In designing the GGOS and any other geodetic infrastructure, however, it is essential to take a user-driven approach. In the next section, we first summarize the general URs for the reference frame. In Section 3.3, we will then discuss requirements resulting from global Earth observations based on the requirements of the nine benefit areas identified by GEO, and in Section 3.4 focus on the relevant IGOS-P Themes. Subsequently, we will address requirements of scientific issues on regional to global scale (Section 3.5). In Section 3.6, focus is on nonscientific applications requiring geodetic observations or products. Finally, we will summarize the URs in Section 3.7

3.2 User requirements for a global and national reference frames

In a modern, high-technology society, the requirements for precise positioning and surveying are steadily increasing. The planning and carrying out of projects, such as, for example, building of roads, railroads, bridges, tunnels, or airports, as well as the security and safety of these entities requires reliable and highly accurate positions. Building a pipeline across national boundaries requires homogeneous reference systems and a common reference frame. An error of a few centimeter can be very costly. For the exploitation of the offshore oil and gas resources, monitoring of the infrastructure is required. Particularly the settlement of the platforms needs constant monitoring in order to be prepared for a once-in-a-hundred-years wave or earthquakes. The settlement and subsidence is also important for improved security, better knowledge of the oil resources, and effectivity of the extraction. The monitoring of important infrastructure, for example, reservoir dams, large buildings, and bridges, is increasingly important in order to detect potential risks from failure due to aging or environmental factors. Similarly, risks associated with instabilities of soil and rocks or processes related to volcanism require increasingly monitoring as both infrastructure and population are growing in hazardous areas. Many of these applications require positions with cm accuracy and millimeter per year stability. Aviation and marine traffic require accurate and timely updating of their position in order to avoid accidents, and the geodatabases used in creating maps have to be of high accuracy and in a consistent reference frame.

The quest for a globally sustainable development necessitates increasingly the development of georeferenced databases for planning, exploitation and management of resources. These databases have to be maintained with coordinates given with respect to a geodetic reference frame with sufficient accuracy and long-term stability.

Earth observation is another area where accurate positioning and coordinates are monumental. As an example, monitoring of sea level is an important contribution to climate change research (Church et al., 2001) and contains important information related to the impact of the anticipated global warming. Under the UNFCCC, a considerable effort is made to ensure sufficient monitoring of sea level (see for example IOC, 1997; GCOS-48, 1998; Plag et al., 2000). However, a major limitation results from the accuracy of the global geodetic reference frame (Blewitt et al., 2006a). For local sea level studies, in particular, for scenarios of future sea level, the required accuracy of vertical land motion is of the order of, or better than, 0.5 mm/yr. For global studies, the relation between geocenter and reference frame needs to be know with an accuracy on the order of 0.1 mm/yr. For scientific studies, Earth scientists depend in most cases on accurate positioning in order to be able to detect changes in the Earth system. Consequently, the international geodetic community has significantly contributed to studies of, for example, plate tectonics (e.g., Kreemer et al., 2003; Carter, 2003), postglacial rebound (Johansson et al., 2002; Park et al., 2002; Milne et al., 2004, e.g.), and Earth rotation (e.g., Plag et al., 1998; Salstein et al., 2001; Chao, 2003; Plag et al., 2005b).

A prerequisite for all these studies are a set of well-defined reference systems. All relevant observations and models for the Earth system dynamics and the nearby space have to be coordinated. Two reference systems are required, namely a celestial system that can be used to describe the Earth's position in relation to the surrounding space, and a terrestrial Earth-fixed system that can be used to refer Earth-related coordinates to. Moreover, these two systems have to be related to each other, and this relation is provided by the *Earth Rotation Parameters* (ERP). The ERP describe how the Earth rotation axis and velocity change over time.

Many of the mentioned tasks require a realization of these systems through stable reference frames that allow the determination of coordinates with millimeter accuracy and a reproducibility of several decades. The national geodetic infrastructure has to ensure that coordinates measured today can be compared to those measured in five or ten years and in some cases in 50 years. The solid Earth is a dynamic body where all points are in slow but constant movement. Plate tectonics results in relative velocities of the plates exceeding in many places 100 mm/yr. In large areas, the plates exhibit intra-plate deformations and particularly in tectonically active regions, relative velocities can reach several tens of mm/yr. In seismically active areas in Norway (for example Ranafjord), relative movements of several mm/yr are expected close to active faults. Changes in glaciers and ice sheets, sea level and hydrology also introduce significant deformations in the solid Earth (for example in Svalbard).

This dynamic nature of the solid Earth complicates the determination and maintenance of a stable terrestrial reference frame considerably. In order to meet the increasing requirements and to allow for full exploitation of the economic advantages of precise point positioning, the national reference frame has to be linked to the *International Terrestrial Reference Frame* (ITRF) as the best maintained and most accurate global reference frame.

3.3 Global Monitoring of the Earth System

Recognizing the need for global monitoring as a prerequisite for understanding the impact of mankind on the Earth system and for devising actions to mitigate the predicted changes and their impacts, the G3OS for Climate (GCOS), Terrestrial (GTOS), and Ocean (GOOS) were initiated and established partly under the United Nations Environmental Program's (UNEP) Earth Watch activities (see http://earthwatch.unep.net). These systems are developing rapidly following the IGOS (IGOS-P, 1999).

As a general requirement, the IGOS emphasizes the necessary transition from a research state to operational observing systems (see, e.g., Williams & Townshend, 1998). This is justified by the requirements for Earth system observations resulting from the nature of the processes in the Earth system. Key requirements for sustainable monitoring, which must be the overall goal of the observing systems, are that it is long-term and homogeneous in time. These requirements can only be met by operational observation systems. Moreover, IGOS requests the monitoring to be multi-parameter, global and integrated. Another focus of IGOS is on the data archives, as well as the accessibility of data, products and information for users. Here, it is stated that data archives resulting from Earth observing systems must be integrated, quality-controlled, homogeneous, consistent, and, most importantly, accessible. The last point cannot be overemphasized. Currently, exploitation of Earth observation data in many areas is still hampered by difficulties in accessing relevant databases.

The Framework document resulting from EOS-II, which formed the basis for the 10-year Implementation Plan for GEOSS (GEO, 2005a) and the Reference Document (GEO, 2005b) identifies nine benefit areas for Earth Observations (see Appendix 2 in GEO, 2005b). These are

- Disaster: reducing loss of life and property from natural and human-made disasters
- Health: understanding environmental factors affecting human health and well being
- Energy resources: improving management of energy resources
- Climate: understanding, assessing, predicting, mitigating, and adopting to climate variability and change
- Water: improving water resource management through better understanding of the water cycle
- Weather: improving weather information, forecasting, and warning
- Ecosystems: improving the management and protection of terrestrial, coastal, and marine ecosystems
- Agriculture: supporting sustainable agriculture and combating desertification
- Biodiversity: understanding, monitoring and conserving biodiversity

Table 2: Requirements for geodetic observables for the nine benefit areas.

The fields and their status are extracted from the discussion of the URs for the nine benefit areas in GEO (2005b). The status is indicated by the follow classes: 0: okay; 1: marginally acceptable accuracy and resolution; 2: could be okay within two years; 3: could be available in six years; 4: still in research.

Observable quantity	Status
Deformation monitoring, 3-D, over broad areas	3
Subsidence maps	3
Strain and creep monitoring, specific features or structures	2
Gravity, magnetic, electric fields - all scales	3
Gravity and magnetic field anomaly data	2/3
Groundwater level and pore pressure	4-1
Tides, coastal water levels	1
Sea level	2-1
Glacier and ice caps	2
Snow cover	2
Moisture content of atmosphere/water vapor	2
Extreme weather and climate event forecasts	3
Precipitation and soil moisture	3-1

Both GEOSS and initiatives like the GMES require an accurate, stable, and easily accessible reference frame as the backbone for all observations. In addition, GEO (2005b) provides for each of these areas an overview of the requirements in terms of quantity and status of the observational capacity. Extracting the quantities relevant for GGOS results in the list compiled in table 2.

The next step is to convert the information provided in the GEOSS Reference document into URs in terms of accuracy, latency and resolution for each of the quantities given in table 2. Many of these URs are discussed in the frame of the IGOS-P Themes, which we consider in the next section in more detail.

Others are still in the state of scientific development and will be addressed in Section 3.5.

3.4 IGOS-P Themes as a specific User Group

Currently, IGOS-P has several approved Themes and others are in the planning or proposal stage. These Themes address different components of the Earth system, different processes, or different societal issues. The Themes are:

- The Atmospheric Chemistry Theme aims to ensure the long-term continuity and spatial comprehensiveness of the monitoring of the atmospheric composition and to integrate ground-based and spaceborne measurements using models and assimilation tools.

- The Carbon Observations Theme is aimed at delivering an improved knowledge base for better policy-making, enhance the scientific understanding of the global carbon cycle, and provide for advanced Earth system observation capabilities.

- The Geohazards Theme aims to integrate disparate, multidisciplinary, applied research into global operational systems, and through this to improve the provision of timely, reliable, and cost-effective information to those responsible for managing geohazards.

- The Ocean Theme has the overall goal to develop a strategy for an observing system for the oceans that serves the research and operational oceanographic communities and a wide range of scientific and nonscientific users.

- The Water Cycle Theme aims to provide a framework for guiding decisions regarding the maintenance and enhancement of water cycle observations that support monitoring of climate, water management and water resource development, provision of initial conditions for numerical weather forecasts and climate predictions, and research related to the water cycle.

- The Coastal Observation Theme, which is under preparation, will aim to coordinate and strengthen present and future coastal observational capabilities, both *in situ* and spaceborne as a basis for a better understanding of the changes in the coastal zone and a service to the decision-making process.

- The Coral Reef Sub-Theme takes into account the unique characteristics of coral reefs requiring special observation techniques in the development of a strategy for the observation system of this particular ecosystem.

- The Cryosphere Theme will create a framework for improved coordination of cryospheric observations and the generation of data and information needed for both operational services and research.

- The Land Theme aims at a global strategy for a land observations system focusing on globally needed observations for topics such as land cover and land use, human settlement and population, managed and natural ecosystems, soils, biogeochemical cycles, and elevation changes.

In general, all these Themes will address spaceborne or airborne observations that require highly accurate positioning of the sensors, and thus are linked to the global geodetic networks through their requirements for access to an accurate and stable reference frame. This requirement is not addressed here further (see Section 3.2 for an overview). Concerning the Atmospheric Chemistry Theme, it is mentioned that atmospheric circulation is relevant for the distribution of atmospheric constituents. Thus, the dynamical state of the atmosphere is relevant to this Theme. The atmosphere dynamics are directly related to Earth rotation and Earth rotation observations have been used in validation of atmospheric circulation models.

The relevant Themes potentially benefiting to a considerable extent from observations of the fundamental geodetic quantities are those addressing dynamics and mass transport in the Earth system or being affected by these processes. These Themes are:

- The Geohazards Theme, where plate tectonics, pre-, co- and post-seismic strain, processes associated with volcanos, early warning for tsunamis, and local and regional predictions of sea level rise are examples of topics that link this Theme to geodetic observations.

- The Ocean Theme, where questions of ocean circulation, sea level rise, and mass balance come into play. Ocean circulation and mass change affect all three geodetic quantities, which in turn can be used to observe variations in circulation and ocean mass. A highly accurate geoid is needed to determine dynamic sea surface topography from satellite altimetry measurements. Measurement of global, regional and local sea level changes require not only a reliable reference frame but the direct involvement of the geodetic observations. Validation of ocean circulation models can be done on the basis of geodetic observations of surface displacements, gravity field variations, and Earth rotation variations.

- The Water Cycle Theme is strongly linked to the geodetic observations, as they provide a unique tool to monitor the global to regional scale movements of water through the Earth system.
- The Coastal Observations Theme, where sea level and ocean circulation are relevant parameters influencing the dynamic processes in the coastal zone.
- The Cryosphere Theme, where the ice mass balance, glacial loading, and induced sea level variations all are important parameters, that are directly observed by the geodetic observation techniques.
- The Land Theme, where changes in the elevation are directly observed by geodetic techniques.

In the following, we comment on the geodesy-related observational requirements of these Themes in more detail.

The Geohazards Theme: Geohazards such as earthquakes, volcanic eruptions, landslides, subsidence, and precarious rocks are intimately connected to displacements and deformations of the Earth's surface. Marsh & the Geohazards Theme Team (2004) state that "*Geohazards driven directly by geological processes all involve ground deformations. Their common observational requirements are for global, baseline topography and geoscience mapping, against which surface deformations ... can be monitored.*" Thus, key observing techniques for an anticipated integrated solid Earth observing system complementing the existing systems such as GOOS, GCOS and GTOS would have to be the geodetic techniques capable of observing surface displacements on local to global scales at the highest possible accuracy. It is likely, that the existing global and regional geodetic networks, in fact, would provide the basis for such a solid Earth observing system. In many regions, the solid Earth observing system dedicated to geohazards would also have to be flexible in spatial and temporal resolution, as well as readiness on demand. Therefore, in many parts of the world, dedicated ground-based networks are needed. In addition to the classical, point-oriented geodetic techniques, also 2-dimensional imaging techiques are needed, such as *Interferometric Synthetic Aperture Radar* (InSAR). These techniques allow the monitoring of relevant areas with high spatial resolution, although not with the low latency and temporal resolution required for some geohazards applications.

The Ocean Theme: The ocean observing system described in the Ocean Theme report (IGOS-P Ocean Theme Team, 2001) explicitly includes several geodetic components, which aim at an improved geoid and the temporally variably gravity field. The current uncertainty in the geoid is a major limitation for the determination of the mean ocean circulation from satellite altimetry. The requirement expressed in the report is an accuracy of 2.5 mm for a wavelength of 200 km. The time dependent variations in the gravity field are related to ocean circulation, and measurements at wavelength of a few hundred kilometers and more provide important constraints on the large-scale overall circulation in the ocean.

The ocean observing system also requires geodetic techniques for positioning of sensors, as well as *in situ* measurements of sea level. The monitoring of the sea surface with satellite altimetry is another contribution of geodesy to the ocean observing system.

The Water Cycle Theme: A major process moving mass throughout the Earth system is the global water cycle. Changes in the distribution of water stored on land, in the ocean and in the atmosphere affect geodetic observations related to the time variable gravity field, shape, and rotation of the Earth. At time scales of months to a decade, loading of the solid Earth by fluids dominates nonsecular variations in the geodetic observables. Space geodetic observations on surface mass variability are inherently strong at the regional to global scale and thus provide a unique tool to complement traditional *in situ* measurements of terrestrial water storage.

The *Global Geophysical Fluid Center* (GGFC) of the IERS was established in acknowledgement of the interactions between the solid Earth and its fluid envelope and the necessity to understand these interactions in order to improve the interpretation of the geodetic observations. The satellite gravity field missions, which are part of the GGOS, already provide new insight into the motion and storage of water in the different components of the Earth system. InSAR is increasingly applied to monitor surface displacements induced by changes in groundwater levels. GNSS is increasingly used to extract information on atmospheric water contents from regional networks (e.g., Elgered et al., 2004).

From the above, it is clear, and also acknowledged in the Water Cycle Theme report (Lawford & the Water Theme Team, 2004), that a strategy for a water cycle observing system will have to rely to a large extent on contributions from geodetic techniques, and in particular, from GGOS. Moreover, geodetic techniques such as *in situ* gravity measurements and InSAR will also have to be integrated, particularly for the management of water resources.

The Coast Observation Theme: The monitoring of sea level and vertical land motion in the coastal zone heavily depends on geodetic techniques like GNSS and InSAR. Changes in local sea level of the order of 0.5 mm/yr have potentially serious impacts on the coastal zone, and the monitoring of both local sea level and the vertical land motion with that accuracy is a demanding task.

The Cryosphere Theme: The concept of a Cryosphere Theme is outlined in Key & the IGOS-Cryo Writing Team (2004), where the importance of the cryosphere in the Earth system and particularly the climate system is strongly emphasized. The long list of quantities required to monitor the state and trends in the cryosphere include the surface elevation, ice thickness, and mass balance. Geodetic observations substantially contribute to determination of these quantities. The surface elevation and small changes in these elevations are determined by radar and laser satellites. Changes in the ice mass cause changes in the gravity field. Observations of the deformations of the Earth and changes in the gravity field associated with the mass changes provide constraints on the overall mass balance of ice sheets and glaciers (e.g., Wu et al., 2003, 2006). For changes in the large ice sheets, the spatial fingerprint in sea level (e.g., Plag, 2006a) and trends in Earth rotation also can be used to constrain the mass balance of the ice sheets. Measurements of vertical displacements and gravity close to the ice sheets are indicative of the mass balance, too (e.g., Wahr et al., 1995, 2001a; Sato et al., 2006b). The temporal variations of the gravity field contain accurate information on global and regional mass transport, including changes in the ice sheets (e.g, Velicogna & Wahr, 2005; Ilk et al., 2005; Tamisiea et al., 2005; Velicogna & Wahr, 2006).

The Land Theme: The Land Theme as proposed by Townshend & the IGOL Writing Team (2004) focuses on the properties of the surface of the solid Earth, its cover and use, the biosphere, soils and the biogeochemical cycles. Geodetic observations contribute marginally to this theme, though surface elevation, changes in surface elevation, and land stability are issues requiring highly accurate positioning.

3.5 URs for scientific applications

The report *Living on a Restless Planet* (Solomon & The Solid Earth Science Working Group, 2002) prepared by the Solid Earth Science Working Group of NASA gives an excellent overview of the many scientific problems that need to be solved in order to better understand the Earth system processes that affect human well-being. The understanding of these processes and their interactions is prerequisite for sustainable development.

The capability to determine highly accurate positions with respect to a global reference frame is crucial for many scientific applications, such as studies of global, regional and local geodynamic processes, seismo-tectonic deformations, motion of the tectonic plates, pre-, co- and post-seismic strain, deformations associated with volcanic areas, changes in sea level and ice sheets, interaction of ocean, atmosphere, and solid Earth as well as geohazards. Traditionally, highly accurate geodetic positions were determined through measurements relative to a set of local reference points with known (fixed) coordinates in a local or regional reference system. The advent of the space geodetic techniques allows for the first time the realization of a global reference system through a globally homogeneous reference frame. Moreover, GNSS techniques like GPS and the future Galileo facilitate the determination of positions in the global reference frame independent of simultaneous measurements at local reference points with increasing accuracy and decreasing latency.

In the so-called precise point positioning method introduced in Héroux & Kouba (1995) and developed further by Zumberge et al. (1997) and Kouba

& Héroux (2001), access to the reference frame is provided through highly accurate satellite orbits and clocks, which in turn are determined on the basis and relative to a global network of tracking stations. However, a reference frame sufficiently accurate and stable in time to satisfy most URs can only be maintained and made available through a system like GGOS providing highly accurate and comprehensive information on changes in the Earth's figure, rotation, and gravity field.

In monitoring the different aspects of the Earth system mentioned above, GPS augmented with the products of the IGS (denoted here as GPS&IGS) has served both as the primary measuring device (e.g., to observe plate kinematics, seismic strain, and vertical land motion required to detect absolute sea level changes) as well as a tool to position sensors with unprecedented accuracy (e.g., in airborne gravimetry, hydrographic survey, and satellite altimetry). Ten years of experience including comparison to model predictions have shown that for many applications requirements are of the order of better than 1 cm in daily or sub-daily positions and better than 1 mm/yr in secular stability.

Considering the Earth system as depicted in fig. 21 (see Section 4), a number of scientific questions and problems can be identified, that are associated with mass transport and thus with changes in the gravity field and displacements of the solid Earth's surface. The following list is indicative of the many open questions and problems related to the Earth system and the mass movements through the components of the system.

- Convection: Are the anomalies in seismic velocities detected by seismic tomography in the Earth's mantle due to chemical anomalies or temperature anomalies? This is equivalent to the question whether convection is throughout the whole mantle or layered.
- Plate tectonics: The location of and the processes at plate boundaries still pose several questions. Likewise, the extent of deformation zones is uncertain in many regions of the Earth surface.
- Solid Earth dynamics: What are the processes at the core-mantle boundary?
- Ice sheets/glaciers and sea level: There are large uncertainties with respect to the ice load history, in particular, for Antarctica. The present-day changes in ice sheets are still associated with large uncertainties leaving even the sign uncertain. Consequently, their contribution to sea level changes are highly uncertain.
- Post-glacial rebound: The appropriate rheology of the Earth mantle and its dependency on time scales is still not well understood.
- Ocean circulation: What part of the circulation is is steric and what non-steric? What is the absolute circulation?
- Hydrological cycle: What are the fluxes between the different reservoirs and how do they change over time? How large are groundwater movements? What are the variations in continental water storage?
- Seasonal variations: What is the contribution of the terrestrial hydrosphere? For the cryosphere: What is the seasonal mass balance? For sea level: What part of the seasonal variations is steric and what nonsteric?
- Atmospheric circulation: How can reconstructions of past wind fields as well as past and present air pressure fields be improved?
- Tides: What is the accuracy of ocean tide models?
- Seismic waves and free oscillations: What is the 3-D structure (including the mechanical parameters) of the solid Earth?

Based on the current state of the art in the different areas, it is possible to derive specific requirements in terms of accuracy, spatial and temporal resolution, and long-term reproducibility for the geodetic quantities that would allow for an improvement in our scientific understanding of the problems, for example, through better constraints for models. As an example, in fig. 7, the differences in predicted present-day local sea level changes, vertical land motion and horizontal land motion are shown for two typical *Post-Glacial Rebound* (PGR) models, which differ only in the viscosity profile of the upper mantle. The differences are a few mm/yr in local sea level trends and vertical displacements, and somewhat less in horizontal displacements. The geoid variations, which are the sum of sea level change and vertical land motion, display differences of about 1 mm/yr. In all cases, the largest differences are found in the formerly glaciated areas. Similar differences are also found for

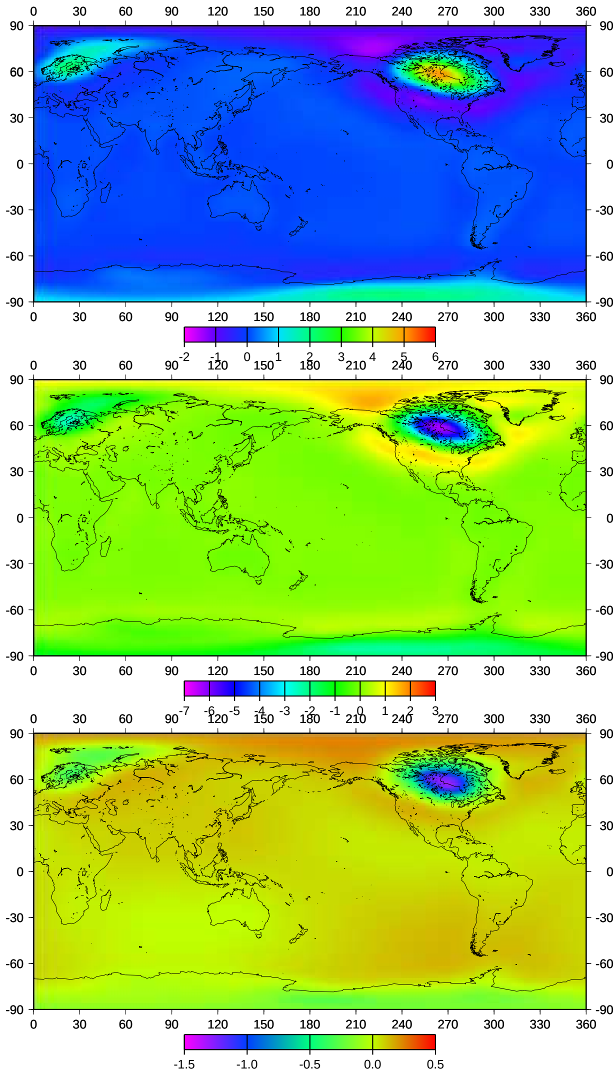

Figure 7: Differences between typical post-glacial rebound model predictions.

The difference are for two predictions by Peltier (2004). Ice load history is ICE-5G, V1.2 and Earth model are VM2 and VM4. The predictions are taken from http://www.sbl.statkart.no/projects/pgs. Difference are for VM4 - VM2. All values are in mm/yr. From top to bottom: (1) sea level trend, (2) vertical displacements, (3) geoid. The models themselves are also shown in fig. 27 on page 61.

models computed on the basis of somewhat different ice load histories. Consequently, observational constraints need to be considerably more accurate in order to be able to distinguish between PGR models and contribute to a better determination of the mantle rheology or better constraints for the ice load history.

Another example is the prediction of the displacements induced by atmospheric and hydrological loading. The predictions depend on the Earth model, the air pressure or hydrological data set, the reference frame, and the computational algorithm used. This is illustrated here for the vertical displacement induced by air pressure loading (fig. 8). Considering different Earth models, air pressure datasets, computational approaches, and reference frames (table 3), differences are about ±5 mm for daily averages. In order to validate the predictions and identify the most accurate one, observational constraints considerably better than these difference are needed.

The static geoid is relevant for studies of ocean circulation (mean dynamic sea surface topography, MDT), as well as the mass distribution in the interior of the Earth (see, e.g., Ilk et al., 2005). In both cases, the accuracy requirement are better than 1 cm, and ocean circulation studies require spatial resolution down to small scales of a few kilometers.

The temporal variation in the Earth's gravity field appears to be the most important quantity for monitoring the mass transport in the Earth system on global to regional scales, which are particularly relevant for the global water cycle, including variations in ocean circulation, water storage on land, sea level changes, ice load changes, etc. (see, e.g., Ilk et al., 2005). The currently accepted accuracy requirements are better than 10^{-9} with a tendency to 10^{-10} (e.g., for ice load changes and ocean circulation changes), and spatial resolution of a few hundred kilometers (Drinkwater et al., 2003). Mass transport in the global water cycle shows strong variations at sub-seasonal scales, and temporal resolution of several weeks are considered as a reasonable requirement (Wahr et al., 1998).

Coupled to the large scale variations in the gravity field are variations in Earth rotation. Moreover, Earth rotation perturbations also originate from dynamical interactions of the solid Earth with its fluid outer layer and core. Thus, the geodetic observations of polar motion and changes in the *Length Of Day* (LOD) can be utilized in the comparison of atmospheric datasets and *General Circulation Models* (GCM) of the atmosphere or the coupled atmosphere-ocean system (see Salstein et al., 2002, for an example).

Table 4 summarizes the requirements for geoid height and gravity anomalies for scientific and non-scientific applications. Currently, the accuracy of regional and global geoid models are far from meeting the requirements. In fact, the insufficient accuracy of the geoid is a limiting factor for many applications, for example, the use of satellite altimetry for the determination of the dynamic sea surface topography and the use of GPS for the determination of ortho-

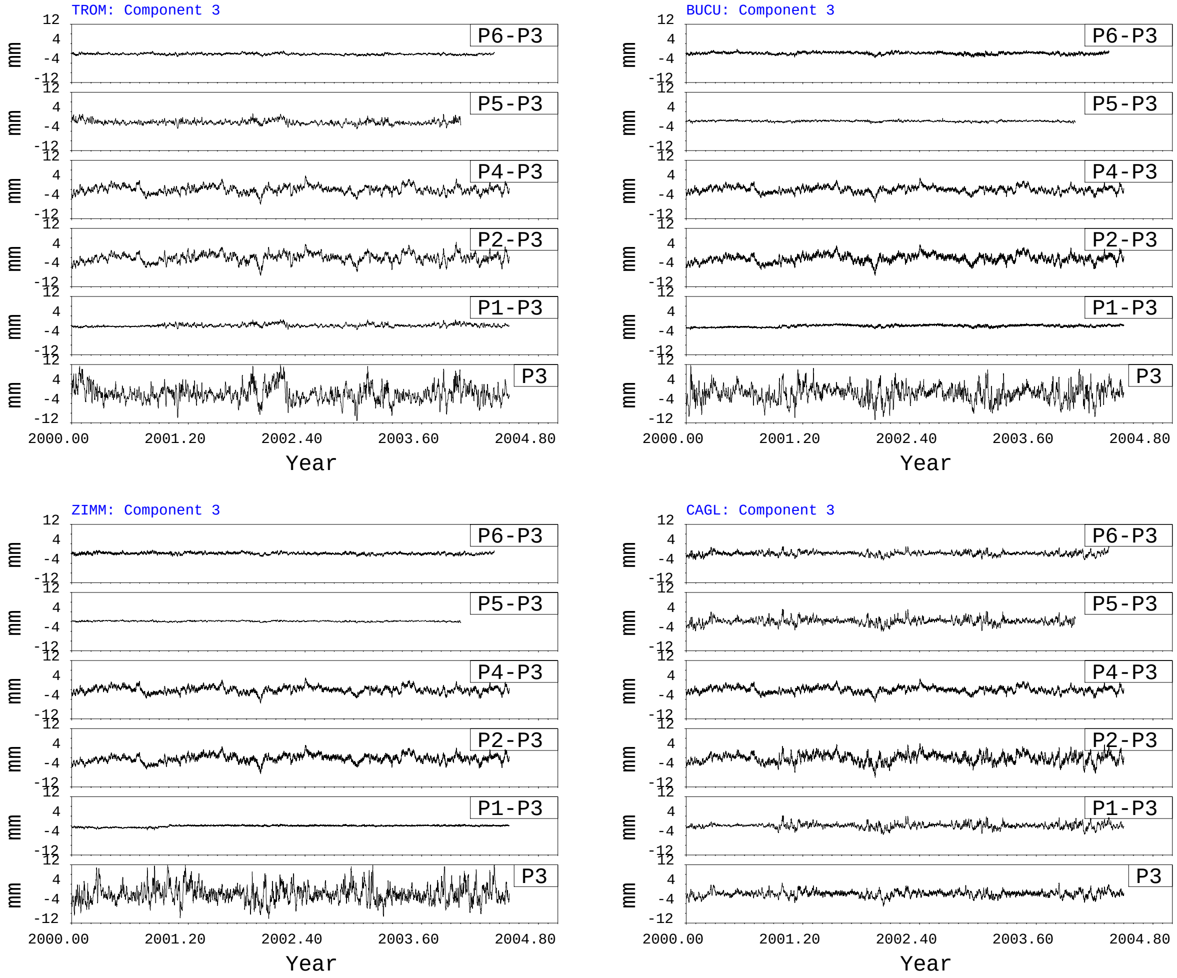

Figure 8: Differences between typical predictions of of vertical displacements atmospheric loading. *Stations are TROM: Tromsø, Norway; BUCU: Bucuresti, Romania; ZIMM: Zimmerwald; CAGL: Caglari, Sardinia, Italy. The predictions are described in table 3. The lower diagram is for the prediction P3.*

Table 3: Models and input data set used for predictions of displacements induced by atmospheric loading. *The predictions are denoted as P1 to P5. Sources for air pressure fields are European Center for Medium Range Weather Forecast (ECMWF) and National Center for Environmental Prediction (NCEP). Origin of the reference frames are the Center of mass of the solid Earth (CE) and the Center of Mass of the Earth system (CM), which in this case means the solid Earth and the atmosphere. Earth models are PREM (Dziewonski & Anderson, 1981) and G+B (Gutenberg - Bullen, see Farrell, 1972). Computation methods are SHE: Summation of spherical Harmonic Expansion, and CGF: Convolution of Green's Function and load anomaly. Authors are PG: Pascal Gegout, TvD: Tonie van Dam. Data source is http://www.sbl.statkart.no.*

Prediction	Input	Ref.Fr.	Earth M.	Comp.	Author
P1	ECWMF	CE	PREM	SHE	PG
P2	ECWMF	CM	PREM	SHE	PG
P3	NCEP	CE	PREM	SHE	PG
P4	NCEP	CM	PREM	SHE	PG
P5	NCEP	CE	G+B	CGF	TvD
P6	ECMWF	CE	G+B	CGF	HPK

metric heights.

Carefully carried out absolute gravity measurements constitute an independent measure of height variations and are therefore an important component in a combined geodetic network (Wilmes et al., 2005). Today, absolute gravity measurements with an accuracy of 10 to 20 nms^{-2} are possible, which converts into an accuracy of height of 3 to 6 mm. However,

Table 4: Measurement requirements in terms of geoid height and gravity anomaly accuracy.

Taken from Drinkwater et al. (2003). Note that the requirements for both scientific and nonscientific applications are given. 1 mGal is equal to 10^{-5} *ms*$^{-2}$.

Application	Accuracy		Spatial Resolution
	Geoid (cm)	Gravity (mGal)	half wavelength (km)
Oceanography:			
Short scale	1-2		100 km
	0.2		200 km
Basin scale	$\sim$ 0.1		1000 km
Solid Earth:			
Lithosphere and upper mantle density structure		1-2	100 km
Continental lithosphere			
– Sedimentary basins		1-2	50-100 km
– Rifts		1-2	20-100 km
– Tectonic motions		1-2	100-500 km
– Seismic hazards		1.0	100 km
Ocean lithosphere and interactions with asthenosphere		0.5 - 1.0	100-200 km
Geodesy:			
Leveling by GPS	1.0		100-1000 km
Unification of worldwide height systems	1.0		100-20000 km
Inertial navigation system		$\sim$ 1-5	100-1000 km
Orbits (1 cm radial orbit error for altimetric satellites)		$\sim$ 1-3	100-1000 km
Ice sheets:			
Rock basement		1-5	50-100 km
Ice vertical movements	2.0		100-1000 km
Sea-level change:	Many of the above applications, with their specific requirements, are relevant to sea-level studies		

this conversion requires that mass changes in the vicinity of the gravimeter are known and their effects are corrected. Combining absolute gravity measurements with measurements of height changes allows for the separation of deformations due to present-day mass changes (e.g., in ice sheets) from those due to former mass changes (e.g., post-glacial rebound Wahr & Han, 1997; Fang & Hager, 2001). The combination of absolute gravity measurements with height changes also helps to tie the geometric reference to the *Center of Mass of the complete Earth system* (CM) (Wilmes et al., 2006).

In studies of many geophysical problems, knowledge of the temporal variability of gravity is required with high temporal resolution. Thus, studies of the Earth's free oscillation, the free modes of the Earth inner core, Earth tides, and mass movements at different time scales benefit from time series of gravity with high temporal resolution and the highest possible accuracy.

Sea level is a quantity closely related to the three fundamental geodetic quantities. Sea level is also a quantity of considerable interest in the ongoing climate change debate as documented for example by the sequence of devoted sea level chapters in the *Intergovernmental Panel on Climate Change* (IPCC) assessments (see Church et al., 2001, and the references therein). There are two main sea level related aspects of relevance, namely (1) global sea level variations as an indicator for volume and mass changes in the ocean as the largest reservoir in the global water cycle, and (2) *Local Sea Level* (LSL) variations as a quantity related to one of the main impacts of global and regional climate change potentially affecting the development of the coastal zones and coastal cities severely. In both cases, the requirements for geodetic input are among the most demanding of all, particularly with respect to the relation between the reference frame and the CM.

Neglecting oceanographic and atmospheric forcing, LSL largely adjusts to an equipotential of the Earth gravitational field, namely the geoid. LSL de-

Table 5: Selected requirements for sea level observations for different applications

Application	Height accuracy	Time accuracy	Spatial resolution	Temporal resolution	Latency/record length
Tsunami	5 cm	1 minute	100 km	30 s	1 minute
Seiches	5 cm	1 minute	50 km, depending on location	30 s	10 minutes
Storm surges	10 cm	1 minute	100 km	15 minutes	1 hour
Depressions	5 cm	1 minute	$<$ 50 km, depending on location	15 minutes	1 hour
Tides and other oceanographic applications	1 cm	$<$ 30 s	50 to 500 km, depending on location	1 hour	Records of 1 months to several years
Studies of intraseasonal sea level variations	1 cm	1 minute	50 to 500 km, depending on location and phenomenon	1 hour, 1 day or 1 month, depending on time scale considered	Records of several years to century
Studies of annual to decadal sea level variations	$<$ 1 cm	1 hour	100 to 1000 km, depending on location and time scale considered	1 month	Records of decades to centuries
Studies of secular changes	$<$ 1 cm, stability $<$ 1 mm/yr	1 hour to 1 day	10 to 1000 km, depending on location and vertical land motion	1 month	Records of several decades to centuries
Model validation Tsunami	1 to 5 cm	$\sim$ 10 seconds	50-100 km	30 s	Records of 1 to several days
Model validation GCM (barotrop and barocline)	1 cm	1 minute	100 km or less	10 minutes to 1 hour	Records of up to several years
Model validation seiches (local, barotrop GCMs)	1 cm	$<$ 1 minute	50 km or less	30 sec	Records of several days
Model validation tides	1 cm	$<$ 1 minute	100 km	1 hour	records of a year or more

pends on the topography of the Earth, in which the total volume of the ocean waters is embedded, as well as Earth rotation, since the gravitational field is a combination of the gravity forces and the centrifugal forces arising from rotation. LSL also changes as a consequence of mass transport in the water cycle, particularly due to mass changes in the grounded ice sheets and continental water reservoirs.

LSL is the output of many Earth system processes acting on a wide range of temporal and spatial scales (fig. 9). Understanding LSL variations or deducing global averages is therefore a complicated process requiring considerable input from geodesy.

Traditionally, geodetic institutes have been involved in the operation of tide gauges for the purpose of defining the datum for height systems. In Scandinavia, a network of tide gauges has been operated since the late 19th century with the goal to determine the land uplift resulting from post-glacial rebound. Today, a major function of the tide gauges is to monitor long-term LSL changes. An increasing number of the gauges are co-located with geodetic infrastructure (both GNSS stations and absolute gravity) to measure the vertical land motion at the tide gauge and thus to be able to separate the land motion from other contributions to LSL changes. Consequently, geodetic institutes are again involved in the operation of an integrated sea level monitoring system.

LSL data serve a broad range of scientific and practical applications (see, e.g., Plag et al., 2000, for a detailed overview). The requirements for the different applications can be given in terms of accuracy (LSL height and time), spatial and temporal resolution, and latency allowed for the delivery of the data to a data or processing center. In table 5, we have compiled the requirements for a set of selected applications according to the latency requirements.

The most demanding requirements in terms of latency are associated with the detection of tsunamis for warning and alert purposes. The speed of

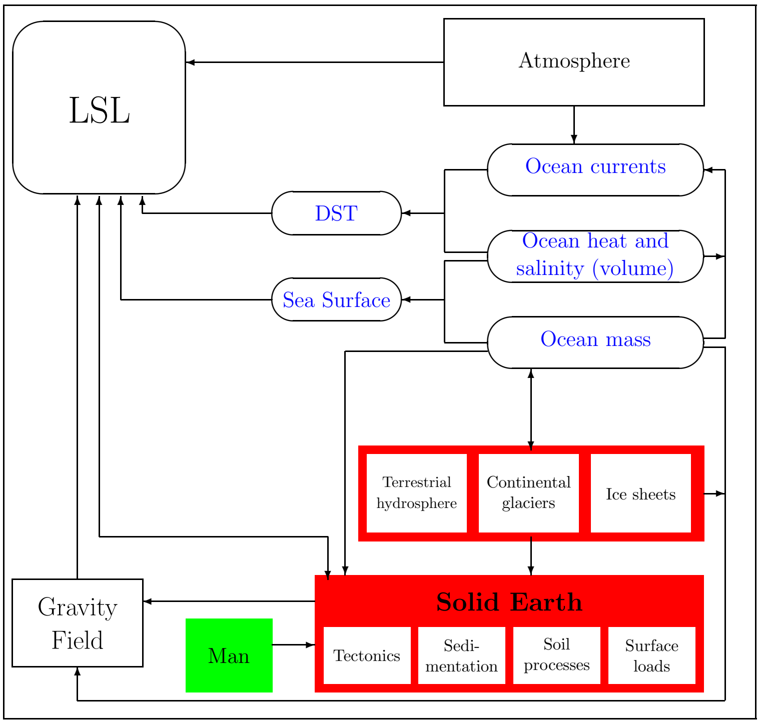

Figure 9: Interaction of processes controlling LSL.

Mass movements in the terrestrial hydrosphere (groundwater, rivers, lakes, and reservoirs) and land-based cryosphere (glaciers and ice sheets) and mass exchange with the ocean load and deform the solid Earth and affect the gravity field. The deformations and the associated gravitational changes result in LSL changes, depending on where mass has been relocated. Ocean mass changes change the sea surface position, similar to ocean volume changes caused by heat and salinity changes. The latter also affect the ocean currents and thus change the Dynamic Sea Surface Topography *(DST). Atmospheric circulation forces regional wind-driven currents affecting the DST. DST and sea surface changes caused by regional and global processes change LSL in any location. The atmosphere also acts locally on the sea surface and thus changes sea level. Past changes in the ice sheets and glaciers lead to post-glacial rebound, which affects sea level through vertical land motion and geoid changes. Tectonic processes in the solid Earth both result in vertical land motion, changes in the size of the ocean basins, and changes in the geoid. In areas where sedimentation takes place, the compaction of the sediments and their load on the solid Earth introduce vertical land motion. Moreover, changes in LSL feed back on the solid Earth and can cause the destruction of peat through oxidation and thus lead to subsidence. Anthropogenic vertical land motion associated with exploitation of groundwater, oil and gas as well as changes in sedimentation affect the solid Earth and can change the Earth surface position. Variations in sedimentation due to river regulation (reduction) or land use (increase) also affect LSL particularly in the vicinity of river deltas.*

tsunamis depends on the water depth. In the deep open ocean, the velocity reaches up to 800 km/h, while at shallow coast locations, it decreases down to 40 km/h and less. In order to have sufficient warning time, a tsunami needs to be detected several minutes before arrival at a vulnerable location. Typical periods of the tsunami waves are between 10 and 60 minutes. Considering the noise level of modern tide gauges for sampling intervals of 30 s, rapid LSL variations of > 1 cm/minute can be detected after a few minutes.

Storm surges are caused by a combination of atmospheric forcing and high tides. Storm surges are predicted today quite reliably on the basis of meteorological forecasts. Tide gauge data are not required to detect storm surges but rather for assimilation in forecasting models. The models are driven by atmospheric forcing (wind and air pressure), and tide gauge data provide an additional observational constraint contributing to an improvement of the accuracy of the predicted surge height.

The main applications of low latency tide gauge data are in the frame of a sea level hazards detection, warning and alert system. However, such a system would require additional sensors, such as ocean bottom pressure sensors and current meters. Particularly tsunamis are associated with rather high horizontal velocities, and these could easily be measured by drifting buoys equipped with GNSS receivers. Both tsunamis and storm surges constitute significant loads on the Earth's surface and induce deformations (Plag et al., 2006), which, in principle could be detected in regional GPS networks. For the latter, real time analyses of GPS data with precision better than 1 cm would be required.

Tide gauge data with a sampling interval of one hour carried out over time intervals from years to centuries have a number of applications not requiring any particular low latency. Records of several months to years can be used to determine harmonic tidal constants, which then can be used to predict the tides for practical purposes such as marine traffic. In areas with low water or close to harbours, the data can be used in case of accidents as evidence for the water level at the time of an accident, or they find use in engineering applications. Tide gauge observations from a number of locations around an ocean basin are indispensible for model validation. Longer time series serve as a basis for many scientific studies of ocean circulation, atmosphere-ocean interaction, and, for longer time scales, climate variability and change. At many coastal locations, the secular trend in LSL is of importance for planning and managing the coastal zone, both from an ecological and economical point of view. In order to understand the secular behavior of LSL, long and stable tide gauge records are required.

Increasingly, it will be important to assess scenarios of future LSL trends. The third IPCC assessment includes global sea level rise scenarios of up to 90 cm by 2100 (Church et al., 2001). Moreover, due to regional and local amplification, LSL trends considerably larger than the global average are possible. Therefore, cities like London and Venice are currently assessing the potential hazards associated with the trends in LSL and decisions on timely measures to mitigate the effects need to be made. An important input for the assessments are reliable tide gauge observations as well as information on the vertical land motion in the area under consideration. For the latter, an accuracy of better than ±0.5 mm/yr is required, which over a 100-year period is equivalent to an uncertainty of ±5 cm.

For all sea level applications discussed here, a quality-ensured database of tide gauge records is required. The records need to be homogeneous in time. For some applications, monthly mean LSL values are sufficient. However, since the storage of hourly LSL values no longer poses any significant problem, today, the hourly values or even the records with sampling rates of 10 minutes or higher should be the base of any LSL database. In this way, it is ensured that the data will also serve future applications.

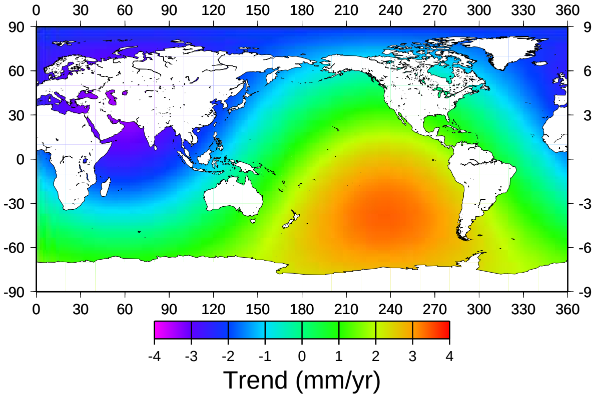

Figure 10: Effect of differential motion between ITRF origin and the CM on local vertical motion.
The vertical motion is given for a differential velocity of $\delta\vec{v} = (-1.5, -2.2, -2.1)$ *mm/yr, which was estimated by Kierulf & Plag (2006) as the geocenter velocity seen by GPS alone with respect to ITRF2000. The mean vertical motion over the complete surface of the ocean is 0.4 mm/yr.*

In table 6, the requirements for the appropriate parameters are given for all scientific questions mentioned so far. The list of relevant parameters includes but is not limited to 3-D displacements and velocities of the Earth's surface, strain rates, the static geoid, temporal variations of the Earth's gravity field, and perturbations of the Earth's rotation.

A rather crucial limitation for applications in both Earth observations and scientific studies originates from a significant uncertainty in the relation between the ITRF origin and the CM. The *International Terrestrial Reference System* (ITRS) is defined to have its origin in the CM. However, due to the particular sensitivity of the different techniques with respect to geocenter variations, there is a time-dependent difference between the origin of ITRF and the CM. This is particularly obvious in the different origins that IGS has chosen for the reference frames implicit in the different IGS products (Kouba, 2003; Ray et al., 2004; Kierulf & Plag, 2006).

The effect of the unknown differential movement between the ITRF origin and the CM, which is estimated to be of the order of 2 mm/yr, on observations of the surface displacements, sea level, and comparative studies between local gravity changes and vertical displacements is severe. As a example, in fig. 10

Table 6: URs for scientific applications.

S.R. stands for spatial resolution, T.R. for Temporal resolution, Fr. stands for Frame, where we distinguish L: local frames, N: national frames, G: global frame. R. stands for Reproducibility and gives the time window over which the parameters are expected to be reproducible with the stated accuracy. 1 μGal is equal to 10^{-8} ms^{-2}.

Application	Parameter	Accuracy	S.R.	T.R.	Fr.	R.
Mantle convection and plate tectonics	3-D velocities	< 1 mm/yr	n/a	n/a	G	several decades and longer
	static geoid	$< 10^{-9}$	n/a	n/a	G	
	secular strain rate	10^{-15} s^{-1}	10^3 km	n/a	G	
Post-glacial rebound	3-D velocities	< 1 mm/yr	10^2 km	n/a	G	several decades and longer
	geoid	$< 10^{-9}$	n/a	n/a	G	
	strain rates	10^{-15} s^{-1}	10^2 km	n/a	G	
	Earth rotation	0.1 mas/yr	n/a	n/a	G	
	local sea level	< 1 mm/yr	2 to $10 \cdot 10^2$ km	n/a	G	
Climate change, including present changes in ice sheets and sea level	3-D displacements	1 mm	10^2 km	months	G	decades
	3-D velocities	< 1 mm/yr	$< 10^2$ km	n/a	G	decades
	local gravity	< 0.3 μGal	$< 10^2$ km	n/a	L	decades
	geoid	< 10 mm	200 km	n/a	G	decades
	Earth rotation	0.1 mas/yr				
	local sea level	< 1 mm/yr	10^2 km	months	n/a	decades
Ocean circulation	gravity field	$< 10^{-9}$	10^2 km	months	G	decades
Hydrological cycle	gravity field	$< 10^{-9}$	10^2 km	months	G	decades
	3-D displacements	< 1 mm	10^2 km	months	G	decades
Seasonal variations	gravity field	$< 10^{-9}$	10^2 km	months	G	decades
	local gravity	< 1 μGal	n/a	months	L	decades
	3-D displacements	< 1 mm	10^2 km	months	G	decades
	Earth rotation	1 mas				
Atmospheric circulation	Earth rotation	1 mas		days		decades
Earth tides	gravity	0.01 μGal	10^3 km	hours	G	years
	3-D displacements	1 mm	10^3 km	hours	G	years
	strain	$^{1}0^{-15}$ s^{-1}				
Surface loading	3-D displacements	< 1 mm	10^2	< 1 day	G	years
	local gravity	0.1 μGal				
Seismotectonics	3-D displacements	1 mm	$< 10^2$ km	days	G	hours to years
	strain					
Volcanoes	3-D displacements	1 mm	1 to 10^2 km			years
	gravity	1 μgal				
Earthquakes, tsunamis	3-D displacements	1 mm to 1 cm	$< 10^2$ km	sec to days		
	local gravity	0.3 μGal				
	earth rotation					

the effect on vertical motion for a differential velocity vector of $\delta\vec{v} = (-1.5, -2.2, -2.1)$ in mm/yr is shown. This translation vector was determined by Kierulf & Plag (2006) for the translation between the origin of ITRF2000 and the origin implicitly defined by the IGS precise products. The latter is a GPS-only reference frame with high internal consistency. Similar differential velocities are reported by, for example, Morel & Willis (2005), and the relative velocity of the recently released ITRF2005 with respect to ITRF2000 is also of the same order (Altamini et al., 2006).

For the example in fig. 10, the effect on a global mean sea level estimate would be as large as 0.4 mm/yr (Plag, 2006b), which is far above the uncertainties discussed in, for example, Warrick et al. (1996) and Church et al. (2001).

3.6 URs for nonscientific applications

For most nonscientific applications, the access to highly accurate positions is the main geodetic requirement. On land, these positions are most often required in a time-independent, national reference frame. Increasingly, monitoring of offshore infrastructure and surveying of the ocean requires access to a reference frame in these regions. Requirements on local gravity are relatively modest. GPS is increasingly used for height determination. Since GPS gives ellipsoidal heights, these need to be converted into orthometric heights, which requires a highly accurate geoid. Earth rotation is not directly of relevance for nonscientific applications. However, errors in Earth rotation parameters map into positions determined with GNSS, and therefore, the implicit requirements for Earth rotation variations are demanding.

The *Standard Positioning Service* (SPS) of GPS on its own is far from satisfying the requirements of applications requiring high accuracy and/or long-term stability. One crucial initiative to improve the accuracy of GPS has been the IGS, which initially served the needs of many scientific applications. The excellent service provided by IGS to scientific and increasingly nonscientific communities is possible through a global network of GPS tracking stations, which currently comprises around 300 stations. Based on this network and a coordinated analysis effort, rapid and precise orbits and satellite clocks are provided together with ionospheric models and tropospheric products. These products meet many though not all requirements of high accuracy applications allowing for considerable latency. The IGS is also responding to the demand for real-time data and products and already has a working real-time prototype component. The experience with applications of IGS products over the last 10 years forms an excellent basis to assess future user requirements.

3.6.1 Surveying

For the most demanding land surveying tasks such as determination of real estate boundaries in densely populated areas (with high values of real estate) or mapping of underground cables and pipelines in cities, accuracy requirements are of the order of 1 to 5 cm with low latency. Therefore, the basic geodetic reference frame should have an precision of better than 1 cm in the horizontal components. In the vertical component, the precision should be better than 1 cm over 1 km.

The cost of surveys strongly depends on the time needed to achieve this accuracy and the integrity and availability of the system. Having access to a reliable accurate position in near-real time would greatly ease the surveying tasks and reduce the costs.

Most users in surveying and administration require currently that coordinates determined with a modern surveying method do not change their position with respect to neighboring points over time. In other words, users expect that coordinates do not change independent of how and when they are measured.

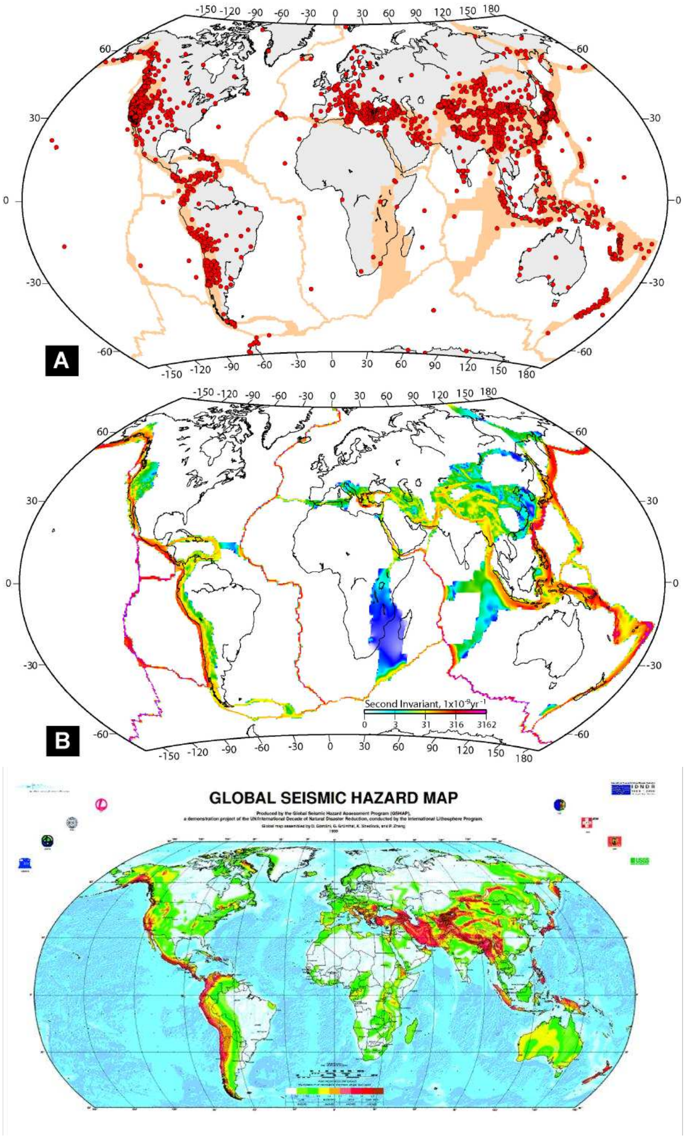

Figure 11: Global map of strain rates.
The upper map displays the distribution of GPS sites used to generate the middle map, which shows the second invariant of the strain rate tensor. From Kreemer et al. (2003). The lower map is the Global Seismic Hazard Map. Shedlock et al. (2000).

For a surveying method that measures coordinates relative to neighboring markers of the NGRF, it is sufficient that the coordinates of these points can be kept fixed. The markers must have coordinates with sufficient precision, and the deformations in the NGRF must be smaller than the requirements in terms of precision.

For a surveying method that measures coordinates in a global reference frame, which has to be time-dependent, it is necessary to know how points move with respect to the global frame in order to compare measurements taken at different epochs.

The requirements for the reference frame depend on the 'surveying area.' For surveying in a local area such as a town, city or county, relative precision over short distances is important. For surveys of larger areas and across country borders, accuracy is more important.

The requirements for the reference frame also depend on the 'observation method.' For most surveying, precise point positioning will be the most economic method, and it can be expected that this method will gain importance for most of the practical applications. For most surveying tasks, a requirement will be that the time-dependent coordinates given in the global reference frame can be transformed into time-fixed coordinates in the national reference frame. In order to transform precise point coordinates given in ITRF to national coordinates, a detailed knowledge of the velocity field of the Earth's surface with accuracy better than 1 mm/yr is required. An error as little as 1 mm/yr introduces an error of 1 cm in precise point positions over 10 years. In some regions, plate tectonic models provide a first order approximation to the horizontal velocity field (see Plag et al., 2005c, for a discussion). However, in many regions intra-plate deformations exceeding the 1 mm/yr level require more detailed (empirical) models. For the height component, even first order models are lacking, except for post-glacial rebound in and around the formerly glaciated areas.

Globally, points on the Earth's surface move with respect to a global terrestrial reference frame with velocity that can exceed 10 cm/yr. For Norway, these velocities are of the order of 3 cm/yr. In some seismic areas, strain rates can be as large as 10^{-10} s^{-1} while intra-plate strain rates are of the order of 10^{-15} s^{-1} to 10^{-17} s^{-1}. In Norway, deformations are expected to be not more than a few mm/1000 km/yr except for a few well confined areas with high seismic activity. It is noted here, however, that there are areas with sediments or neotectonic activity, where surface deformations are considerably larger than that.

The choice of the observation methods determines to what extent these motion and deformation have to be taken into account. For relative positioning, where access to the reference frame is through the neighboring reference points with fixed coordinates, neither the motion nor the deformation is important as long as the distances in space and time are not too large. For precise point positioning, where the reference frame is provided by the satellite orbits, both motion and deformation are important if coordinates for different epochs are to be compared or coordinates are to be transformed into the national reference frame.

3.6.2 Contributions to geohazards

Geohazards due to earthquakes, volcanic eruptions, landslides, precarious rocks, and soil subsidence are increasingly causing severe damage to properties and human lives. An increasing and spreading population puts more stress on land usage and as a consequence, the number of people living in areas with geohazards are increasing, too. Therefore, the detection of potential hazards as well as the monitoring of hazardous areas are important societal tasks, improving the environmental security and required to mitigating the impact of natural disasters on human life and property.

Geodetic techniques are fundamental in the detection and monitoring of hazardous areas. Of particular importance are observations of the surface displacements associated with the processes leading to geohazards. Networks of GPS stations have been a very important source of information for displacements and strain rates. Thus, the world strain map (fig. 11) has been created on the basis of *Continuous GPS* (CGPS) and GPS campaign measurements (Kreemer et al., 2003). However, there are still large gaps in this map due to insufficient observations. Nevertheless, the high correlation of the strain rates with the seismically active zones as indicated by the seismic hazards map (fig. 11) is obvious.

GPS has played a fundamental role in the study of earthquakes and the monitoring of pre, co, and postseismic displacements and the determination of the strain and strain rate field associated with seismogenic areas. Example are the *Southern California Integrated GPS Network* (SCIGN, see http://www.scign.org) with about 200 stations, and the Japanese GPS network operated by the Geographical Survey Institute with more than 1200 stations (see http://mekria.gsi.go.jp/ENGLISH/index.html).

The main objectives of SCIGN are to provide the observational basis for estimating the earthquake potential, identify active blind thrust faults, measure local variations in strain rate, and, in the event of an earthquake, to measure the permanent crustal deformation, which cannot be detected by seismographs (Hudnut et al., 2001). In order to reach these objec-

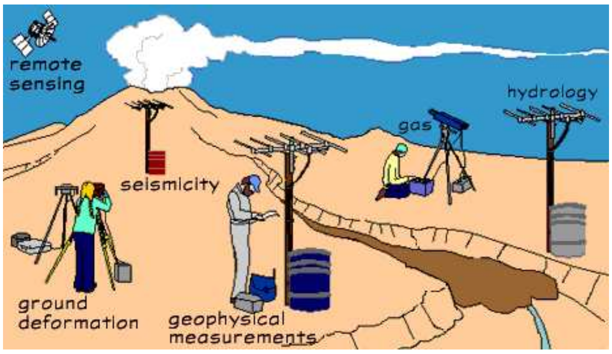

Figure 12: Components of a volcano monitoring system.
Surface displacements and gravity are pivotal components of a modern volcano monitoring system. Today, surface displacements are observed with GPS/GNSS and InSAR.

tives, the requirements are positions with low latency and at the sub-centimeter level.

The Japanese network with a spatial resolution of 20 km is used for surveying as well as earthquake and volcano research for which it measures crustal movement in real time. Continuous analysis of the network with low latency provides a continuous picture of the displacements of the Earth's surface with high spatial resolution. Based on the network, Japanese scientists have provided valuable new insight into earthquake-related processes and have also detected slow earthquakes. Moreover, the network is increasingly used to monitor pre-seismic deformations and thus support mitigation of disasters.

GPS and gravity measurements are integral parts of any monitoring system of potentially hazardous volcanoes. The sketched observations system shown in fig. 12 includes gravity and surface displacements as crucial components. The importance of surface displacements is illustrated by the surface displacements taking place at Westdahl Peak (Alaska), which were not accompanied by increased seismicity. These displacements were observed by InSAR (fig. 13) and agree very well with the model predictions for a subsurface magma intrusion.

Precarious rocks and areas of potentially instable ground cause disasters recurrently in many countries. Norway has experienced a number of catastrophic rock slides, with the Lodalen Disasters being most prominent. In 1905 and 1936, large portions of Ramnefjellet fell down several hundred meters into the lake below and created devastating flood waves reaching up to 70 m in height (see fig. 14 for the rock slide area, and Nesdal, 1983, for more details). Different sources quote different numbers of people killed with the maximum numbers being 63 and 74 for the first and second slides.

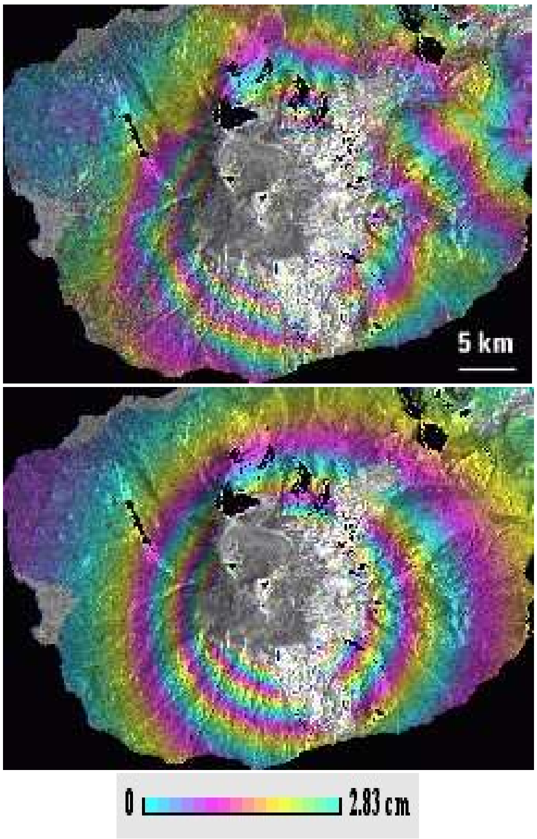

Figure 13: Observed and modeled displacements at Westdal Peak, Alaska.
Upper: Interferogram showing the observed displacements in the period 1993 - 1998. Lower: modeled displacements. Taken from http://volcanoes.usgs.gov.

The combination of steep topography with lakes and fjords has the potential of large waves created by rockslides into the lake or fjord below and pose a potential threat in many areas of Norway. Moreover, in many areas, the steep hill sides are potentially a threat for the people living at the base of these slopes or for the infrastructure at the bottom of such hills. In many areas, slow landslides pose a problem, too.

In known instable areas, networks of campaign-type or permanent GPS/GNSS stations can be used to detect a change in the motion and thus indicate a potentially perilious situation. However, the recurrence period of land- and rockslides can be very large and, in many areas, the risk is not obvious. InSAR is an emerging technology, which allows the determination of surface deformation with high spatial resolution and accuracy in many regions. InSAR

Figure 14: Rock slide area at Ramnefjellet, Norway.

is expected to play a leading role in the detection of geohazards and the monitoring of hazardous areas. InSAR has been successfully applied, for example, to the mapping of co-seismic displacements (e.g., Massonet et al., 1993), deformations at volcanoes (see fig. 13), silent landslides (Ferretti et al., 2004) and anthropogenic subsidence (see next Section). In particular, the combination of permanent GPS stations with InSAR is expected to improve the resulting time series of deformation considerably.

3.6.3 Anthropogenic hazards

Soil subsidence is a major anthropogenic hazard caused by groundwater, oil, and gas extraction as well as mining activities. Anthropogenic hazards also include earthquakes induced by mining and the filling of reservoirs, flooding as a consequence of river regulations or due to failure of reservoir dams, and land- and rockslides due to the effects of roads, railroad tracks, tunnels and buildings on the ground stability or anthropgenic changes in vegetation..

The anthropogenic hazards lead to considerable damage of property, and in the case of landslides, induced earthquakes, and flooding, also to loss of life. To illustrate the associated problems, in fig. 15, examples of damage to buildings and roads are shown for locations in Nevada, where groundwater extraction and the lowering of the groundwater level for mining purposes have rendered houses uninhabitable and have created large cracks in the soil and offsets in roads.

Figure 15: Damage caused by groundwater extraction.

The examples are a house in the Las Vegas area (upper and middle picture) severely damaged by soil subsidence due to groundwater extraction, and a major highway in Northern Nevada damaged by soil cracks and subsidence resulting from lowering the groundwater level for mining (lower picture). Courtesy John Bell.

The anthropogenic geohazards (subsidence,

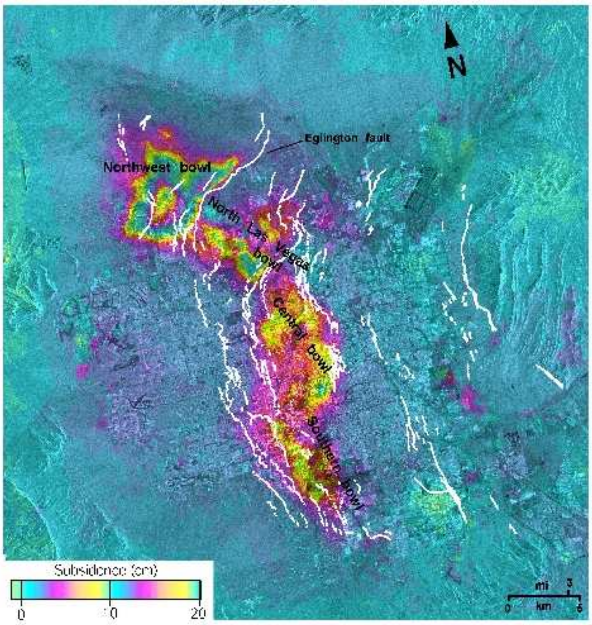

Figure 16: Subsidence pattern detected by SAR Interferometry in the Las Vegas area. Courtesy John Bell.

earthquakes, land- and rockslides) are associated with surface deformations which can be monitored with GPS/GNSS and InSAR. For example, interferograms of the Las Vegas area (fig. 16) show that the subsidence induced by groundwater extraction has a complex spatial pattern, which indicates that the aquifer response is strongly controlled by faults, and that these faults are barriers for subsidence (J. Bell, 2005, personal commun.).

In coastal areas, anthropogenic subsidence can combine with local sea level changes to constitute a severe threat to the coastal population and infrastructure. In the northern part of the Gulf of Mexico, a combination of sediment loading and oil extraction has caused local sea level in Galveston to rise nearly 1 cm/yr over the last 50 to 100 years. In Porto Corsini in the Adriatic, excessive ground water extraction has caused large subsidence of the soil and a local sea level increase reaching peak values of several cm/yr. Another example is the city of Venice and the Lagoon, where pumping of groundwater during the first half of the 20th century led to significant anthropogenic subsidence, which was superimposed on a natural subsidence of the lagoon due to tectonic and sediment-processes. The tide gauge record in Venice clearly shows a nonlinear behaviour (fig. 17) introduced by the anthropogenic subsidence (Woodworth, 2003). InSAR in combination with GPS allows the monitoring of the present-day subsidence, revealing the large spatial variability in subsidence caused by natural processes (e.g., chemical processes in the soil, Gambolati et al., 2005) and still ongoing anthropogenic processes (fig. 18).

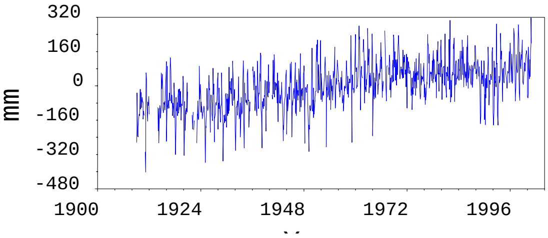

Figure 17: Monthly mean sea levels in Venice. *The record is for the tide gauge at Punta Della Salute in Venice. Data are taken from the PSMSL database.*

The monitoring of anthropogenic subsidence requires a high spatial resolution and the determination of changes in the secular velocity of vertical land motion on the level of 1 mm/yr. In areas with active mining and groundwater extraction, changes in secular land motion have to be available with low latency in order to detect potential hazards in a timely manner.

In order to detect seismic hazards induced by mining, monitoring of the strain rates in the mining area is the appropriate tool. The seismic hazard associated with the filling of large reservoirs is thought to be caused by changes in the subsurface pore pressure and not the loading-induced stress (Roeloffs, 1988; Talwani & Acree, 1985).

Potentially hazardous landslides, also slow landslides, associated with human activities can increasingly be detected by using InSAR. An example is given by Ferretti et al. (2004), who, in an analysis of InSAR-based time series of surface displacements, detected several instable areas in the San Francisco Bay area. In order to reveal such areas at an early stage of the development towards landslides or larger deformations, an accuracy of 1 mm/yr and high spatial resolution are required.

3.6.4 Monitoring of infrastructure, sensors, and processes

Increasingly, GPS&IGS is used to monitor the motion and stability of large infrastructures such as oil platforms, reservoir dams, and bridges. In areas of instabilities (potential landslides, precarious rocks, natural and anthropogenic subsidence, volcanic erup-

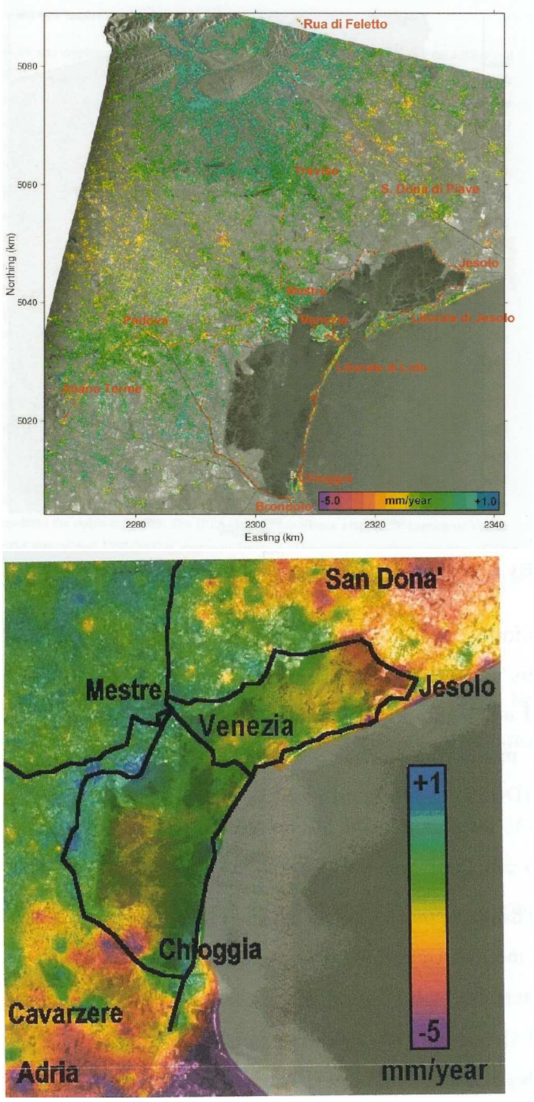

Figure 18: Natural and anthropogenic subsidence in the Venice area.
From Strozzi et al. (2003).

tions), the surface displacements of the Earth may have to be monitored as well. In some cases, these measurements can be carried out relative to a reference point that can be assumed to be stable. However, in many cases no such point can be identified and the optimal reference is a regional or global network.

Experience with oil platforms shows that user requirements for monitoring of such infrastructure are less than 1 cm for sub-daily positions available with a latency of a few days and 1 mm/yr for long-term stability. Similar requirements apply to reservoir dams and large bridge, however, here the tolerable latency may be much lower.

Fig. 19 gives an example of monitoring the motion of an oil platform with the help of GPS. The vertical movement of the platform is dominated by the settlement into the ocean floor, which is theoretically expected to be proportional to $\sqrt{t}$, where t is time. Daily coordinates determined from GPS measurements with precise point positioning allow the estimation of physically relevant parameters of the settlement curve. Combining the GPS observations with independent measurements of the settlement, which are obtained by monitoring the movement of the platform with respect to an invar rod solidly fixed to the ocean bottom, leads to the determination of the motion of the sea floor in a geocentric reference frame. This, in turn, is important information for reservoir modeling.

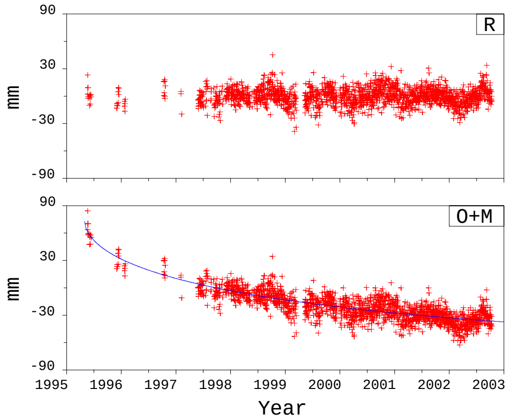

Figure 19: Monitoring of vertical motion.
Lower diagram: Daily vertical displacements (symbols) determined from GPS measurements on an oil platform and fitted settlement curve ($\sqrt{t}$ plus linear trend, where t is time, solid line). Upper diagram: residuals with respect to the settlement curve. O: Observations, M: Model, R: Residuals.

In the example, sea floor turns out to be uplifting by a few mm/yr relative to ITRF2000. An unsolved question is how much this number is affected by long-term trends in ITRF2000 and its approximation through GPS (Kierulf & Plag, 2006). The residual vertical motion with respect to the settlement curve contains intra-annual variations of the order of ±2 cm, which are largely due to so-called *Common Mode Variations* (CMV) affecting precise point positioning based on GPS.

Another example is the determination of instantaneous subsidence rates of oil platforms on monthly to annual time scales. In the absence of a local stable reference frame, the global network of IGS tracking stations can be used as reference. From time series of daily coordinates determined by precise point positioning, velocities can be determined on the ba-

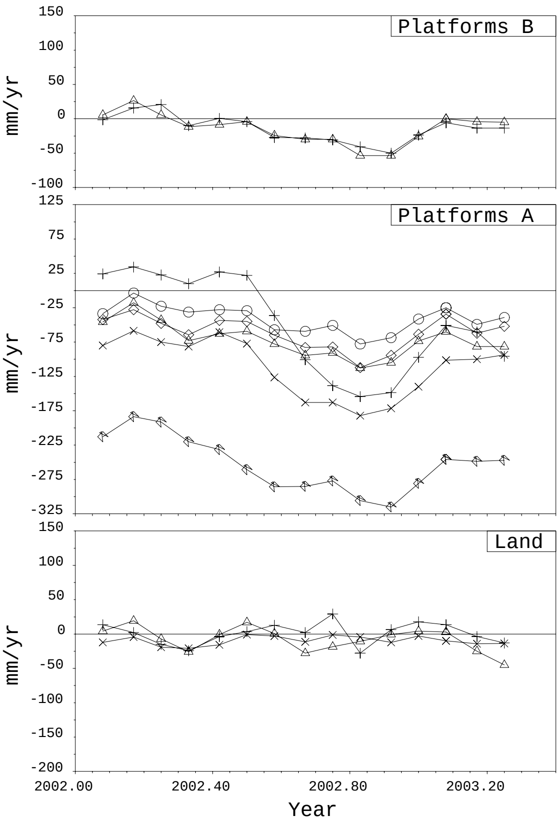

Figure 20: Monitoring of vertical velocities.

Vertical velocities determined on the basis of a moving four-month window. Upper diagram: For two offshore platforms assumed to be not or very moderately subsiding. Middle diagram: For six different offshore installations known to be subsiding and separated by up to 30 km. Lower diagram: For three reference stations in Europe (namely Stavanger, Norway, Herstmonceux, U.K. and Westerbork, The Netherlands). The velocities are computed from time series of daily coordinates determined by precise point positioning. No corrections for CMVs have been made. The velocities of the reference stations on land indicate the order of magnitude of CMV effects on velocities.

sis of a moving window. In fig.20, the vertical velocities resulting from a four-month moving window are shown for both offshore locations (oil platforms) and reference stations on land. The reference stations (selected arbitrarily in the region around the North Sea) are Stavanger in Norway, Herstmonceux in the U.K., and Westerbork in The Netherlands. The sites, though separated by up to a thousand kilometers, show some coherent variations which indicate the effect of CMV with large spatial scales and temporal scales of several months on the velocities. The velocities for the platforms show larger variations than those found at the reference sites. However, decontamination of the coordinate time series for the CMVs prior to the determination of velocities is a crucial issue. For that, the global network of tracking stations provides the observational basis.

Highly accurate positioning of sensors for example for airborne gravimetry and hydrographic surveys require on the one hand positions with high temporal resolution (down to 1 second) and an accuracy of the order of 10 cm. On the other hand, they also require a high long-term stability as measurements are carried out over long time intervals (decades) and should be interconnectable without loss of accuracy. Hydrographic surveys on, for example, marine oilfields require an accuracy of 5 cm over a time span of up to 50 years, which is equivalent to a long-term stability of 1 mm/yr.

Today, geodatabases are collected at a rate that has increased by several orders of magnitude over the last few decades. The databases collected today can be expected to be in use for many years. Even without assuming likely increased future requirements for the accuracy, this will demand a high long-term stability of the reference frame used for the databases.

GPS is increasingly used for control of processes in agriculture, construction work, and maintenance, for example. For all these applications, a high accuracy of 10 cm (for most agricultural applications) down to 1 cm (for snow clearing) and even subcentimeter (for construction work) is required in real time. Currently, for all these applications, local augmentation systems have to be set up. However, improved satellite orbits and clocks made available in real time will allow basing many of these applications on GNSS and precise point positioning.

3.6.5 Navigation and real time positioning

GPS is increasingly used for positioning in real time and navigation. When the U.S. Department of Defense on May 1, 2000, switched off the noise on the satellite clocks (*Selective Availability*, SA), this resulted in an increase in accuracy of the SPS of GPS from approximately 50 m to now 10 m for a single frequency GPS receiver. Such a receiver computes the receiver position as it receives broadcast satellite orbits and clocks as well as pseudo-ranges from several satellites.

For many applications in navigation, an accuracy of 10 m is not sufficient. An overview of the requirements is given in the *Proposed Baseline European Navigation Plan* (ERNP, see Booz-Allen & Hamilton, 1995). In the ERNP, the term 'navigation' is used for applications related to the security of persons (safety-of-life), while the term 'positioning' is used for all other applications. For navigation, the ERNP distinguishes between marine traffic, aviation, and traffic on land.

For most applications in navigation, integrity, reliability, and accessibility of the system are critical parameters, while accuracy is mostly not critical and easier to achieve. However, for docking and landing, both integrity and accuracy are critical.

For positioning, the ERNP identifies the following broad applications:

- mapping;
- engineering (surveying of infrastructure);
- monitoring of infrastructure;
- hydrography and oceanographic studies;
- exploration of resources;
- development of GIS;
- political and administrative borders;
- environmental monitoring;
- research (geodetic, geophysical, geodynamic);
- Earth observation;
- determination of satellite orbits;
- control of processing;
- outdoor activities;
- time and frequency transfer.

A complete overview of the requirements and specifications for these areas can be found in ERNP Exhibits 2-11 to 2-13. In the previous sections, we have already discussed most of them in detail. Those that have requirements less demanding than those discussed above are, for example, political borders, outdoor activities, exploration of resources, GIS, and many mapping applications. However, up to now, many of these use national reference frames with fixed coordinates, which creates problems when transformations between the global and national reference frames need to be updated. Also, for these cases it is advantageous to use a global, time-dependent reference frame at least for the database and to transform these coordinates into the national reference frame when needed.

3.6.6 Nongeodetic applications

When traveling through the troposphere, the electromagnetic waves experience a path delay, which can be used to extract information on the precipitable water content of the troposphere (see Chapter 2 in Elgered et al., 2004, for details). Currently, the meteorological observation systems do not provide sufficient information on this valuable parameter. In the context of the COST Action 716[2], it is demonstrated that having available the path delays in near-real time (< 1 hour latency) is an asset for numerical weather prediction, and a future use of ground-based GPS or Galileo networks for numerical weather prediction and climate applications seems likely. The quality of the path delays depends on the orbit and clock accuracy and the accuracy in position for the sensor stations. The accuracy requirements for numerical weather prediction applications are of the order of 1 cm in day-to-day position while climate applications require a long-term stability of the order of 0.1 mm/yr or better (Elgered et al., 2004).

The requirements for different meteorological and climatological applications are compiled in table 7. The generic requirements are independent of any particular observation system. The GPS meteorology requirements are specific for the GPS network in Europe. Meteorological nowcasting, or very short-range weather prediction, is based on a quantitative assessment of weather parameters and requires very low latency and high spatial resolution. Numerical weather prediction has similar accuracy requirements but can tolerate slightly longer latency and lower spatial resolution. Climate applications pose a very high demand on the long-term stability, which currently is not achievable with the available reference frame.

3.7 Summary of User Requirements

The current and likely future accuracy requirements for access to positions in a terrestrial reference frame are summarized in table 8. These requirements can be set up as function of time scales or as function of latency. Depending on time scales, expected accuracy requirements for a large range of high-accuracy applications are less than 5 mm for diurnal and sub-diurnal time scales, 2-3 mm on monthly to seasonal time scales, better than 1 mm/yr on decadal to 50 years time scales.

Using the acceptable latency as independent parameter, we can identify three main *User Categories* (UC) for high accuracy applications requiring or benefiting from precise point positioning. ***Real time positioning*** constitutes the first category (UC1). For these users, the most extreme accuracy requirements are expected to be considerably less than 10 cm (e.g., sensor positioning, hydrographic measurements, automated snow-plowing), and in some cases even less than 1 cm (e.g., control of large mining and construc-

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[2] See http://www.oso.chalmers.se/~kge/cost716.html.

Table 7: Requirements for meteorological applications of GPS.

Accuracy requirements are for IPWV in kg/m^2 or path delay in mm. Values are from Elgered et al. (2004).

Nowcasting		
Requirement	Generic	GPS Meteorology network
Horizontal domain	Sub-regional	Europe to national
Horizontal sampling	5-50 km	10-100 km
Repetition cycle	0.25 - 1 h	5 min - 1 h
Absolute accuracy	1-5 kg/m^2	1-5 kg/m^2
Timeliness	0.25-0.5 h	5 - 30 min

Numerical Weather Prediction				
Requirement	Generic		GPS Meteorology network	
Horizontal domain	Global	Regional	Global	Regional
Horizontal sampling	50-500 km	10-250 km	50-300 km	30-100 km
Repetition cycle	1-12 h	0.5-12 h	0.5-2.0 h	0.25-1.0 h
Integration time			MIN(0.5 h, rep. cycle)	MIN(0.25 h, rep. cycle)
Absolute accuracy	1-5 kg/m^2	1-5 kg/m^2	3-10 mm	3-10 mm
Timeliness	1-4 h	0.5-2 h	1-2 h	0.5-1.5 h

Climate Monitoring		
Requirement	Generic	GPS Meteorology network
Horizontal domain	regional-global	All
Horizontal sampling	10-100 km	10-250 km; indiv. stat.
Time domain	>> 10 years	Weeks to many years
Repetition cycle	1 h	1 h
Absolute accuracy	0.25-2.5 kg/m^2	1 kg/m^2
Long-term stability	0.02-0.06 kg/m^2/decade	0.04-0.06 kg/m^2/decade
Timeliness	3-12 h	1-2 months

tion equipment). Some real time applications will require high integrity (e.g., process control) and high update rates. The next category (UC2) comprises ***Near-real time positioning and other near-real time applications***. Here, accuracy requirements will be close to 1 cm in most of these applications (monitoring of infrastructure, meteorological applications) while other applications will require less accuracy (e.g., of the order of 5 cm) but higher integrity (e.g., land surveying). Finally, UC3 includes all ***Post-processing with extreme requirements***. Most of these applications can accept considerable latency but will require accuracy at the 1 cm level or better for daily coordinates and a few millimeters or better on intraannual time scales. For long-term monitoring tasks, 1 mm/yr or better in stability seems to be a critical boundary both for scientific and nonscientific tasks. This number also applies to collection of geodatabases, which are to be maintained over time scales of several decades.

Depending on the time scale, we see the latency and accuracy requirements for high accuracy applications summarized in table 9. Presently, GPS&IGS satisfy most of the requirements for UC3, though the stability of this combined system is still not meeting the 1 mm/yr limit due to deficiencies in the stability of the underlying ITRF and its relation to the CM. Moreover, too many and uncoordinated changes in the IGS tracking network with respect to number of stations, hardware, software, processing strategy, and theory for programs further decrease the stability of the system. Thus, the GPS&IGS system still appears to be in a research and pre-operational state.

GPS&IGS does not meet the UC1 requirements due to properties of the GPS-alone system combined with the large latency for required IGS products. For this UC, local and regional augmentations are currently required.

Some but not all needs of the UC2 are met by GPS&IGS but the large latency of the precise IGS products and the insufficient accuracy of the rapid IGS products leave a considerable share of this UC in need of local or regional augmentation systems.

While UR1 and partly UR2 in table 9 can be met by local to wide-area augmentation systems, UR3 and UR4 depend crucially on the quality of ITRF and the available products. Moreover, achieving UR1 and UR2 through a *Signal in Space* (SiS, that is the signal received from the GNSS satellites) only system would considerably increase the areas of applications

Table 8: URs for access to position.

Fr. stands for Frame, where we distinguish L: local frames, N: national frames, G: global frame. Repro. stands for Reproducibility and gives the time window over which positions are expected to be reproducible with the stated accuracy. Note that navigation has been excluded since it has complex requirements depending on the particular application.

Application	Parameter	Accuracy	Latency	Fr.	Repro.
Surveying with precise point positioning	3-d coor. velocity	10 to 50 mm 1 mm/yr	days n/a	N	decades
Monitoring	3-d coor velocity	< 10 mm < 10 mm/yr	days weeks	L L	decades decades
Control of processes	horizontal	10 to 100 mm	seconds to minutes	L	decades
Construction	3-d	< 10 mm	seconds to minutes	L	months to years
Early warning	3-d	10 mm	seconds to minutes	G	days
Hazards and risk assessments	3-d	< 10 mm	days to months	G	decades
Numerical weather prediction	IPWV	1-5 kg/m^2	5-30 minutes	G	decades
Climate variations	IPWV	1 kg/m^2	1-2 months	G	decades
Scientific studies	3-d coor. velocity	< 10 mm < 1 mm/yr	n/a n/a	G G	decades decades
Earth observations	3-d coor. velocity	< 10 mm < 1 mm/yr	days n/a	G G	decades decades

Table 9: Overview of latency and accuracy requirements of main user categories.

Class	Requ.	Latency	time scales	accuracy
UC1	UR1	real time	seconds to minutes	< 10 cm
UC2	UR2	hours to days	sub-diurnal to diurnal	< 5 mm
UC3	UR3	weeks to months	monthly to seasonal	2-3 mm
	UR4	$>$ months	interannual to secular	< 1 mm/yr

and provide significant economic advantages (see Section 8).

For most scientific applications requiring knowledge of the Earth surface kinematics, we have identified the accuracy requirement to be of the order of 1 mm/yr or less. Similarly, using precise point positioning for the determination of coordinates in a national reference frame, also requires knowledge of the velocity field with an accuracy of 1 mm/yr in all three components. Monitoring of infrastructure and hazardous areas have the same requirement on the accuracy of the velocity field.

The accuracy requirements for the geoid for the full utilization of satellite altimetry are of the order of 1 cm for wavelengths down to a few tens of kilometers, translating into an accuracy of 10^{-9} or better. In order to monitor the mass movements in the Earth system and particular the global water cycle, accuracy requirements are on the order of 10 mm of equivalent water column for spatial wavelengths of 500 km, which translates into 0.2 mm in geoid height and 3 nms^{-2} for gravity. Temporal resolution is on the order of 1 month.

For practical applications, the requirements for Earth rotation are dominated by the effect on positioning and the operation of satellite systems. For precise point positioning, errors in Earth rotation map directly into position errors. For example, an error of 1 mas (milliarcseconds) in polar motion corresponds to errors in horizontal displacements of the

Earth's surface of about 30 mm, while an error of 1 ms (millisecond) in time corresponds at the equator to an error of about 460 mm in displacement. These numbers illustrate the high consistency between the terrestrial reference frame and Earth rotation, which is required to links the satellite frame to the terrestrial frame. For a low-latency access to precise point positions with an accuracy of 1 cm, the corresponding instantaneous accuracy for Earth rotation would be 0.3 mas and 0.02 ms in polar motion and rotation, respectively. Rothacher et al. (2001) report discrepancies between Earth rotation parameters determined with high temporal resolution from GPS and those determined from VLBI and SLR to be orders of magnitude better than these requirements.

However, particularly at sub-daily temporal resolutions, the present low-latency or near-real time accuracy of Earth rotation observations and predictions is likely to contribute significantly to the error budget at the 1 cm level. de Viron et al. (2005) point out that for the determination of gravity field changes with missions like GRACE, diurnal and sub-diurnal effects of the atmosphere on Earth rotation are of importance for the orbit determination. Based on a model study, they find that atmospheric angular momentum variations at diurnal timescale can produce polar motion near 0.2 mas. On time scales of several days, atmospheric effects can reach several milliarcseconds (Lambert et al., 2006), corresponding to 10 cm or more in displacement.

Other requirements on Earth rotation result mainly from scientific applications, and for these applications, an increasing accuracy of the observations normally leads to new applications. Examples are questions related to the effect of earthquakes (e.g., Chao & Gross, 2005), volcanic eruptions, and seasonal mass motion on the Earth's surface (e.g., Chen & Wilson, 2003; Gross et al., 2004) on Earth rotation, where the current accuracy of the observations as well as the sophistication of models (see Salstein et al., 2001) are limiting the scientific understanding of the processes on a rotating Earth. Likewise, the current accuracy is at the margin of what is required to achieve improvements in understanding and modeling of Earth rotation changes induced by interactions of the solid Earth with its fluid envelop (e.g., Plag et al., 2005b). For studies of the interaction between fluid core and solid mantle, the length of the space-geodetic Earth rotation record with high accuracy appears to be the main limitation. Secular rates are compromised by the lower accuracy and potential instabilities of the older parts of the record, which limits its application to studies of, for example, postglacial rebound effects on Earth rotation (see, e.g., Mitrovica & Milne, 1998).

4 Characteristics of the fundamental geodetic observables

4.1 Introduction

Changes in the Earth's shape, its gravitational field and its rotation are caused by external forces acting on the Earth system and internal processes involving mass transfer and exchange of angular and linear momentum. Thus, variations in these geodetic quantities are the consequence of the mechanical and thermodynamic processes in the Earth system.

For the modeling of the mechanical processes in the Earth system, the system can be viewed as composed of subsystems such as crust and mantle, outer and inner cores, and the fluid envelop of the solid Earth (fig. 21). The latter consists of ocean, atmosphere, and terrestrial hydrosphere, which are the prominent components of the climate system. The biosphere is also interacting with the components of the climate system, and, considering the anthroposphere as part of the biosphere, also the solid Earth. We have chosen not to separate the cryosphere from the ocean and terrestrial hydrosphere, but rather consider the ice load on land as part of the terrestrial hydrosphere and sea ice as part of the ocean.

The subsystems depicted in fig. 21 interact through surface forces at the joining boundaries and through volume forces due to gravity or electromagnetic fields. The overall system is subject to external forces including tides and the extra-terrestrial magnetic field. Additionally, radiation absorbed in the system and interaction with solar wind change the dynamical state in the system and thus these external forcings have to be considered as input to the mechanical system.

The Earth's rotation is an integral quantity affected, in principle, by all processes changing the mass distribution and the dynamics of the system. Thus, the rotation is ultimately coupled to deformations and variations of the gravity field of the Earth.

In this mechanical view, the geometry of the solid Earth as well as the mass distribution in its interior are determined by the forces acting on the solid Earth, such as tidal forces, surface loading, and

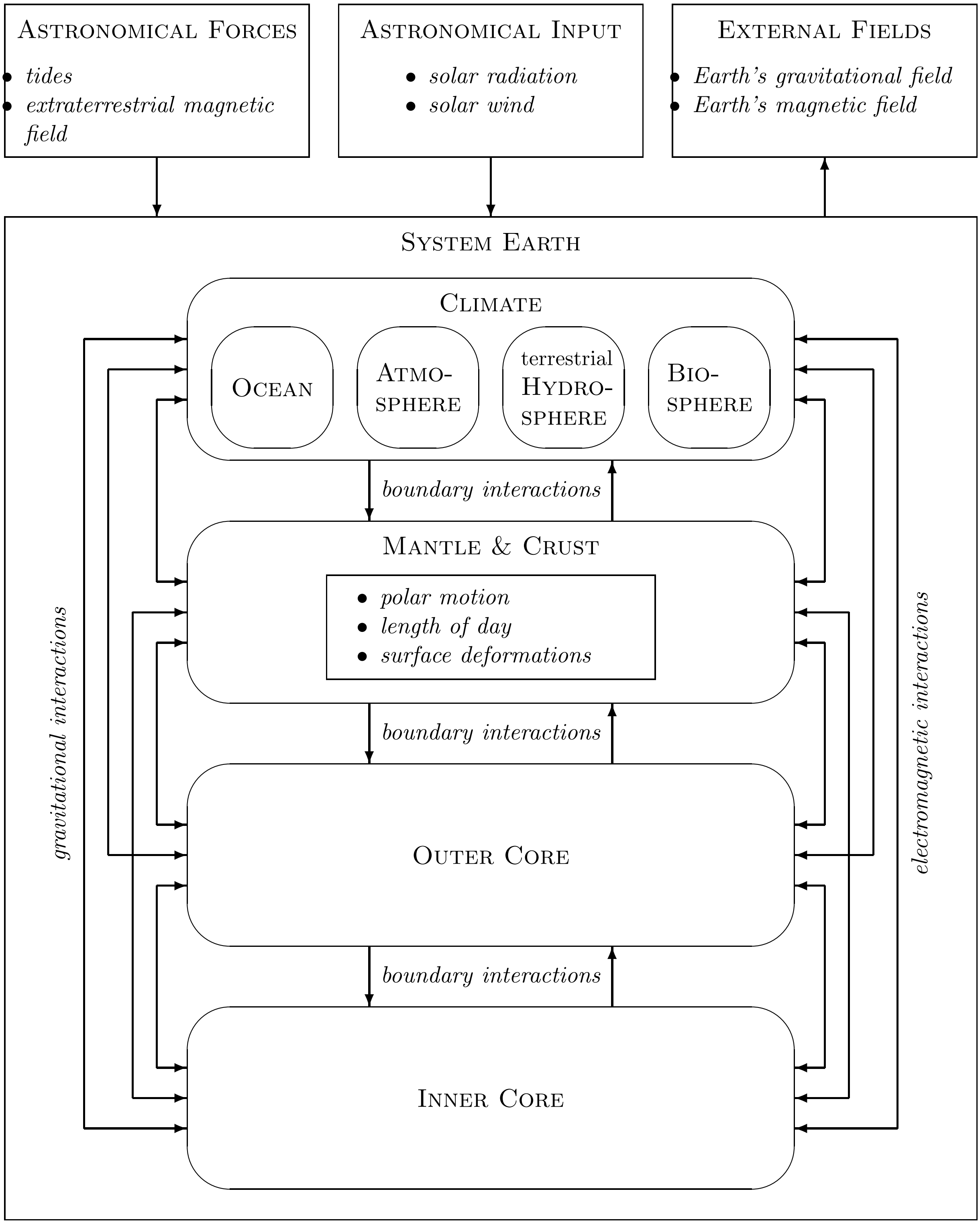


Figure 21: Components of the Earth system and their mechanical interactions.

variation in the Earth's rotation and gravitational field, as well as forces inside the solid Earth, such as slow redistribution of mass due to convection. With respect to surface loading due to mass redistribution in the ocean, the atmosphere, and the terrestrial hydrosphere, it is important to note that any of these mass movements changes the Earth's gravitational fieldprimarly due to the mass movements, and, secondarily, due to deformations of the solid Earth. Any of these changes will affect the mass distribution in the ocean and thus create additional loads and variations in the three geodetic quantities.

In addition to the mechanical forces, on longer time scales we also have to consider thermodynamic forces driving the convection in the Earth's mantle and core and creating phenomena such as volcanism and plate tectonics. However, for a description of the main characteristics of the geodetic variables, the mechanical view provides a valid basis.

4.2 Changes in the shape of the Earth

The Earth's surface is perpetually deforming due to a variety of internal and external forces, acting on time scales from seconds to millions of years (table 10). Earthquakes lasting from seconds to several minutes may lead to displacements of several meters in large areas with the associated displacement field extending from several hundred kilometers for medium earthquakes to global for the largest earthquakes such as the recent Sumatra earthquake of M_w 9.2 (see, e.g., Kreemer et al., 2006a; Plag et al., 2006, and the references therein). Seismic waves including free oscillations of the Earth have periods of up to 1 hour, and far away from the seismic source, these waves can have amplitudes of the order of 1 mm. The barotropic waves of tsunamis constitute a high-frequency load on the Earth's surface, displacing the surface on the order of 1 cm. Earth tides lead to surface motions of up to 40 cm on semi-diurnal time scales and somewhat smaller on diurnal ones. Ocean tidal loading may contribute at the same periods as the Earth tides up to several centimeters in vertical displacement at coastal sites and several millimeters in the horizontal components. Atmospheric and hydrological loading induces vertical displacements of more than 1 cm on up to seasonal time scales. Polar motion contributes motion of several millimeters at the annual and the Chandler period (the latter being about 14 months). Current changes in the ice sheets and glaciers can introduce large local trends in vertical displacements of the order of 10 mm/yr due to unloading (e.g., James & Ivins, 1995; Wahr et al., 2001a,b; Sato et al., 2006b), which are also associated with significant changes in the local and regional geoid (e.g., Velicogna & Wahr, 2005) and sea level (e.g., Plag & Jüttner, 2001; Mitrovica et al., 2001; Tamisiea et al., 2001). Post-glacial rebound leads to secular vertical motion of up more than 10 mm/yr in the center of uplift and horizontal motion of several mm/yr (e.g., Milne et al., 2001; Peltier, 2004) while geoid changes are of the order of a few mm/yr. Plate tectonic motion contributes secular horizontal motion of up to 10 cm/yr while in some deformation zones at plate boundaries even larger velocities can occur. Human activities such as groundwater and oil extraction as well as mining, often over several decades, can induce surface motion with vertical velocities of several cm/year and spatial scales from a few to several hundred kilometers. Subsidence due to, for example, extraction of groundwater, oil and gas can exceed 20 to 30 cm/year locally and cause severe damage. Close to artificial reservoirs, the changes in the water load can induce vertical displacements of the order of a few millimeters (e.g., Kaufmann & Amelung, 2000). On longer time scales of several years to decades, mass redistribution in the ocean, the terrestrial hydrosphere, and the cryosphere loads and deforms the Earth with vertical displacements of the Earth's surface in the order of several mm/yr and spatial scales ranging from local to global.

For many of the contributions listed in table 10, models exist for high-accuracy predictions of displacements of the Earth's surface, if the forcing is known. An overview of the state of the art is given in McCarthy & Petit (2003). Thus, contributions from solid Earth tides, ocean tidal loading, and polar motion can be modeled on the millimeter level. In stable areas of the tectonic plates, secular motion due to plate tectonics can be predicted for horizontal motion on the level of a few mm/yr on most plates (DeMets et al., 1994; Kreemer & Holt, 2001; Kierulf et al., 2003; Kreemer et al., 2003), while models for vertical displacements are absent. Only for the vertical motion induced by post-glacial rebound, the secular velocities can be predicted to the level of a few mm/yr in most areas of the globe, but with less accuracy for the regions around Greenland and Antarctica. The larger uncertainty in these two regions is due to large uncertainties in the ice history, particularly over the last 10,000 years.

A good means to understand the remaining, un-

Table 10: Factors causing motion of points on the Earth's surface.

Some of the contributions caused by surface loading are discussed in Van Dam et al. (2003).

Factor	Time scale	spatial scale	amplitude range	Model accuracy
Earthquakes	Minutes	depending on magnitude, up to several 100 km for large earthquakes and globally for great ones	several meters in the near-field, and order 1 mm and more in the farfield.	Past-event models have accuracy of 5 mm in the far field and a few cm in the medium range field.
Free Oscillation	up to 1 hour	global	mm	-
Tsunamis	up to 1 hour	up to 300 km	order 1 cm in vertical	limited due to only a static solution being available
Semi-diurnal and diurnal tides	approx. 12 and 24 hours	global	40 cm	1 cm
Ocean tidal loading	approx. 12 and 24 hours	several 100 km	at costal sites several cm	$<$ 1 cm, in some coastal locations worse. Mainly determined by the accuracy of the ocean tide model
atmospheric loading	days to inter-annual	increasing with temporal scales, 100 to several 1000 km	1-2 cm vertical, few mm horizontal	better than 1 cm
nontidal ocean loading	mainly five to seven months, also secular	increasing with temporal scale, 50 to 200 km on short time scales, up to several 1000 km on long time scales	1 cm vertical, few mm horizontal, order of 1 mm/yr secular	limited for secular time scales due to problems with mass conservation of models
terrestrial hydrological loading	days to interannual, also secular	increasing with temporal scale, $<$ 50 to several 1000 km	1 cm vertical, few mm horizontal, order of 1 mm/yr secular	mainly limited by accuracy of models of terrestrial water storage.
anthropogenic extraction (oil, gas, ground water, mining)	years to decades	local	several cm/yr	limited by the available information on the load changes.
polar motion	Annual and Chandler Wobbles, secular	global	several mm	$<$ 1 mm
current ice load changes	decades	local to regional	20 mm/yr and more in the vertical	mainly limited by the knowledge of the load changes.
post-glacial rebound	secular	1000 km and more	order of 10 mm/yr vertical, few mm/yr horizontal	1-2 mm/yr
plate tectonics	secular	size of plate in stable area, small scales (10-100 km) in deformation zones	several cm/yr horizontally, several mm/yr vertical in deformation zones	in stable areas: a few mm/yr, several cm/yr in the horizontal otherwise

modeled displacements of the Earth surface is the analyses of coordinate time series determined with geodetic analyses of long CGPS observations. Time series of daily or weekly point coordinates are determined on an operational basis for a large number of CGPS sites by the IGS and EUREF ACs as well as a number of other groups. In the analysis, a detailed geophysical model for the ground motion at the station is taken into account, thus removing the major part of the motion due to solid Earth tide, loading tides and polar motion. The resulting time series facilitate the study of any additional station motion not taken into account in the station motion model. Examples of daily coordinate time se-

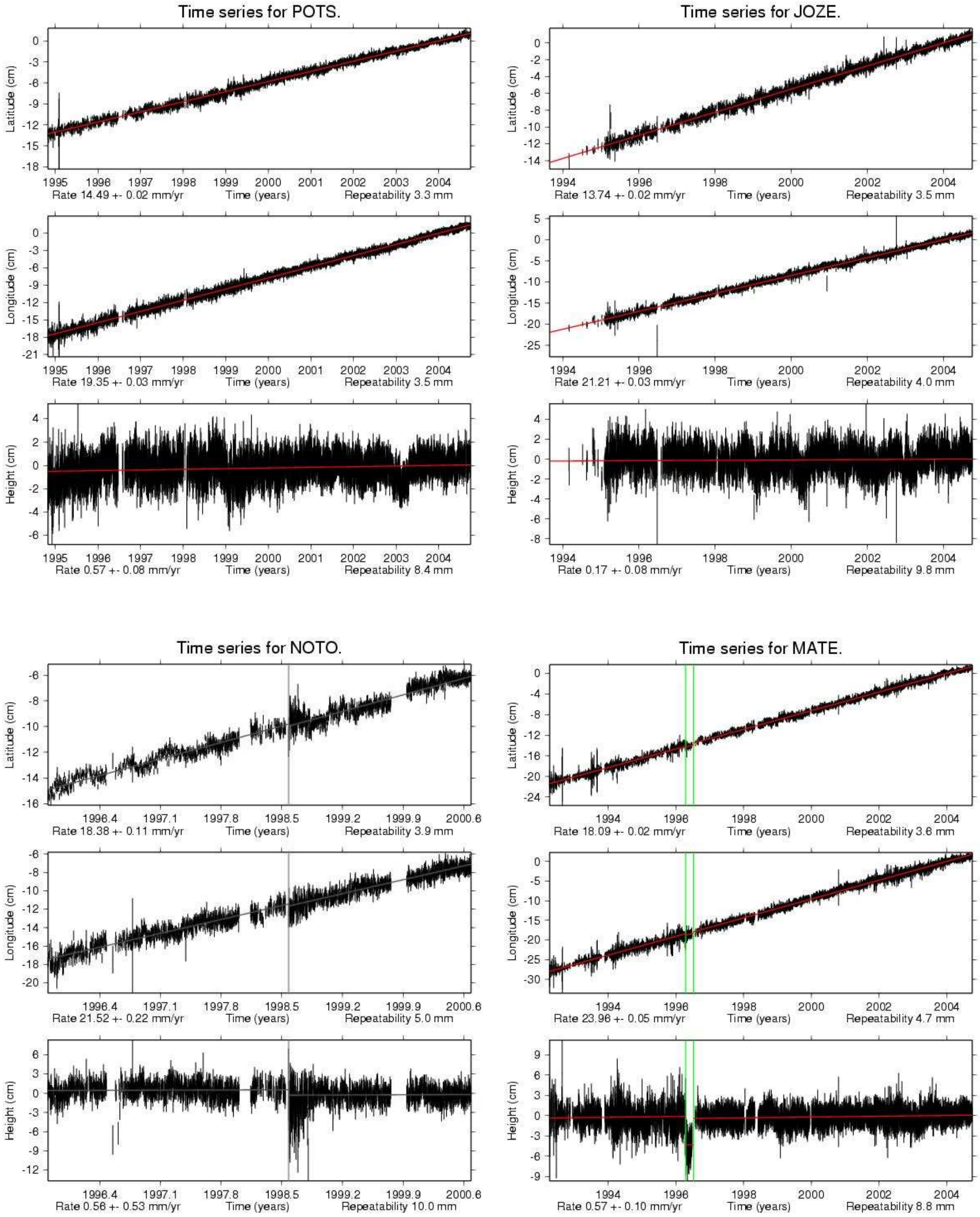


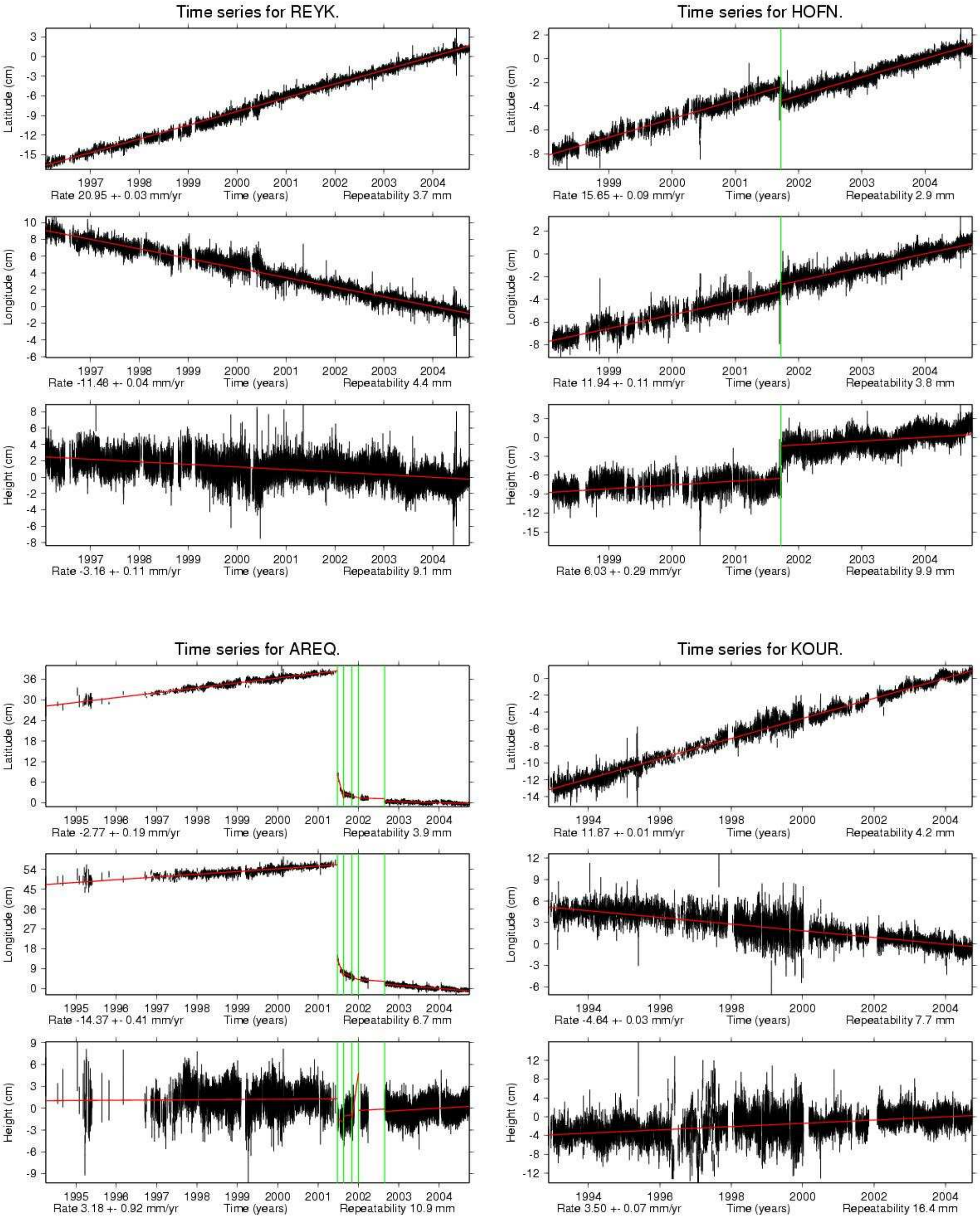
Figure 22: Examples of CGPS time series for continental European locations.

The sites are POTS: Potsdam, Germany; JOZE: Jozefosl, Poland, NOTO: Noto, Italy; MATE: Matera, Italy. The plots are taken from http://sideshow.jpl.nasa.gov/mbh/all/POTS.html and http://sideshow.jpl.nasa.gov/mbh/all/JOTZ.html.

ries for a large number of CGPS sites can be found, for example, on the web page with GPS time series (http://sideshow.jpl.nasa.gov/mbh/series.html) maintained by the *Jet Propulsion Laboratory* (JPL).

At most sites in tectonically passive areas, the CGPS time series of daily or weekly coordinates exhibit a linear velocity superimposed with intra-seasonal to seasonal nearly periodic signals. In fig. 22, the time series for four sites at continental European locations are shown. The two Central European sites (POTS and JOZE) are in a region, which is considered to be tectonically stable. The horizontal components show a nearly linear trend which is primarily due to tectonic plate motion. The horizontal velocities at these two sites are in good agreement with the velocities predicted by plate tectonic models. The day-to-day variations are of the order of 1 to 2 cm, except for a few isolated spikes. There are only minor long-period variations in the time series of the horizontal components.

The vertical component shows a significantly higher noise level (of the order of 2 to 3 cm). More-



Time series for REYK.

Time series for HOFN.

Time series for AREQ.

Time series for KOUR.

Figure 23: Examples of CGPS time series.

The sites are REYK: Reykavik, Iceland; HOFN: Hofn, Iceland; AREQ: Arequina, Peru; KOUR: Kourou, French Guyana. The plots are taken from http://sideshow.jpl.nasa.gov/mbh/all/NOTO.html and http://sideshow.jpl.nasa.gov/mbh/all/MATE.html.

over, there are long-period variations on intra-annual to inter-annual time scales. Vertical trends are small at the two locations and in good agreement with the expectations from geophysical considerations.

The two sites in Italy shown in fig. 22 (MATE and NOTO) display a horizontal motion comparable to the two Central European sites. However, these two sites reveal another characteristics found in many CGPS time series, that is, temporal inhomogenieties. Partly, such inhomogeneities are due to changes of equipment or changes in the micro-environment close to the GPS antenna. The higher noise level found for older parts (prior to approx. 1997), also visible for the station KOUR (see fig. 23) can at least partly be attributed to lower density of the IGS network and a less developed processing methodology leading to satellite orbits and clocks of lower accuracy. In some case, though, this may also be due to equipment changes and receiver performance.

In tectonically more active areas close to plate boundaries, such as Iceland, sites not far away from each other can show significantly different secular rates (for example, REYK and HOFN, see fig. 23). Reykjavik is on the American plate and consequently moves towards the North-West, while Høfn on South-Eastern Iceland has an North-East velocity. Moreover, in all three components nonlinear movements are discernable, which may be associated with earthquakes or changes in the plate motion. The length of the baseline between the two sites increases with more than 20 mm/yr.

In many regions of the world, only a few sites have been recording for ten years or more. In South America, sites on the East and West Coasts show different East-West velocities (for example, KOUR and AREQ, respectively, see fig. 23) indicating the intraplate effect of plate tectonics particularly at the West Coast (i.e. shortening of the base line between KOUR and AREQ of more than 10 mm/yr). In 2001, earthquakes caused significant offsets in all three components at AREQ and also induced changes in the secular trend in the horizontal components. Similar, but much larger offsets are found for great earthquakes, where local offsets reach more than 20 m horizontally and of the order of 5 m vertically (e.g., Lay & 13 others, 2005). Great earthquakes can induce geodetically significant displacements of the order of > 10 mm over a radius of more than 2000 km (e.g., Plag et al., 2006), and globally the offsets are > 0.1 mm. Moreover, post-seismic deformation go on over a long period (several years) and, for great earthquakes, can degrade the reference frame in a large area for a long time. As an example, the post-seismic displacements for two stations in East Asia caused by the two recent Sumatra earthquakes are shown in fig. 24.

Considering the spectrum of the coordinate time series, residual periodic signals have been reported with amplitudes of up to 10 mm (e.g., Dong et al., 2002). For the seasonal period, a large part of the signal is assumed to originate from atmospheric and hydrological loading (see, e.g., Blewitt & Lavallée, 2002; Dong et al., 2002) while the origin of several intraseasonal signals remains obscure. Spatially, the seasonal signal is dominated by large spatial scales, and models are emerging for the removal of the signal from the time series using, for example, a regional filtering approach (Wdowinski et al., 1997; Nikolaides, 2002). After regional filtering, the day to day variations can be at the 1 mm level for the horizontal components and a few millimeters for the vertical component (e.g., Blewitt et al., 2005; Hammond & Plag, 2005). However, if not carried out carefully, regional filtering can have the disadvantage of weakening the tie of the resulting time series to the global reference frame. On shorter time scales, incorrectly modeled station motion due to Earth tides, ocean tidal and other surface loading, and polar motion can contribute to periodic signals in the coordinate time series.

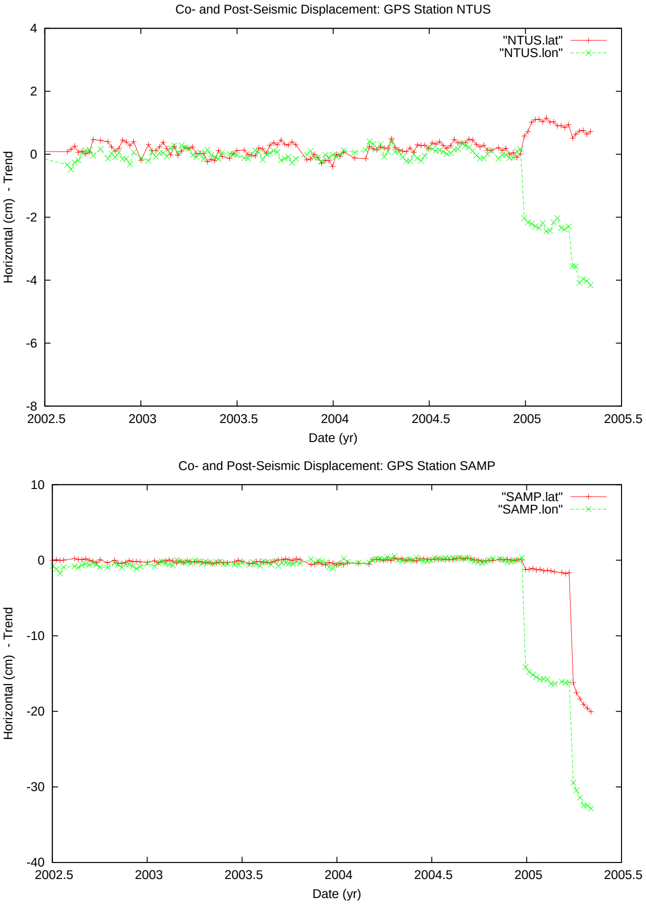


Figure 24: Post-seismic nonlinear displacements. *The sites are NTUS and SAMP. From Plag et al. (2005a).*

In fig. 25, the variance spectrum for all three components are shown for two stations on the Norwegian mainland and Svalbard. In the height component, significant peaks are located at the annual and semiannual frequency with typical amplitudes of 3-4 mm and 2-3 mm, respectively. These signals are expected to be related to atmospheric and other surface loading not taken into account in the GPS analysis. Moreover, multipath may exhibit seasonal variations and contribute to the periodic signals in the spectrum. There are some higher frequency intra-annual signals, but these do not show spatial coherency. At frequencies lower than one cycle per year, no signals are found.

For the East component, an annual constituent

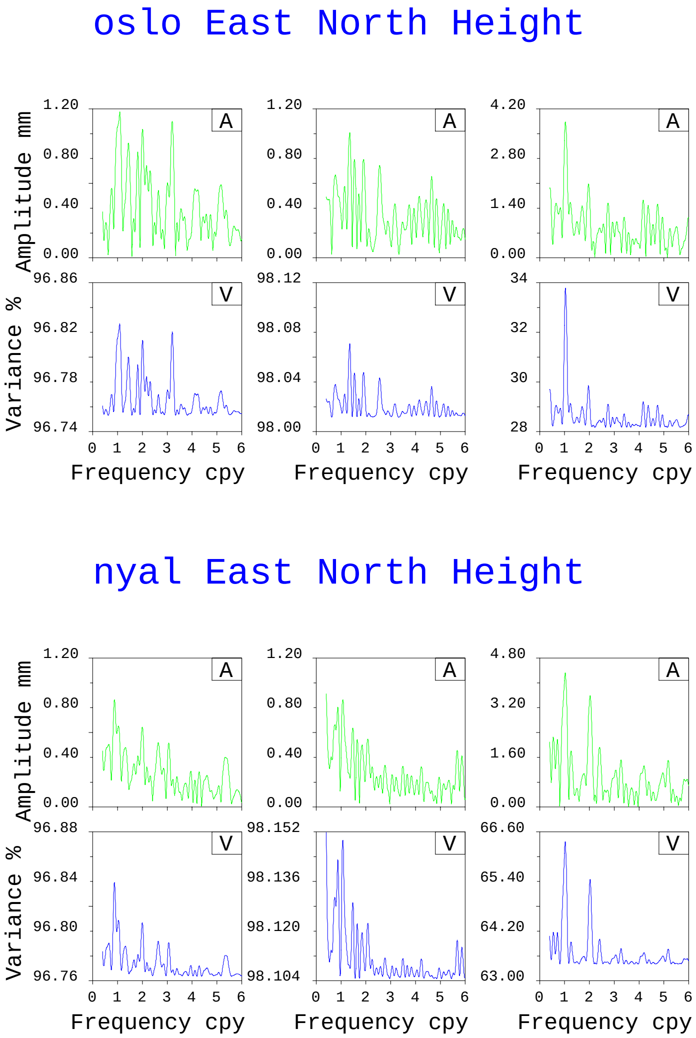


Figure 25: Variance spectra of CGPS time series for Norway.

The sites are from top to bottom Oslo (SATREF site OSLO), and Ny Ålesund, Svalbard (IGS site NYAL). CPY stands for Cycle Per Year. See Plag (1988) for more details on the Variance Spectrum.

of about 1-1.5 mm is present in the spectra of all the Norwegian stations. Moreover, there appears to be a minor semi-annual signal. However, other spectral peaks are local and may well be noise. For the North component, no clear seasonal signal can be detected and peaks in the spectra appear to be local, only.

In summary, it can be stated that the spectra of detrended coordinate time series, which have been corrected for artificial and natural offsets, are dominated by a nearly white noise (Williams, 2003; Williams et al., 2004) and a few periodic signals, which are mainly associated with seasonal variations. Moreover, the periodic signals only explain a small fraction of the total variance of the time series. Partly they are likely to be caused by instrumental effects including multipathing. Recent comparison of time series produced by different analysis strategies (own, unpublished study) reveals that much of the daily to interannual variability is analysis-dependent. This indicates that the geophysical signals have been largely removed by the station motion model acounted for in the analysis. Based on the noise level and the remaining signals in the time series, the presently available models for station motion can be assumed to be correct on the 1-2 cm level (see, e.g., McCarthy & Petit, 2003) or less.

In many regions particularly close to the plate boundaries and associated deformation zones, areas of volcanic activities, sedimentary basins, as well as areas of human activities like mining and extraction of subsurface fluids, the time series can also contain nonlinear motions caused by changes in the strain field of the level of human activities. In seismically active areas, earthquakes can induce large offsets in all three components.

Thus, the accuracy of point coordinates in the NGRF determined with precise point positioning will primarily depend on the ability to predict the secular

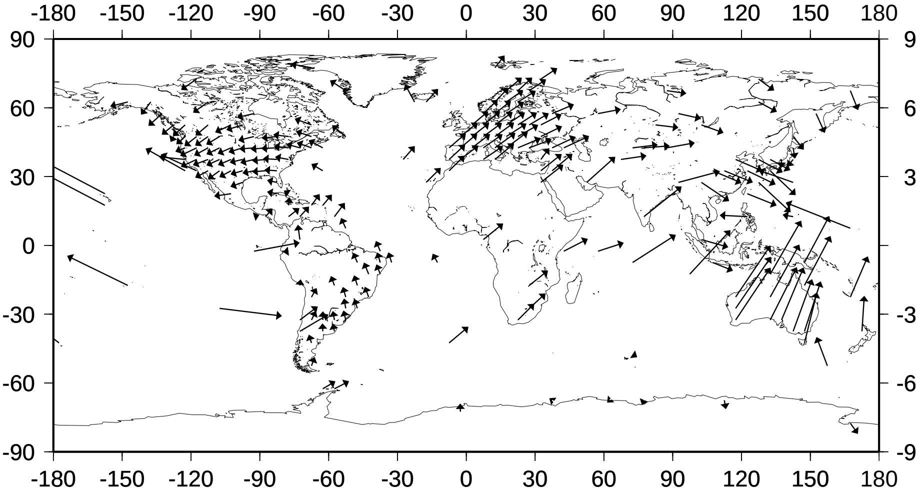


Figure 26: Global horizontal velocity field determined by GPS.

The horizontal velocities are given in ITRF2000. Velocity data provided by Lavallee (2006, personal commun.). The vectors show are mean velocities for grids of 5° × 5 °.

linear and nonlinear velocities. Consequently, in the remaining part of this chapter, we will concentrate on the linear secular velocity. Moreover, we will also consider nonlinear changes in the position, including processes causing sudden changes.

4.3 Secular point motion

All points on the Earth's surface exhibit a secular velocity relative to a global reference frame such as the ITRF. In order to determine transformations between the time-dependent ITRF and the fixed NGRF, or to be able to compare coordinates taken at the same point at different epochs, models to predict the secular point motion with sufficient accuracy are required. Considering a time window of, for example, 30 years, an uncertainty in the velocity model of 1 mm/yr would already result in a coordinate uncertainty of 30 mm over this time window. Thus, in order to be useful for the transformation of coordinates from ITRF to NGRF with a accuracy matching most URs, a velocity model would have to meet an accuracy requirement of better than 1 mm/yr.

Fig. 26 illustrates the global pattern of the horizontal motion as determined on the basis of the global IGS network and some additional stations. Velocities are given with respect to ITRF2000, that is, with respect to a reference frame that attempts to realize the *No-Net-Translation* (NNT) and *No-Net-Rotation* (NNR) conditions for the Earth's surface. Horizontal velocities of up to 80 mm/yr are found at the sites included in the plot. However, in some locations at plate boundaries, secular horizontal velocities may reach magnitudes larger than 100 mm/yr. For most sites on Eurasia, the linear horizontal velocity is of the order of a few cm/yr while vertical velocities, particularly in the formerly glaciated regions, can exceed 10 mm/yr (e.g., Johansson et al., 2002).

The presently most widely accepted global model of the horizontal velocities is the NUVEL-1a-NNR model (DeMets et al., 1994) which is primarily based on geomagnetic data. This model gives average estimates for horizontal velocities over the last 3 Myrs (million years). Models based on present-day geodetic observations have been presented for example by Drewes (1998); Kreemer & Holt (2001); Bird (2003) and Kreemer et al. (2003). For some tectonic plates the present-day geodetically determined models show discrepancies of up to 40 % with respect to the 3 Myrs average velocities as represented by NUVEL-1a-NNR.

For the vertical velocities no global model taking into account most major processes exists. However, for post-glacial rebound, which is one of the major causes for vertical motion in Northern Europe, Canada, and Antarctica, geophysical models provide predictions with an accuracy on the 2-3 mm/yr level (see, e.g., Plag et al., 2002; Kierulf et al., 2003; Plag et al., 2005c, see also fig. 7 on page 35). Depending mainly on the viscosity structure in the upper mantle and asthenosphere, post-glacial models predict veloc-

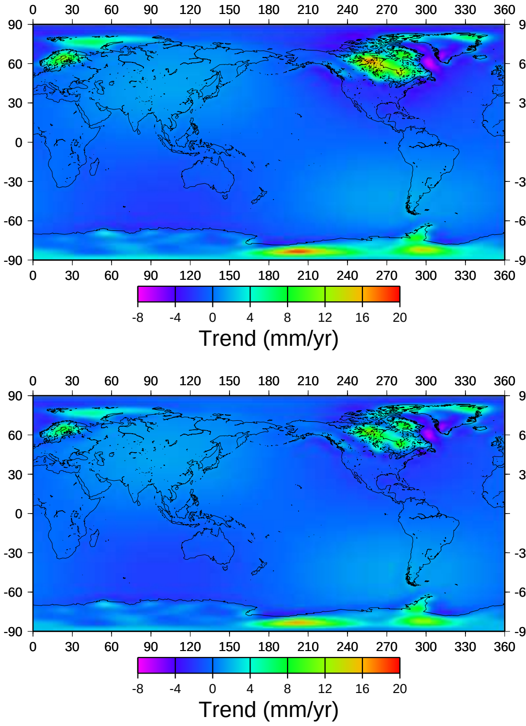


Figure 27: Predictions of present-day vertical land motion due to post-glacial rebound.

The model predictions are for the VM2 (upper diagram) and VM4 (lower diagram) viscosity structure, with VM4 having a lower viscosity in the upper mantle and asthenosphere than VM2. Ice history is that of ICE-5G (Peltier, 2004). All values are in mm/yr. The predictions are taken from the webpage of the IERS GGFC Special Bureau for Loading Plag & the SBL Team (2002) at http://www.sbl.statkart.no/projects/pgs. The differences in the predictions are shown in fig. 7 on page 35.

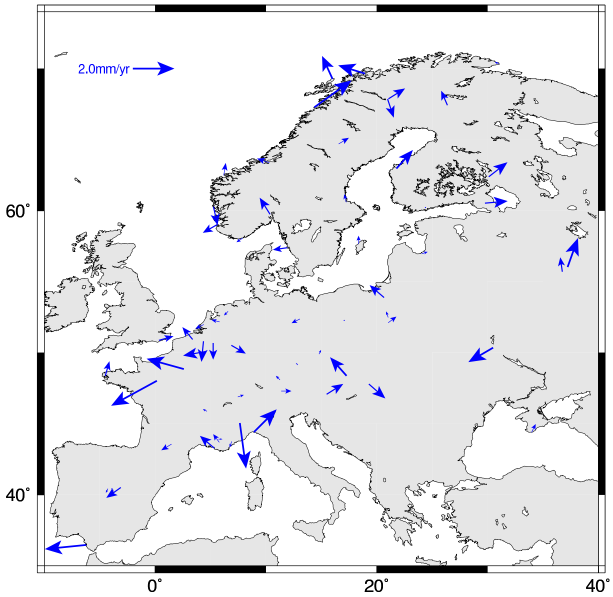


Figure 28: Uncertainty of the Eurasian velocity model.

Shown are residual velocities at the European ITRF sites with respect to the combined rigid plate motion and post-glacial rebound model determined by Kierulf et al. (2003).

ities of up to 20 mm/yr close to Hudson Bay and in some areas on Antarctica. Fig. 27 shows two of these models predictions computed by Peltier (2004). It is interesting to note that models with softer upper mantle and asthenosphere result in smaller present-day vertical velocities.

Since its formation, EUREF has made an attempt to realize a *Eurasian Terrestrial Reference System* (ETRS), that would result in minimum velocities for any point on the Eurasian plate with respect to the ETRS. The degree of success of EUREF in achieving this goal provides a good measure of how good coordinates can be maintained over time without additional measurements.

Originally, EUREF used the NUVEL-1A-NNR pole of rotation (DeMets et al., 1994) to describe the plate tectonic motion of the stable part of Eurasia. Altamimi & Boucher (2002) showed that in some parts of Europe the discrepancy between this model and observations was as large as 3 mm/yr resulting in an error of 3 cm per decade. Nocquet et al. (2001) studied the problem in defining a stable part of a tectonic plate on the basis of selected stations and showed that there is a significant dependency on the station selection. Based on a considerations by Plag et al. (2002), Kierulf et al. (2003) showed that using a combined model for rigid plate motions and intra-plate motion, the accuracy of the model horizontal velocity field can be close to 1 mm/yr for most of the Eurasian plate (see fig.28). Based on similar consideration, Nørbech & Plag (2003) were able to determine a transformation between the ITRF and different realizations of the ETRS on the same accuracy level.

Thus, it can be assumed that for the horizontal components, velocity models with an accuracy of 1-2 mm/yr seem to be achievable in many regions (particularly, the stable part of the plates, see fig. 29 for an indication of deformation areas). However, currently the uncertainty of the velocity models are still the main limitation for utilizing precise point positioning for the determination of positions in a fixed NGRF. For time spans of 20 and 40 years, respectively, uncertainties of 30 and 60 mm are likely.

For the vertical component, the situation is far

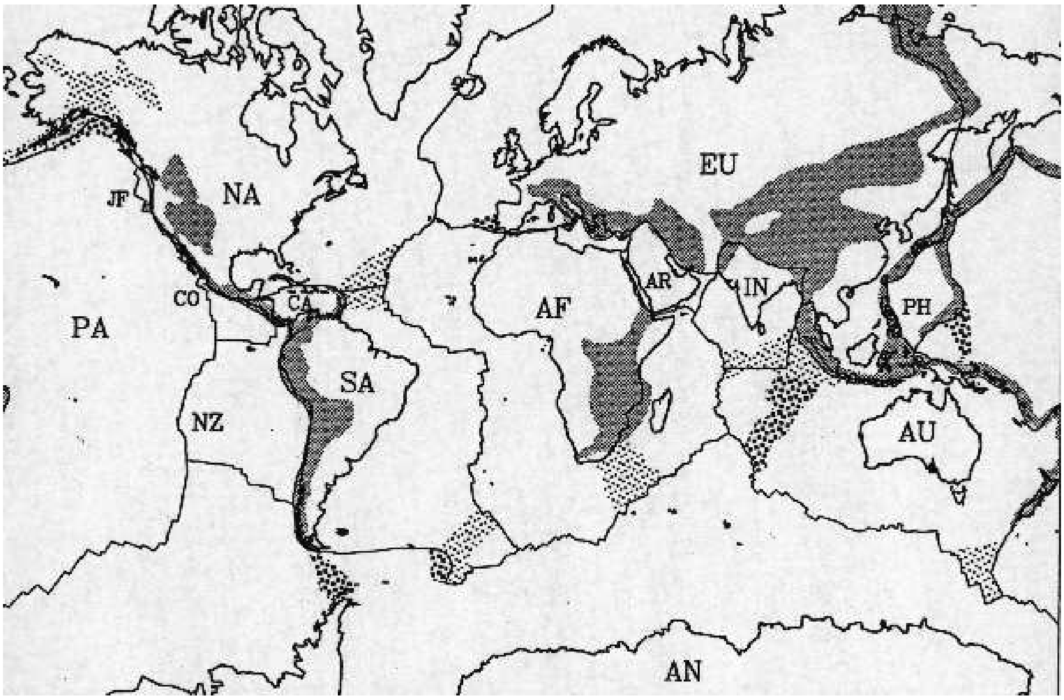


Figure 29: Global distribution of deformation zones.

Deformation zones are indicated as shaded areas. In these areas, the horizontal motion may deviate significantly (several mm/yr and more) from those predicted for stable parts of the plates by, for example, the NUVEL-1A-NNR model. In addition, vertical motion of several mm/yr can be expected. In many parts, the true extension of deformation zones is somewhat uncertain. The figure is taken from Stein (1993).

more complicated. Except for regional phenomena of post-glacial rebound, the spatial scales in the vertical motion are much shorter than for the horizontal components (typically of the order of a few km) and large differences (several mm/yr) can be found over distances of a few tens of kilometers. In some locations, considerable nonlinear vertical motion of up to several centimeters per year is caused by human activities such as ground-water and oil exploitation. Presently, no models exist to predict these motions.

4.4 Nonlinear point motion

In tectonially active regions, large discrepancies between the linear velocities predicted by models and those observed can be expected. Additionally, in these regions nonlinear motion has been observed, particularly in connection with earthquakes (see, for example, fig. 23). In the worst cases, offsets in the coordinates of several meters can occur within minutes over several 100 km. fig. 30 shows an example of such a horizontal offset of more than 2 m distorting a railroad track.

An extreme example was provided very recently by the great Sumatra-Andaman earthquake. Great earthquakes like this event of 26 December 2004 with an magnitude $M_w = 9.2$ (Stein & Okal, 2005) are associated with a number of geodynamic phenomena on a wide range of spatial and temporal scales including co-seismic strong motion and permanent displacements, free oscillations of the solid Earth, and,

Figure 30: Railroad track distorted by an earthquake.

A 2.3 m co-seismic displacement has distorted the railroad track near the railway station Tepetarla in the region between Sapanca Lake and Izmir Gulf. Taken from http://www.geo.tudelft.nl/fmr/research/insar/izmir/railroad.jpg.

Table 11: List of largest earthquakes since 1900.

Mag.	Year	Location
9.0	1952	Kamchatka
9.1	1957	Andreanof Islands, Alaska
9.5	1960	Chile
9.2	1964	Prince William Sound, Alaska
9.2	2004	Sumatra

if located in an oceanic region, tsunamis. The relocation of water masses in the ocean associated with the tsunami induces transient perturbations of the Earth's surface and gravity field.

The Sumatra-Andaman earthquake is the largest event ever observed by space-geodetic techniques and thus provides a unique opportunity to test models, observations and analysis methods as well as to study new phenomena leading to new discoveries. However, this earthquake is not the largest occurring in the last 100 years (table 11), and the displacement field of this earthquake can easily be exceeded by the fields associated with the larger earthquakes. Nevertheless, the displacement field determined from models and validated by GPS (fig. 31) indicates that over an area of more than 4000 km in diameter, co-seismic displacements reached more than 1 cm in the horizontal component, thus affecting the reference frame itself.

For most of the deformation areas, presently no models exist to predict the kinematics of the points. Most of the global deformation zones are associated with plate boundaries, but in some cases they extend far into the plates and their actual extension remains uncertain (see fig. 29).

Human activities such as groundwater and oil exploitation can also induce nonlinear motion, particularly in the vertical component. In some locations such as the River Po Delta, displacements of several cm/yr have been observed. No models exist currently to predict such movements.

4.5 Changes in the Earth's gravity field

Changes in the Earth's gravity field are intimately connected with the deformations of the solid Earth caused by external forces such as tidal forces and external torque, or mass movements in the interior of the solid Earth and its fluid envelope. Consequently, gravity field variations occur on similar time scales as those indicated for surface displacements in table 10. On time scales of less than 1 hour, seismic eigenmodes are causing the largest changes in gravity, comparable in amplitude to the diurnal and semi-diurnal tidal variations. Tidal gravity variations are a combination of solid Earth tides and ocean tidal loading, with the ocean loading signal having much larger spatial scales in gravity than in surface displacements. Atmospheric and nontidal ocean loading are associated with variations in the gravity field on characteristic time scales of days and months, respectively, and the signal is a combination of the Newtonian contribution resulting from the mass movements in atmosphere and ocean and a secondary contribution caused by the deformation of the solid Earth.

Temporal variations in continental water storage causes changes in the gravity field on time scales from weeks to decades. On time scales of weeks to months, variations on watershed-scale are of the order of ±300 mm in water column (particularly at low latitudes), and these changes produce gravity field variations detectable by dedicated satellite missions such as the GRACE mission. On seasonal time scales, amplitudes of the order of 100 mm are found in large regions. Knowledge about changes on interannual to multi-decadal time scales is sparse, but in large regions, long periods of droughts can introduce trends of the order of several cm/yr in water column.

Variations in the cryosphere have a strong signal at seasonal time scales, and also at interannual to century time scales. Particularly close to the changing ice loads, the gravity field is changed due to the added or removed mass, and at coastal locations, the changes in the geoid have a strong effect on LSL. Secular trends in the gravity field originate from the changes due to the repeated occurance of ice ages and the subsequent deglaciations, which change the geoid on time scales of kilo-years at the several meter level.

4.6 Changes in Earth rotation

Earth rotation changes are caused by internal processes in the solid Earth as well as dynamical interactions of the solid Earth with the fluid envelope and external forces. Mass redistributions in the solid Earth change the moment of inertia and thus influence both the Length of Day (LOD) and the position of the axis of rotation with respect to the figure axis (polar motion, PM). Mass redistribution in the ocean, terrestrial hydrosphere, atmosphere, and cryosphere all load and deform the solid Earth and thus affect LOD and PM. Dynamical interactions between atmosphere and ocean on the one side, and the

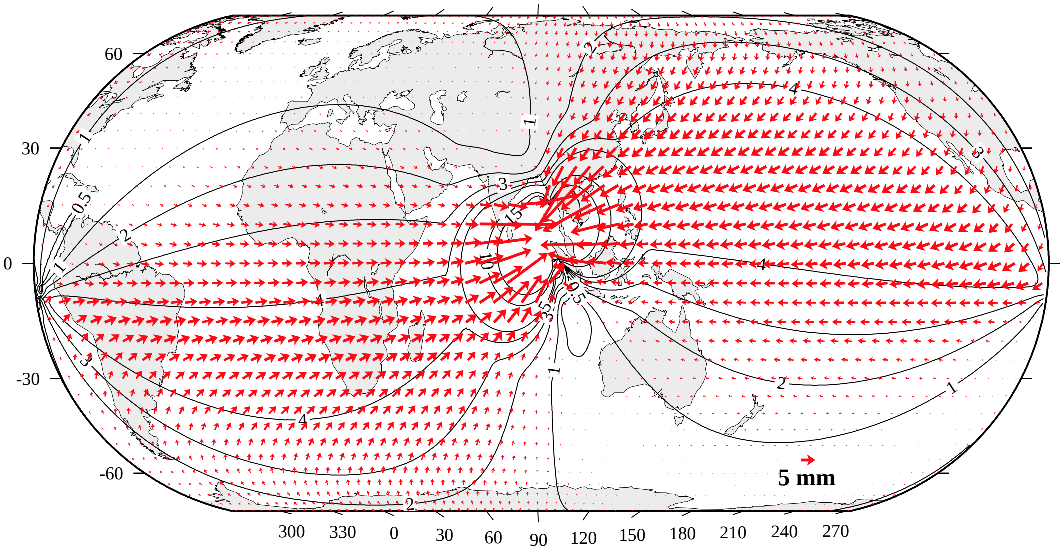


Figure 31: Predicted co-seismic displacement field of the Sumatra-Andaman 2004 earthquake. *The predictions are for a layered elastic spherical Earth model and a rupture model that best fits the offsets computed by Kreemer et al. (2006b). Taken from Plag et al. (2006).*

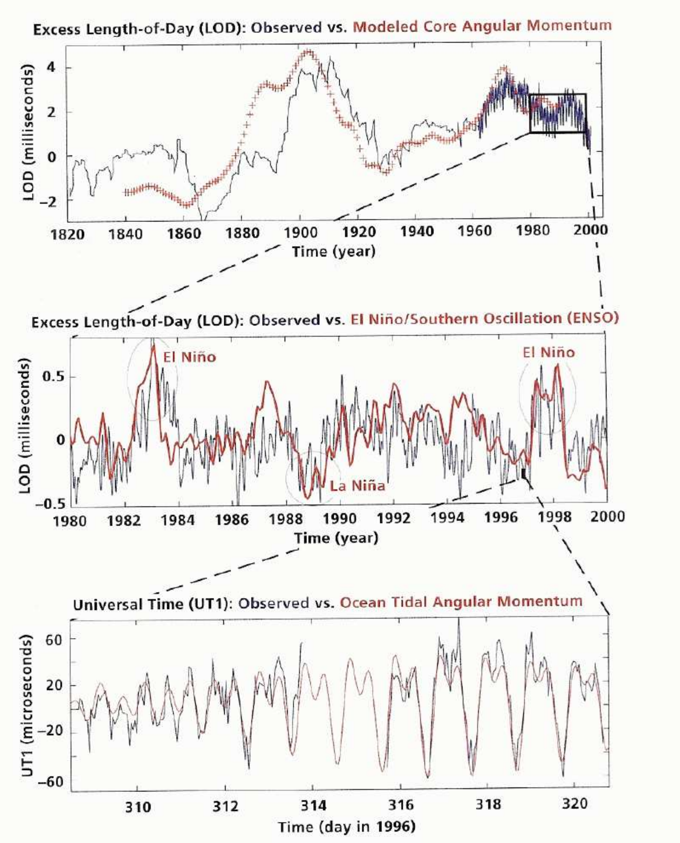


Figure 32: Variations in the Length Of Day. *From Solomon & The Solid Earth Science Working Group (2002).*

solid Earth on the other side can transfer angular momentum between these system components and thus induce changes in LOD and PM.

In fig. 32, variations in LOD are shown with three different temporal resolutions. On decadal time scales, LOD shows variations on the order of a few milliseconds, and these variations can be explained by angular momentum exchange between the Earth's core and mantle. At interannual time scales, the main LOD variations are caused by coupled atmosphere-ocean phenomena such as El Niño/Southern Oscillation. At diurnal and sub-diurnal time scales, ocean tides appear to be the main driver of LOD variations.

In polar motion, the most dominant features are the Annual and Chandler Wobble, and a secular trend. The Chandler Wobble is a resonant wobble at the rotational eigenfrequency of close to 435 days, which is forced by a combination of atmospheric and oceanic excitation (see, e.g., Liao, 2005, and the references therein). Similarly, the Annual Wobble is the result of forcing from the atmosphere, ocean, terrestrial hydrosphere, and cryosphere. The secular trend in the position of the pole is mainly a consequence of the still ongoing rebound of the solid Earth from the deformations caused by the last ice age.

5 Specifications for a global geodetic observing system

A major purpose of the geodetic observing system is to deliver the observational basis for the determination of the reference frames required for any positioning. Therefore, in the next section we give a rather brief introduction to reference systems and frames, while more details can be found in Appendix A. There, we introduce the basic terms and concepts underlying the definition of geodetic reference systems and their realization through reference frames. Based on these concepts, we specify in Section 5.2 the observing system required for the determination and monitoring of the reference frame. As pointed out in Section 2, the geodetic infrastructure contributes relevant observations to Earth observation, and in Sections 5.3 and 5.4 we elucidate the components required for geohazards and global change monitoring, respectively. Finally, in Section 5.5, we address the specifications for geodetic infrastructure serving other applications.

5.1 Reference systems and reference frames: a brief introduction

Conventional geodetic reference systems are defined by specifying the origin of the system, the orientation of the three main axis, and the scale. Moreover, a number of physical quantities need to be defined as part of the reference system.

In order to make the reference system accessible, it needs to be realized through a reference frame. Terrestrial reference frames are today given by a set of points, as evenly distributed on the Earth's surface as possible, for which so-called regularized coordinates are given. This set of points can be visualized as a polyhedron, and the regularized coordinates describe how this polyheadron deforms over time. For a reference point with index i, the time-dependent regularized coordinates $\vec{x}_{\mathrm{r}}^{(i)}(t)$ are given by

$$\vec{x}_{\mathrm{r}}^{(i)} = \vec{x}_0^{(i)} + \vec{v}_0^{(i)}(t - t_0) \; , \tag{1}$$

where $\vec{x}_0^{(i)}$ and $\vec{v}_0^{(i)}$ are the coordinates at a reference epoch t_0 and a constant velocity, respectively (McCarthy & Petit, 2003).

In the determination of the reference frame, point coordinates are modeled by

$$\begin{aligned} \vec{x}^{(i)}(t) &= \vec{x}_{\mathrm{r}}^{(i)}(t) + \sum_{j=1}^{k} \delta\vec{x}_j^{(i)}(t) \\ &= \vec{x}_{\mathrm{r}}^{(i)}(t) + \vec{\Delta}^{(i)}(t) \; , \end{aligned} \tag{2}$$

where the second term on the right-hand side of eq. (2), that is $\vec{\Delta}^{(i)}$, contains time-dependent deviations of the station coordinates from the regularized coordinates. What processes to include in this term for the determination of the reference frames is a matter of convention. For the ITRS and its realization through ITRF, the processes to be included and the geophysical models to be used are specified in the IERS Conventions (McCarthy & Petit, 2003).

For a given ITRF, for example, ITRF2000 (Altamimi et al., 2002), the regularized coordinates $\vec{x}_{\mathrm{r}}^{(i)}$ are the results of a complex adjustment process, and, therefore, they depend on the explicit form of eq. (2) used in a particular adjustement. For consistency, it is therefore important to comply with the conventions that were used during the reference frame determination when computing coordinates for new points in that reference frame. However, increasing accuracy requirements lead to a constant development particularly of the $\vec{\Delta}^{(i)}$ term, which can introduce considerable inconsistency between reference frame determination and later application.

Due to the adjustment errors associated with the constants $\vec{x}_0^{(i)}$ and $\vec{v}_0^{(i)}$, the errors in the regularized coordinates increase with $\delta t = t - t_0$. Moreover, processes not taken into account in eq. (2) during the adjustment also increase the errors. Finally, deviations of the actual point motion through time due to periodic or nonlinear processes not accounted for in the reference frame determination can render a given reference frame inaccurate after a relatively short time. Consequently, the global ITRF has been updated frequently, in the start almost every year and currently, after a significant reduction in the errors of the regularized coordinates, with a three to four year interval.

Facing increasing accuracy demands on the regularized coordinates, it may be necessary to reconsider the definition of the regularized coordinates. There have been suggestions to include at least a seasonal cycle either in the $\vec{\Delta}$ term or as part of the regularized coordinates. Coordinate time series are often given with a daily sampling interval. In this case, a seasonal cycle would naturally be part of the time series. Therefore, it would have to be part of the regularized coordinates. A possible future form of these modified regularized coordinates could be

$$\begin{aligned} \vec{x}_{\mathrm{r}}^{(i)} = {} & \vec{x}_0^{(i)} + \vec{v}_0^{(i)}(t - t_0) + \\ & \sum_{m=1}^{M} \left(\vec{A}_m^{(i)} \sin(\omega_m) + \vec{B}_m^{(i)} \cos(\omega_m) \right) + \\ & \sum_{n=1}^{N} \vec{\alpha}_n^{(i)} H(t - t_n) \; , \end{aligned} \tag{3}$$

where the sine and cosine terms describe the seasonal variation and the Heaviside functions H are included to account for rapid displacements at times t_n normally associated with large earthquakes. A further extension would be to account in eq. (3) for significant post-seismic deformations as seen, for example, after the 26 December 2004 Sumatra-Andaman earthquake (Kreemer et al., 2006a).

The advantage of including the seasonal components as well as co-seismic and post-seismic displacements in the regularized coordinates and not the Δ-term of the station motion model, is that these terms can be updated after the reference frame determination without compromising consistency but avoiding a warping of the reference frame with respect to the actual form of the polyhedron. It is also a principle of IERS, at least implicitely, to include only contributions in the Δ-term, if there are general models available for a process considered. Both for the seasonal cycle and the co- and post-seismic deformations, no general (and technique-independent) models are presently available at the time of the reference frame determination.

In the following, we will discuss the specifications for the infrastructure required to determine and maintain the global geodetic reference frame having a potential extension of eq. (1) towards eq. 3 in mind.

5.2 Specification for reference frame determination and monitoring

5.2.1 General characteristics

In order to meet the user requirements specified in Section 3, the following general system characteristics can be specified for the observing system required for the determination and monitoring of ITRF as well as for the provision of access to the ITRF:

- For the determination of the reference frame, the global geodetic observing system shall:
  - consist of a global network of reference stations for at least VLBI, SLR, and GNSS, with a well distributed subset of fundamental stations with co-located techniques;
  - provide fully integrated observations of the three geodetic quantities, that is the shape of the Earth, the gravity field and the rotation;
  - ensure, through appropriate combination of geometric and gravimetric techniques, that the reference frame origin is well connected to the CM;
  - have a consistency of processing of all observations on the level of better than 10^{-9};
  - ensure long-term operation of the infrastructure for the reference frame determination as well as for the contribution of geodetic observations to GEOSS (long observational records);
  - include an operational kernel, providing long-term stability and compatibility of successive versions of ITRF;
  - give easy access to integrated and homogeneous (in time) databases of observations and products, including station coordinates and velocities, and station time series.
- For the monitoring of the reference frame, the global geodetic observing system shall:
  - carry out continuous monitoring of a sufficiently dense network of reference stations in order to determine any distortions of the network with respect to the regularized coordinates and the conventional station motion model;
  - provide time series of station coordinates in ITRF for at least a subset of the reference stations based on multi-technique solutions.
- For access to the ITRF, the global geodetic observing system shall:
  - provide satellite orbits and clocks as well as Earth rotation parameters in order to allow for *ad hoc* access to precise point positions at anytime and anywhere on the Earth's surface or above;
  - ensure that these products (satellite orbits and clocks and Earth rotation parameters) are given in a unique, "technique independent" ITRF;
  - make available detailed information about system state, including technique dependent effects (CMV) and the Earth's surface velocity field;
  - include quality information to document quality-assured and reliable products;
  - make progress towards "easy," operational access to precise point positions in ITRF.

It is emphasized here that in order to serve both scientific and nonscientific users for high-accuracy applications, it is mandatory that GGOS includes a sufficient operational core system, which is as stable as possible over a long time. It is this specification which will be most difficult to meet considering both the expected progress in technology and changes in funding sources and priorities as well as the key players and their interests.

For the time series of reference coordinates, it is also necessary to consider what these time series should represent. Ideally, for reference frame purposes, the time series would be of coordinates of the primary reference marker at a reference station. These time series should be technique-independent. Thus, for a given station with several co-located techniques, the coordinate time series for this station ideally would be a combination of the individual, technique-dependent time series. However, that would require that the local ties between the primary marker at a reference station and the reference points of the individual techniques are known at all times. Such time series would not suffer from offsets due to equipment changes, since these would be taken into account in the combination. The time series would describe as close as possible the temporal evolution of the polyhedron defined by the primary markers at the reference stations.

5.2.2 The global geodetic networks

The necessary spatial density of the reference networks required for the determination of ITRF on the 1 cm level in terms of position and the 1 mm/yr level in terms of velocity depends on the available observational technology and the mode of access to the ITRF. Of pivotal importance are the fundamental stations which link the different techniques such as SLR, VLBI, GPS, GLONASS, DORIS and the future Galileo together. A fundamental station has at least 3 techniques co-located (where all GNSS techniques combine to count as one technique). In view of the requirements discussed above, the current number of fundamental stations, particularly those with more than three techniques, is far too small and the geographical distribution is too uneven (see fig. 42 on page 80 and Boucher et al., 2004). A number of 30 to 40 well distributed fundamental stations is considered to be a minimum in order to utilize the different advantages of the individual techniques and to mitigate their limitations (Pearlman & others, 2006). Moreover, such a core network would ensure the long-term stability of the ITRF.

The specific strengths of each of the observing techniques are required to compensate for weaknesses in the other techniques and to maintain a stable reference frame. A sufficient number of well distributed VLBI stations is crucial in order to maintain an accurate account of Earth's rotation and thus to link not only the terrestrial reference frame to the celestial one, but also to connect the GNSS satellite to the solid Earth reference frame. Currently, about 30 stations are contributing on a regular basis to the globally coordinated observing program, and this number is required to ensure the current accuracy of Earth rotation parameters.

In the determination of the origin of the reference frame, which according to the definition of the ITRS should be as close as possible to the CM, SLR plays a crucial role. Currently, the uncertainty in the tie of the reference frame origin to the CM, which is estimated to be of the order of 2 mm/yr (J. Ries, 2005, personal commun., Kierulf & Plag, 2006), is a major limitation in studies of global change, and particular global and local sea level changes. However, the number of SLR stations is currently low and potentially decreasing. Together with VLBI, SLR also defines the scale of the system.

Absolute gravimetry also can support the connection of the origin of the geometric terrestrial frame to the CM (see, e.g., Wilmes et al., 2006). Therefore, a global network of carefully chosen and well distributed absolute gravimetry sites should be an integral part of the reference networks. These sites would have to be away from areas with current mass changes (e.g., ice sheets, glaciers) and on the stable parts of the tectonic plates. In order to tie the geometric frame to CM, these sites need to be collocated with a geometric technique, preferably GNSS.

The ITRF monitoring system requires a sufficient number of continuously tracking reference stations in order to ensure the NNR condition and to provide continuous access to the ITRF. Today, such a tracking network can only be based on GPS and in the future, more general, on GNSS. For a homogeneous network of high quality stations operated under optimal conditions, a number of 100 to 150 tracking stations appears to be sufficient for the sole purpose of monitoring the ITRF (J. Ray, 2003, personal commun.). However, in order to avoid a single-technique influence, including system biases, on the monitoring, it would be important to calibrate the GNSS-determined monitoring products by other techniques. Moreover, GNSS inherently has a long-term stability less than the other space-geodetic techniques, such as SLR and VLBI. In particular, a firm tie of the origin of the monitoring frame to the CM would require a frequent calibration of the GPS-based products by SLR, given that the SLR tracking network is sufficiently dense to constrain the CM, and the long-term stability of the Earth rotation observations as ensured by VLBI is essential for the reference frame, too.

The tracking network operated under the coordination of the IGS appears to be sufficient with respect to the number of stations. However, when taking into account that not all stations are operated according to the standards, or delivering data with large latency, it is clear that the network requires considerable redundancy in order to meet the requirements. Moreover, technical changes at the stations take place frequently, introducing temporal inhomogeneities. In addition, temporal inhomgeneities of the GNSS themselves, for example, due to technological developments or changes in the satellite constellation, also have effects on the apparent coordinates of the GNSS tracking stations.

In summary, the ITRF depends heavily on the quality of each single technique network and suffers with any network degradation over time (Pearlman & others, 2006). Equally important is the proper link between these techniques.

5.2.3 Linking the space-geodetic techniques together

The quality of a modern reference frame depends crucially on the combination of different space-geodetic techniques, which have their specific advantages and limitations. The link between the techniques is provided through co-location of two or more techniques at the same site. In order to utilize the co-location sites fully, the local tie vectors between the reference points of each technique need to be known with high accuracy at each site. This requires frequent site surveys, which allow the determination of local ties and the detection of any changes in these ties.

The field surveys necessary to determine the local ties can be rather demanding and the quality of the local tie vectors notoriously has been a limitation for the ITRF determination. The IERS is actively promoting the standardization of the survey routines as well as the documentation of the results in order to provide better and complete documentation of the local ties (see the papers included in the proceedings of a recent IERS workshop, Richter et al., 2005).

In order to overcome the current negative situation with respect to the inter-technique links, it would be worthwhile to design new methods of determining these links. In some case, it may be possible to have different techniques on the same monument (e.g., SLR and GPS or VLBI and GPS) while in other case, the automatic determination of local ties may be feasible. It would also be a big improvement to monitor the motion of monuments through better integration of, for example, tiltmeter and other sensors in the monuments.

5.2.4 Local ground motion or monument instabilities

Local motion of a point relative to its environment can also cause degradation of coordinates over time. Such motion can result from movements of the monument itself, the ground or building bearing the monument, or small-scale tectonic or other movements. All of these movement would render a site as unsuited for reference purposes.

In Fennoscandia usually the monumentation for space geodetic techniques can be mounted directly in bed rock. However, large parts of the European continent (and also locations on other continents) do not have these favorable conditions and thus great care has to be taken for the foundation of the monuments for a permanent GNSS (or any other monitoring) site.

In places where firm monumentation cannot be achieved or local small-scale movements cannot be exclude, it may be necessary to monitor the local stability of the stations. Any local motion with respect to a geodetic footprint has to be detected at an early stage to guarantee a sufficient coordinate accuracy. Thus, surveys of the stability of the antenna monuments have to be performed if local motion is suspected. This type of measurement is standard procedure for space-geodetic stations and usually includes observation campaigns involving traditional geodetic measurement techniques as well as satellite-based techniques, (see, e.g., Haas & Kirchner, 2001; Kierulf et al., 2002; Bockmann et al., 2002). As an example, it can be reported that NMA, in studies of the footprint of the fundamental geodetic station in Ny Ålesund, Svalbard, detected small-scale (a few kilometers) differential movements of the order of 1 mm/yr, which introduce local distortions of point coordinates of the order of 1-2 cm over 15 to 20 years.

Local effects can also be due to human activities, which can induce localized motion particularly in the vertical component as a consequence of, for example, groundwater and oil extraction, coal mining, and geoengineering activities. In cases where such processes take place in the vicinity of a reference site, particular care has to be taken to detect potential nonlinear coordinate changes.

5.2.5 Apparent or actual coordinate changes due to technical or other causes

Any changes in the equipment (on-site hardware, on-site software, processing software) can introduce changes in the coordinates of a reference site. The changes easily can be of the order of several cm. Sometimes, such changes are intentionally and the time of such changes is exactly known. In principle, the new reference coordinates can be determined after any such changes. If the reference coordinates are given for a primary marker, then offsets due to anthropogenic effects would have to be corrected and eliminated from coordinate time series of the marker. Better yet, intentional changes should be kept to a minimum and, where possible, offsets that are created measured.

From the experience in IGS and other permanent GPS networks, it is known that changes in receiver or antenna hardware, changes in radom, upgrading of receiver software and changes in the processing software introduce not only offsets in the coordinates but also changes in the noise level and characteristics of the data.

Changes in the electrical receiving conditions of the antenna can also introduce apparent changes in the coordinates. Such changes may originate from variations in the conditions for wave scattering around the antenna due to variable ground reflectivity (i.e. changes in multipath), occasionally perching of birds on the antenna, obscuring vegetation, electromagnetic jaming, etc. The resulting coordinate variations may be periodic, sudden or slow trends. Without further investigations, such variations cannot be distinguished from actual physical dislocations of the antenna.

5.2.6 Low-latency access to the reference frame

Highly accurate access to the global reference frame is possible today through GPS (and in the future more general, GNSS) anywhere on the globe. If considerable latency of days and weeks is acceptable, then an accuracy as good as a few cm in ITRF can be achieved through a combination of GPS observations and the IGS products. However, for users requiring a higher accuracy in real time than offered by the GPS SPS, this can be achieved by two different approaches, namely (1) differential corrections computed on the basis of a local or regional reference network of CGPS stations, and (2) highly accurate satellite orbits and clocks as well as Earth rotation parameters. Both methods have in common that they currently require additional information besides the SiS.

In the first method, a regional or local network of reference stations providing observations in real time is required for the computation of differential corrections. Under the assumption that the coordinates of the reference stations are known, corrections for deviations due to orbit and clock errors and atmospheric effects can be computed. Based on these corrections, a user can achieve real-time accuracy on the 30 to 50 cm level with a single-frequency receiver. For high-density networks, locally a precision of well below the 10 cm level is possible today. However, users must be careful to enquire the source of reference station coordinates, their accuracy, and the reference frame.

The second method is based on the global network of tracking stations, which deliver data in near-real time. Accurate satellite orbits and clocks as well as Earth rotation parameters are computed in near-real time. These precise products are distributed to users (normally via internet). Due to a relatively small amount of data to be distributed, the demands for broadcasting are moderate. The disadvantage of this approach is that the users may not get any corrections for atmospheric and ionospheric effects, which limits the accuracy of single-frequency receivers to several meters. A higher accuracy is possible if the user computes these corrections, which is possible for dual-frequency receivers. In this case, an accuracy on the level of a few cm is possible, particularly if sidereal filtering is carried out (e.g, Choi et al., 2004).

A third method could be based on a combination of methods 1 and 2, which would utilize the global tracking network for improved orbit, clock and EOP computations and the national/regional network for atmospheric corrections. In this combination, the motion of the reference stations would have to be modeled with sufficient accuracy. In a modification, the atmospheric corrections could be computed on the basis of meteorological data obtained from numerical weather forecasting.

It is worthwhile to mention here that NMA has carried out a project investigating the incremental system specifications for Galileo, which would turn Galileo into a system with geodetic accuracy based on the SiS only (Plag et al., 2004). A key result was that a global tracking network of approximately 50 tracking stations would be sufficient to compute highly accurate satellite orbits and clocks for broadcasting, which would allow achieving 10 cm accuracy in real time based on SiS only.

For the determination of orthometric heights in real time, the service described above would have to include the position-dependent information which describes the relation between the national heights and ellipsoidal heights. Ideally, this relationship would be the geoid. However, currently available geoid models for Norway have an accuracy of approximately 20 cm. Moreover, the national height system in Norway (and most other countries) has significant biases with respect to the geoid. Therefore, an empirically determined reference surface is required if heights are to be determined with an accuracy of better than 20 to 30 cm based on GNSS observations.

5.3 Geohazards observation system

Space-geodetic techniques are fundamental for a solid Earth observation system aiming at the detection of geohazards and the monitoring of hazardous areas. For the purpose of geohazards, the observing system would have to rely on a strong global geodetic component providing the stable reference frame as well as the technologies and products required to get easy and reliable access to this frame. This is one of the prime objectives of GGOS, and the required frame and associated products are partly available today through the IERS and the other IAG services, particularly the IGS. However, the part of the observing system dedicated to geohazards would also have to be flexible in spatial and temporal resolution, as well as readiness on demand. Therefore, in many parts of the world, dedicated ground-based networks are needed, some of them on temporary basis (e.g., at certain volcanoes, in areas with instable slopes and large precarious rocks), which could be established under the umbrella or guidance of GGOS and in coordination with the IGOS-P Geohazards Theme. Developing cheap receivers that could be disposed of would support the establishment of temporary monitoring networks in hazardous areas.

GGOS would be a rather important utility for any dedicated geohazards observing system. GGOS also provides information on the dynamics of the solid Earth not directly relating to geohazards but of importance for the third group of users identified in the Geohazards Theme report (Marsh & the Geohazards Theme Team, 2004), namely the research scientists studying geohazards.

A key component of the geohazards observing system are networks of permanent or campaign-type GNSS stations that are operated according to the specific requirements in terms of spatial resolution, accuracy and latency, which are dependent on the location. Another important component is provided by InSAR. Currently, application of InSAR to monitoring are limited through the number of SAR sensors available, the accessibility of the SAR data, and the nonoperational status of the data processing required to create the interferograms. In order to fully utilize the potential of InSAR, the number of available satellites needs to increase so that nearly daily coverage can be achieved. This request is also strongly emphasized by GEO (GEO, 2005b). Moreover, InSAR needs to be transferred into an operational technology. Finally, the methodology for the combined analysis of SAR and GPS/GNSS observations needs to be developed.

The establishment of an international *Interferometric Synthetic Aperture Radar* (InSAR) service has been suggested as an important step towards coordination, capacity building, and the transition to operational applications. A link between InSAR and the global terrestrial reference frame, for example, through integration of GNSS and InSAR, is a step that would greatly improve the applicability of InSAR for monitoring surface displacements with high spatial resolution.

Stimulated by the Sumatra earthquakes, currently there is progress towards GPS seismology. GPS allows the detection of the permanent offset associated with an earthquake, an information currently not available in near-real time. Particularly for large earthquakes, this information made available in real-time would provide very early estimates of the magnitude of an earthquake (Plag et al., 2006; Blewitt et al., 2006b). However, this application would require a major densification of the global GPS tracking network and the availability of observations in near-real time.

5.4 Global change monitoring

Most global change processes are associated with mass transports and mass relocations in the Earth system. These processes affect the three fundamental geodetic quantities. Consequently, observations of surface displacements, gravity field variations and variations of the Earth's rotation are important contributions to the monitoring of global change processes. Space-geodetic techniques including dedicated gravity missions are inherently strong on global to regional scales. Therefore, the geodetic observing system for the monitoring of global changes processes on global to regional scales has to be an integrated system based on global station networks and satellite missions, with the latter probing the Earth's gravity field and measuring the surface of the ocean and ice sheets.

A major component in the global *in situ* network of space-geodetic stations monitoring the displacement of the Earth surface with high spatial and temporal resolution comes from the GNSS. Many problems related to the global water cycle require spatial resolutions of a few hundred kilometers. For sea level monitoring, the co-location of GNSS and tide gauges at a sufficient number of well distributed tide gauges is required, with the number of co-located tide gauges being estimated to be between 70 and 200 hundred.

In situ observations of gravity variations contain important information on climate-related processes, particularly from annual to secular time scales. Absolute gravimeter measurements in carefully selected regions are therefore a valuable contribution to the monitoring system aiming at global change processes. However, absolute gravimeters need to be calibrated through appropriate intercomparison with other gravimeters (see, e.g., Wilmes et al., 2005, for more details). Continuous observations of a superconducting gravimeter reach a resolution of about 10^{-10} ms^{-2}. In order to determine the drift of the instrument, frequent comparisons with absolute gravimeters are necessary.

5.5 Additional, nongeodetic observations

Increasingly, the determination of IPWV from GPS and other GNSS observations are considered a valuable observational constraint for meteorological and climatological applications. The requirements and system specifications in terms of accuracy, spatial resolution and latency are detailed in Elgered et al. (2004) and summarized above.

The observation system for numerical weather prediction applications requires a spatial resolution of 30 to 100 km, which appears to be much smaller than for most geodetic applications. Latencies of less than 1 hour for the delivery of the IPWV estimates pose high demands on the communication linking the stations to data centers and the processing of the observations. However, the demonstration project described in Elgered et al. (2004) showed that these requirements can be met with the available station networks and processing utilities.

5.6 Organizational considerations with respect to long-term stability

Key qualities of GGOS relevant for many user requirements are, as the name implies, its truely global nature and its long-term stability, which are not only required for scientific applications and Earth observation but also most other applications. The current organizational background consists of a number of mainly science-driven IAG services, which all are based on voluntary contributions. The services are therefore inherently unstable. Consequently, it would by a significant improvement, if the organizational background would allow for an operational kernal of the geodetic infrastructure.

Since the resources required to maintain the geodetic reference frame and to provide the geodetic observations are considerable, the appropriate organizational level for the operational kernel would be intergovernmental. Many of the practical issues related to the global geodetic reference frame necessitate an operational nature of the basic activities. The increasing importance of the global reference frame for national reference frames as well as for Earth observation and satellite missions in general also point towards an intergovernmental commission as the natural organizational background to ensure the availability of a long-term stable global reference frame, including the tools to access this frame. A potential setting for such an anticipated *International Geodetic Commission* (IGC) would be under an appropriate UN Agency such as UNESCO or UNEP.

6 Specification for a national geodetic infrastructure

6.1 Contributions to GGOS

GGOS is solely based on voluntary national contributions. Without these contributions from particularly the countries having access to the necessary economic resources, GGOS can not be implemented at the required level and the main product, that is ITRF, cannot be maintained for the global community. The importance of ITRS and ITRF has been underlined recently, when the European Union and the USA agreed to align the reference frames of GPS and the future Galileo system as closely as possible to ITRS (European Commission, 2004). Moreover, the GEOSS Implementation Plan (GEO, 2005a) and the associated reference document (GEO, 2005b) emphasize the fundamental role of the reference frame for all Earth observation. In several of the IGOS-P Themes, the importance of the geodetic observations is acknowledged.

The national geodetic infrastructure of any country, if it can afford it, should be designed and developed in order to provide the necessary support for the implementation and operation of GGOS. Taking into account the structure of GGOS, which is an umbrella system for the IAG services, this contribution breaks down into a number of individual contributions to the IAG services. In the case of Norway, of particular importance are the observations delivered to the IVS, IGS, and GLOSS, as the global services and EUREF, the ECGN, and ESEAS as regional networks and services. Moreover, the engagement in the implementation of the NGOS is of importance for the Nordic area.

Considering the extension of the geographical region adjacent to the Norwegian mainland and islands, Norway faces a particular challenge. The administrative responsibility for the Svalbard archipelago and Jan Mayen put Norway into a position to contribute significantly to the appropriate geographic distribution of the global geodetic networks. The fundamental station in Ny Ålesund extends the global IVS and IGS network into a high-latitude arctic location. This station is also co-located with DORIS, a superconducting gravimeter contributing to GGP, frequent absolute gravity measurements, as well as a tide gauge contributing to ESEAS and GLOSS. Thus, the station is of particular importance linking a number of techniques together. The continuous operation of this station is therefore considered a major Norwegian contribution to GGOS.

Geodetic infrastructure on Jan Mayen with its location in the northern North Atlantic would significantly improve the geometry of the geodetic networks in that region. Therefore, the establishment of an IGS-level *Continuous GNSS* (CGNSS) site together with a modern tide gauge should have a high priority. Special focus should be on data communication allowing for low-latency data delivery.

An additional IGS station should be committed for a location in Southern Norway. A particularly well suited candidate is the CGPS station in Trysil, which could easily be committed to IGS. This would close the large gap in the spatial coverage of the southwestern part of Scandinavia. This site is also well suited for the co-location with other technologies, in particular other GNSS sensors, frequent absolute gravity measurements, and a super-conducting gravimeter.

Potentially, the station in Trysil could be developed into a fundamental station combining, for example, GPS, GLONASS, DORIS and the future Galileo. If a much improved (with respect to operational requirements) SLR station becomes available, the addition of SLR should be considered adding a very important technique to the national geodetic infrastructure.

6.2 Serving science

Geodetic observations of changes in the shape of the Earth, the gravitational field and the rotation are of interest for many scientific problems. On a global scale, these products are made available through the IAG services and GGOS. On regional scale, EUREF, the *European Permanent Network* (EPN), the ESEAS and in future the ECGN provide access to time series and data sets. These global and regional datasets need to be complemented through national data sets derived from the national infrastructure.

The delivery of time series of station coordinates (displacements) particularly for those stations not committed to international networks should be an integral part of the national geodetic infrastructure.

6.3 Maintaining the NGRF

The maintenance of the NGRF is preferably based on a hierarchical infrastructure having as its top layer the continuously operating stations, which are integrated in global and regional networks, in the middle

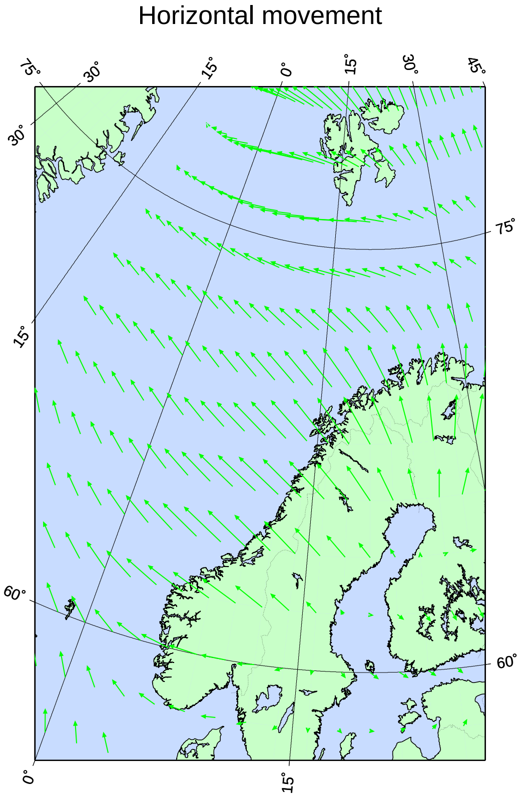


Figure 33: Horizontal motion due to post-glacial rebound.

The model is from Milne et al. (1999). The arrows point in the direction of the motion. The longest arrows correspond to ~ 3.5 *mm/yr.*

layer the continuously operating stations of the national densification, and at its base the campaign-type markers for episodic measurements. In the following, we describe the specifications for these components from the viewpoint of maintaining the NGRF. The importance of the contribution of the top layer to global and regional network was emphasized in Section 6.1 above. Therefore, focus will be here on the middle and bottom layer. The main goal of these two layers is the provision of an accurate velocity field that will enable the transformation of coordinates determined *ad hoc* in ITRF into the NGRF. Moreover, the monitoring of the NGRF should also provide information on intraplate deformations.

6.3.1 The Permanent CGNSS network

The permanent CGNSS (which today is mainly based on GPS) has to provide a sufficiently dense coverage of Norway, that will allow quantifying the land motion in the ITRF with an accuracy of 1 mm/yr or better. One main factor contributing to intraplate deformations in Norway is the process of post-glacial rebound, which is associated with vertical and horizontal deformations of the order of 10 mm/yr and 4 mm/yr, respectively, over the whole of the Norwegian mainland (figs. 33 and 34). In some areas like southwestern Norway, intraplate deformations can also arise from tectonic processes, though the extent and order of magnitude is not yet fully known.

Taking into account the relatively smooth spatial pattern of post-glacial rebound as predicted by geophysical models, a station spacing on the order of 250 km could be considered sufficient. This would lead to approximately 25 evenly distributed stations for the mainland. However, the empirical model shown in fig. 34 shows more spatial variability than predicted by the geophyscial models. Therefore, a spacing of 150 km is considered more appropriate.

The operation of the CGNSS stations should be according to IGS standards. Moreover, an operational quality control and analysis of the observations is mandatory in order to ensure the proper operation of the stations and to detect problems in a timely manner.

The CGNSS network provides the history of the national reference stations with high temporal resolution. However, the spatial resolution is not sufficient to establish the velocity field for all locations with the required 1 mm/yr accuracy. Therefore, a densification of the CGNSS network is needed. This is achieved through the network of 4-D points.

6.3.2 The 4-D network

The network of 4-D points is a densification of the CGNSS network. 4-D points are well monumented points for GPS or GNSS observations, which easily can be revisited for campaigns of several days duration. The monuments are such that the antenna can be remounted with an accuracy in the vertical and horizontal components of about 0.1 mm and in orientation of the order of 1° or better.

Taking into account the relatively high stability of the Norwegian mainland with low strain rates and large wavelength of present-day deformations, the 4-D network should provide a spatial resolution of about 100 km, with some densification in areas of neotectonic deformations, for example, the regions of the Oslo graben and the Ranafjord. These points should be revisited every three to four years in order to achieve velocities with accuracy of 1 mm/yr or better after a period of 10 to 15 years (fig. 35).

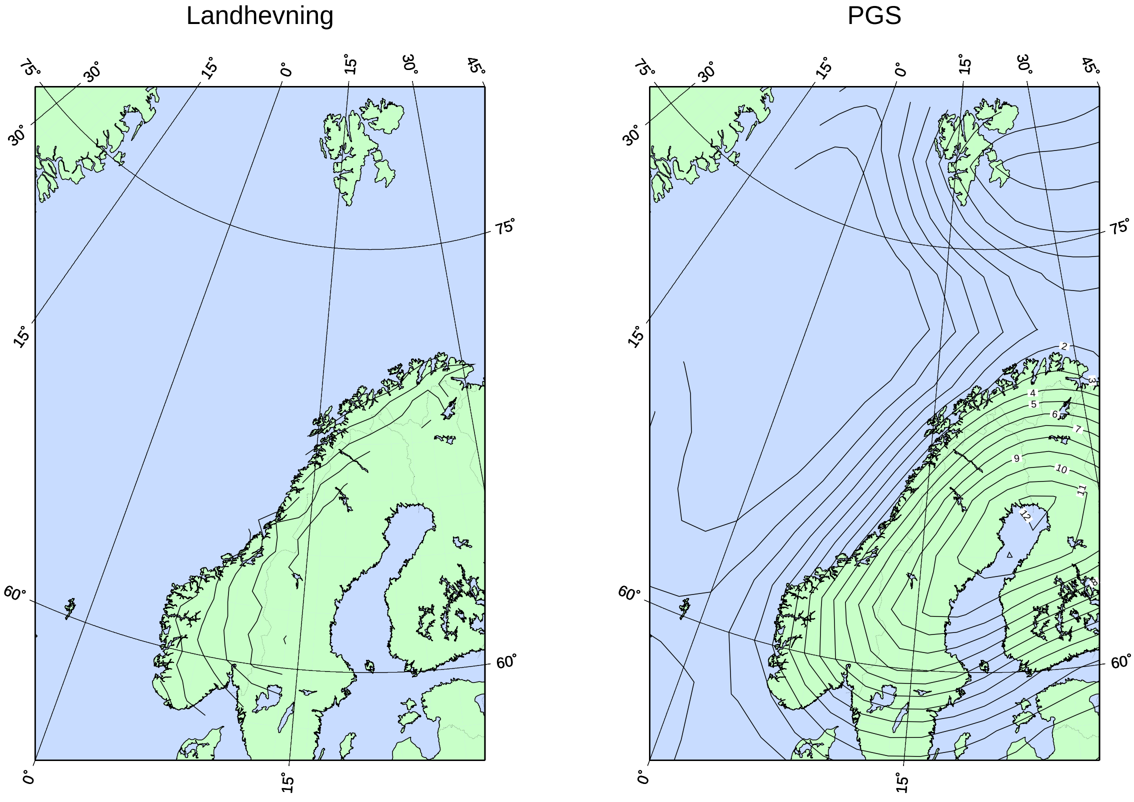


Figure 34: Vertical velocity predicted by an empirical land uplift model and a geophysical post-glacial rebound model.

The left diagram shows the empirical model of Danielsen (1999). The right diagram shows the uplift predicted by a geophysical PGR model (Milne et al., 1999). Distance between isolines is 1 mm/yr.

Campaign duration at individual stations should be at least four days.

The observations from individual 4-D campaigns can be analyzed in a global reference frame using the precise point positioning method and corrected for CMVs. The latter corrections can be determined on the basis of the continuous observations provided by the CGNSS network. Already without any correction of CMVs, the velocities determined from three individual campaigns on selected points show a velocity pattern that deviates from the prediction of the plate motion model recommended in the IERS Conventions (see figs. 35 and 36).

6.3.3 The national gravity network

The national gravity basenet provides access to gravity values mainly for gravity campaigns with relative gravimeters needed to improve the national geoid, as well as practical applications, such as the provision of a gravity reference point, for example, in laboratories. Relative gravimeters need to be calibrated prior and after measurements at new points, normally, at the start and end of measurement campaign during a day. Therefore, point spacing should be such that a basenet point can be reached within a few hours driving from anywhere in the country.

Originally, relative networks were established in single large national campaigns based on very few absolute points located in Europe. Today, transportable absolute gravimeters can be used to establish a number of absolute points as part of the national basenet. These points can then be used to improve the accuracy of the national basepoints with relative gravimeter campaigns. For this purpose, a number of about 10 absolute points distributed equally throughout the country appears sufficient for logistic reasons.

6.4 Providing access to NGRF

6.4.1 Real time and near-real time access

As pointed out in Section 5.2.6, there are several methods to provide access to the reference frame in real time or with low latency, namely, through the

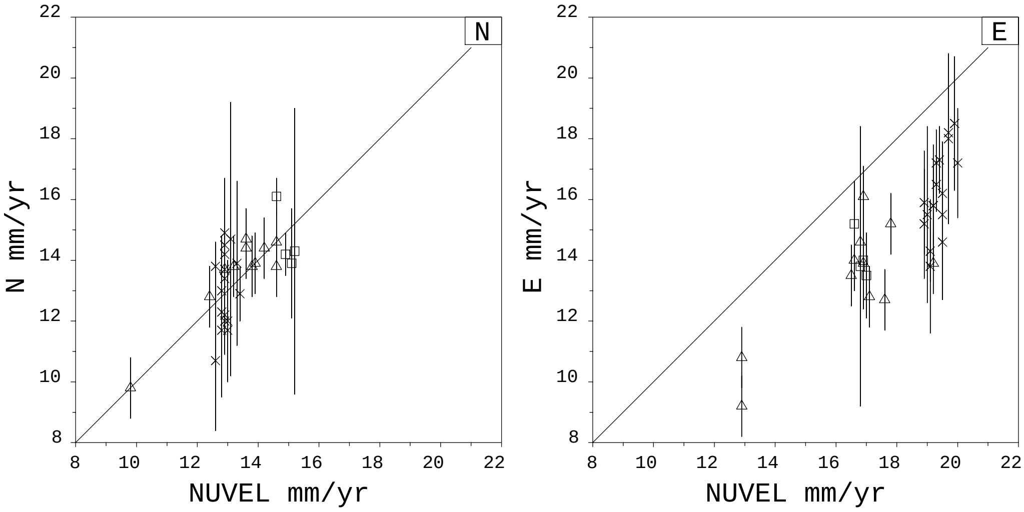


Figure 35: Comparison of GPS-determined and NUVEL-1A-NNR predicted horizontal velocities.
The diagrams show on the x-axis the horizontal velocities predicted by the NUVEL-1A-NNR model and on the y-axis the observed velocities. The left diagram is for the north component and the right for the east component. For optimal agreement, points are on the diagonal. Triangles are for the CGPS stations, '+' for 4-D points in southern Norway and squares for 4-D points in northern Norway. From Plag et al. (2002).

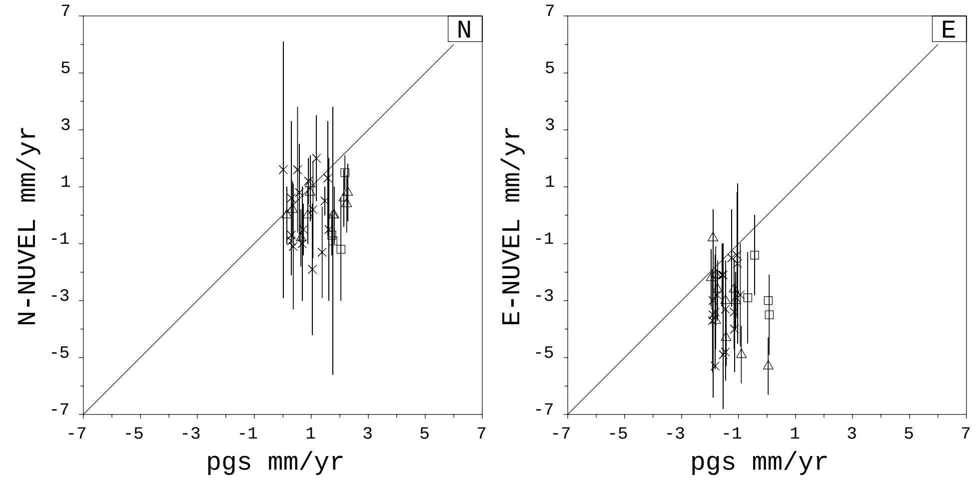


Figure 36: Residual velocities in north and east component compared to post-glacial rebound model velocities.
The diagrams show on the x-axis the horizontal velocities predicted by the geophysical model shown in fig. 33. On the y-axis, the differences between observed and NUVEL-1A-NNR predicted velocities is shown. The left diagram is for the north component and the right one for the east component. Symbols are the same as in fig. 35. From Plag et al. (2002).

provision of high-accuracy satellite orbits and clocks in real time or through the provision of differential corrections for the GPS SPS. For the NGRF, the current solution is a hierarchical system providing services with accuracy at levels from meters down to centimeters (see http://www.satref.no/ for more information in Norwegian). These services are based on the information available from the national real-time CGNSS networks SATREF (see fig. 48 on page 85).

As pointed out in Section 3, the most demanding real-time applications require an accuracy on the centimeter level with respect to the NGRF. In order to serve these user needs, the real-time service should provide for this accuracy. This requires that

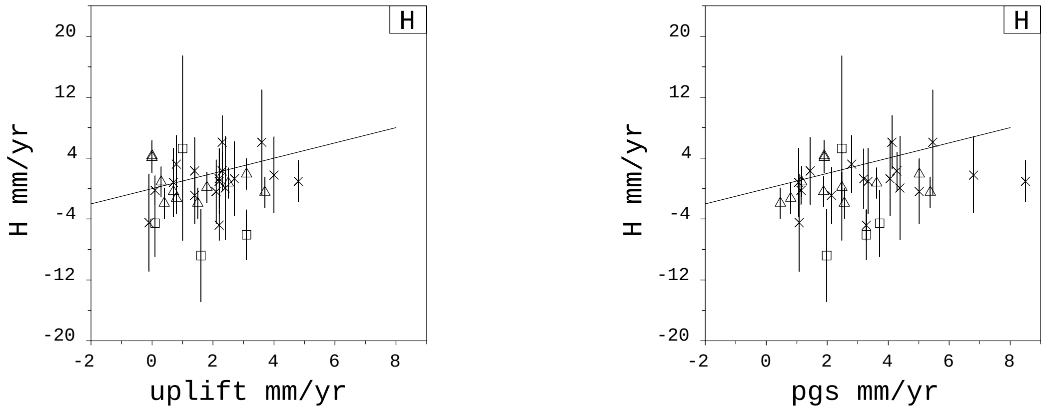


Figure 37: Comparison of the GPS-determined vertical velocities to those predicted by a post-glacial rebound model.

The diagrams show on the y-axis the observed vertical velocities. Left diagram: the x-axis shows the velocities computed from the empirical land uplift model (Danielsen, 1999). Right diagram: the x-axis shows the predictions from a geophysical PGR-model (Milne et al., 1999). Note that the scales on the x- and y-axis are different. The line indicates perfect agreement between observed and predicted velocities. Symbols are the same as in fig. 35 on page 75. From Plag et al. (2002).

the reference frame implicitly realized by the reference network of SATREF is closely aligned to the NGRF as determined through the national reference points (Stamnett, see next section).

6.4.2 High accuracy access

In order to get high accuracy access to the NGRF, the processing tools to compute highly accurate coordinates in ITRF as well as to transform these coordinates into the NGRF need to be available. These tools are considered part of the NNGI.

The NNGI should offer the tools or the service to processes GPS (and in the future GNSS) observations in a standard way consistent with the IERS Conventions, providing as a result highly accurate coordinates in ITRF. Preferably, such tools would be provided through a web page. In order to correct the ITRF coordinates for the effects of CMVs, the provision of a CMV model for Norway based on the national CGNSS network should be an integral part of such tools.

For the transformation of the ITRF coordinates given for the central epoch of measurements into the NGRF, the velocity field for Norway in the ITRF needs to be made available together with a (preferably web-based) tool for the transformation from ITRF to NGRF.

6.5 Ensuring continuity

In order to ensure the continuity and required quality of the national geodetic infrastructure, the national geodetic authority in any country needs to be a center of excellence capable of providing the required high-level service to society. The present rapid transition of the geodetic techniques and methodology requires an active involvement in research and development.

Considering the complexity of the tasks involved in the determination and maintenance of the ITRF and NGFR as well as the full utilization of the geodetic techniques for Earth observation, the required expertise spans a wide range from Earth sciences, geodesy, mathematics to information technologies. Particularly for a country like Norway, where the mere size of the population limits the available relevant human resources, cooperation with national and foreign universities is crucial in order to ensure the required expertise. The cooperation of the Nordic national geodetic authorities and relevant geodetic institutes in the frame of the Nordic Geodetic Commission is an important framework to achieve a sufficient human resource basis on Nordic level. It should therefore be considered whether a Nordic center of excellence in Geodesy is a viable option, and more appropriate to ensure the necessary expertise and capacities than a Norwegian national center of excellence.

7 Assessment of the current geodetic infrastructure

7.1 Introduction

Based on the user requirements described in Section 3 we have derived specifications for the global (Section 5) and national (Section 6) geodetic observation systems and the required infrastructure. In this section, we will use these specifications to assess the currently available infrrastructure and to identify eventual gaps. In order to consider the complete infrastructure, both the organizational background and the networks will be considered.

7.2 Global geodetic infrastructure

7.2.1 Recent developments in global geodesy

Over the last decade, the organizational development within international space geodesy has been inspired by the success of the IGS, which was established by IAG in 1994. Since then, the IGS has facilitated the creation of a global network of GPS tracking stations which today consists of more than 300 stations (fig. 38). These stations provide observations on an hourly or daily basis to data centers, from where the data are freely available. A sub-set prototype network of over 30 stations is already providing data in real time. A number of IGS *Analysis Centers* (AC) determine satellite orbits and clocks as well as ERP on a routine basis with a variety of latency and accuracy (Ray et al., 2004), which are widely used in scientific and, increasingly, also nonscientific applications.

The success of the IGS stimulated the establishment of other technique-specific space-geodetic services by IAG, such as the IVS, the ILRS, and the *International DORIS Service* (IDS). These services provide continuous observations from their ground-based tracking networks (see figs. 39 to 41), which are also used to determine station displacements, deformations of the solid Earth, geocenter motion, and ERPs. Both observations and products, are made available to a wide range of users, though mainly in scientific fields.

The products of the technique-specific services are the basis on which the IERS determines and monitors the ITRF as the most accurate realization of the ITRS. For that purpose, a number of ITRF ACs provide single and multi-technique solutions, which are then combined to provide the so-called regularized station coordinates and secular velocities (McCarthy & Petit, 2003) of a given ITRF version. In 2001, the ITRF2000 was introduced, and at that time, it was considered to be the most accurate realization of the ITRS so far (Altamimi et al., 2002). ITRF2000 is based on a network of more than 400 stations, many of them co-located by two or more techniques (fig. 42). Recently, the ITRF2005 was released, and it is expected that ITRF2005 is of the same or a better accuracy and internal consistency than ITRF2000 (Altamini et al., 2006).

The IERS also includes the GGFC, which was established in 1998. The GGFC and the associated seven *Special Bureaus* (SB) for Atmosphere, Oceans, Tides, Hydrology, Mantle, Core, Gravity/Geocenter, and Loading have the responsibility of supporting, facilitating, and providing services to the worldwide research community, in areas related to the variations in Earth rotation, gravitational field and geocenter that are caused by mass transport in the geophysical fluids. The GGFC provides a general frame for research related to the further development of the products delivered by the IERS and the IAG services.

Very recently services related to the gravitational field were initiated. In particular, the *International Gravity Field Service* (IGFS) takes the responsibility for all aspects of the Earth's gravitational field. In addition, the establishment of an *International Altimetry Service* (IAS) is contemplated. Such a service was pointed out as missing and an evident complement of the IAG system of services. The increasingly important role of InSAR for many applications, ranging from the monitoring of small scale surface displacements to changes in the biosphere, has brought up the idea of setting up an international InSAR service (Labreque, 2004, personal communication). InSAR observations are relevant to geodetic applications and therefore should be studied and developed under the umbrella of IAG. The organizational model of the IAG services has also been applied to interdisciplinary fields, for example, to the *European Sea Level Service* (ESEAS), which integrates geodetic and hydrographic techniques into a sea level observing system (Plag, 2002).

The structure of the IAG Services is currently complemented by the GGOS, which will integrate the Services into an interacting system and form a new, unique, user-oriented interface for the geodetic observing systems. From an organizational point of view, GGOS is particularly needed to create a unique interface between GEOSS and other users on the one

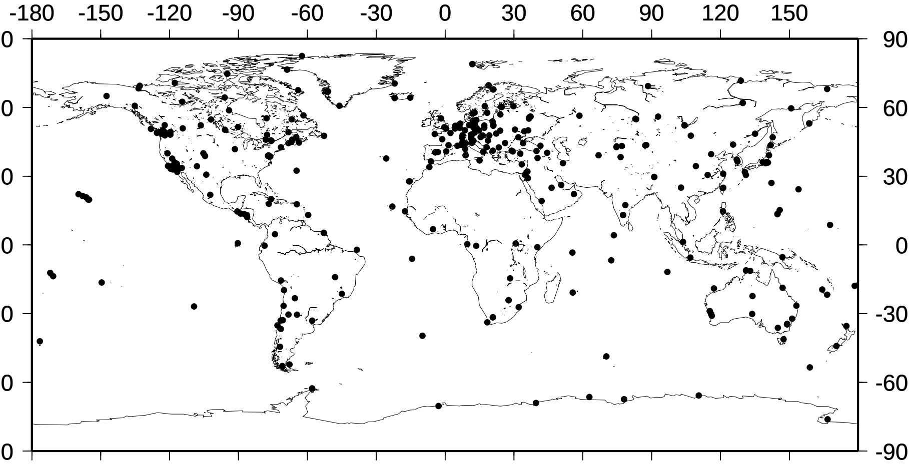


Figure 38: Global network of IGS GPS tracking stations.

Stations shown are the 378 stations included in the IGS Stations SINEX file of November 6, 2006.

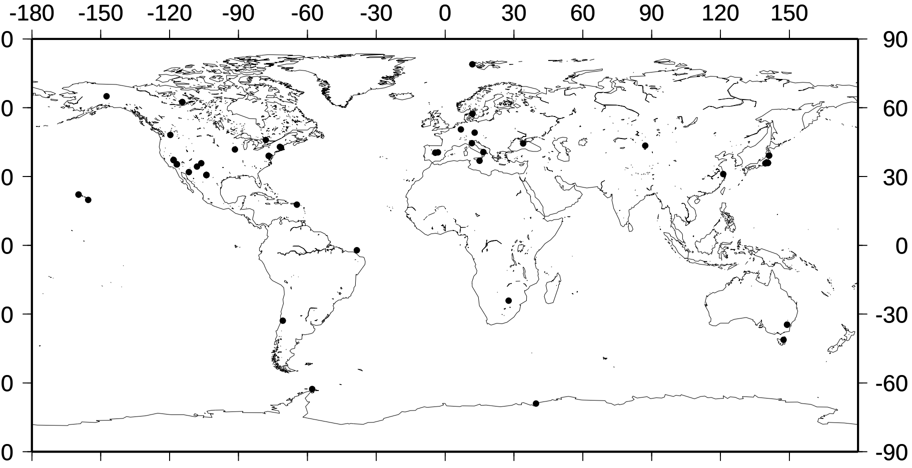


Figure 39: Global network of IVS and associated tracking stations.

side and the IAG Services on the other side.

In parallel to the development of the IAG services, a number of satellite missions and projects loosely related to IAG have aimed at a better observation of the Earth's gravity field, both *in situ* and remotely.

The *Global Geodynamics Project* (GGP, see Crossley et al., 1999) is a project monitoring changes in the Earth's gravity field *in situ* at periods of seconds and longer. Accurate local measurements of the Earth's gravity field in a global network of stations are essential to answer a number of scientific questions related to the dynamics of the Earth's interior (ranging from seismic normal modes, tides, core modes and wobbles to long-period variations due to tectonic deformations) as well as the dynamics of the coupled atmosphere-ocean-solid Earth system (see, for example, http://www.eas.edu/GGP/ggppg.html for an overview of the problems).

The GGP is currently in its second phase. Phase 1 ran from 1 July 1997 to 1 July 2003. At the 2003 IUGG meeting in Sapporo, GGP was officially integrated into the IAG as an Intercommission Project reporting to Commission 3 (Earth Rotation) and Commission 2 (The Gravity Field). The second phase will last until the next IUGG in Perugia, Italy, 2007. Its purpose is to record the Earth's gravity field with high accuracy at a number of stations worldwide

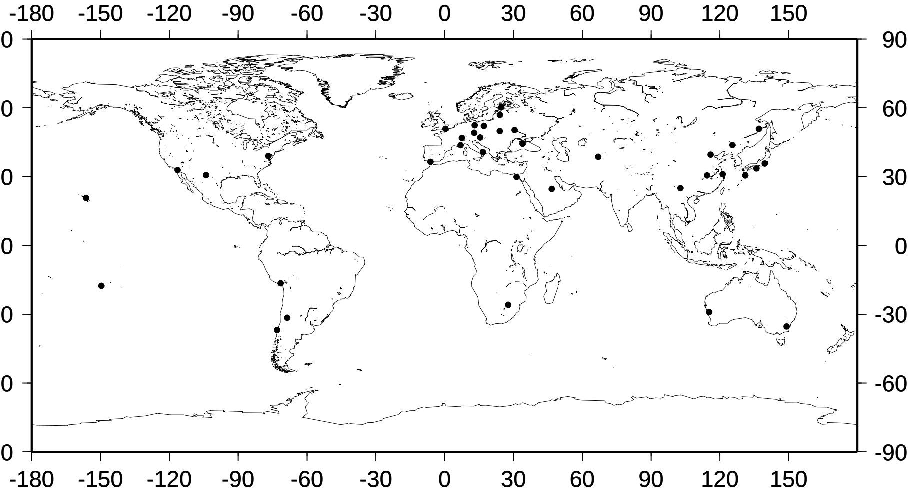


Figure 40: Global network of ILRS tracking stations.

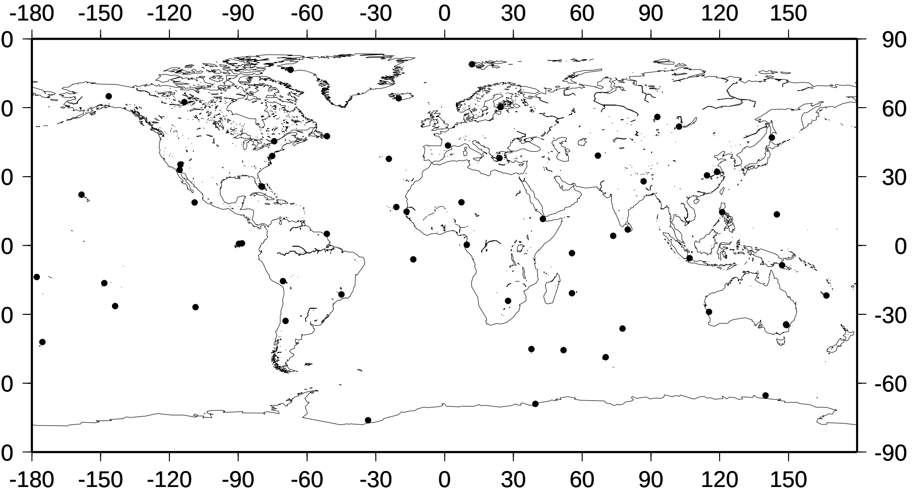


Figure 41: Global network of IDS tracking stations.

(fig. 43) using superconducting gravimeters (SGs) with frequent monitoring of absolute gravity at each site to co-determine secular changes. The SG stations are run independently by national groups of scientists who send data each month to the GGP Data Centre at the *International Centre for Earth Tides* (ICET) in Brussels.

The ongoing gravity field missions CHAMP and GRACE, as well as the upcoming GOCE mission scheduled for launch in 2006 will lead to or are already leading to a dramatic improvement in Earth gravity field recovery. At the same time, the satellite altimetry missions TOPEX/Poseidon, ENVISAT, Jason-I, GFO, and ICESat observe the surface of the ocean and the ice sheets with a high spatial and temporal sampling. The synthesis of all these missions will significantly improve the understanding of Earth system processes related to mass transports.

The CHAMP mission (Reigber et al., 1999), which was launched in 2000, is the first dedicated gravity field mission, which has already lead to considerable improvements of the static long-wavelength gravitational field (Reigber et al., 2003). The GRACE mission (Tapley et al., 2004b) has the objective to map the global gravity field with unprecedented accuracy over a spatial range from 400 to 40,000 km every 30 days, thus allowing the determination of nontidal temporal variations of the gravitational field. These are mainly due to seasonal, interannual and long-period redistributions of mass in

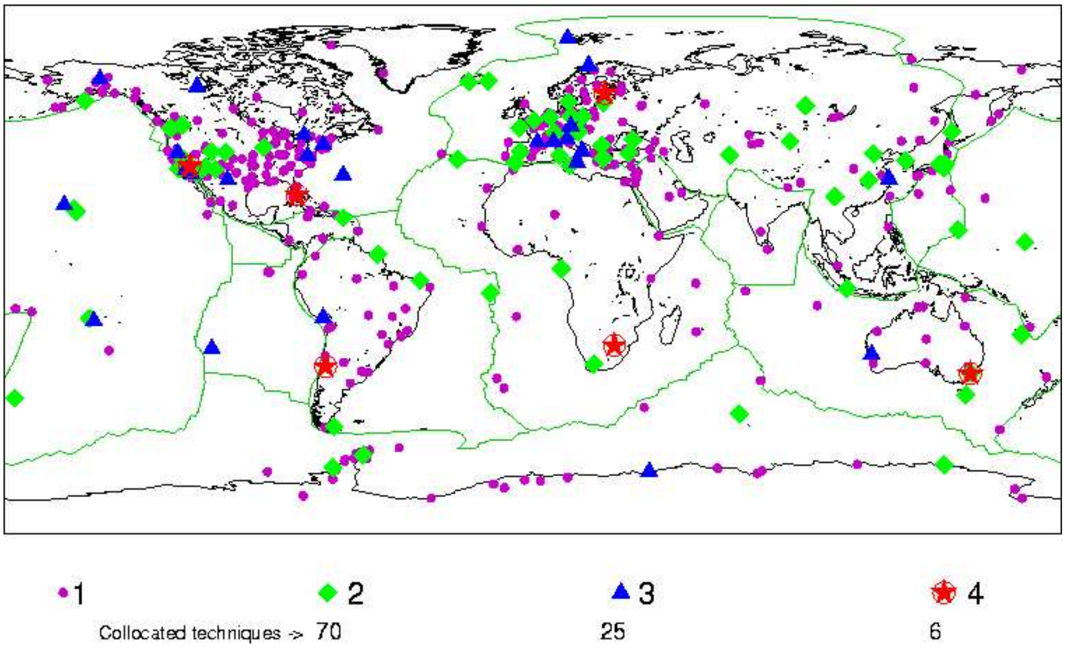


Figure 42: Global network of sites used in the determination of ITRF2000.

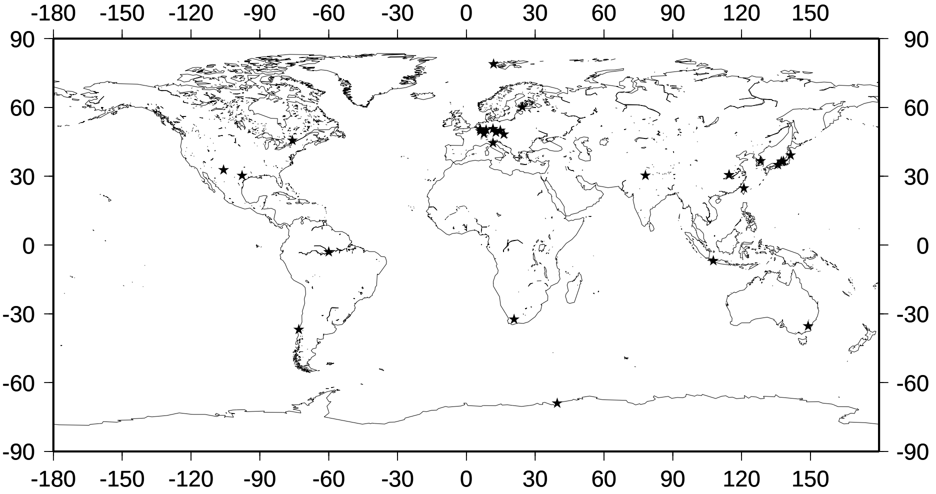


Figure 43: Global network of the Global Geodynamics Project.

Red circles are sites disconnected after the first GGP phase, yellow circles the sites continuing in the second GGP phase, and green circles new sites joining for the second phase. From http://www.eas.edu/GGP/ggpmaps.html.

the atmosphere, hydrosphere, cryosphere and solid Earth. Since its launch, the GRACE mission has already led to novel results concerning the seasonal global scale continental water storage variations (e.g., Tapley et al., 2004a; Kusche & Schrama, 2005; Wu et al., 2006), presentday changes in ice sheets and glaciers (e.g., Tamisiea et al., 2005; Velicogna & Wahr, 2005, 2006), and basin-scale hydrology (e.g., Crowley et al., 2006). The mission also stimulates research in many areas (see, e.g., Peltier, 2004; Bao et al., 2005, for application to postglacial rebound and tsunamis, respectively).

The third dedicated gravity mission will be the GOCE satellite (Drinkwater et al., 2003), This mission has the goal to determine the Earth' static gravitational field and the geoid with an accuracy of 10^{-8} ms^{-2} and 1 cm, respectively, down to length scales of 100 km (i.e. spherical harmonic degree and order 200).

On regional European level, the EPN of EUREF and the proposed ECGN need to be mentioned. The EPN is a steadily growing CGNSS net-

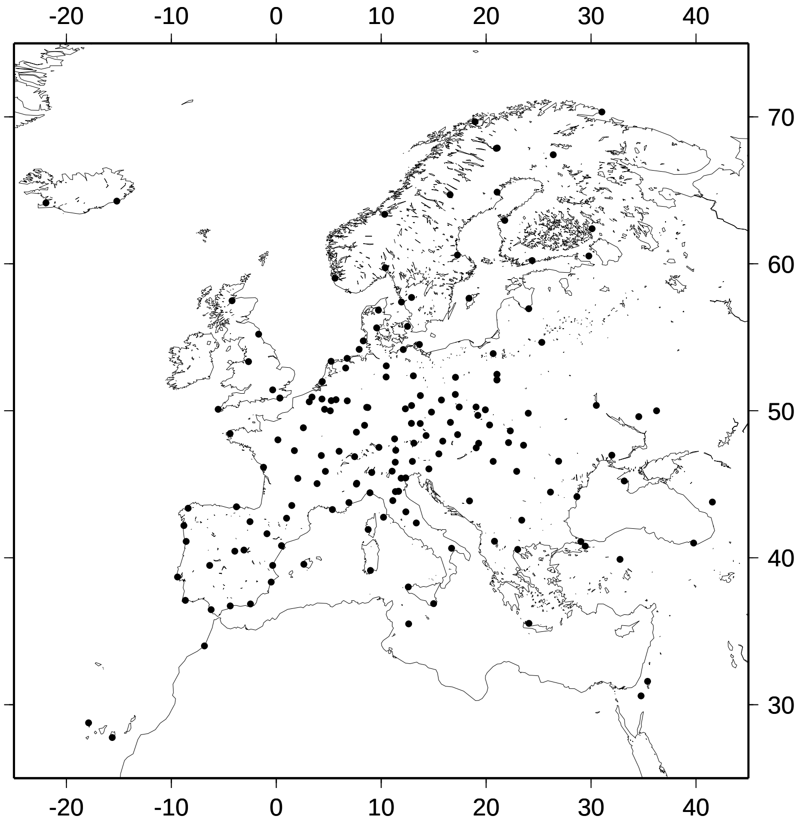


Figure 44: The current stations in the European Permanent Network.

Stations are those included in the combined EUREF solution for Week 33 in 2006 (see http://www.epncb.oma.be/_trackingnetwork/coordinates/).

work (presently mainly CGPS) with currently about 100 stations (fig. 44). The ECGN is a proposed network of multi-technique stations, which includes both space-geodetic and gravimetric techniques (fig. 45). NMA is contributing to both networks with a number of stations.

7.2.2 Gaps and limitations on global level

The global geodetic infrastructure, which is based solely on the voluntary contributions of national institutes and organizations, is in surprisingly good shape, particularly if compared to most other global observation systems, where significant gaps in spatial and temporal coverage exist. Nevertheless, the global geodetic infrastructure is suffering from reduced funding and increasingly scarce resources, while in some countries, governmental decisions led to closure of major infrastructure.

A major limitation originates from the low number of fundamental stations and their insufficient geographical distribution. A central technique is SLR, which is able to tie the origin of the reference frame to the CM. However, the number and geographical distribution of SLR stations is insufficient. This is likely to be one of the greatest obstacles for global geodesy and the accuracy of the reference frame. Moreover, more low-orbiting SLR-dedicated satellites would also increase the sensitivity of SLR to the CM. The insufficiently defined relation between the origin of the reference frame and the CM not only introduces a large uncertainty in important global quantities such as global sea level change, but also compromises the comparison of model predictions (given with respect to a well defined reference frame) and observations of changes in Earth's shape, gravity field and rotation.

Fundamental stations with several techniques co-located on the same site are crucial for the quality of the reference frame. However, the full utilization of these station is only possible if the local tie vectors between the reference points for the various co-located techniques are accurately known and monitored (see the papers in Richter et al., 2005, for an

Figure 45: The proposed stations of the European Combined Geodetic Network.
The map is taken from http://www.bkg.bund.de/ecgn/.

overview of the related requirements and problems). Unfortunately, this is not the case for all fundamental stations.

With respect to the gravity satellite missions, a key problem is the long-term operation and consistency. Similarly, changes in the satellite configuration, data format and products also affects the long-term consistency of the observation systems of satellite altimetry and InSAR.

InSAR is increasingly recognized as a technique for monitoring of surface displacements with high resolution at small spatial scale from a few tens of meters to 100 km. In particular, the combination of InSAR with CGPS is expected to provide a new and efficient monitoring technique. However, there is currently little recognition of this emerging technology in the global geodetic community and most of the development takes place outside the IAG/GGOS community.

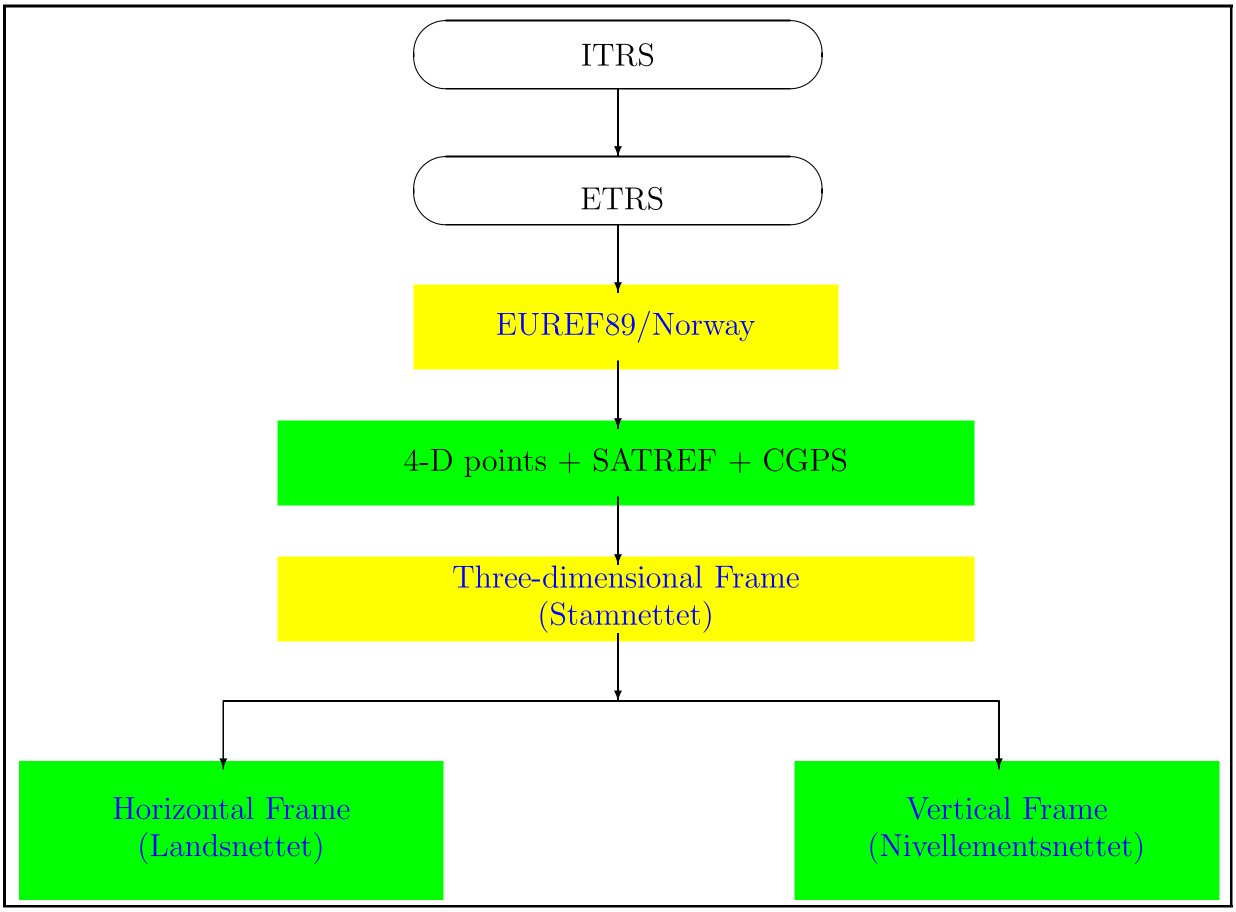


Figure 46: Hierarchical structure of the NGRF.

The NGRF is built in a hierarchical structure. At its bottom a dense network of monuments provides access to the NGRF for users using relative positioning for horizontal coordinates (Landsnett) and heights (nivellementsnett). The approximately 900 monuments of the national three-dimensional network (Stamnettet) bind these two networks together into a three-dimensional frame, which defines EUREF89 in Norway. More than 140 points form the 4-D network, which is used to monitor the movement of the Earth's surface with respect to ITRF and provides the basis to refer ad hoc *coordinates to the reference epoch 1 January 1989. The SATREF stations monitor the Earth surface continuously and provide information on nonlinear movements. These stations are used together with the 4-D points to improve the models and to determine the transformations between observation epochs and EUREF89. All these components together realize the ETRS as EUREF89 in Norway and connect this reference frame to the different ITRFs.*

7.3 Norwegian national geodetic infrastructure

7.3.1 Present Situation

The NGRF is linked into a hierarchical structure of reference frames ranging from the ITRF over the ETRS to the national realization of the ETRS through EUREF89 and further down to the dense networks of markers (fig. 46).

The *in situ* observational part of the NNGI consists of a layered pyramid of station networks providing the observations for the determination and monitoring of the NGRF as well as access to it (fig. 47). Moreover, this infrastructure contributes observations to global and regional networks and thus supports the determination and monitoring of the ITRF as well as Earth observation in general. This pyramid can be separated into three segments, namely (1) the global monitoring segment (with two levels) contributing to the determination and monitoring of the global reference frame, (2) the national monitoring segment (with two levels) providing the time-dependent relation between the global and the national reference frame, and (3) the national access segment (with currently one level), allowing access to the national reference frame through relative positioning.

The global segement: The global segment, which comprises the *in situ* infrastructure contributing to the determination and maintenance of the

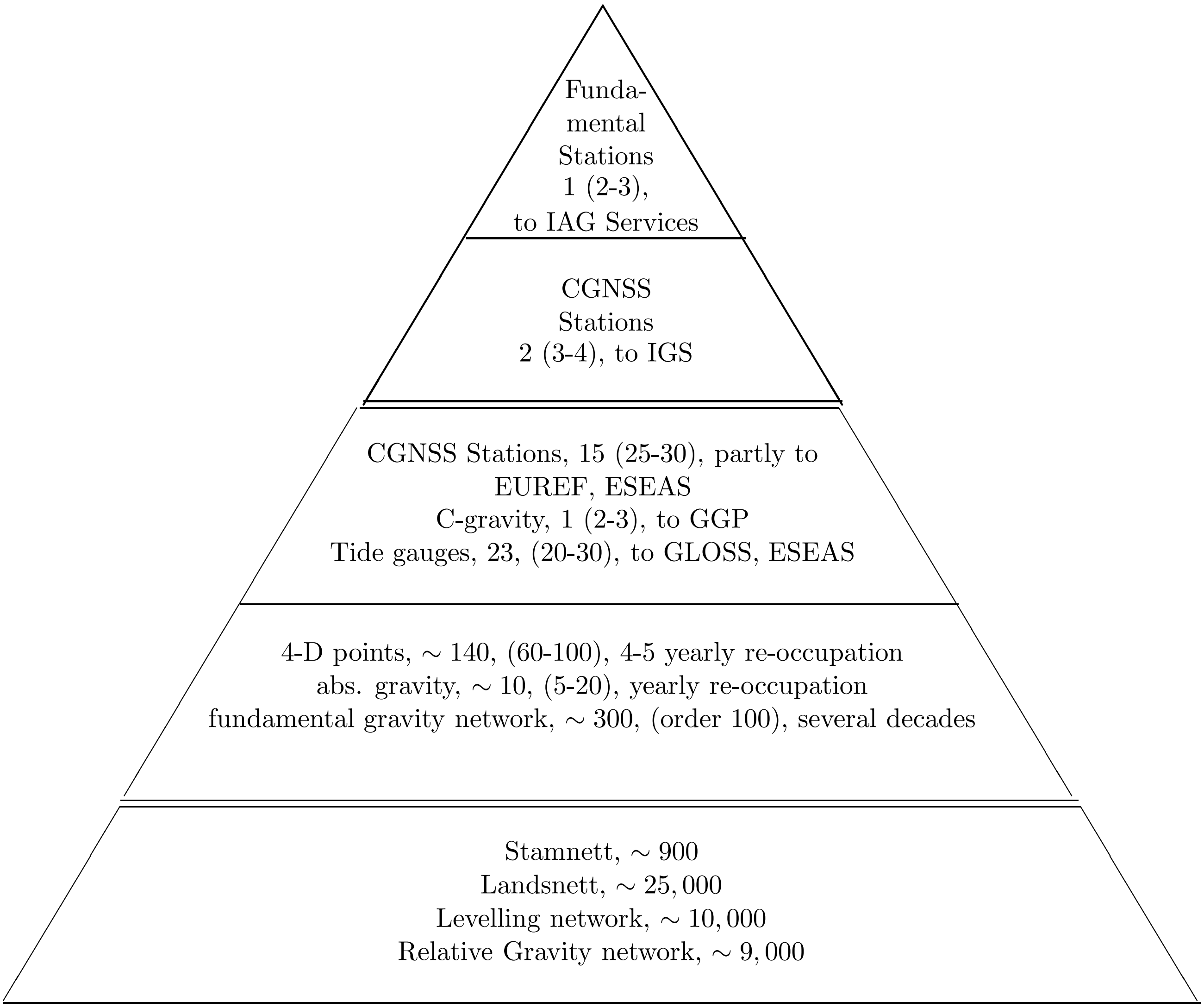


Figure 47: The geodetic *in situ* pyramid for Norway.

The top triangle is the contribution to global networks required to determine and maintain the ITRF. The middle trapezoid contains the national networks required to determine the transformations between the time-dependent ITRF and the fixed NRF. The lower trapezoid contains the dense networks of permanent markers which currently are used for relative positioning and which in the future will ensure some level of persistence of the geodetic reference frame in (the unlikely) case of ITRF and precise point positioning becoming unavailable.

global reference frame, has two levels, namely (1a) the fundamental stations, and (1b) the global CGNSS reference stations.

Fundamental stations: On the top of the pyramid, in the global segment, the fundamental station in Ny Ålesund provides an important contribution to the global network of ITRF stations, and it is also a crucial component in the network of VLBI stations operated under the coordination of the IVS. Moreover, this station contributes to IGS and ESEAS/GLOSS and hosts a DORIS reference station. In co-operation with the Japanese Astronomical Institute, a superconducting gravimeter is operated and contributes to the GGP (Sato et al., 2006a). In co-operation with a number of European Institutes, absolute gravimeter measurements are carried out frequently in order to calibrate the superconducting gravimeter and to determine the secular changes in gravity (Sato et al., 2006b). A number of local site surveys have been carried out (see, e.g., Bockmann et al., 2002), demonstrating the importance of such campaigns for the assessment of the station stability and representativity.

The importance of the Ny-Ålesund station is partly due to its location in the high Arctic, and partly to the combination of geodetic and geophysical observation techniques. The continuation and further development of the station is considered an important Norwegian contribution to the global geodetic networks, the ITRF, and Earth observation, while simultaneously providing the primary reference point for the NNRF.

Global reference stations: The next level of the *in situ* pyramid, which still belongs to the global segment, consists of the CGNSS stations which are commited to the global IGS network and thus contribute to the determination of the satellite orbits and clocks required for high-accuracy access to the global reference frame. Currently, this level includes two stations at Tromsø and Ny-Ålesund.

National monitoring segment: The national monitoring segment also has two levels, namely (2a) the continuously monitoring stations, and (2b) the episodic monitoring sites. These two levels have the main purpose to establish and maintain the relation between the global reference frame (i.e. ITRF) and the NGRF (i.e. EUREF89). This segment of the pyramid provides the basis for the determination of the velocity field of the Earth's surface in ITRF.

Continuous monitoring stations: The upper level of the national monitoring segment contains all the continuously monitoring stations. First of all, these are the CGNSS stations (see fig. 48), which partly also contribute to regional networks such as the EPN and the ESEAS. Moreover, this level also includes the continously recording super-conducting gravimeters (currently only one), which contribute to GGP, and the tide gauges, which are part of GLOSS and/or ESEAS.

Episodic monitoring sites: The lower level of the national monitoring network includes campaign-type infrastructure, which is frequently reoccupied. First of all, these are the so-called 4-D points, which are stations well monumented for highly accurate episodic GNSS measurements. These points have been re-occupied every four to five years and provide a densification of the velocity field derived from the CGNSS network.

The combination of a low-density network of CGNSS sites with a densification with campaign points is a cost-effective approach to monitoring the secular surface kinematic with high spatial resolution. If analysed with the observations of the CGNSS, then a relatively low frequency of reoccupations of the compaign sites is sufficient to achieve velocities with precisions on the order of 1 mm/yr from three campaigns distributed over eight to ten years. Similar results are also reported by, for example, Blewitt et al. (2005).

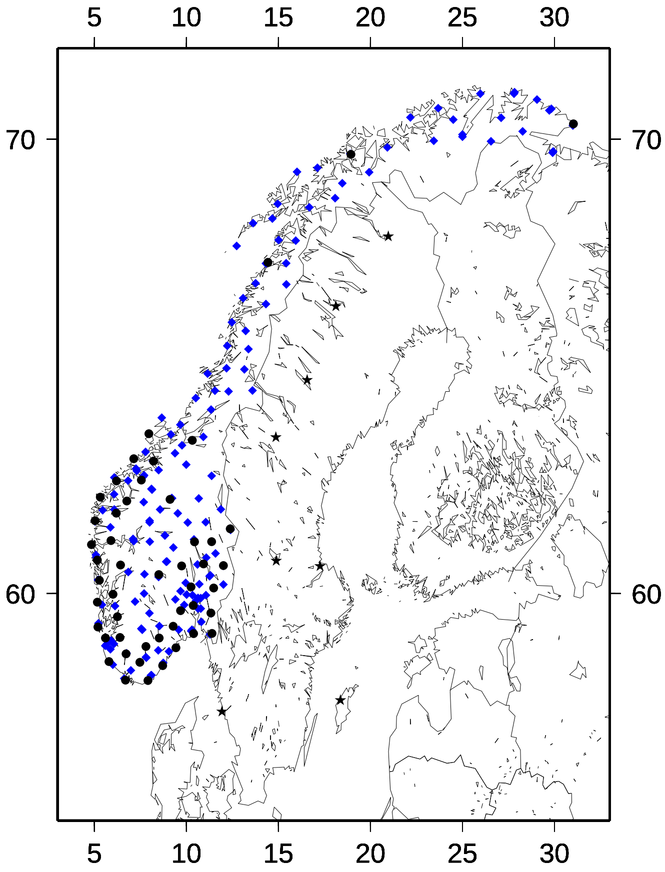


Figure 48: Permanent GPS stations and 4-D points. *Circles: CGPS sites (including SATREF and CPOS sites); diamonds: 4-D points; stars: CGPS in Sweden contributing to IGS. Note that the station Ny-Ålesund on Svalbard is not shown.*

There are a small number of stations prepared for episodic absolute gravity measurements, of which some have been occupied several times since 1991 (fig. 49). Currently, not all of these absolute gravity points are co-located with CGNSS sites. These sites should be augmented with nearby CGNSS stations. The absolute gravity sites should be reoccupied on a yearly or biennual basis; however, in the past this has not been possible for human resource and budget reasons, and sometimes, the sites were not reoccupied for three or four years.

The fundamental gravity network consists of approximately 300 points (fig. 50), which were measured in the early 1970-ties and computed in the

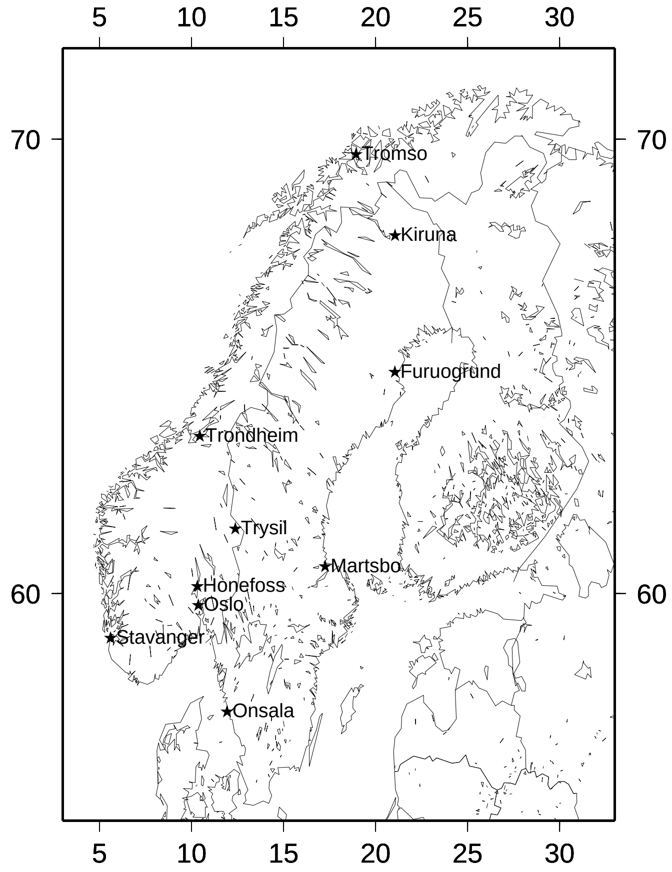


Figure 49: Network of absolute gravity points in Norway.
Shown are only those points that have been reoccupied several times since 1991. See, for example, Wilmes et al. (2006) for a more detailed discussion of the campaigns.

IGSN71 (B. G. Harrson, 2006, personal commun.). For some of these points, the current status is not known. The precision of the network is on the order of 100 nms^{-2}. Based on reobservations of comparable national gravity networks it can be expected that the network has an offset of the order of 100 nms^{-2}, while today a point accuracy of ±50 nms^{-2} is achievable (see, e.g., Richter et al., 1998, for the example of the German network). Moreover, the network has been deformed by postglacial rebound with spatial differences in rates of the order of 20 nms^{-2}/yr (Wilmes et al., 2006), resulting over 35 years in point effects as large as 700 nms^{-2}. Therefore, this national gravity network should be remeasured in order to maintain the precision and accuracy at the 100 nms^{-2} level or better. Consequently, the network is considered here as part of the monitoring segment.

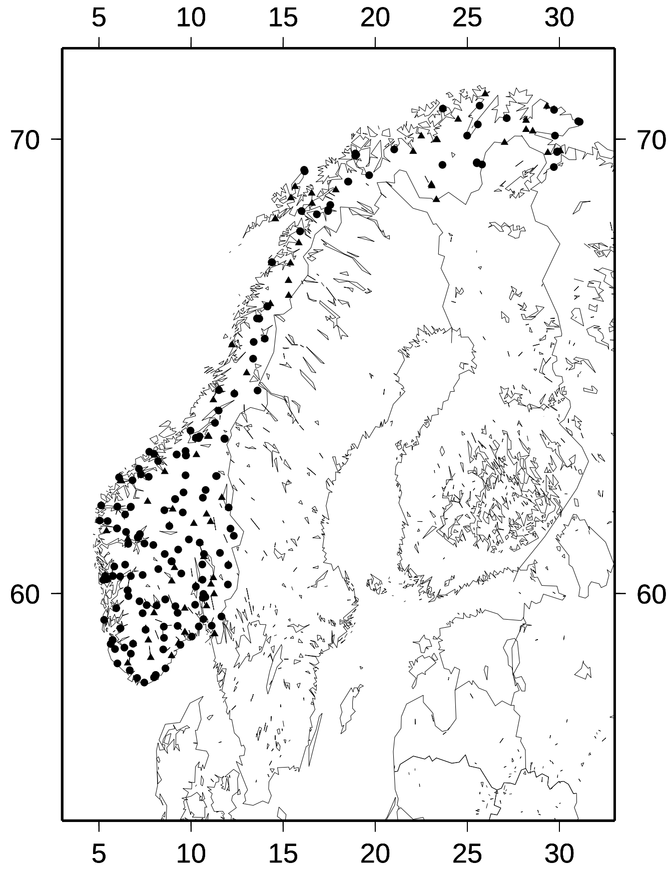


Figure 50: The national gravity base network.
Circles are gravity point that were found in good shape during the last inspection, while triangles indicate points either gone or with unknown status.

The national access segment: The national access segment comprises all the networks which have the main function of giving access to the reference frame in the traditional, relative positioning approach. The backbone of this segment is the three-dimensional frame (Stamnett, see Kristiansen & Harsson, 1999) with approximately 900 well distributed points with accurate 3-D coordinates (on the 3 to 4 cm level). The Landsnett can be considered as a densification of Stamnett, which provides the basis to transform coordinates given in older national reference frames into EUREF89. It was also intended to give access to EUREF89 locally for relative positioning. However, with the rapid technological improvements towards precise point positioning, this function may easily become obsolete in the near future. The levelling network, which has of the order of 10,000 points, provides the basis for the national height reference, together with the relative gravimeter network of some 9,000 points. However, the rapidly improving accuracy of GPS for height determination combined with improved geoid models will also soon lead to the height system being based on a combined GNSS-geoid approach, particularly for the determination of height differences on spatial scales from 100 km or more.

7.3.2 Gaps and limitations on national level

The fundamental station in Ny Ålesund, Svalbard, is a central component of the NNGI as well as a key contribution to the global networks. However, dwindling resources have made the operation insecure and reduced the contribution of this station to the global networks. The operation of this important station at a high level should have high priority.

A fundamental station is lacking on the Norwegian mainland. No such station is available in Scandinavia. This gap could be closed through, for example, the development of Trysil into a fundamental station. Besides GPS, this site should be equipped with a DORIS and at a later stage, a SLR station. Trysil is located close to the maximum land uplift of the Norwegian mainland and the main focus of this anticipated fundamental station should be on height changes. Therefore, in addition to the frequent absolute gravity measurements carried out at this station, a superconducting gravimeter should be operated at the site for several years together with the required monitoring of relevant environmental parameters.

The number of CGNSS stations in southern Norway appears to be sufficient, particularly if the stations established for the high accuracy real-time service (CPOS) can be considered as part of the geodetic CGNSS network. However, in northern Norway, a densification of tht CGNSS network is needed.

A severe limitation of the current CGNSS network is the lack of operational quality control of the incoming data and the lack of an operational geodetic analysis providing important feedback on the operation of the network and the status of the reference frame. Moreover, such an analysis would provide the station coordinate time series that could be made available for scientific users. An example of time series made available freely for any user is provided by the JPL, where coordinate time series for most of the IGS reference station resulting from a standard analysis are available for downloading.

The number of 4-D points in most parts of Norway appears to be sufficient. However, in northern Norway, for logistic reasons during the initial campaign, the spatial resolution is too low and should be improved through the establishment of a few additional 4-D points or CGNSS sites.

Currently, no operational service for the high accuracy access to ITRF and NGRF coordinates is available. Users who need support in getting either ITRF coordinates or coordinates in the NGRF are required to contact the Geodetic Institute and to get an individual processing of their observations. An official velocity model for the transformation from ITRF to the NGRF is not available. Only a prototype of such a model has been set up.

8 Cost-benefit considerations

A detailed and well-founded cost-benefit analysis for the national geodetic infrastructure in Norway is a task exceeding by far the scope of this report. However, we can take a starting point in a study carried out recently in Canada (Williams et al., 2005), which used considerable resources on estimating the costs and benefits of the national geodetic reference frame. In a pioneering economic impact analysis of the *Canadian spatial reference system* (CSRS), Williams et al. (2005) found that the CSRS directly contributes between \$60 and \$90 billion annually to Canada's *Gross Domestic Product* (GDP), with their ultra conservative estimate being \$25 billion (numbers in Canadian dollars).

The study was based on the *Gross Value Added* (GVA) approach, which is an input-output approach. GVA and GDP are often used interchangeable but they are technically different, although GVA is a major component of GDP with only taxes and subsidies on products subtracted. Thus the link between GVA and GDP can be defined as GVA + taxes on products - subsidies on products = GDP. Based on the statistical data available for Canada, a number of economic sectors were identified, for which there were the most users of the CSRS. The economic sectors considered were (1) Air, Marine and Land transportation, (2) Utilities, (3) Construction, Architecture, Surveying and Engineering, (4) Federal, Provincial, Municipal Governments, (5) Agriculture and Forestry, (6) Mining and Oil and Gas Extraction, (7) Solicitors, Waste Management and Environmental Consultancies, (8) Computer System Design and Related Services. These sectors in fact represent a large component of the GDP. For these sectors, their GVA was calculated and the level of economic activity in that sector depending on the CSRS was estimated. A CSRS Dependency Index was defined on the basis of the proportion of GVA, with the 10%-ranges from 41-50% down to 1-10% being denoted as 'High', 'Moderate to High', 'Moderate', 'Low to Moderate' and 'Low', respectively. This index scale was mapped on each of the identified sectors. Finally, the CSRS-dependent GVA was computed.

The Canadian Power, Gas and Water Utilities, and the Federal, Provincial and Municipal Governments were found to be in the 'Moderate to High' range, Air, Marine and Land Transportation and Architecture, Engineering, Surveying and Construction in the 'Moderate' range, Mining, Oil and Gas Extraction in the 'Low to Moderate' range, and the remaining sectors of Agriculture and Forestry and Computer Systems Design and Related Services in the 'Low' range. A similar study for Norway would most likely result in some modifications of the mapping but the general result is considered applicable to the situation in Norway.

Taking the relation of the CDP in Norway and Canada (approximately US$170 billion and US$800 billion, respectively), then under similar conditions, the GVA for Norway depending on the national geodetic reference frame is estimated to be of the order of US$10 to US$15 billion with the ultra-conservative estimate being roughly US$4 billion. As pointed out by Williams et al. (2005), the estimates provided by them as a result of their detailed study are rather uncertain due to the large uncertainties in the statistical data base. Nevertheless, they consider their estimates as understated for several reasons, including a substantial downward adjustment of all estimates, the omission of other sectors also influenced to some extent by the CSRS, and the neglect of societal value created by the CSRS.

Therefore, the minimum estimate of US$4 billion and the still conservative range estimates of US$10 to US$15 billion can be taken as an indication of the GVA that depends on the national geodetic reference frame and infrastructure in Norway. Based on these numbers, the actual costs for the determination and maintenance of the NGRF and the infrastructure for the access to it appears well justified. Compared to other countries such as Canada, U.S.A., France, Germany and Australia, the estimated costs for the operation of the geodetic services and the maintenance of the geodetic infrastructure per km^2, per capita, and per $100,000 of GDP are relatively high (see the table on page ES- vii in Williams et al., 2005), but these costs are of the order of 0.1% or less of the GVA that depends on the geodetic products. The benefit to cost ration for the NNGI of 1,000 or more is extremely high.

9 Conclusions

The requirements of a modern society with respect to access to accurate positioning and information on the Earth system state and development on the one hand and the potential of the space-geodetic techniques on the other hand have put geodesy in a rapid transition if not a revolution. A global geodetic reference frame is now available allowing for the first time interoperability of geographic databases and positioning systems with high accuracy and globally.

The national geodetic infrastructure of a modern society serves a large number of users and creates substantial benefits in terms of economy and security, and it supports the well-being of the population. A large part of the national economy depends on the availability of the NGRF and a substantial fraction of the GVA is generated on the basis of the NGRF. The geodetic references frame is indispensable for the functioning of a modern society.

The global reference frame maintained through the voluntary contributions of national institutions and the cooperation in the global geodetic community is the foundation of all Earth observation and its metrological basis. The contribution of the national geodetic infrastructure to regional and global Earth observation systems provides crucial input for the understanding of key processes in the Earth system, a prerequisite for achieving sustainable development.

The importance of the global and regional geodetic infrastructure is increasingly acknowledged in international agreements and organizations. GEO and the European Commission have put emphasis on the importance of the geodetic reference frame and the observations provided by geodetic networks. IGOS-P focuses in several of its theme reports on the crucial contributions from geodetic observation techniques.

The global geodetic infrastructure developed over the last two decades is in rather good shape, considering the fact that the global networks and the data processing depends solely on voluntary contributions of national institutions. To a large extent, this progress has been facilitated by the IAG, and the implementation of GGOS is expected to further improve the global cooperation and quality of the geodetic products. Nevertheless, severe limitations result from several gaps in the observational networks, particularly for SLR and VLBI.

Currently, the organizational background for global geodesy is a mainly science-driven system of services based on voluntary commitment of the contributors. This introduces considerable fluctuation in the observing system and the available results, and prevents the formation of a strong and well-maintained operational kernel of the global geodetic obsering system. An intergovernmental organization dedicated to the coordination of global geodetic activities and issues is lacking but urgently needed in order to make progress towards a fully operational system providing a stable geodetic utility for the large number of applications requiring either a stable reference frame or observations of key quantities of the Earth system. An appropriate organizational form for the governmental counterpart to the science-driven global geodesy could be an intergovernmental geodetic commission under the United Nations.

On Norwegian national level, the geodetic infrastructure in general is on a relatively high level, which has resulted in a well structured and precisely determined NGRF. The Norwegian contribution to the global and regional networks is at an appropriate level and should be continued at this level, though with a few improvements required.

In order to serve the needs of a modern society, the geodetic institute needs to be a center of excellence which is involved in research and the further development of the geodetic techniques. The continuing rapid development in both the user requirements and the technical solutions requires a permanent engagement of the Geodetic Institute in international research projects and operational programs.

A particular challenge arises from the lack of sufficient, high-level human resources to carry out the tasks of such a center of excellence. For Norway, this challenge can only be met through extended cooperation with Nordic and international institutions.

10 Recommendations

10.1 Recommendations for the Norwegian contribution to global geodesy and in particular GGOS

It is recommended

- that the contribution to IVS, IGS, EUREF, ESEAS/GLOSS, and GGP be continued at least at the current level;

- that the fundamental station in Ny Ålesund be maintained at a high level with continuous contribution to IVS, IGS, GGP, and DORIS, and that the station be further developed into a multi-sensor geodetic and geophysical observing site;

- that the high-level program of site-surveys at the fundamental site in Ny Ålesund be continued;

- that on Jan Mayen a co-located CGPS and tide gauges site be established with low-latency access to the data;

- that a co-located GPS and tide gauge site be established on Bjørnøya;

- that the CGPS station in Trysil be committed as an IGS station and further developed towards a multi-sensor site with co-location of a GLONASS receiver, a super-conducting gravimeter, and frequent absolute gravity measurements;

- that the establishment of an SLR station in Trysil be considered if an appropriate, modernized SLR station becomes available, and that Trysil be developed as the fundamental station on the Norwegian mainland;

- that Norway consider the financial and human support of geodetic infrastructure in less developed regions as an important contribution to the global community;

- that Norway support progress towards an intergovernmental geodetic commission under a UN agency, such as UNESCO.

10.2 Recommendations for the maintenance of a national geodetic reference frame

It is recommended

- that the network of CGPS sites be extended to a network of about 50 evenly distributed stations with particular focus on a densification in northern Norway;

- that the 4-D network be complemented in northern Norway to achieve a more evenly distributed network, which would also be in better agreement with the likelihood of deformations;
- that the 4-D points be re-occupied on a 4 to 5 year interval;
- that the Geodetic Institute establish an operational, low-latency quality control and geodetic analysis of the observations from the CGPS network;
- that the velocity field for Norway in ITRF be improved to the 1 mm/yr accuracy level and made available for users;
- that the Geodetic Institute establish a service for high accuracy post-processing which allows the determination of ITRF coordinates and the transformation of these coordinates into the NGRF;
- that an effort be made to contribute data towards global real-time networks, so that global real-time products required for precise point positioning become available;
- that data and products relevant for scientific studies (including but not limited to time series of station coordinates, tropospheric estimates, velocity estimates) be made available through appropriate web interfaces;
- that the efforts to improve the geoid over the land and the adjacent ocean be continued in order to allow the determination of accurate heights in the national height system with GPS.

10.3 Recommendations for the national geodetic infrastructure in Norway

It is recommended

- that the geodetic infrastructure be developed in agreement with international standards established under the coordination of GGOS and GEO;
- that the geodetic infrastructure be operated according to the international recommendations and standards;
- that the Geodetic Institute continue to participate in national and international research projects aiming at the exploitation of geodetic observations for Earth observation and global change studies;
- that the Geodetic Institute fill the role of a center of excellence in geodesy and Earth observation for the Norwegian society, and that this role be developed in close cooperation with other Nordic geodetic institutes.

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References

Altamimi, Z. & Boucher, C., 2002. The ITRS and ETRS89 relationship: new results from ITRF2000, in *EUREF Publication No. 10*, edited by J. A. Torres & H. Hornik, no. 23 in Mitteilungen des Bundesamtes für Kartografie und Geodäsie, pp. 49–52, Verlag des Bundesamtes für Kartographie und Geodäsie, Frankfurt am Main.

Altamimi, Z., Sillard, P., & Boucher, C., 2002. A new release of the International Terrestrial Reference Frame for earth science applications, *J. Geophys. Res.*, **107**, 2214, doi: 10.1029/2001JB000561.

Altamini, Z., Coulot, D., Berio, P., & Exertier, P., 2006. How can combination help to achieve consistency at the 0.1 ppb level?, Position paper presented at the GGOS 2006 Workshop 'Towards a Consistent Geodetic Foundation for Earth Observations, October 8-9, 2006,Munich, Germany. Available at http://geodesy.unr.edu/ggos/ggosws_2006/.

Andersen, P. H., 1997. Processing of data from the Space Geodesy Systems VLBI, GPS, SLR, PRARE and DORIS, in *Geodetic Applications of GPS*, edited by B. Jonsson, pp. 257–268, National Land Survey, Gävle, Sweden.

Andersen, P. H., 2000. Multi-level arc combination with stochastic parameters, *J. Geodesy*, **74**, 531–551.

Arias, E. F., Charlot, P., Feissel, M., & Lestrade, J.-F., 1995. The extragalactic reference system of the International Earth Rotation Service, ICRS, *Astron. Astrophys*, **303**, 604–608.

Bao, L. F., Piatanesi, A., Lu, Y., Hus, H. T., & Zhou, X. H., 2005. Sumatra tsunami affects observations by GRACE satellites, *EOS, Trans. Am. Geophys. Union*, **86**, 353,356.

Beutler, G., Drewes, H., Reigber, C., & Rummel, R., 2003. Proposal to Establish the Integrated Global Geodetic Observing System (IGGOS) as IAG's First Project, distributed to IVS and IGS mailing lists on 21 August 2003.

Bird, P., 2003. An updated digital model of plate boundaries, *Geochemistry Geophysics Geosystems*, **4**(3), 1027, doi:10.1029/2001GC000252.

Blewitt, G. & Lavallée, D., 2002. Effect of annual signals on geodetic velocity, *J. Geophys. Res.*, **107**, DOI 10.1029/2001JB000570.

Blewitt, G., Lavallee, D., Clarke, P., & Nurutdinov, K., 2001. A new global mode of earth deformation: Seasonal cycle detected, *Science*, **294**, 2342–2345.

Blewitt, G., Hammond, W. C., Kreemer, C., & Plag, H.-P., 2005. Nevada Earthquake Response GPS Network (NEARNET), *EOS, Trans. Am. Geophys. Union*, **86**(52), Abstract G11A–1182.

Blewitt, G., Altamimi, Z., Davis, J., Gross, R., Kuo, C., Lemoine, F., Neilan, R., Plag, H.-P., Rothacher, M., Shum, C. K., Sideris, M. G., Schöne, T., Tregoning, P., & Zerbini, S., 2006. Geodetic observations and global reference frame contributions to understanding sea level rise and variability, in *Understanding Sea-level Rise and Variability, A World Climate Research Programme Workshop and a WCRP contribution to the Global Earth Observation System of Systems, 6-9 June 2006, UNESCO, Paris*, edited by T. Aarup, J. Church, S. Wilson, & P. Woodworth, pp. 127–143, WCRP, World Meterological Organization, Paris.

Blewitt, G., Kreemer, C., Hammond, W., Plag, H.-P., Stein, S., & Okal, E., 2006. Rapid determination of earthquake magnitude using GPS for tsunami warning systems, *Geophys. Res. Lett.*, **33**, L11309.

Bockmann, L., Grimstveit, L., Harsson, B. G., Kierulf, H. P., Kristiansen, O., & Plag, H.-P., 2002. Site surveys at the fundamental geodetic station in Ny-Ålesund, Svalbard, in *Proceedings of the NKG Meeting, October 1-4, 2002, Helsinki*, edited by M. Poutanen, pp. 89–93, Finish Geodetic Institute.

Booz-Allen, X. & Hamilton, x., 1995. Proposed baseline European Radionavigation Plan, unpublished report, France.

Boucher, C., 1990. Definition and realization of terrestrial reference systems for monitoring the Earth rotation, in *Variations in Earth Rotation*, edited by D. D. McCarthy & W. E. Carter, pp. 197–201, AGU.

Boucher, C., Altamani, Z., & Sillard, P., 1999. The International Terrestrial Reference Frame (ITRF97), IERS Technical Note 27, IERS, Observatoire de Paris, Paris.

Boucher, C., Altamimi, Z., Sillard, P., & Feissel-Vernier, M., 2004. *The ITRF2000*, IERS Technical Note, No. 31, Verlag des Bundesamts für Kartographie und Geodäsie, Frankfurt.

Carter, B., 2003. Geodetic contribution helped validate plate tectonics, *EOS, Trans. Am. Geophys. Union*, **84**(19), 179.

Chao, B. F., 2003. Geodesy is not just for static measurements anymore, *EOS, Trans. Am. Geophys. Union*, **84**(16), 145–150.

Chao, B. F. & Gross, R., 2005. Did the 26 December 2004 Sumatra, Indonesia, earthquake disrupt the Earth's rotation as the mass media have said?, *EOS, Trans. Am. Geophys. Union*, **86**(1), 1.

Chen, J. L. & Wilson, C. R., 2003. Low degree gravitational changes from earth rotation and geophysical models, *Geophys. Res. Lett.*, **30**(24), 2257, doi:10.1029/2003GL018688.

Choi, K., Bilich, A., Larson, K. M., & Axelrad, P., 2004. Modified sidereal filtering: Implications for high-rate GPS positioning, *Geophys. Res. Lett.*, **31**, L22608, doi:10.1029/2004GL021621.

Church, J. A., Gregory, J. M., Huybrechts, P., Kuhn, M., Lambeck, K., Nhuan, M. T., Qin, D., & Woodworth, P. L., 2001. Changes in sea level, in *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, edited by J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, & C. A. Johnson, pp. 639–693, Cambridge University Press, Cambridge.

Commission, E. & ESA, 2003. Global Monitoring for Environment and Security: Final report for the GMES initial period (2001-2003) version 3.5, Draft report, European Commission, Available at http://www.gmes.info/library/.

Crossley, D., Hinderer, J., Casula, G., Francis, O., Hsu, H.-T., Imanishi, Y., Jentzsch, G., Kaarianen, J., Merriam, J., Meurers, B., Neumeyer, J., Richter, B., Shibuya, K., Sato, T., & van Dam, T., 1999. Network of superconducting gravimeters benefits a number of disciplines, *Trans. Am. Geophys. U.*, **80**, 121–126.

Crowley, J. W., Mitrovica, J. X., Bailey, R. C., Tamisiea, M. E., & Davis, J. L., 2006. Land water storage within the Congo Basin inferred from GRACE satellite gravity data, *Geophys. Res. Lett.*, **33**, L19402, doi:10.1029/2006GL027070.

Dahl, A. L., 1998. IGOS from the perspective of the Global Observing Systems and their sponsors, in *Proceedings for the 27-th Int. Symp. on Remote Sensing of Environment: Information for Sustainability, June 8-12, 1998, Tromsø, Norway*, pp. 92–94, Norwegian Space Centre.

Danielsen, J., 1999. Landhevningen i Norge, Report, Geodetic Institute, Norwegian Mapping Authority.

Davis, J. L., Elsegui, P., Mitrovica, J. X., & Tamisiea, M. E., 2004. Climate-driven deformation of the solid Earth from GRACE and GPS, *Geophys. Res. Lett.*, **31**, L24605, doi:10.1029/2004GL021435.

de Viron, O., Schwarzbaum, G., Lott, F., & Dehant, V., 2005. Diurnal and subdiurnal effects of the atmosphere on the Earth rotation and geocenter motion, *J. Geophys. Res.*, **110**, B11404, doi:10.1029/2005JB003761.

DeMets, C., Gordon, R. G., Argus, D. F., & Stein, S., 1994. Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions, *Geophys. Res. Lett.*, **21**, 2191–2194.

Dickey, J. O., Marcus, S. L., & de Viron, O.and Fukumori, I., 2002. Recent earth oblateness variations: unraveling climate and postglacial rebound effects, *Science*, **298**, 1975–1977.

Dong, D., Fang, P., Bock, Y., Cheng, M. K., & Miyazaki, S., 2002. Anatomy of apparent seasonal variations from GPS-derived site position time series, *J. Geophys. Res.*, **107**, xxx–xxx.

Drewes, H., 1998. Combination of VLBI, SLR and GPS determined station velocities for actual plate kinematic and crustal deformation models, in *Geodynamics*, edited by M. Feissel, Springer.

Drewes, H., 2006. The science rationale of the Global Geodetic Observing System GGOS, in *Dynamic Planet 2005*, Springer Verlag, Berlin, In press.

Drinkwater, M. R., Floberghagen, R., Haagmans, R., Muzi, D., & Popescu, A., 2003. GOCE; ESA's first Earth Explorer Core mission, in *Earth Gravity Field from Space - from Sensor to Earth Sciences*, edited by G. B. Beutler, M. R. Drinkwater, R. Rummel, & R. von Steiger, vol. 18 of **Space Science Series of ISSI**, pp. 419–432, Kluwer Academic Publishers, Dordrecht.

Dziewonski, A. M. & Anderson, D. L., 1981. Preliminary reference Earth model, *Phys. Earth Planet. Int.*, **25**, 297–356.

Elgered, G., Plag, H.-P., Marel, H. v. d., Barlag, S., & Nash, J., 2004. *COST 716 Exploitation of Ground-based GPS for Operational Numerical Weather Prediction and Climate Applications*, vol. EUR 21639, European Commission.

Elgered, G., Plag, H.-P., Marel, H. v. d., Barlag, S., & Nash, J., 2005. *COST Action 716 Exploitation of Ground-based GPS for Operational Numerical Weather Prediction and Climate Applications*, no. EUR 21639 in COST European cooperation in the field of scientific and technical research, European Commission.

Ellsaesser, H. W., MacCracken, M. C., Walton, J. J., & Grotch, S. L., 1986. Global climatic trends as revealed by the recorded data, *Rev. Geophys.*, **24(4)**, 745–792.

European Commission, 2004. Agreement on the promotion, provision and use of Galileo and GPS satellite-based navigation systems and related applications, Available at http://europe.eu.int/comm/dgs/-energy_transport/galileo/documents% -/doc/2004_06_21_summit_2004_en.pdf.

Fang, M. & Hager, B. H., 2001. Vertical deformation and absolute gravity, *Geophys. J. Int.*, **146**, 539–548.

Farrell, W. E., 1972. Deformation of the Earth by surface loads., *Rev. Geophys. Space Phys.*, **10**, 761–797.

Ferretti, A., Novali, F., Bürgmann, R., Hilley, G., & Prati, C., 2004. InSAR permanent scatterer analysis reveals ups and downs in San Francisco Bay area, *EOS, Trans. Am. Geophys. Union*, **85**(24), 317,324.

Fricke, W., Schwan, H., & Lederle, T., 1988. Fifth fundamental catalogue (fk5), Tech. Rep. 32, Part I. Veröff. Astron. Rechen Inst. Heidelberg, Part I.

Gambolati, G., Putti, M., Teatini, P., Camporese, M., Ferraris, S., Gasparetto Stori, G., Nicoletti, V., Silvestri, S., Rizzetto, F., & Tosi, L., 2005. Peat land oxidation enhances subsidence in the Venice watershed, *EOS, Trans. Am. Geophys. Union*, **86**(23), 217,220.

GCOS-48, 1998. Report on the adequacy of the global climate observing systems, Tech. rep., World Meteorological Organisation, Report to the Fourth Conference of the Parties of the United Nations Framework Convention on Climate Change, November 2-13, 1998, Buenos Aires, Argentina. Available e.g. at http://www.unfccc.de as document FCCC/CP/1998/MISC.2.

GEO, 2005. The Global Earth Observing System of Systems (GEOSS) - 10-Year Implementation Plan, Distributed at and endorsed by the EOS-III Meeting, Brussels, 16 February 2005. Document prepared by the *Ad hoc* Group on Earth Observations (GEO) Impementation Plan Task Team IPTT. Available at http://earthobservations.org.

GEO, 2005. Global Earth Observing System of Systems GEOSS - 10-Year Implementation Plan Reference Document - Draft, Tech. Rep. GEO 204/ESA SP 1284, ESA Publication Division, ESTEC, PO Box 299, 2200 AG Noordwijk, The Netherlands, Final Draft Document 204, prepared by the *Ad hoc* Group on Earth Observations (GEO) Impementation Plan Task Team IPTT. Avaliable at http://earthobservations.org.

Gross, R. S., Blewitt, G., Clarke, P. J., & Lavallée, D., 2004. Degree-2 harmonics of the earth's mass load estimated from gps and earth rotation data, *Geophys. Res. Lett.*, **31**, doi:10.1029/2004GL019589.

Haas, R. & Kirchner, M., 2001. Local survey activities at the onsala space observatory 1999-2001, in *Proc. of the 15th Working Meeting on European VLBI for Geodesy and Astrometry*, edited by D. Behrend & A. Rius, pp. 177–184, Institut d'Estudis Espacials de Catalunya, Consejo Superior de Investigaciones Cientificas, Barcelona, Spain.

Hammond, W. C. & Plag, H.-P., 2005. Assessing vertical land motion of Venice, Italy with GPS: Effects of regional filtering on vertical estimates, *EOS, Trans. Am. Geophys. Union*, pp. Abstract G41B–0359.

Héroux, P. & Kouba, J., 1995. GPS precise point positioning with a difference, in *Proceedings of Geomatics'95, Ottawa, Canada, June 13-15*.

Hudnut, K. W., Bock, Y., Galetzka, J. E., Webb, F. H., & Young, W. H., 2001. The Southern

California Integrated GPS Network (SCIGN), in *Proceed. 10th FIG Intern. Symp. on Deformation Measurements*, pp. 129–148.

IGOS-P, 1999. Integrated global observing strategy, Tech. rep., IGOS Partnership, Document adopted by IGOS-P in November 1999; available at http://ioc.unesco.org/oceanteacher/oceanteacher2/01_GlobOcToday/07_ProgAgen&Orgs/-IGOS/IGOS.htm.

IGOS-P Ocean Theme Team, 2001. An Ocean Theme for the IGOS Partnership, Tech. rep., IGOS Integrated Global Observing Strategy, Available at http://www.igospartners.org.

Ilk, K. H., Flury, J., Rummel, R., Schwintzer, P., Bosch, W., Haas, C., Schröter, J., Stammer, D., Zahel, W., Miller, H., Dietrich, R., Huybrechts, P., Schmeling, H., Wolf, D., Götze, H. J., Riegger, J., Bardossy, A., Günter, A., & Gruber, T., 2005. Mass transport and mass distribution in the earth system, Tech. rep., GOCE-Projectbüro Deutschland, Technische Universität München, GeoForschungsZentrum Potsdam.

IOC, 1997. Global Sea Level Observing System (GLOSS) Implementation Plan - 1997, Tech. rep., Intergovernmental Oceanographic Commission, Technical Series, vol 50, 91 pp plus Annexes.

James, T. S. & Ivins, E. R., 1995. Present-day Antarctic ice mass changes and crustal motion, *Geophys. Res. Lett.*, **22**, 973–976.

Johansson, J. M., Davis, J. L., Scherneck, H.-G., Milne, G. A., Vermeer, M., Mitrovica, J. X., Bennett, R. A., Jonsson, B., Elgered, G., Eløsegui, P., Koivula, H., Poutanen, M., Rønnang, B. O., & Shapiro, I. I., 2002. Continuous GPS measurements of postglacial adjustment in Fennoscandia 1. Geodetic results, *J. Geophys. Res.*, **107**, DOI 10.1029/2001JB000400.

Kaufmann, G. & Amelung, F., 2000. Reservoir-induced deformation and continental rheology in vicinity of Lake Mead, Nevada, *J. Geophys. Res.*, **105**(B7), 16,341–16,358.

Key, J. & the IGOS-Cryo Writing Team, 2004. Concept of an IGOS-Cryosphere Theme (IGOS-Cryo), Tech. rep., IGOS Integrated Global Observing Strategy, Version 2.2, October 7, 2004, available at http://www.igospartners.org.

Kierulf, H. P. & Plag, H.-P., 2006. Precise point positioning requires consistent global products, in *EUREF Publication No. 14*, edited by J. A. Torres & H. Hornik, vol. BKG 35 of **Mitteilungen des Bundesamtes für Kartografie und Geodäsie**, pp. 111–120, Bundesamtes für Kartografie und Geodäsie, Frankfurt am Main.

Kierulf, H. P., Bockmann, L., Kristiansen, O., & Plag, H.-P., 2002. Foot-print of the space-geodetic observatory, Ny-Ålesund, Svalbard, in *Proceedings of the Second IVS General Assembly, Tsukuba, Japan, 4-6 February 2002*, edited by N. Vandenberg & K. Beaver, pp. 86–90, NASA Goddard Space Flight Center, Greenbelt, MD.

Kierulf, H. P., Plag, H.-P., & Kristiansen, O., 2003. Towards the true rotation of a rigid Eurasia, in *EUREF Publication No. 12*, edited by J. A. Torres & H. Hornik, no. 29 in Mitteilungen des Bundesamtes für Kartografie und Geodäsie, pp. 118–124, Verlag des Bundesamtes für Kartographie und Geodäsie, Frankfurt am Main.

Kouba, J., 2003. A guide to using International GPS Service (IGS) products, IGS report, International GPS Service, available at ftp://igscb.jpl.nasa.gov/igscb/resource/pubs/-GuidetoUsingIGS -Products.pdf.

Kouba, J. & Héroux, 2001. Precise point positioning using IGS orbit and clock products, *GPS Solutions*, **5**(2), 12–28.

Kovalevsky, J., 1997. Connection of the HIPPARCOS catalogue to the extragalactic reference frame, in *Proceedings from the Hipparcos Venice '97 symposium Presenting The Hipparcos and Tycho Catalogues and first astrophysical results of the Hipparcos astrometry mission*, ESTEC, The Netherlands, available at http://astro.estec.esa.nl/SA-general/Projects/Hipparcos/hipp_venice.html.

Kreemer, C. & Holt, W. E., 2001. A no-net-rotation model of present-day surface motions, *Geophys. Res. Lett.*, **28**, 4407–4410.

Kreemer, C., Holt, W. E., & Haines, A. J., 2003. An integrated global model of present-day plate motion and plate boundary deformation, *Geophys. J. Int.*, **154**, 8–34.

Kreemer, C., Blewitt, G., & Hammond, W. C., 2006. Using geodesy to explore correlations between crustal deformation characteristics and geothermal resources, *Geothermal Resources Council Transactions*, **30**, 441–446.

Kreemer, C., Blewitt, G., Hammond, W. C., & Plag, H.-P., 2006. Global deformations from the great 2004 Sumatra-Andaman earthquake observed by GPS: implications for rupture process and global reference frame, *Earth Planets Space*, **58**, 141–148.

Kristiansen, O. & Harsson, B. G., 1999. The New Norwegian National Geodetic Network - EUREF89, in *EUREF Publication No. 7/I*, edited by E. Gubler & H. Hornik, vol. Band 6 of **Mitteilungen des Bundesamtes für Kartographie und Geodäsie**, pp. 104–116, Verlag des Bundesamtes für Kartographie und Geodäsie, Frankfurt.

Kusche, J. & Schrama, E. J. O., 2005. Surface mass redistribution inversion from global GPS deformation and Gravity Recovery and Climate Experiment (GRACE) gravity data, *J. Geophys. Res.*, **110**, B09409, doi:10.1029/2004JB003556.

Lambert, S. B., Bizouard, C., & Dehant, V., 2006. Rapid variations in polar motion during the 2005-2006 winter season, *Geophys. Res. Lett.*, **33**, L13303, doi:10.1029/2006GL026422.

Lawford, R. & the Water Theme Team, 2004. A Global Water Cycle Theme for the IGOS Partnership, Tech. rep., IGOS Integrated Global Observing Strategy, Report of the Global Water Cycle Theme Team, April 2004, available at http://www.igospartners.org.

Lay, T. & 13 others, 2005. The great Sumatra-Andaman earthquake of 26 December 2004, *Science*, **308**, 1127–1133.

Liao, D.-C., 2005. A brief review of atmospheric and oceanic excitation of the Chandler wobble, in *Forcing of polar motion in the Chandler frequency band: A contribution to understanding interannual climate variations*, edited by H.-P. Plag, B. Chao, R. Gross, & T. van Dam, vol. 24, p. This issue, Cahiers du Centre Européen de Géodynamic et de Séismologie.

Ma, C. & Feissel, M., eds., 1997. *Definition and Realisation of the International Celestial Reference System by VLBI Astrometry of Extragalactic Objects*, IERS Technical Note 23, Observatoire de Paris.

Marsh, S. & the Geohazards Theme Team, 2004. Geohazards Theme Report, Tech. rep., IGOS Integrated Global Observing Strategy, Available at http://www.igospartners.org.

Massonet, D., Rossi, M., Carmosa, C., Adragna, F., Peltzer, G., Feigl, K., & Rabaute, T., 1993. The displacement field of the Landers earthquake mapped by radar interferometery, *Nature*, **364**, 138–142.

McCarthy, D. D., ed., 1992. *IERS Standards (1992)*, IERS Tech. Note 13, Observatoire de Paris, 150 pages.

McCarthy, D. D. & Petit, G., 2003. *IERS Conventions 2003*, IERS Technical Note 32, International Earth Rotation Service, Also available at http://www.iers.org.

Milne, G. A., Mitrovica, J. X., & Davis, J. L., 1999. Near-field hydro-isostasy: the implementation of a revised sea-level equation, *Geophys. J. Int.*, **139**, 464–482.

Milne, G. A., Davis, J. L., Mitrovica, J. X., Scherneck, H.-G., Johansson, J. M., Vermeer, M., & Koivula, H., 2001. Space-geodetic constraints on glacial isostatic adjustment in Fennoscandia, *Science*, **291**, 2381–2385.

Milne, G. A., Mitrovica, J. X., Scherneck, H.-G., Davis, J. L., Johansson, J. M., Koivula, H., & Vermeer, M., 2004. Continuous GPS measurements of postglacial adjustment in Fennoscandia: 2. Modeling results, *J. Geophys. Res.*, **109**, B02412, doi:10.1029/2003JB002619.

Mitrovica, J. X. & Milne, G. A., 1998. Glaciation-induced perturbations in the Earth's rotation: A new appraisal, *J. Geophys. Res.*, **103**(B1), 985–1005.

Mitrovica, J. X., Tamisiea, M. E., Davis, J. L., & Milne, G. A., 2001. Recent mass balance of polar ice sheets inferred from patterns of global sea-level change, *Nature*, **409**, 1026–1028.

Morel, L. & Willis, P., 2005. Terrestrial reference frame effects on mean sea level determined by TOPEX/Poseidon, *Adv. Space Res.*, **36**, 358–368.

Mulholland, J. R. & Carter, W. E., 1982. Seth Carlo Chandler and the observational origins of geodynamics, in *High-precision Earth rotation and*

Earth-Moon dynamics, proceedings of the 63rd colloquium of the International Astronomical Union, held at Grasse, France, May 22 - 27, 1981, edited by O. Calame, pp. XV–XIX, D. Reidel Publishing Company, Dordrecht, Boston, London.

Nerem, S. M., Rachlin, K. E., & Beckley, B. D., 1997. Characterization of global mean sea level variations observed by TOPEX/POSEIDON using empirical orthogonal functions, *Surveys Geophys.*, **18**, 293–302.

Nesdal, S., 1983. Lodalen - fager og fårlig, see also http://www.riksarkivet.no/bergen/-publikasjoner/artiklar/andre/loen1905.html.

Nikolaides, R. M., 2002. *Observation of geodetic and seismic deformation with the Global Positioning System*, Ph.D. thesis, University of California, San Diego.

Nocquet, J.-M., Calais, E., Alamimi, Z., Sillard, P., & Boucher, C., 2001. Intraplate deformation in western Europe deduced from an analysis of the International Terrestrial Reference Frame 1997 (UTRF) velocity field, *J. Geophys. Res.*, **106**, 11,239–11,257.

Nørbech, T. & Plag, H.-P., 2003. Transformation from ITRF to ETRF89 (EUREF89) in Norway, in *EUREF Publication No. 12*, edited by J. A. Torres & H. Hornik, no. 29 in Mitteilungen des Bundesamtes für Kartografie und Geodäsie, pp. 217–222, Verlag des Bundesamtes für Kartographie und Geodäsie, Frankfurt am Main.

Park, K., Nerem, R. S., Davis, J. L., Schenewerk, M. S., Milne, G. A., & Mitrovica, J. X., 2002. Investigation of glacial isostatic adjustment in the northeast U.S. using GPS measurements, *Geophys. Res. Lett.*, **29**(11), 1509, doi:10.1029/2001GL013782.

Pearlman, M. & others, ., 2006. GGOS Working Group on ground networks and communications, in *Dynamic Planet 2005*, Springer Verlag, Berlin, In press.

Peltier, W. R., 2004. Global glacial isostasy and the surface of the ice-age Earth: The ICE-5G(VM2) model and GRACE, *Ann. Rev. Earth Planet Sci.*, **32**, 111–149.

Plag, H.-P., 1988. A regional study of Norwegian coastal long-period sea-level variations and their causes with special emphasis on the Pole Tide, *Berl. Geowiss. Abhandl. Reihe A*, **14**, 1–175.

Plag, H.-P., 2000. Integration of geodetic techniques into a global Earth monitoring system and its implication for Earth system sciences, in *Towards an Integrated Global Geodetic Observing System*, edited by R. Rummel, H. Drewes, W. Bosch, & H. Hornik, vol. 120 of **International Association of Geodesy Symposia**, pp. 73–83, Springer, Berlin.

Plag, H.-P., 2002. European Sea Level Service (ESEAS): Status and plans, in *Proceedings of the 14-th General Meeting of the Nordic Geodetic Commission, Espoo, Finland, 1-5 October 2002*, edited by M. Poutanen & H. Suurmüki, pp. 80–88, Nordiska Kommissionen för Geodesi.

Plag, H.-P., 2006. Recent relative sea level trends: an attempt to quantify the forcing factors, *Phil. Trans. Roy. Soc. London, A*, **364**, 1841–1869.

Plag, H.-P., 2006. The concepts in sea level studies: A detailed analysis of errors, Poster presented at the Workshop “Understanding Sea-level Rise and Variability, A World Climate Research Programme Workshop and a WCRP contribution to the Global Earth Observation System of Systems”, 6-9 June 2006, UNESCO, Paris, France.

Plag, H.-P. & Jüttner, H.-U., 2001. Inversion of global tide gauge data for present-day ice load changes, in *Proceed. Second Int. Symp. on Environmental research in the Arctic and Fifth Ny-Ålesund Scientific Seminar*, edited by T. Yamanouchi, no. Special Issue, No. 54 in Memoirs of the National Institute of Polar Research, pp. 301–317.

Plag, H.-P. & the SBL Team, 2002. Solid earth deformations and gravity changes due to surface loading: the new IERS/GGFC Special Bureau for Loading, *Geophys. Res. Abstracts*, **4**, Invited Presentation at EGS 2002.

Plag, H.-P., Ambrosius, B., Baker, T. F., Beutler, G., Bianco, G., Blewitt, G., Boucher, C., Davis, J. L., Degnan, J. J., Johansson, J. M., Kahle, H.-G., Kumkova, I., Marson, I., Mueller, S., Pavlis, E. C., Pearlman, M. R., Richter, B., Spakman, W., Tatevian, S. K., Tomasi, P., Wilson, P., & Zerbini, S., 1998. Scientific objectives of current and future WEGENER activities, *Tectonophysics*, **294**, 177–223.

Plag, H.-P., Axe, P., Knudsen, P., Richter, B., & Verstraeten, J., eds., 2000. *European Sea Level Observing System (EOSS): Status and future developments*, vol. EUR 19682, Office for Official Publication of the European Communities, Luxembourg, 72 pages.

Plag, H.-P., Nørbech, T., & Kristiansen, O., 2002. Effects of intraplate deformations on fixing regional reference frames, in *EUREF Publication No. 10*, edited by J. A. Torres & H. Hornik, vol. 23 of **Mitteilungen des Bundesamtes für Kartografie und Geodäsie**, pp. 118–124, Verlag des Bundesamtes für Kartographie und Geodäsie, Frankfurt am Main.

Plag, H.-P., Johansson, J. M., Jarlemark, P., Bergstrand, S., Elgered, G., Emardson, R., Hoppe, H.-P., Jaldehag, K., Kristiansen, O., & Stoew, B., 2004. Test experimentation results, Delivery Report, Project *GSTB-V1 Stand-Alone test case - Geodetic Galileo: High accuracy geodetic applications of Galileo* GT-DD-NMA-STC/0182, 167 pages, Norwegian Mapping Authority, Hønefoss, Norway.

Plag, H.-P., Blewitt, G., Kreemer, C., Hammond, W., & Titov, V., 2005. Effects of the Mw 9.0 Sumatra earthquake and tsunami on earth's shape, *Geophys. Res. Abstracts*, **7**, EGU05-A-10129.

Plag, H.-P., Gross, R., Chao, B. F., & Van Dam, T., 2005. Forcing of polar motion in the Chandler frequency band: An opportunity to evaluate interannual climate variations, *EOS, Trans. Am. Geophys. Union*, **86**(3), 26.

Plag, H.-P., Kreemer, C., & Kierulf, H. P., 2005. Improved determination of rigid plate motion by incorporating intraplate deformation models, *Geophys. Res. Abstracts*, **7**, EGU05–A–10068.

Plag, H.-P., Blewitt, G., Kreemer, C., & Hammond, W. C., 2006. Solid Earth deformations induced by the Sumatra earthquakes of 2004-2005: GPS detection of co-seismic displacements and tsunami-induced loading, in *Dynamic Planet 2005*, Springer Verlag, Berlin, In press.

Poutanen, M., Knudsen, P., Lilje, M., Plag, H.-P., & Scherneck, H.-G., 2004. The nordic geodetic observing system (ngos) as a tool for geodynamics studies, *Geophys. Res. Abstracts*, **6**, 03909, Invited presentation at the EGU General Assembly, April 2004, Nice, France.

Prandle, D. & Flemming, N. C., eds., 1998. *The Science Base of EuroGOOS*, EuroGOOS Publication No. 6, Southampton Oceanography Centre, Southampton, ISBN 0-90417530-8.

Ray, J., Dong, D., & Altamimi, Z., 2004. IGS reference frames: Status and future improvements, *GPS Solutions*, pp. DOI:10.1007/s10291–004–0110–x.

Reigber, C., Schwintzer, P., & Lühr, H., 1999. The CHAMP geopotential mission, *Boll. Geof. Teor. Appl.*, **40**, 285–289.

Reigber, C., Schwintzer, P., Neumayer, K.-H., Barthelmes, F., König, R., Förste, C., Balmino, G., Biancale, R., Lemoine, J.-M., Loyer, S., Bruinsma, S., Perosanz, F., & Fayard, T., 2003. The CHAMP-only EIGEN-2 Earth Gravity Field Model, *Adv. Space Res.*, **31**(8), 1883–1888.

Richter, B., Wilmes, H., Franke, A., Falk, R., Reinhart, E., & Torge, W., 1998. Das deutsche Schweregrundnetz 1994 (DSGN94), *Z. f. Vermessungswesen*, **123**(11), 363–370.

Richter, B., Dick, W. R., & Schwegmann, W., eds., 2005. *Proceedings of the IERS Workshop on site co-locations*, IERS Technical Note No. 33, Verlag des Bundesamts für Kartographie und Geodäsie, Frankfurt.

Roeloffs, E. A., 1988. Fault stability changes induced beneath a reservoir with cyclic variations in water level, *J. Geophys. Res.*, **93B**, 2107–2124.

Rothacher, M., Beutler, G., Weber, R., & Hefty, J., 2001. High-frequency variations in Earth rotation from Global Positioning System data, *J. Geophys. Res.*, **106**(B7), 13,711–13,738.

Rotman, J., 1998. Global change and sustainable development: towards an integrated conceptual model, in *Earth System Analysis - Integrating Science for Sustainable Development*, edited by H.-J. Schellnhuber & V. Wenzel, pp. 421–453, Springer, Berlin and others.

Rummel, R., 2000. Global Integrated Geodetic and Geodynamic Observing System (GIGGOS), in *Towards an Integrated Global Geodetic Observing System*, edited by R. Rummel, H. Drewes, W. Bosch,

& H. Hornik, vol. 120 of **International Association of Geodesy Symposia**, pp. 253–260, Springer, Berlin.

Rummel, R., Drewes, H., & Beutler, G., 2002. Integrated Global Geodetic Observing System (IGGOS): A candidate IAG project, in *Vistas for Geodesy in the New Millennium*, edited by J. Adam & K.-P. Schwarx, vol. 125 of **International Association of Geodesy Symposia**, pp. 609–614, Springer, Berlin.

Rummel, R., Rothacher, M., & Beutler, G., 2005. Global Geodetic Observing System (GGOS): Science rationale, *J. Geodynamics*, **40**, 357–362.

Salstein, D., Rosen, R. D., Dickey, J. O., & Marcus, S. I., 2002. Assessments of atmospheric angular momentum in AMIP-2 simulations, in *The Second Phase of the Atmospheric Model Intercomparison Project (AMIP2) - Towards innovative model diagnostics*, edited by P. Gleckler, pp. 26–??, Lawrence Livermore National Laboratory, UCRL-PROC-209115, available at http://www-pcmdi.llnl.gov/projects/amip/-amip2_workshop_proceedings.pdf.

Salstein, D. A., Viron, O., Yseboodt, M., & Dehant, V., 2001. High-frequency geophysical fluid modeling necessary to understand earth rotation variability, *EOS*, **82**, 237–238.

Sato, T., Boy, J. P., Tamura, Y., Matsumato, K., Asari, K., Plag, H.-P., & Francis, O., 2006. Gravity tides and seasonal gravity varitations at Ny Ålesund, Svalbard in Arctic, *J. Geodynamics*, **41**, 234–241.

Sato, T., Okumo, J., Hinderer, J., MacMillan, D., Plag, H.-P., Francis, O., Falk, R., & Fukuda, Y., 2006. A geophysical interpretation of the secular displacement and gravity rates observed at Ny-Ålesund, Svalbard in the Arctic - Effect of postglacial rebound and present-day ice melting, *Geophys. J. Int.*, **165**.

Schellnhuber, H.-J., 1998. Earth system analysis: The scope of the challenge, in *Earth System Analysis - Integrating Science for Sustainable Development*, edited by H.-J. Schellnhuber & V. Wenzel, pp. 3–195, Springer, Berlin and others.

Schellnhuber, H. J., Block, A., Cassel-Gintz, M., Kropp, J., Lammel, G., Lass, W., Lienenkamp, R., Loose, C., Lüdeke, M. K. B., Moldenhauer, O., Petschel-Held, G., Plöchl, M., & Reusswig, F., 1997. Syndromes of global change, *GAIA*, **6**(1), 19.

Shedlock, K. M., Giardini, D., Grünthal, G., & Zhang, P., 2000. The GSHAP Global Seismic Hazard Map, *Seismological Res. Let.*, **71**, 679–689.

Smith, D. B., 1998. The emerging IGOS partnership, in *Proceedings for the 27-th Int. Symp. on Remote Sensing of Environment: Information for Sustainability, June 8-12, 1998, Tromsø, Norway*, pp. 99–102, Norwegian Space Centre.

Solomon, S. C. & The Solid Earth Science Working Group, 2002. *Living on a restless planet*, NASA, Jet Propulsion Laboratory, Pasadena, California, also available at http://solidearth.jpl.nasa.gov.

Stein, S., 1993. Space geodesy and plate motion, in *Contributions of Space Geodesy in Geodynamics: Crustal Dynamics*, edited by D. E. Smith & D. L. Turcotte, vol. 23 of **AGU Geodynamics Series**, pp. 5–20, AGU.

Stein, S. & Okal, E., 2005. Speed and size of the Sumatra earthquake, *Nature*, **434**, 581–582.

Strozzi, T., Wegmüller, U., Werner, C., Wiesmann, A., Tosi, L., Teatini, P., & Carbognin, L., 2003. Venzia: Subsidence monitoring service in the Lagoon of Venice for regional administrative and water authorities data user programme (DUP), II Period - Executive Summary, Tech. rep., Gamma Remote Sensing, Muri, Switzerland, and Istituto di Scienze Marine, Venezia, Italy.

Talwani, P. & Acree, S., 1985. Pore pressure diffusion and the mechanism of reservoir-induced seismicity, *Pure Appl. Geophys.*, **122**, 947–965.

Tamisiea, M. E., Mitrovica, J. X., Milne, G. A., & Davis, J. L., 2001. Global geoid and sea level changes due to present-day ice mass fluctuations, *J. Geophys. Res.*, **106**(B12), 30,849–30,864.

Tamisiea, M. E., Mitrovica, J. X., Tromp, J., & Milne, G. A., 2002. Present-day secular variations in the low-degree harmonics of the geopotential: Sensitivity analysis on spherically symmetric earth models, *J. Geophys. Res.*, **107**(B12), 2378, doi:10.1029/2001JB000696.

Tamisiea, M. E., Leuliette, E. W., Davis, J. L., & Mitrovica, J. X., 2005. Constraining hydrological and cryospheric mass flux in southeastern Alaska using space-based gravity measurements, *Geophys. Res. Lett.*, **32**, L20501, doi:10.1029/2005GL023961.

Tapley, B. D., Bettadpur, S., Ries, J. C., Thompson, P. F., & Watkins, M. M., 2004. GRACE measurements of mass variability in the Earth system, *Science*, **305**, 503–505.

Tapley, B. D., Bettadpur, S., Watkins, M., & Reigber, C., 2004. The gravity recovery and climate experiment: mission overview and early results, *Geophys. Res. Lett.*, **31**, L09607, doi: 10.1029/2004GL019920.

Townshend, J. R. & the IGOL Writing Team, 2004. Integrated Global Observations of the Land: A proposed theme to the IGOS Partnership - Version 2, Tech. rep., IGOS Integrated Global Observing Strategy, Proposal prepared by the IGOL Proposal Team, May 2004, available at http://www.igospartners.org.

Van Dam, T., Plag, H.-P., Francis, O., & Gegout, P., 2003. GGFC Special Bureau for Loading: current status and plans, in *Proceedings of the IERS Global Geophysical Fluid Center Workshop, Munich, November 20-21, 2002*, edited by B. Richter, W. Schwegman, & R. Dick, no. 30 in International Earth Rotation and Reference System Service, IERS Technical Note, pp. 180–198.

Velicogna, I. & Wahr, J., 2005. Greenland mass balance from GRACE, *Geophys. Res. Lett.*, **32**, L18505, doi:10.1029/2005GL023955.

Velicogna, I. & Wahr, J., 2006. Measurements of time-variable gravity show mass loss in Antarctica, *Science*, **311**, 1754–1756.

Wahr, J., Molenaar, M., & Bryan, F., 1998. Time variability of the Earth's gravity field: Hydrological and oceanic effects and their possible detection using GRACE, *J. Geophys. Res.*, **103**, 30,205–30,229.

Wahr, J., van Dam, T., Larson, K., & Francis, O., 2001. Geodetic measurements in Greenland and their implications, *J. Geophys. Res.*, **106**, 16,567–16,581.

Wahr, J., van Dam, T., Larson, K., & Francis, O., 2001. Gps measurements of vertical crustal motion in Greenland, *J. Geophys. Res.*, **106**, 33,755–33,759.

Wahr, J. M. & Han, D., 1997. Predictions of crustal deformation caused by changing polar ice on a viscoelastic Earth, *Surveys Geophys.*, **18**, 303–312.

Wahr, J. M., Dazhong, H., & Trupin, A., 1995. Prediction of vertical uplift caused by changing polar ice volumes on visco-elastic earth, *Geophys. Res. Lett.*, **22**, 977–980.

Warrick, R. A., Provost, C. l., Meier, M. F., Oerlemans, J., & Woodworth, P. L., 1996. Changes in sea level, in *Climate Change 1995–The science of climate change*, edited by J. T. Houghton, L. G. Meira Filho, B. A. Callander, N. Harris, A. Kattenberg, & K. Maskell, pp. 359–405, Cambridge University Press, Cambridge, UK.

Wdowinski, S., Bock, Y., Zhang, J., & Fang, P., 1997. Southern California Permanent GPS geodetic array: spatial filtering of daily positions for estimating cosesimic and postseismic displacements induced by the 1992 Landers earthquake, *J. Geophys. Res.*, **102**, 18,057–18,070.

Williams, D. & Townshend, J. R. G., 1998. The concept of an Integrated Global Observing Strategy, in *Proceedings for the 27-th Int. Symp. on Remote Sensing of Environment: Information for Sustainability, June 8-12, 1998, Tromsø, Norway*, pp. 95–98, Norwegian Space Centre.

Williams, D., Rank, D., Kijek, R., Cole, S., & Pagiatakis, S., 2005. National geodetic infrastructure requirements study, Study report NRCan 03 - 0628, Natural Resources Canada, Final unpublished Report, prepared by BearingPoint; available on request from NRC.

Williams, S. P. D., 2003. The effect of coloured noise on the uncertainties of rates estimated from geodetic time series, *J. Geodesy*, **76**, 483–494.

Williams, S. P. D., Bock, Y., Fang, P., Jamason, P., Nikolaidis, R. M., & Prawirodirdjo, L., 2004. Error analysis of continuous GPS position time series, *J. Geophys. Res.*, **109**, B03412, doi:10.1029/2003JB002741.

Wilmes, H., Richter, B., & Ihde, J., 2005. The contribution of gravity to the European Combined

Geodetic Network (ecgn), in *Proceedings of the EUREF Symposium in Toledo, Spain, 4-7 June 2003*, vol. EUREF Publication no. 13 of **Mitteilung des Bundesamtes für Kartographie und Geodäsie, no. 33**, pp. 182–189, Bundesamt für Kartographie und Geodäsie, Frankfurt aM.

Wilmes, H., Falk, R., Klopping, F., Roland, E., Lothammer, A., Reinhold, A., Richter, B., Plag, H.-P., & Mäkinen, J., 2006. Analysis of absolute gravity measurements in the Fennoscandian postglacial rebound zone for the period 1991 to 2003, *Geophys. Res. Lett.*, Submitted.

Woodworth, P. L., 2003. Some comments on the long sea level records from the Northern Mediterranean, *J. Coastal Res.*, **19**, 212–217.

Wu, X., Heflin, M. B., Ivins, E. R., Argus, D. F., & Webb, F. H., 2003. Large-scale global surface mass variations inferred from GPS measurements of load-induced deformation, *Geophys. Res. Lett.*, **30**, 1742, doi: 10.1029/2003GL017546.

Wu, X., Heflin, M. B., Ivins, E. R., & Fukumori, I., 2006. Seasonal and interannual global surface mass variations from multisatellite geodetic data, *J. Geophys. Res.*, **111**, B09401, doi:10.1029/2005JB004100.

Zumberge, J. F., Heflin, M. B., Jefferson, D. C., & Watkins, M. M., 1997. Precise point positioning for the efficient and robust analysis of GPS data from large networks, *J. Geophys. Res.*, **102**, 5005–5017.

A Tutorial in reference systems and reference frames

A.1 Introduction

Position and movement are not absolute quantities. Therefore, observations of any celestial body, be it natural or artificial, or of a point in the Earth system, can be used to describe the motion of this body only if the observations can be referred to a well defined coordinate system. Such a system is defined through axes that are either fixed in space or have a known movement with respect to something else that is fixed. The set of axes is called a **celestial reference system** (CRS). Such a system is required to describe motions of galaxies, stars, the sun, planets including the Earth itself, moons, and artificial satellites.

Observations of points on the Earth surface are often easier to relate to movements of these points if they are referred to a coordinate system with axis fixed in some way to the Earth body and moving with the Earth in space. Such a system is called a *Terrestrial Reference System* (TRS).

It is of obvious practical advantage to agree upon one definition of the celestial or terrestrial reference system. This has led to the adoption of conventional celestial and terrestrial reference systems (CCRS and CTRS, respectively, see fig. 51).

A conventional reference system is defined by specifying the origin and direction of the axes and the scale of the system in an appropriate way. The IERS defines: *By Reference System it is meant the set of prescriptions and conventions together with the modeling required to define at any time a triad of axes.* For a celestial system, it is easy to comprehend that the axes can only be accessed indirectly. But also for the Earth, where all points on the surface are in constant movement, the axes of a terrestrial reference system cannot be realized in a simple way, for example by giving one point for each axis on the Earth surface. Therefore, these reference systems need to be made accessible through reference frames. The IERS defines: *By Reference Frame it is meant a practical realization with given fiducial directions agreeing with the concepts introduced in the Reference System.* Such practical realizations for both celestial and terrestrial systems can, for example, be achieved through the coordinates of a set of fiducial objects or points that are utilized to define the origin, axes, and scale implicitly.

Modern conventional celestial and terrestrial reference systems in fact are realized through coordinates of a set of fiducial points determined from observations. This realization is denoted by celestial and terrestrial reference frame, respectively. In practice, the realization of a reference system through such a frame requires continuous monitoring of the fiducial points.

A realization may also require the specification of additional boundary conditions the reference frame should fulfill. Moreover, models used to analyze the observations and to correct for disturbances in the coordinates of the fiducial points are an integral part of the realization and therefore have to be included in the convention specifying the reference system or its realization.

It is not always clear whether the boundary conditions and models are considered as part of the conventional reference system, part of the reference frame realizing the system or subject of an additional convention. There is certainly a trade-off between the completeness of the conventions specifying the reference system and the need to change the reference system when models or constants improve.

Fig. 52 gives an overview illustrating the conventional reference systems and their realizations presently adopted by the relevant international scientific unions. The two fundamental systems accepted by the relevant international scientific bodies are the *International Celestial Reference System* (ICRS) and the *International Terrestrial Reference System* (ITRF), which are realized through the *International Celestial Reference Frame* (ICRF) and the *International Terrestrial Reference Frame* (ITRF), respectively.

In addition to the above mentioned CCRS and CTRS, it is also important to mention here the need for a Conventional Dynamic Reference Frame (CDRF) thar provides the planetary and lunar ephemerides in the selected ICRF. Such a frame will be derived from preferably all relevant observational data. The adjustment of the observations requires a number of astronomical constants as well as the planetary masses, and these numbers are considered an integral part of the CDRF.

A.2 Celestial Systems and Frames

In the past, catalogs of position and proper motion of fundamental stars were defined from dynamical modeling of the Earth's orbital motion. The fixed

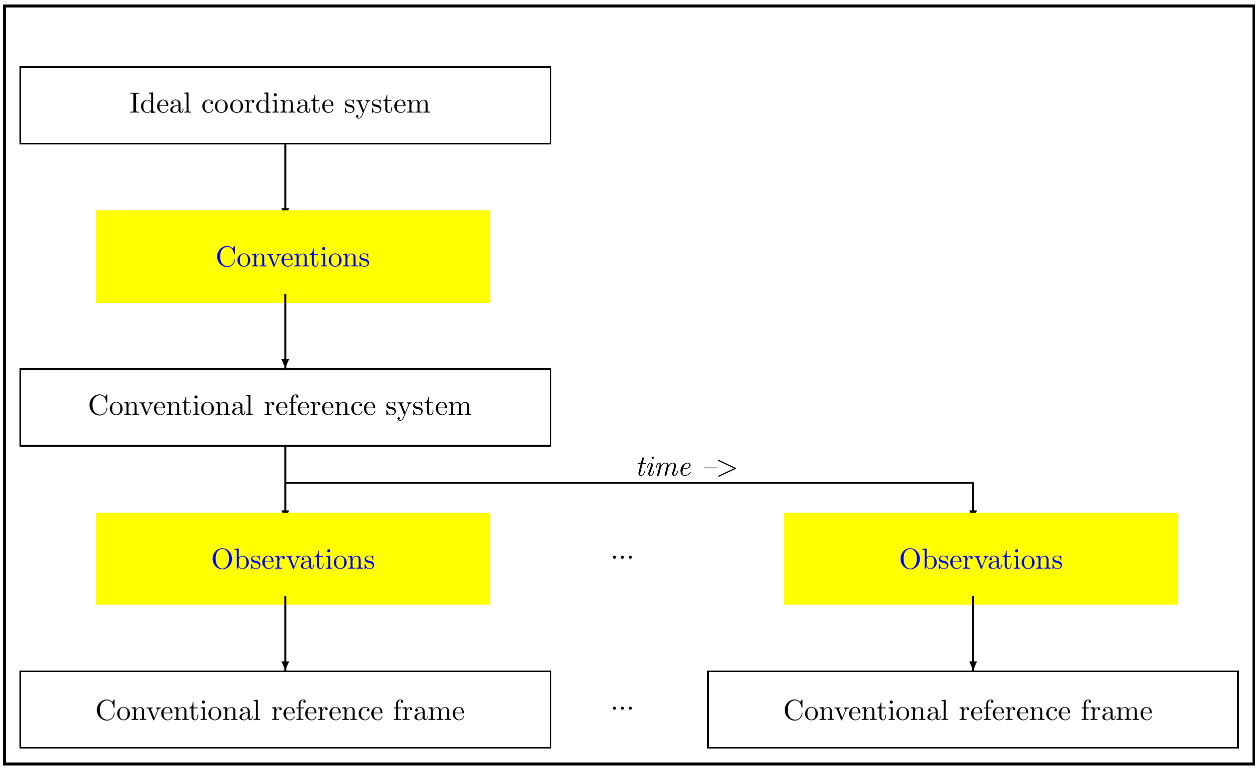

Figure 51: Principal scheme for practically accessible coordinate systems.
Starting from an ideal reference system, a set of conventions, algorithms, and constants sufficient to estimate coordinates of points in a specific ideal reference system is agreed upon. The conventional system takes into account the major applications of the reference system, the state of the art in observing techniques, the state of knowledge with respect to models, and other relevant aspects. Based on available observation techniques and analysis methods for these observations, the conventional reference system can be realized through an appropriate reference frame. The way this reference frame is to be determined normally is part of the conventions. Since realizations are based on observations with certain errors, their accuracy decrease if extrapolated in time. Therefore, reference frames need a constant monitoring and frequent readjustments. Moreover, improvements in observation techniques and the mere progress of time and length of available observations will allow for an ever better determination of the reference frame.

directions underlying these catalogs were considered conventional for some decades and had to be changed from time to time particularly to take into account advances in the modeling of the motion of solar system objects. The most recent system following these principles is the FK5 (Fricke et al., 1988).

It is well assessed that the FK5 reference system does not fulfill the demands of modern astrometry (Kovalevsky, 1997). As an example, it can be mentioned that the FK5 constant of precession is wrong by 0.3 arcsec/century. Therefore, since 1987, the International Earth Rotation Service (IERS) had determined Earth rotation parameters with respect to extragalactic objects using VLBI. The results were then transformed into the FK5 system, which was the "official" system.

Significant progress was made when the *International Astronomical Union* (IAU) in 1991 decided to base the realization of its CCRS on kinematic rather than a dynamical definition by using distant extragalactic objects and to adopt directions which would be fixed with respect to a selected set of these objects. One fundamental advantage of selecting extragalactic objects is that they are so distant that their proper motions are not detectable even with the most precise techniques presently available. Moreover, this new concept in the history of the IAU is expected to make coordinate axes fixed with respect to distant matter in the Universe and to ensures that the reference coordinates do not rotate with respect to a large portion of the Universe surrounding our galaxy. In this sense, the new CCRS is quasi-inertial.

The related IAU recommendations (see McCarthy, 1992) specify that the origin of the new CCRS is to be at the barycenter of the solar system and the axes are to be fixed with respect to the quasars. The directions would be consistent with their previous realizations, that is the FK5 origin of

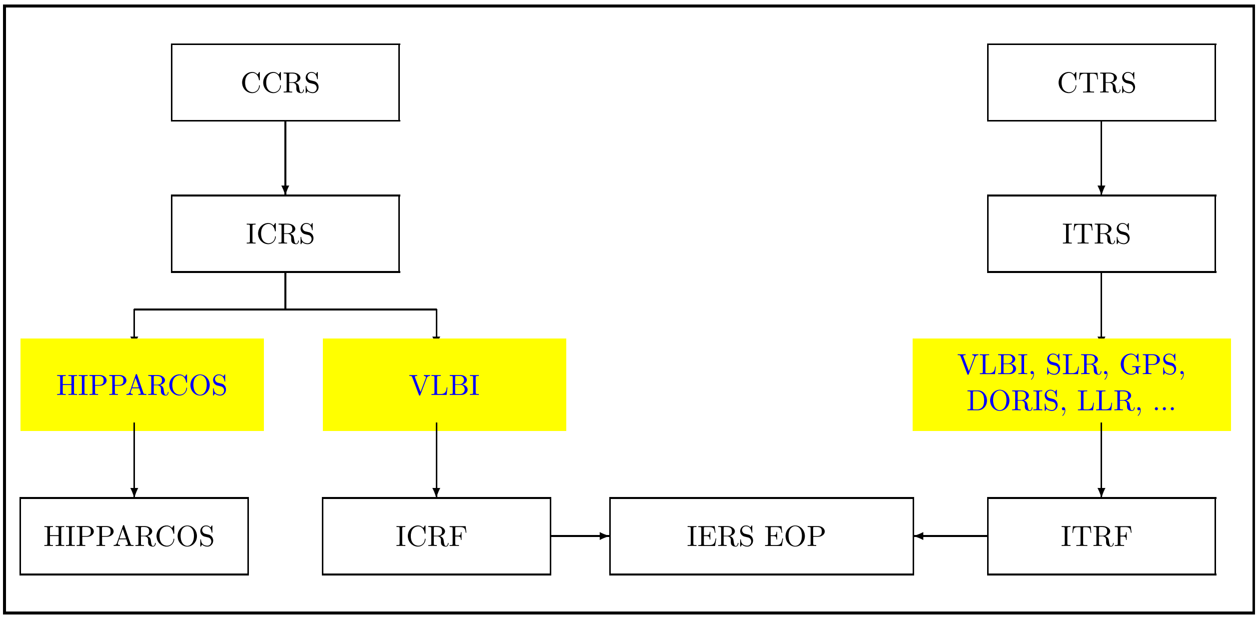

Figure 52: Overview over current conventional reference systems and their realizations.

The current Conventional Celestial Reference Systems (CCRS) adopted by the IAU is the International Celestial Reference System (ICRS). In the radio-wavelength, this system is realized as ICRF through VLBI measurements of extragalactical objects and as such maintained by the IERS. At optical wavelengths, the observations made with the HIPPARCOS satellite allowed the materialization of the ICRS through the HIPPARCOS stellar frame. The tie between the HIPPARCOS and the ICRS is determined to a high degree of accuracy. The current Conventional Terrestrial Reference Systems (CTRS) accepted by IUGG is the International Terrestrial Reference System, which is realized through the International Terrestrial Reference Frames (ITRF) maintained by the IERS. The tie between the ICRF and ITRF is provided by the IERS Earth Orientation Parameters (EOP). These describe the orientation of the Celestial Ephemeris Pole (CEP) in the terrestrial and celestial systems through the polar coordinates x *and* y *and the nutation offsets* $\mathrm{d}\psi$ *and* $\mathrm{d}\epsilon$*, respectively, and the orientation of the Earth around this axis through UT1-TAI as function of time.*

right ascension and pole (see below), within the uncertainties of the FK5.

The IAU resolutions explicitly introduce the Theory of General Relativity as the basis for all theoretical and data analyses related to space and time. With this, it was made sure that the new CCRS would not be detrimental to the analysis of observations from the highly accurate astrometric techniques.

The choice of extragalactic objects to realize the fiducial directions was possible due to the availability of a mature and highly accurate observing technique, namely the Very Long Baseline Interferometry (VLBI). Already in 1991, it could be imagined that a realization of the CCRS would become available soon for radio wavelength. However, also in 1991, the IAU decided that such a reference system will not become the actual reference frame for astronomy until it would be completed by a catalogue in the optical range, having in mind the HIPPARCOS Catalogue.

Based on the 1991 IAU resolutions, the ICRS is defined in Arias et al. (1995). Based on the definition provided in this article, the IERS published in 1997 the International Celestial Reference Frame (ICRF) (Ma & Feissel, 1997).

The ICRF includes the positions of 606 extragalactic radio-sources, out of which 212 are considered to be fundamentally defining the frame. The positions of the other sources are given in the frame, but since they are observed less, their positions are less accurate. The positions of the 212 fundamental sources are determined better than 0.6 mas in α and δ.

The ICRF is maintained by high-accuracy observations of extragalactic radio sources by VLBI. This maintenance algorithm ensures stable directions of its axies within ±20 microarcseconds (for more details, see Ma & Feissel, 1997; Arias et al., 1995)

In parallel, the HIPPARCOS stellar reference frame was astrometrically aligned with the ICRF (based on the 212 fundamental sources) to within ±0.6 mas at the central observation epoch of HIP-

PARCOS at 1991.25 and in spin/rotation within ±0.25 mas/year (Kovalevsky, 1997). It thus provided the primary realization of the ICRS at the optical wavelengths.

Therefore, in 1997, the IAU accepted the ICRS as the new CCRS and the ICRF and HIPPARCOS as its materialization in the radio and optical wavelengths, respectively.

A.3 Terrestrial Reference Systems

Attempts to define and realize reference systems or at least global reference surfaces and parameters of the Earth were made in the beginning of the 19th century, though mainly on national or regional level. An example is the sequence of reference ellipsoids starting with the one defined by Bessel in 1841, which was used for the German national reference frame (DHDN) determined by triangulation. Other such national reference frames were the OSGB36 in the U.K. and NTF in France. After world war II, the ED50 was introduced as a European unification.

It should also be mentioned that separate attempts were made for systems for geographical coordinates on the one hand and height datum on the other hand. Geoidal reference surfaces provide another example for a reference, which, in principle, could have been used as a global reference for height.

One of the first geodetic application requiring a precise global terrestrial reference system in three dimensions was the observation of Earth rotation starting around the middle of the 19th century (see Mulholland & Carter, 1982, for a historical overview). Subsequently, a number of global reference systems were introduced on national or international level and realized in various ways. A prominent role was attached to the international scientific bodies responsible for Earth rotation monitoring, such as the International Latitude Service (ILS), the International Polar Motion Service (IPMS), the Bureau International de l'Heure (BIH), and, currently, the IERS. The IAG has a historical role in the development of conventional reference frame responding to or even prompting the development of observational techniques. Thus, the IAG Commission RETRIG continued to update ED50 until 1987 through ED79 and ED87. In 1967, the IAG and also the IAU adopted the Conventional International Origin (CIO) frame, with a pole defined for the epoch 1903.0 as the mean of the ILS observations of the pole during the period 1900.0 to 1906.0. These two scientific bodies also introduced the systems presently used for most accurate applications (see below).

Until 1984, the international accepted TRS was the CIO-BIH system, which was realized by use of Earth Rotation Parameters (EOP). The frame was a network of astronomical instruments with coordinates determined by astronomical observations. In 1984, the BIH started to produce the BTS, which was realized through a new type of TRF based on space geodesy.

In 1987, the IERS was established by IUGG and IAU as a FAGS services with the mission to materialize the a CRS and a TRS as well as determine EOP. The IERS replaced the BIH.

As milestones in the development of the scientifically promoted (i.e. through IUGG and IAG) system, it should be mentioned that in 1979, the IUGG accepted the Geodetic Reference System 1980 (GSR80), which, among others, specifies relevant constants and the geometrical and physical parameters of the figure of the Earth (table 13).

The need for global terrestrial reference systems allowing, in principle, for materializations on the subcentimeter level did not arise before the invention of the space- and satellite-geodetic techniques allowing for ground-based geodesy on global scale. At the same time, these techniques for the first time provided the means for high-accuracy materializations of such systems. These techniques are the satellite- and space-geodetic methods (such as Transit, SLR, GPS, LLR, VLBI) developed over the last four decades.

The development of particularly VLBI and SLR led to a number of single or two-technique defined reference frames used mainly for scientific geodetic purposes. The successor of the BIH, the IERS started to produce a sequence of annual realizations of the IERS Terrestrial Reference System (again the successor of the BTS) with the IERS Terrestrial Reference Frame 1988 (ITRF88).

The ground for a formal acceptance of this TRF through the relevant international scientific organizations as the CTRS was laid at the 1991 IUGG Assembly in Vienna, when the IUGG in its Resolution 2 specified the Conventional Terrestrial Reference System to be used (see Appendix B.1).

The system specified by this Resolution was at that time already under implementation by the IERS and several realizations through IERS Terrestrial Reference Frames had already been determined (ITRF88, ITRF89, ITRF90) and published.

Following this Resolution, the IAG in 1991

Table 12: List of reference ellipsoids introduced in the past.

Name of ellipsoid	semimajor axis a [m]	flattening $f = (a-b)/a$	applied for
Geodetic Reference System 1980 (GRS80)	6 378 137.	1 : 298.25722	World Geodetic System 1984
World Geodetic System 1972 (WGS72)	6 378 135.	1 : 298.26	World Geodetic System 1972
Geodetic Reference System 1967	6 378 160.	1 : 298.25	Australian Datum 1966 South American Datum 1969
Krassovski (1942)	6 378 245.	1 : 298.3	Pulkovo Datum 1942
International (Hayford 1924)	6 378 388.	1 : 297.0	European Datum 1950
Clark (1866)	6 378 206.	1 : 294.98	North American Datum 1927
Bessel (1841)	6 377 397.	1 : 299.15	German DHDN

Table 13: Geodetic Reference System 1980 (GRS80).

The GRS80 was adopted by IAG during the General Assembly 1979. Here, the principal parameters are given.

parameter	**symbol**	**value**
defining constants		
equatorial radius of the Earth	a	6378137 m
geocentric gravitational constant (including the atmosphere)	GM	$3986005 \cdot 10^{8}$ m^{3}s^{-2}
dynamical form factor (excluding permanent tides)	J_2	$108263 \cdot 10^{-8}$
angular velocity of the Earth	ω	$7292115 \cdot 10^{-11}$ rad s^{-1}
derived geometrical parameters		
semiminor axis (polar radius)	b	6356752.3141 m
first excentricity	e^2	0.00669438002290
flattening	f 1 : 298.257222101	
mean radius	R_1	6371008.7714 m
radius of sphere with same surface	R_2	6371007.1810 m
radius of sphere with same volume	R_3	6371000.7900 m
derived physical parameters		
normal potential at ellipsoid	U_0	62636860.850 m^{2}s^{-2}
Normal gravity at equator	g_{e}	9.7803267715 m s^{-2}
Normal gravity at pole	g_{p}	9.8321863685 m s^{-2}

adopted the Resolution 1, which specifies the currently accepted CTRS (Appendix B.2.

Today, the most accurate global terrestrial reference system is maintained by the IERS through international cooperation. The ITRS is specified in detailed in the IERS Conventions (McCarthy & Petit, 2003).

In Newtonian theory, the underlying ideal Terrestrial Reference System can be considered to be a three-dimensional coordinate system with origin close to the Earth and co-rotating with it. The geometry of an Euclidian affine space of dimension 3 provides a standard model of such a system. Using the affine frame (O, E), where O is a point in space called origin and E a vector base of the associated vector space. Currently, E is restricted to be orthogonal with all base vectors having the same length. The common length of the base vectors is named the scale of the TRS. However, it should be kept in mind that this this Newtonian model is valid to visualize the concept for practical users, but the actual definition of the CTRS today has to be based on the General Theory of Relativity, where the CTRS is a local Earth system as specified in the IAU 1991 resolutions.

The ITRS follows the criteria given in Boucher (1990):

a) It is geocentric, the center of mass being defined for the whole Earth, including oceans and atmosphere.

b) Its scale is that of a local Earth frame, in the meaning of a relativistic theory of gravitation.

c) Its orientation was initially given by the BIH orientation at 1984.0.

d) Its time evolution in orientation will create no residual global rotation with respect to the crust.

In agreement with the relevant IAU 1991 resolutions, the unit of length is the SI meter. The scale is obtained by appropriate relativistic modeling. The orientation is defined by adopting IERS Earth orientation parameters at a reference epoch. In case of dynamical observation techniques, an additional constraint in longitude is necessary to remove ill-conditioning.

The IERS Reference Pole (IRP) and Reference Meridian (IRM) are consistent with the corresponding directions of the BTS within ±5 mas. The BIH reference pole was adjusted to the CIO in 1967 and was kept stable until 1987. The uncertainty in the tie of the IRP with the CIO is ±30 mas. The time evolution of the orientation is to be ensure by using a No-Net-Rotation (NNR) condition with respect to horizontal tectonic motion averaged over the whole Earth.

It should be mentioned here that there are several controversial conventions, including the implementation of the NNR condition, but also the treatment of the permanent tide, which is in disagreement with the conventions in gravity and IUGG resolutions.

A.4 The realization of ITRS through ITRF

The ITRS is realized through a reference frame specifying a set of coordinates for a network of stations. These coordinates are given as Cartesian equatorial coordinates triples $x_i \equiv (X, Y, Z)$ by preference. The IERS Conventions suggest that if geographical coordinates are needed, the GRS80 ellipsoid should be used.

Realizations of the ITRS are determined by the IERS in a nearly annual sequence and denoted as ITRF_nn, where nn identifies the epoch of the frame (see, for example Boucher et al., 1999). These realizations are determined through combination of results from individual techniques. They are based on results provided by the different IERS analysis centers. The realization consists of lists of coordinates and velocities for a selection of IERS sites, which may be tracking stations or related ground markers. The station coordinates are expressed through

$$x_i(t) = x_i^0 + v_i^0(t - t_0) + \sum_{j=1}^{k} \delta x_i^j(t), \quad i = 1, 2, 3 \quad (4)$$

where x_i^0 and v_i^0 are the position and velocity at epoch $t = t_0$ and δx_i^k are corrections due to the k-th process inducing time variable contributions to the coordinates. Such processes are, for example, solid Earth tide displacements, ocean loading, atmospheric loading, and post-glacial rebound.

The first two terms in eq. (4), that is

$$\tilde{x}_i(t) = x_i^0 + v_i^0(t - t_0), \quad (5)$$

are denoted as regularized coordinates (McCarthy & Petit, 2003). These regularized coordinates are listed in the ITRF publications. They depend on the selection of processes included in eq. (4), that is the geophysical model used in the modeling of

$$\Delta_i(t) = \sum_{j=1}^{k} \delta x_i^j(t). \quad (6)$$

The agreed upon processes to be included and the underlying geophysical models are specified in the IERS Conventions (for a critical discussion of the regularized coordinates, see Section 5.1 on Page 65).

For different realizations of the ITRS, transformations are given to convert coordinates from one ITRF to another. The basic transformation formula is a seven parameter similarity transformation, often denoted as Helmert Transformation. This is given by

$$x_i' = sR_{ij}x_j + t_i, \; i = 1, 2, 3 \quad (7)$$

where x_i and x_i' are the coordinate vectors of the point in the unprimed and primed frame, respectively, and t_i is the vector describing the offset of the origin between the primed and unprimed system measured in scale units of the primed system. s is the scale change of the primed frame with respect to the unprimed frame, and R_{ij} is a rotation matrix

$$R_{ij} = R^{(1)}_{ik}(\epsilon) R^{(2)}_{kl}(\psi) R^{(3)}_{lj}(\omega). \tag{8}$$

Here, the $(R^{(n)}_{ij}(\alpha))$ are rotation matrices describing a rotation around the n-th axis. For $j = n(\text{modulo}3) + 1;\ k = j(\text{modulo}3) + 1$, we have

$$\begin{aligned} R_{nn} &= 1 & (9) \\ R_{nj} &= R_{jn} = R_{nk} = R_{kn} = 0 \\ R_{jj} &= R_{kk} = \cos\alpha \\ R_{jk} &= \sin\alpha & (10) \\ R_{kj} &= -\sin\alpha \end{aligned}$$

For infinitesimal rotations, (7) can be written as

$$x'_i = (1 + \delta s)\tilde{R}_{ij} x_j + t_i \tag{11}$$

where δs is the incremental scale change and with

$$(\tilde{R}_{ij}) = \begin{pmatrix} 1 & \omega & -\psi \\ -\omega & 1 & \epsilon \\ \psi & -\epsilon & 1 \end{pmatrix} \tag{12}$$

where ϵ, ψ, and ω are given in radian. Then,

$$x'_i = x_j + \delta s \tilde{R}_{ij} x_j + t_i \tag{13}$$

which is the form given in the IERS Conventions (McCarthy & Petit, 2003).

For later versions of the ITRF (from 1993 onwards), not only the transformation parameters are give but also rates of changes of these parameters. In this case, for a given transformation parameter q valid at the epoch t_0, its value at time t is given by

$$q(t) = q(t_0) + \dot{q}(t - t_0). \tag{14}$$

The coordinate transformation described by equations (13) and (14) are rigid and thus not able to account for any deformations of two reference frames. This is a significant deficiency of the transformation. With increasing time, the subsequent ITRFs are based on a growing number of techniques (including VLBI, SLR, GPS, DORIS, and, for ITRF2000, also GLONASS), improved global networks, improved information on the local ties between individual techniques at sites where techniques are collocated, improved analyses procedures for the single techniques, and improved methodologies for the combination of the single-technique reference results (see Boucher et al., 1999, for a recent example). This leads inevitably to deformations of two subsequent reference frames and renders the transformations inaccurate.

For many applications, it is necessary to compare coordinates of a point determined at different epochs or to refer coordinates to a reference epoch different from the central epoch of observations. Within the same reference frame, this can be achieved by

$$x_i(t_r) = x_i(t_c) + (t_r - t_c) \cdot v_i \tag{15}$$

where t_r and t_c are the reference epoch and the central epoch of measurement, respectively, and x_i and v_i are the position and velocity vectors given in the relevant ITRF. If positions given for different epochs in different versions of the ITRF are to be compared, then equations (13 to (15) should be, in principle, sufficient. However, due to the deformation of the reference frames with respect to each other, these equations are not accurate and the error increases with time.

It should be mentioned here, that some criticism has been articulated concerning appropriateness of the combination of results from single techniques in order to form the ITRF. It has been claimed that a combination on the observation level will lead to a more stable and more accurate realization of the ITRS (Andersen, 1997, 2000). However, the superiority of the combination at the observational level advocated, for example, by (Andersen, 1997) has not been demonstrated up to now. In fact, the current combination (at the normal equation level), when done properly, should be equivalent to the observation level combinations.

Today, the accuracy of the ITRF is estimated to be of the order of 10-20 mm in station coordinates. This accuracy refers to the regularized coordinates. In order to understand the effect of periodic point motion (see table 10 for an overview of the periodic motions) on coordinate accuracy, it is necessary to take into account the the definition of point coordinates given above. ITRF does not only consist of the coordinates and velocities given for the ITRF points but also of the IERS Conventions which give many details on what models are to be used when processing geodetic observations from, for example, VLBI, SLR, and GNSS in order of get ITRF coordinates. The conventions are to a very large extent followed by the IERS Analysis Centers contributing to the determination of ITRF. Violations of the conventions by a user of the ITRF will lead to non-ITRF or at least biased ITRF coordinates.

It needs to be mentioned here that highly accurate geodetic coordinates determined with daily or longer datasets are free of period movements due to tides and polar motion: these are taken into account in the station motion model used in the different softwares to model the point motion over time. Thus, we expect time series of daily coordinates to be "tide-free" and to show basically linear trends and some long-period movement due to, for example, surface loading. This also implies that "accuracy in ITRF" refers to "tide-free" coordinates.

Consequently, in order to provide reference coordinates that are of a certain accuracy in ITRF, these coordinates have to be as far as possible free of periodic movements. However, for a global frame, the secular motion has to be part of the temporal dependency of the coordinates.

Considering higher temporal resolution than one day for geodetic GPS analyses, one may choose to leave the tides in the time series or one may still choose to model them. Nevertheless, when considering "reference coordinates," it is implicitly assumed that these are "tide-free."

Moreover, for many national reference system such as the EUREF89 realizations in the different countries, the reference coordinates are not only "tide-free" but they are considered to be free of regional secular motion. In most national reference systems, the coordinates are kept fixed over long time intervals (hopefully several decades) as long as intraplate deformation is very small (except for the vertical).

A.5 Relation of the ITRS to other terrestrial reference systems

It is worthwhile to look at the relation of the ITRF to other global frames. For practical purposes, some global systems were introduced on national level. Of particular interest here is the World Geodetic System (WGS), which is still widely used in nonscientific applications. A first World Geodetic Reference System was in 1960 introduced by the U.S. Department of Defense (DoD) as WGS60 and later updated through WGS66 and WGS72.

In 1984, the DoD introduced the World Geodetic System 1984 (WGS84). The first materialization of the WGS84 was based on observations from the U.S. Navy Navigation Satellite System (Doppler Transit). This materialization of the WGS84 was achieved by aligning as closed as possible the DoD reference frame NSWC-9Z2 to the BIH Conventional Terrestrial System (BTS) at the epoch 1984.0. The latler was realized by the adopted coordinates of a globally distributed set of tracking stations with an estimated accuracy of 1-2 meters.

In January 1987, the U.S. Defense Mapping Agency (DMA) started using the WGS84 for the computation of the precise ephemerides of the TRANSIT satellites. Using these ephemerides, the coordinates of the ten DoD GPS monitoring stations were determined by Doppler tracking. Until recently, GPS broadcast orbits were generated from GPS tracking data from these stations, fixing the Doppler derived coordinates of these stations (i.e. neglecting any station movement, including tectonic plate motions).

Based on broadcast ephemeries, GPS receivers provide coordinates in the WGS84, and for many practical purposes such as air navigation, the WGS84 is in use[3]. Therefore, it is worthwhile to consider the current relation between WGS84 and the more accurate ITRF. In 1994, the DoD made an attempt to align WGS84 with ITRF. For that, new coordinates for the ten DoD tracking stations were determined at the epoch 1994.0 used GPS tracking data collected at these sites together with a subset of the IGS tracking stations, with the ITRF91 coordinates of the later stations being held fixed in the process. This refined WGS84 realization is denoted as WGS84 (G730), with the 'G' indicating that the frame is GPS derived and '730' denoting the GPS week number when the new coordinates where implemented by DMA in their orbit processing. Moreover, the original WGS84 GM value was replaced by the value given in the IERS 1992 standards (see McCarthy, 1992, the value there is $3986004.418 \cdot 10^8\ \mathrm{m}^3/\mathrm{s}^2$). The introduction of this new frame for GPS resulted in more precise ephemeris in the GPS broadcast messages.

For the original realization of the WGS84, transformation parameters between the ITRF and WGS84 are available for the ITRF90. Based on a comparison of ITRF and WGS84 (G730) and the later WGS84 (G873), it is found that these new WGS84 realizations are coincident with ITRF at about the 0.1 meter level. For these realizations there are no official transformation parameters available. This means that one can consider ITRF coordinates also to be expressed in WGS84 at the 10 cm level.

The importance of the ITRF as the most accu-

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[3] see `http://www.wgs84.com/default.htm` for an example

rate global reference frame is increasingly acknowledged outside the scientific community. For example, the European Commission and the Government of the United States of America recently agreed to align the reference systems of Galileo and GPS as close as possible to the ITRS, in order to ensure the interoperability of the two GNSS (European Commission, 2004).

A.6 Dynamical Reference Frames

A Conventional Dynamical Reference Frame (CDTF) specifies the planetary and lunar ephemerides, which are required, among other purposes, to determine the tidal potential at any point in the solar system, to determine the barycentre of the solar system, and to compute the geometry of the space-time continuum in the solar system. Besides orbital parameters, the CDTF also specifies the mass values of the bodies in the solar system.

The most recent frame for planetary and lunar ephemeries are the JPL Development Ephemeris DE405 and the Lunar Ephemeris LE405, respectively (see http://ssd.jpl.nasa.gov/iau-comm4 and the link "Where to obtain ephemerides"). These ephemerides have been adjusted to all relevant observational data and are given in the ICRF. It is interesting to note that some of the planetary mass values have changed considerable from the older IAU 1976 values over the DE200 to the values used for DE405 (see table 3.1 in McCarthy & Petit, 2003).

A.7 Earth rotation

The Earth rotation vector links the celestial and terrestrial reference system. The rotation can be separated into (1) nutation and precession and (2) motion of the pole and variations in the length of the day. Based on this separation, the transformations from the terrestrial into the celestial reference frame are described through *Earth Orientation Parameters* (EOP). The EOP are determined mainly from VLBI observations. GPS and SLR observations can also be used to determine some of the EOP with high accuracy but with lower long-time stability.

The coordinate transformation between ITRF and ICRF is given by

$$x_i^{\mathrm{ICRS}} = N_{ik} R_{kl} W_{lj} x_j^{\mathrm{ITRF}} \qquad (16)$$

where N, R and W are time dependent rotation matrices. N gives the movement of the celestial pole (CEP) in ICRS resulting from precision and nutation. The matrix R describes the Earth rotation over the axis from the geocenter to the CEP, and the matrix W describes the polar motion.

Earth rotation observations have a long history starting in the middle of the 19th century with optical methods. After the discovery of latitude variations through Küster in 1885, international monitoring of Earth rotation parameters has continued to the present.

B Resolutions related to Reference Systems

B.1 IUGG 1991 Resolution

Resolution No. 2

The International Union of Geodesy and Geophysics

considering the need to define a Conventional Terrestrial reference System (CTRS) which would be unambiguous at the millimetre level at the Earth's surface and that this level of accuracy must take account of relativity and of Earth deformation, and

noting the resolutions on Reference Systems adopted by the XXIst General Asssembly of the International Astronomical Union (IAU) at Buenos Aires, 1991,

endorses the Reference System as defined by the IAU at their XXIst General Asssembly at Buenos Aires, 1991, and

recommends the following definition of the CTRS:

1) *CTRS to be defined from a geocentric nonrotating system by a spatial rotation leading to a quasi-Cartesian system,*

2) *the geocentric nonrotating system to be identical to the Geocentric Reference System (GRS) as defined in the IAU resolutions,*

3) *the coordinate-time of the CTRS as well as the GRS to be the Geocentric Coordinate Time (TCG),*

4) *the origin of the system to be geocentre of the Earth's mass including oceans and atmosphere, and*

5) *the system to have no global residual rotation with respect to horizontal motion at the Earth's surface.*

B.2 IAG 1991 Resolution

The International Association of Geodesy,

considering the IUGG Resolution on Conventional Terrestrial Reference Systems (CTRS), and noting

1. *that the International Earth Rotation Service (IERS) is currently implementing such a system under the name of the International Terrestrial Reference System (ITRS) from VLBI, SLR, LLR and now GPS data, and*
2. *that the ITRS is within one metre of WGS84,*

recommends:

1. *that groups making highly accurate geodetic, geodynamic or oceanographic analysis should either use the ITRS directly or carefully tie their own systems to it,*
2. *that IERS standards should contain all necessary documentation to assist this task,*
3. *that for mapping, navigation or digital databases where sub-metre accuracy is not required, WGS84 may be used in the place of ITRS,*
4. *that for high accuracy in continental areas, a system moving with a rigid plate may be used to eliminate unnecessary velocities provided it coincides exactly with the ITRS at a specific epoch (e.g., the ETRS 89 system selected by the EUREF subcommission)".*

B.3 IUGG 2003 Resolution establishing GGOS

Resolution 3: Integrated Global Geodetic Observing System (IGGOS):

IUGG Recognizing,

1. *The great progress made in the use of space and terrestrial techniques for monitoring the phenomena and processes in the System Earth during the last decades; and*
2. *The efforts made towards the integration of space techniques in the management of observations, data processing, evaluation, and modelling of the observable parameters, in particular by the different international services; and*
3. *The urgent need to further develop and strengthen the scientific and organizational collaboration of geodesy within the geosciences; and*
4. *The necessity of generation and accessibility of consistent products for users in Earth sciences, neighbouring disciplines and society in general.*

Considering,

That the International Association of Geodesy (IAG) has taken an initiative towards the realization of IUGG Resolution no.1 adopted at the 22nd General Assembly in Birmingham 1999 by installing the integrated Global Geodetic Observing System (IGGOS).

Strongly supports the establishment of the IGGOS Project within the new IAG structure as geodesy's contribution to the wider field of geosciences and as the metrological basis for the Earth observation programs within IUGG and the international organizations mentioned in the 1999 Resolution no.1.

and Urges,

That Associations cooperate with the new project by providing data, models, products, and knowhow useful for IGGOS and the benefit of geosciences; and

The participating in the IGGOS project by joining the relevant components in its structure and assisting its symposia and meetings.

C Acronyms and abbreviations

AC	Analysis Center
CDR	Critical Design Review
CGNSS	Continous GNSS
CGPS	Continuous GPS
CHAMP	Challenging Minisatellite Payload
CM	Center of Mass of the whole Earth system
CMV	Common Mode Variations
CSRS	Canadian Spatial Reference System
CTRS	Conventional Terrestrial Reference System
DORIS	Doppler Orbitography by Radiopositioning Integrated on Satellites
ECGN	European Combined Geodetic Network
EOP	Earth Orientation Parameters
EOS	Earth Observation Summit
EPN	European Permanent Network
ERNP	European Radio Navigation Plan
ERP	Earth Rotation Parameter
ESEAS	European Sea Level Service
ETRS	Eurasisan Terrestrial Reference System
EUREF	European Reference Frame
EuroGOOS	European Part of the Global Ocean Observing System
FR	Final Review
G3OS	Global Three Observing Systems
GCM	General Circulation Model
GCOS	Global Climate Observing System
GDP	Gross Domestic Product
ad hoc**GEO**	*ad hoc*Group on Earth Observations
GEO	(permanent) Group on Earth Observations
GEOSS	Global Earth Observation System of Systems
GGFC	(IERS) Global Geophysical Fluid Center
GGOS	Global Geodetic Observing System
GGP	Global Geodynamics Project
GLONASS	Global Navigation Satellite System
GLOSS	Global Sea Level Observing System
GMES	Global Monitoring of Environment and Security
GNSS	Global Navigation Satellite System
GOCE	Gravity field and steady-state Ocean Circulation Explorer
GOOS	Global Ocean Observing System
GPS	Global Positioning System
GPS&IGS	GPS system combined with IGS products
GRACE	Gravity Recovery and Climate Experiment
GRS80	Geodetic Reference System 80
GTOS	Global Terrestrial Observing System
GVA	Gross Value Added
IAG	International Association of Geodesy
IAS	International Altimetry Service
IAU	International Astronomic Union
ICET	International Center for Earth Tides
IDS	International DORIS Service
IERS	International Earth Rotation and Reference Systems Service
IGFS	International Gravity Field Service
IGOL	Integrated Global Observation for Land
IGOS	Integrated Global Observing Strategy
IGOS-P	Integrated Global Observing Strategy Partnership
IGS	International GNSS Service
ILRS	International Laser Ranging Service

InSAR	Interferometric Synthetic Aperture Radar
IOC	International Oceanographic Commission
IPWV	Integrated Precipitable Water Vapor Content
ITRF	International Terrestrial Reference Frame
ITRS	International Terrestrial Reference System
IUGG	International Union of Geodesy and Geophysics
IVS	International VLBI Service
JPL	Jet Propulsion Laboratory
LLR	Lunar Laser Ranging
LOD	Length of Day
LSL	Local Sea Level
NGOS	Nordic Geodynamic Observing System
NGRF	Norwegian Geodetic Reference Frame
NKG	Nordic Geodetic Commission
NMA	Norwegian Mapping Authority
NNGI	Norwegian National Geodetic Infrastructure
NNR	No Net Rotation
NNT	No Net Translation
PGR	Post-Glacial Rebound
PPP	Precise Point Positioning
PRR	Preliminary Requirement Review
RRR	Roling Requirement Review
SA	Selected Availability
SB	Special Bureau
SBL	(IERS GGFC) Special Bureau for Loading
SCIGN	Southern California Integrated GPS Network
SG	Superconducting gravimeter
SiS	Signal in Space
SLR	Satelitte Laser Ranging
SOC	Satelitte Orbits and Clocks
SPS	Standard Positioning Service
SATREF	Satellite based reference system
TEC	Total Electron Content
UC	User Categroy
UNEP	United Nations Environmental Programme
UNFCCC	United Nations Framework Convention on Climate Change
UR	User Requirement
WGS84	World Geodetic System 1984
WMO	World Meteorological Organisation
VLBI	Very Long Baseline Interferometry