Assessing and forward planning of the **G**eodetic **A**nd **G**eohazard **O**bserving **S**ystems for GMES applications

- GAGOS -

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Contents

1 Abstract

The GAGOS project provides an assessment of the state-of-the-art of two major components of the Earth observing system, namely the global geodetic and global geohazards observing systems as indispensible preqequisites for the consistent global monitoring of the Earth system environment and security aspects of population. The assessment was carried out in view of the three major goals of the Global Monitoring for Environment and Security (GMES) project, namely (1) to provide information for the definition, negotiation, implementation and verification of the European environmental policies, national regulations and international conventions, (2) to be a contribution to global monitoring of the Earth system environment aiming at the provision of the data and information base required for a successful quest for sustainable development, and (3) to constitute, on a regional and global level, monitoring capacities required to ensure security for the population. The compliance of the networks and data systems of IGOS-P (Integrated Global Observing Strategy Partnership) and GEO (Group on Earth Observation) with GEOSS (Global Earth Observation System of Systems) were taken into account. The assessment also considers criteria such as the overall continuity, comparibility of the in-situ observations with space data, interoperability, synergies through co-location. Particular focus of the assessment is on the existing infrastructure to monitor geohazard related parameters and thus, the results of the project are essential to improve the observational networks in order to provide information for better understanding of processes and risks for natural hazards and eventually also mitigation and management of disasters. It strengthens the European Research Area through trans-national cooperation and addresses the potential synergies through an integrated approach to Earth observation, data management and spatial data information systems. Thus the GAGOS project has a profound effect not only on global Earth system monitoring for sustainable development, but also a large number of services for the security of the society such as disaster warning, assessment of natural hazard risks, estimation of post-hazard damages, rescue aids and many other applications.

The assessment of the status quo was performed in the following fields: (1) Reference frames and Earth orientation parameters, (2) Earth physical shape and gravity field, (3) geohazards, (4) man-made problems and monitoring of infrastructure, and (5) data acquisition, data flow, data archiving and data information management. The assessment of the current situation was compared to the present and future requirements and the adaption required to fully exploit new technologies for the benefit of various users was outlined. Towards this aim a forward planning was performed to close the deficiencies and gaps of the present situation. Recommendations for future global geodetic and geohazards observing systems to serve applications within GMES are provided. Finally, the GAGOS project addresses the European activities and contributions to the implementation of the Global Geodetic Observing System (GGOS), a component of the International Association of Geodesy (IAG).

2 Introduction

The helplessness felt in the wake of recent natural disasters (e.g., the devastating Sumatra earthquake and tsunami of 2004) has made it abundantly clear that our understanding of the Earth system is far from being complete. Although many of these critical events and developments often have only a regional impact, they must be understood as part of global change processes. Therefore gaining deeper insight into such global processes and their interactions in the Earth system is one of the most urgent challenges facing society. The development of accurate and reliable numerical and analytical models will be an indispensable basis for meaningful predictions of the future behaviour of the Earth system. This must go hand in hand with the continuous global monitoring and detection of Earth processes, occurring at local to global spatial scales and over timescales ranging from extremely short (e.g., earthquakes, volcanic eruptions, land slides) to long (e.g., melting of ice sheets, sea-level change, glacial-isostatic adjustment, plate tectonics). This implies extreme challenges to the detection and quantification of catastrophic events in (near) real-time on the one hand and the barely detectable, but critical long-term trends (e.g., sea-level rise) on the other.

Thus, a dense global Earth observing system, aiming at high temporal and spatial resolution and accuracy, will have to integrate the required large variety of complementary ground- and space-based observational data. Within a broader international context, the need for such an integrated observing system is being met by organizations such as GEO (with GEOSS) and GMES. The long time series of geodetic, geodynamic, and geophysical parameters obtained from such an observing system provide crucial information about the Earth system, i.e., about the shape and deformation of the Earth, its internal structure, the behaviour of the hydrosphere, cryosphere and atmosphere, land surface characteristics, the Earth's variable rotation, the static and time-variable gravity field, and crustal motion. These quantities are direct evidence of the many global processes that have a critical impact on human society.

An accurate, global terrestrial reference frame, i.e., the International Terrestrial Reference Frame (ITRF) is a necessary pre-requisite for all Earth observation and monitoring both, from space and from the ground. Moreover, in order to detect slow changes in the Earth system, the long-term stability of this reference frame is crucial.

Realising the importance of an integrated approach, the International Association of Geodesy (IAG) recently (July 2003) decided to implement the Global Geodetic Observing System (GGOS) as the umbrella for all global geodetic observing networks required to maintain the International Terrestrial Reference Frame and to monitor variations of the Earth's rotation and gravity field. In April 2004 the IAG, represented through GGOS, became a participating organization of GEO (Group on Earth Observation) for the realization of GEOSS (Global Earth Observing System of Systems). In May 2006 GGOS was accepted as an official member of IGOS-P (Integrated Global Observation Strategy Partnership). GGOS is presently working on a reference document, called GGOS2020, that will describes the future GGOS as an observing system in the year 2020. This reference document will eventually contain a significantly larger amount of information, based on a broader community than that available for this report. A major contribution to GGOS-related activities comes from Europe that will have an important role in the full implementation of the GGOS. In the proposed project, the expertise of this community has been utilised (by organizing GAGOS meetings and workshops) for the report presented here.

GGOS contributes to Earth observation in two distinct ways:

- it provides the infrastructure and observations to determine and maintain an accurate and stable global terrestrial reference frame as the basis for all Earth observations,
- it delivers observations of the changes in the geometry and rotation of the Earth as well as changes in the Earth's gravity field.

Today, the International Terrestrial Reference Frame (ITRF) is the most accurate global frame available. The ITRF is maintained on the basis of a mix of space-geodetic techniques through international cooperation. Each of these techniques contributes in a specific way to the determination of the ITRF. Most of the cooperation is based on voluntary commitment of governmental and non-governmental institutions to the international services that contribute to the ITRF, such as the IERS, IGS, IVS, ILRS and the IDS. Fluctuations in the contributions due to changes in the funding situation severely affect the long-term stability of the ITRF and, consequently, the accuracy of many if not most other parts of the observing system, particularly the space-borne ones. The present report has to take into account this peculiar situation.

Changes in the Earth's geometry, gravity field and rotation are caused by mass movements and dynamical processes in the Earth system. Consequently, observations of these quantities provide a means to monitor the dynamics of the Earth system and associated mass movements, such as fluxes in the hydrological cycle including ocean circulation, ground water storage, terrestrial surface flows, sea level changes and ice changes.

The existing in-situ component of the terrestrial geophysical observation system is composed of a number of observational networks with spatially extremely variable quality and quantity. On a global scale, the coordination between different networks is spatially highly variable and most often very low. In large areas, important parameters related to hydrology, soil composition, seismic activity, volcanic processes, flooding risks, and landslides are not sufficiently monitored.

In some areas with high risks of natural hazards due to earthquakes, volcanoes, flooding, avalanches, landslides, dedicated observational networks exist in some geographical regions while they are nearly completely absent in others.

The geodetic observations not only provide the reference frame required for long-term Earth observations but also information related of displacements and strain of the Earth surface caused by tectonic and seismogenic processes, man-induced subsidence and motion of man-made infrastructure. The geophysical observations provide the necessary data to assess natural hazards risks and to implement services to mitigate the damage due to such processes. Thus, these two components vitally contribute to the GMES goal of increased security.

In the context of the G3OS, the existing terrestrial in-situ component of the Earth observation infrastructure (i.e. the infrastructure focusing on the solid Earth parameters) may well be the least developed component. Moreover, integration of the various in-situ observation networks is very low and regional highly variable. Both the GCOS and the GOOS have undergone considerable development during the last 10 years and much is available in terms of assessment reports and strategies. To our knowledge, the terrestrial component has not reached a similar level in the assessment of the available infrastructure.

The proposed project should help to close the current gap in the assessment concerning the terrestrial geodetic and geophysical observation system. In particular, through inclusion of the in-situ component required for the determination and maintenance of the reference frame itself, the project will provide the basis for a better understanding of the crucial role played by the reference frame for all Earth system monitoring.

This report will start in Chapter 3 with a description of the role of Geodesy in Earth observation. Chapter 4 will put together the requirements for a geodetic and geohazards observing system. An assessment of the present status of the already existing components of such a system is performed in Chapter 5, followed by the identification of deficiences and gaps in the present space- and ground-based infrastructure in Chapter 6. Chapter 7, finally, will consider the planning for a future, improved geodetic and geohazards observing system and will give recommendations for such improvements. The report ends with the conclusions in the final Chapter 8.

3 Earth Observations and Geodesy

3.1 Introduction

Geodesy is classically defined as the science of the measurement and mapping of the Earth's surface (Helmert 1880). The determination of the Earth's outer gravity field is included in this definition (e. g., Torge 2001). We may therefore subdivide according to the measuring techniques into geometric and gravimetric geodesy. Geometric geodesy has the classical objectives of determining the figure of the Earth and its orientation in space, coverage of topographic structures and constructions, and the positioning of political and property borders. Gravimetric geodesy determines the outer Earth gravity field in terms of its potential and anomalies, and derives among others the reference surfaces (e. g., equipotential surfaces) for physical heights of the Earth's surface.

Accuracy of geodetic observing techniques has increased enormously during the last decades, in particular due to extremely precise time measurements. Nowadays, distances are nearly exclusively derived from the travel times of electromagnetic waves. This holds true for geometry (distance networks) as well as for gravimetry (free falling probe masses). The development in space research enables measurements from Earth to the Moon and to artificial satellites as well as from satellites to Earth and to other satellites. From these measurements, we derive the connection between points at the surface of the Earth and in space even without direct visibility. The three-dimensional survey of the Earth's surface is directly achievable. As a consequence of the dramatic increase of the effectiveness of computers, we may apply completely new mathematical approaches to data analysis and evaluation. The high accuracy of measurements and the large amount of data can thus be completely exhausted.

These three technical developments: the increasing accuracy of observations, the extension of space techniques, and the enormous achievement in data processing lead to a significant expansion of the objectives of geodetic research (Drewes 2006). The "classical" geodetic products (point positions, surfaces, Earth rotation and gravity) and its even smallest variations in time can be monitored significantly with high resolution and in global extension. The "measuring of the Earth", which was done stationary and static in the past, is extended to the "measuring and analysis of phenomena and effects of physical processes in the System Earth". The term "system" here refers to the complete coherence within the planet Earth itself as well as the space immediately surrounding it. As the processes always show geometric and gravimetric components, both methods have to be treated in an integrative way, i. e., simultaneously and combined.

3.2 Geodetic observations and parameter estimation

Fig. 3.2.1 demonstrates the principle of geodetic observations and parameter estimation. The observations, i. e., the geometric and gravimetric measurements, always refer to and reflect reality. As the features are very complex and therefore difficult to describe, we create simplifying physical models, which are represented by mathematical parameters. The geodetic data processing connects the observation data only with these parameters, not with reality. To connect the observations with the parameters, we need reference systems that define to which frame the parameters refer to. Point positions, e. g. are not directly estimable, but they require the definition and realization of a coordinate reference system. The reference systems are defined together with the physical model and realized by the mathematical algorithm. They must be valid for both geometric and gravimetric observations. If, for example, the gravity field parameters refer to the centre of mass of the Earth (geo-centre), the geometric parameters require a geo-centric reference, too. This is extremely important for geodetic space methods, where satellite orbits are computed using gravity field models and station positions are computed using the orbit ephemeris. In the parameter estimation procedure, the reference systems have to be realized exactly according to their definition.

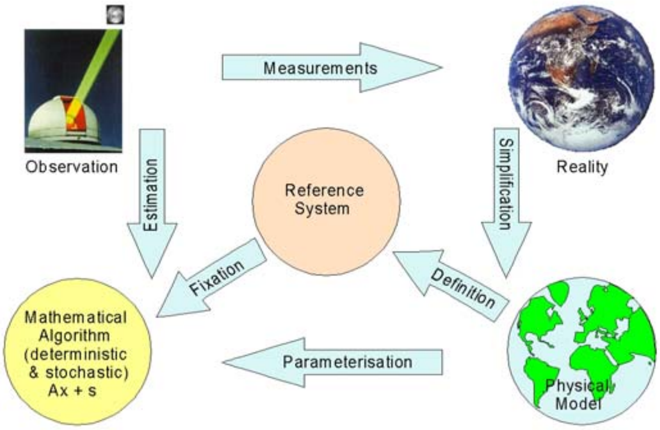


Fig. 3.2.1: Principle of geodetic observations and parameter estimation

The physical models underlying the parameterisation are the basis of geodetic data processing. An erroneous model leads to wrong parameter estimation, even with flawless measurements. These models could be kept simple in the past (mainly geometric), because the objective of geodesy and the limited accuracy of the measurements didn't require the representation of complicated interrelations. At present, however, they have to be comprehensive and precise in order to be capable of representing all the effects in the model parameters that are also affecting the observations. The physical models relevant for geodesy shall therefore be discussed in the following.

3.3 Elements of Earth Observations

The Earth System consists of elements of solid, liquid and gaseous materials. One may divide it into the geosphere (solid lithosphere, viscous asthenosphere, solid inner and liquid outer core), the hydrosphere (liquid water), cryosphere (ice covered areas), atmosphere (troposphere and ionosphere), and biosphere (biologic masses). Each of these elements has some characteristics to be observed by geodetic (geometric or gravimetric) measurements, e. g., their shape and mass. Physical processes within individual or among different elements (e. g., gravitation, thermodynamics, pressure, tension and drag) produce signals that may be measured by geodetic observing systems. These signals are e. g., variations of geometric quantities and/or gravity changes.

The signals do not affect individual geodetic quantities independently. In general, several groups of parameters are included simultaneously: Variations in geometry also produce gravity changes. Therefore, the physical models must not be designed considering only individual signals, but they rather have to comprise all the elements and processes. The shape and the deformations of the solid Earth, oceanic and atmospheric currents and loadings, and all the mass displacements caused by the water cycle and vegetation have to be modelled consistently with respect to the estimable parameters (point positions at and the shape of the Earth's surface, orientation of Earth in space and the Earth's gravity field). In the same way, the geodetic data processing procedure has to consider all types of observations. They have to refer to consistent reference systems, in which the satellite orbits and extraterrestrial sources (e. g. Quasars) may also be represented (Fig. 3.3.1). The signals of the System Earth are represented in a comprehensive way by this means.

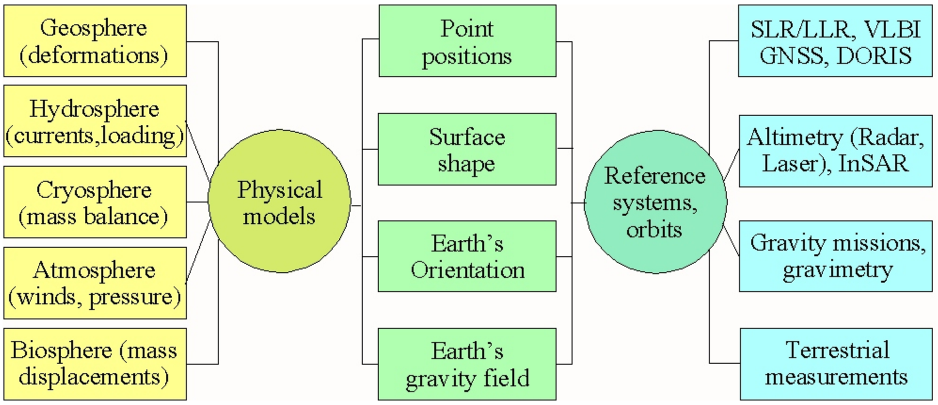


Fig. 3.3.1: Relations between signals of the System Earth and geodetic observations

The integration of all elements and all observation data is a basic requirement for the correct representation of the properties and processes of the System Earth. If we model the individual elements separately, the estimated parameters may be incorrect due to the effects of signals from other elements, which were not modelled. If we model the elements by one observation type only, the properties and processes may be represented incompletely or wrong, because important information from other measurements is missing. In the following, we'll discuss some mutual affects by examples.

3.4 Interrelations between Earth signals and geodetic parameters

Signals in the solid Earth are produced, e. g., by mantle convection, plate tectonics, earthquakes, volcano eruptions and isostatic compensation processes. In the hydrosphere and cryosphere, we receive signals from the complete water cycle by precipitation, evaporation, surface flow-off, and melting of ice masses. The atmosphere affects geodetic observations and parameters, e. g., by the water vapour, air pressure, winds and ionised layers. Mass displacements in the biosphere are mainly caused the varying vegetation, principally in seasonal cycles. On the one hand, the processes affect the measurements directly, e. g., by refraction and acceleration of instruments. On the other hand, they change the parameters, e.g., by point movements, sea surface variations, gravity changes, polar motion and variations of the rotational velocity (length of day).

Tab. 3.4.1 shows examples of how the different processes of the solid, fluid and gaseous elements of the Earth System are acting and which geodetic parameters they affect. It is obvious that the same processes act on several parameter groups by different effects. As a consequence, we may not attribute an individual process to a single effect, but all the geodetic quantities are concerned. Thus we have to include all the geodetic observations and parameters into the modelling of the geophysical processes. Vice-versa, the geodetic observations are affected by several phenomena and processes simultaneously. Tab. 3.42 shows that variations of the individual geodetic parameters may not be explained by a single process. The complete System Earth has to be considered, e. g., all the system elements have to be included into the modelling of the processes and the parameter estimation. By this means, we get a complex system of observations and parameters to be integrated into one consistent modelling.

Table 3.4.1: Examples of geophysical processes affecting different geodetic parameters

Process	acts as	and affects
Core/mantle convection	**- plate driving force** **- mass displacement** **- angular momentum**	**- point position** **- gravity field** **- Earth rotation**
Precipitation	**- ground water storage** **- moment of inertia** **- water flow off**	**- gravity field** **- Earth rotation** **- sea surface**
Atmospheric and oceanic currents	**- loading force** **- pressure** **- angular momentum**	**- point position** **- Earth surface** **- Earth rotation**

Table 3.4.2: Examples geodetic parameters affected by different geophysical processes

Parameter	**is affected by**	**of processes in**
Point position	- plate motion - loading effects	- solid geosphere - ocean, hydro-/ atmosphere
Earth surface	- deformation - water flow-off - air pressure	- solid geosphere - hydrosphere - atmosphere
Earth rotation	- winds, pressure - ocean currents - deformation	- atmosphere - hydrosphere - solid geosphere
Gravity field	- geodynamics - ground water - deformation	- geosphere - hydrosphere - solid geosphere

3.5 Integration of geometric and gravimetric techniques

Most processes of the System Earth produce geometrically as well as gravimetrically observable effects. The results of both types of measurements have therefore to be included into the parameter estimation simultaneously. This is usually done by combination in a common processing algorithm. The most important observations are at present those of the geodetic space techniques and missions:

- Global Navigation Satellite Systems (GNSS),
- Satellite and Lunar Laser Ranging (SLR, LLR),
- Very Long Baseline Interferometry (VLBI),
- Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS),
- Satellite Radar- and Laser Altimetry (e.g., Jason, ENVISAT, GFO, ICESat),
- Interferometric Synthetic Aperture Radar (InSAR),
- Challenging Minisatellite Payload Mission (CHAMP),
- Gravity Recovery and Climate Experiment Mission (GRACE).

The scientific services of the International Association of Geodesy (IAG) are currently combining these observations for parameter estimation. They are the International GNSS Service (IGS), the International Laser Ranging Service (ILRS), the International VLBI Service for Geodesy and Astrometry (IVS), the International DORIS Service (IDS) and the International Earth Rotation and Reference Systems Service (IERS):

- Point positions and velocities are computed by combination of the different geometric techniques (GNSS, SLR/LLR, VLBI, DORIS). This is done by the corresponding services (IGS, ILRS, IVS, IDS) and by the Combination Centres of the IERS for the International Terrestrial Reference Frame (ITRF, e. g., Altamimi et al. 2002, Angermann et al. 2004, Drewes et al. 2006).

- The Earth's surface and its deformation are determined above the oceans by combination and cross calibration of different satellite altimetry missions above the oceans (e. g., Bosch 2003). Above continents combined InSAR and GNSS measurements are used (e. g., Delouis et al. 2000).

- The orientation of the Earth in space and variations of the Earth's rotation are derived by combining geometric observations similar to the point positions (e. g., Gambis 2004). Variations of the angular momentum by movements of masses in the atmosphere and oceans are computed by coupled models (e.g., Seitz et al. 2004).
- Parameters of the Earth's gravity field are determined globally by combining spaceborne, airborne, sea and terrestrial gravimetry (e.g., Kern et al. 2003).
- Regional densifications are mainly done by airborne and terrestrial measurements.

There are, however, some shortcomings in the combination procedure. Identical constants, conventions and models are not always applied; e. g., the IERS Conventions (McCarthy and Petit 2004) and the Geodetic Reference System 1980 (GRS80, Moritz 2000) are sometimes not followed completely. The estimated parameters often already differ in their definition, causing different results. As an example we mention non-linear point velocities, which may be estimated as pure mathematical functions or dependent on physical effects (e. g., pressure loading). The reference systems are not always identical either. The definition of the actual reference frames for geometry (ITRF, McCarthy and Petit 2004) and gravimetry (IGSN71 and absolute gravity measurements, Torge 1989) differ by the reduction or non-reduction of the permanent tides (tide-free or zero-tide, respectively). Furthermore, not all computations done today are at the latest state of science, e.g., because the software used has not been updated.

The joint combination of geometric and gravimetric data is rarely fully executed. Normally the effects of the respective other technique are considered by specific models or reduced from the observations. For point positioning, as an example, we generally use a static gravity field model, although we want to detect deformations that cause gravity variations. In the same way, we normally do not consider the non-linear motions of the tracking stations for determining gravity field parameters or sea surface variations, respectively, from satellite orbits, although we want to model, e.g., seasonal gravity field or sea level variations.

The rigorous integration of observations by combination requires a consistency of measurements, constants, models, reference systems, processing methods and estimated parameters. Only if complete compatibility is guaranteed we can provide reliable results that fulfil the high requirements for the representation of the complex phenomena and effects of the processes in the System Earth.

3.5.1 Consistent measurements

The basis of nearly all observations in modern geodesy is time measurement (travel time of electromagnetic signals, epoch time). The requirement for consistency of measurements therefore implies identical time systems (atomic time TAI, geocentric time TCG, epoch time UT1). Travel time measurements in a medium (atmosphere) have to be reduced in the same way for physical effects (atmospheric refraction, environmental and instrumental effects). All the observations at the same site have to refer to a precisely defined reference point. The relation between geometric and gravimetric reference points has to be known exactly (local time measurements) and all relevant information about the measurements has to be documented and provided together with the observation data (meta data).

3.5.2 Consistent constants, conventions, models

The fundamental constants, conventions and models of geodesy have been discussed intensively in the past. A change of the Geodetic Reference System 1980 (GRS80) and of the corresponding resolutions of IAG, however, has not been considered necessary (e.g., Groten 2004), although there are discrepancies with respect to other definitions (e.g., in the IERS Conventions) and the frequent use by some individuals or groups of scientists and scientific services. The common practice in geometric coordinate determination to reduce the permanent tides from the parameters (tide free system) is in contradiction to a resolution of IAG in 1983. Gravity field parameters are in general computed without this reduction (zero tide). In this case, we may not use the fundamental relation $h – H = N$ between ellipsoidal heights h derived from ITRF coordinates, orthometric heights H from gravimetrically reduced spirit levelling, and geoid heights N taken from those gravity field models.

The Love numbers normally used for transformation of gravity changes and loading into deformations are quite uncertain for lower frequencies. For mass reductions, the crust density is generally used (2,67 g/cm^3), which is not consistent with common geophysical models (2,6 g/cm^3 in PREM, Dziewonski and Anderson 1981). The reduction of tropospheric refraction is done by different mapping functions from vertical to slant lines.

3.5.3 Consistent reference systems

Geometric and gravimetric reference systems may be defined and realized by different parameters. The geodetic datum of a system is always defined, it cannot be observed or estimated directly. The origin of a three-dimensional geometric coordinate system is given by the coordinate values X0, Y0, Z0; the origin of a gravimetric system, e.g., by the coefficients C10, C11, S11 of the spherical harmonic expansion of the Earth gravity field. Using a gravity field model with C10 = C11 = S11 = 0 for satellite orbit determination always implies an origin of the coordinate system in the centre of mass of the Earth (geo-centre). The derived geometric coordinates (positions) of terrestrial stations are then automatically geo-centric. There is no degree of freedom for variations of the geo-centre or the origin. The effects derived from station coordinate variations, often referred to as geo-centre variations, are in fact the average motions of the reference network.

The same holds true for the orientation of the coordinate system, which is given geometrically by the position of the Earth rotation pole (XP, YP) and the time difference UTC-UT1, and gravimetrically by the coefficients of degree two of the spherical harmonic expansion of the Earth gravity field (C21, C22, S21, S22). It’s worthy to remark that in geodesy, the pole position is not defined physically (direction of the axis of maximum inertia corresponding to S21) but by convention (evolution of the position in the BIH system of 1984). Geometrically determined variations of “Earth rotation” are in fact rotational changes of the reference network of observation stations. Because of network deformations, these do not necessarily have to be identical to changes of the axis of maximum inertia, which may be determined from models of mass displacements. Finally, the scale of coordinates is derived geometrically from the speed of light and gravimetrically from the geocentric gravitational constant (GM). These two have also to be kept consistent.

3.5.4 Consistent processing methods and algorithms

Geodetic parameters may be estimated consistently if the processing methods and algorithms are fully compatible. Parameters and residuals, for example, are treated differently when using least squares adjustment methods or filter techniques, respectively. If solutions shall be combined they must not be deformed internally, e. g., by over-constrained datum parameters. Free normal equations in adjustment procedures must have a rank defect with respect to the datum (seven in three-dimensional stationary networks). Most discrepancies between different types of observations are caused by systematic errors. Therefore one should use robust estimators. One of the biggest problems in combination is the weighting. The variance-covariance estimation must be done in a strict way.

3.5.5 Consistent parameters

Physical effects may be estimated as parameters or reduced from the observations, if they are of no use in the further processing (e. g., refraction, tides, loading effects). They should be reduced only if the error of reduction is negligible with respect to the accuracy of the measurements. Identical models of reduction have to be used for the different types of observations. Loading effects may serve as an example: Sometimes they are reduced, sometimes they are included in physical models (e. g. ocean loading), and sometimes they are estimated as parameters (e. g. deformation due to atmospheric loading). Effects may also be transferred between parameters. Troposphere parameters and station heights, for example, or station velocities and Earth rotation parameters, respectively, are highly correlated. If one parameter is modelled and the other estimated, model errors enter into the estimated values.

3.6 Conclusions

The objectives of geodesy as an Earth science have extended to the observation and analysis of phenomena and effects of processes in the System Earth. The fundamental observation types and methods of data processing are widely taken or derived from the classical approaches. The new challenge is the combination of heterogeneous geometric and gravimetric data in a common consistent procedure, which has to be modified to match a physical model as closely as possible to reality, in order to allow geophysical analyses and interpretations. The Global Geodetic Observing System (GGOS) of IAG shall provide the basis for that (Drewes 2006).

4 Requirements for a Geodetic and Geohazard Observation System

4.1 Introduction

The fundamental basis for a geodetic and geohazard observing system is a uniform terrestrial reference frame, which must be realized for geometry and global gravity field models with the highest accuracy, spatial and temporal consistency and stability over decades. In the first part of this chapter general requirements for a global geodetic observing system are provided, followed by specific requirements from various applications.

4.2 General Requirements for a Global Observing System

Global observing systems like GGOS form the basis of a comprehensive monitoring of the Earth system. Taking into account the nature of the task, a sustainable monitoring requires

- long-term stability
- operational mode
- homogeneity in time
- multi-parameter sites
- global coverage and participation
- often low latency (data provision in near real time or real time) and
- integrated observation and data sets.

The accuracy level targeted by GGOS for the three fundamental geodetic quantities (geometry and kinematics, Earth orientation and rotation, and gravity field and its variability) is 10^{-9} or better.

4.3 Specific Requirements From Various Applications

4.3.1 Climatologically Induced Mass Transports

Simultaneous and complementary observations from a multiple of geo-scientific and environmental near-Earth orbiting satellites enable to contribute significantly to the understanding of global Earth dynamics. The key parameters are of physical and geometric nature and allow, when combined, an enhanced modelling of the mass distribution and mass transport within the Earth, at the Earth's surface and its envelope. The knowledge of the Earth's mass distribution and redistribution is of crucial importance for the exploration of geodynamic, convective and climatologically driven processes within the Earth system. The temporal scales addressed by these processes range from sub-seasonal and interannual to decadal and secular variations on a global to regional spatial scale.

Table 4.3-1 and Table 4.3-2 list the requirements for static and time variable gravity field signal components. The necessary observables can be provided by dedicated satellite gravity field missions based on the satellite-to-satellite tracking principle (e.g. GRACE) and of satellite gravity gradiometry (like GOCE). Further data comes from precise tracking of these satellites by means of GNSS (Global Navigation Satellite Systems: GPS, GLONASS, later GALILEO) and from altimetric Earth observing missions (ICESAT, JASON, ENVISAT, later CRYOSAT-2, JASON-2).

Prerequisite for a consistent use of satellite data is a precise geodetic-geodynamic reference frame as well as improved computation standards.

Table 4.3-1: Static gravity field requirements for mass transport and mass distribution modelling.

Application		***Accuracy***		***Resolution [km half-wavelength]***
		geoid [cm]	***gravity [mGal]***	
ocean circulation and transport	short scale sea surface topography	1		100
	basin scale sea surface topography	0.1		1000
ice dynamics	rock basement		1	50
	ice height reference	1		100
Earth mantle and crust	crust and lithosphere structure, plate boundaries	10	1	50
	mantle convection	10	1	200
	mantle plumes	10	1	50
	sublithospheric convection, oceanic astenosphere	10	1	100
geodesy	unified height systems, tide gauges	1		100
	GPS levelling	1		100
	orbits (LEO)		0.01	200

Table 4.3-2: Requirements for time variable gravity field signal components. (Secular signal amplitudes are given in mm/yr, µm/yr or µGal/yr. Amplitudes referring to other time periods are given in mm or µGal.)

Application		***Amplitude***		***Spatial scales (km)***	***Main periods***
		geoid	***gravity***		
ocean circulation and transport, sea level	ocean currents, deep circulation, eddies, sea level	10 mm	10µGal	30-5000	(sub-)seasonal to interannual
		0.01 mm/yr		1000-5000	secular
ice	ice sheet mass balance	1 mm	1µGal	100-4000	(sub-)seasonal to interannual
		0.01 mm/yr		5000	secular
Earth mantle and crust	glacial isostatic adjustment	1 mm/yr	1µGal/yr	500-10000	secular
	mantle plumes, slabs	1 µm/yr	0.01µGal/yr	100-2000	secular
	tectonics, orogens	1 µm/yr	1µGal/yr	100-2000	secular
continental hydrology	water storage, evapo-transpiration, runoff, exchange with oceans	10 mm	10µGal	100-5000	some weeks to interannual
atmosphere		10 mm	10µGal	50-5000	annual, seasonal, daily, others
tides	solid Earth and ocean tides	1000 mm	100µGal	10-10000	daily, semi-daily, semi-monthly

4.3.2 Geodynamics

Precise observations of the Earth surface - land and ocean - are important inputs for the improvement of geodynamical Earth models. Contributing observation techniques include the geometrical measurements of the Earth crust with space-based techniques (GPS, SLR, VLBI), measurements of the ocean surface (radar altimetry, tide gauges), ground-based gravimetrical observations as well as space-based observations of the gravity field.

A list of effects and the required accuracies for the geoid and the gravity field are already given in Tables 4.3-1, 4.3-2 and should be not repeated here.

Measuring sea level variations with radar altimetry and tide gauges and modeling the associated effects by ocean circulation models is the primary means to derive consistent statements about regional and global sea level change patterns. The altimeter measurements should have an accuracy below a few centimetres without any significant trend bias to be able to derive accuracies of less than 1 mm/y over decades. The tide gauges have to be combined with continuous GPS benchmarks to derive absolute sea level change records with high resolution and long history. For that purpose the trend in the vertical GPS position must have an accuracy of clearly less than 1mm/y.

A variety of geodynamical effects is connected with changes on the Earth crust:

- Plate tectonics
- Post-glacial rebound
- Loading effects (ocean, atmosphere, ground water, snow)
- Seismic events
- Volcano dome effects

They cover a broad range of effects with various spatial (local, regional, global) and temporal (constant velocity, inter-annual, annual, sub-daily, sub-second) resolutions and are either steady processes or sudden events.

Plate tectonics (global, regional, plate boundary zones) and post-glacial rebound - being steady and slow processes - can be described by daily or weekly mean station positions. This includes also the special silent Earth quake effects. However, the loading effects have to be monitored with a sub-daily resolution. An important aspect of the loading models is the connection to changes in the geocenter and by this also to the absolute station heights needed for sea level monitoring and post-glacial rebound. For all those effects an accuracy of 1 mm in the horizontal and a few mm in the vertical component is required allowing finally to derive velocity accuracies of much better than 1 mm/y based on a reasonable long time series. A long-term stability (over decades) of the underlying reference frame is a prerequisite for geodynamical studies (see 5.1.2). The monitoring can be performed in a post-processing regime.

Much higher frequencies (1 to 50 Hz) are required for monitoring the behaviour of the Earth crust in case of seismic events. From the study of seismic disturbances of the crust over larger regions with GPS (GNSS) networks and of seismic waves in the affected region, and even in the far-field, the existing models can be improved.

Continuous monitoring of volcano domes can be done with different techniques, among them continuous GPS. The dome behaviour can be monitored with a medium (30 s) to low (daily) time resolution.

As soon as the monitoring of seismic zones and volcanoes are part of geohazard systems real-time high-frequency data streams are needed and the associated real-time analyses have to be performed (see separate description in 4.3.5).

4.3.3 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 a 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 greatly eases the surveying tasks and reduces 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. For a surveying method that measures coordinates relative to neighboring markers of the national geodetic reference frame it is sufficient that the coordinates of these points can be kept fixed.

The markers have to have coordinates with sufficient precision, and the deformations in the reference frame have to 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 be able 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, the relative precision over short distances is important. For surveys of larger areas and across country borders, the accuracy is more important.

The requirements for the reference frame also depend on the 'observation method'. For most surveying, *ad hoc* 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 *ad hoc* coordinates given in ITRF to national coordinates, a detailed knowledge of the velocity field of the Earth's surface with an accuracy better than 1 mm/yr is required. An error of 1 mm/yr introduces already an error of 1 cm in *ad hoc* positions over 10 years. In some regions, plate tectonic models provide a first order approximation to the horizontal velocity field. 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 in most areas.

The choice of the observation methods determines to what extent the 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 *ad hoc* 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.

4.3.4 Navigation and Real-Time Positioning

The present satellite navigation is based on GPS broadcast orbits and clocks, which have not sufficient precision for sub-meter positioning. Therefore differential techniques and augmentation systems (like EGNOS) were implemented to achieve the required accuracy by computing correction terms via reference stations.

For the ease of real-time positioning it would be interesting for many applications to use a so-called precise point positioning technique, which is not depending on a second nearby GPS reference receiver like in the differential mode. The Galileo system will already provide a global (non-differential) service with 60 cm accuracy with imbedded integrity, but there are applications, which need even higher precisions.

The geodetic community would be able to provide precise, globally valid orbits (<10 cm) and satellite clocks (<1 ns) capable of real-time precise point positioning with sub-decimeter accuracy for non-safety-of-life applications like (accuracy level given in parenthesis):

- Agriculture (10 cm)
- Snow cleaning (few cm)
- Monitoring of oil platforms (cm)
- Construction work (sub-cm)
- Maintenance (sub-cm)

Using the present IGS products precise point positioning can already achieve accuracies of a few mm and 1 cm in the horizontal and vertical component, respectively, in a post-processing mode using long observation sessions.

4.3.5 Contributions to Geohazards

Geological and geophysical hazards have a tremendous impact on society. Every year volcanoes, earthquakes and landslides claim thousands of lives, injure thousands more, devastate homes and destroy livelihoods. These geohazards are driven directly by geological processes involving ground deformation and mass transfer. For this reason, there is an obvious and crucial contribution from Geodesy to the study of geohazards.

There are several reports and publications available that assess the current state and identify deficiencies in the study of geohazards. Most notably, the Geohazards theme group of the Integrated Global Observing Strategy Partnership (IGOS-P) issues yearly reports on the subject (Marsh et al., 2004), and the ad hoc Disaster Management Support Group (DMSG) of the Committee on Earth Observation Satellites (CEOS) delivered a report in November 2002 on the utilization of existing and planned Earth Observation (EO) satellite data (CEOS, 2002). These two documents are the basis and starting point for the fraction of the present report dealing with geohazards. However, to the best of our knowledge, there has been no similar initiative focusing on the role of geodetic methods for the monitoring and analysis of geohazards, despite the key function of Geodesy in the study of such phenomena.

All geohazards involve ground deformation, so that to a certain extent similar modelling and observational techniques can be used to address all of them. Ground deformation associated to geohazards spans very different time-scales and ranges several orders of magnitude. It can be sudden, for catastrophic events like landslides, more gradual, due to processes such as the inflation of a volcano during recharge of its magma chamber, or ongoing, as in the motion of

Earth's crustal plates that leads to the build-up and release of strain during earthquakes. Motion can be on the scale of kilometres, in the case of major landslides or lava flows, metres, which is typical of many earthquakes, and millimetres, as found for the steady growth of a lava dome on a volcano or for silent earthquakes. All these motions can be in either horizontal or vertical planes and occur over a period of days, months or even years. Also, there is good evidence that small motions are the precursor to more significant events and so they must be monitored, for all the geohazards, as a first step towards forecasting hazard events. In addition to deformation, physical processes in the eruption cycle often involve mass transfer, and can therefore be studied by means of gravity change measurements.

Table 4.3-3 summarizes the requirements for the parameters observed when addressing earthquakes, volcanoes and landslides. For each observable, there are different requirements as to accuracy, frequency, latency, the frame at which they are to be carried out and its reproducibility (the latter understood as the time window over which the parameters are expected to be reproducible with the stated accuracy).

In the case of earthquakes, the requirements depend on the phase of the seismic cycle to be studied. The slow steady deformation taking place due to tectonic loading can be observed by means of yearly campaigns, carried out in a wide frame possibly involving several countries (e.g. Klotz et al., 2001). When an earthquake occurs, the co-seismic displacement has to be documented, usually by a one-time campaign as soon after the event as possible. After the main shock, several post-seismic processes can be observed, ideally by continuously recording stations during several months to years (e.g. Bürgmann et al., 2002). Also, recent studies show the possibilities of using 1 Hz GPS data for recording the dynamic signal of a rupture (e.g. Larson et al. 2003), although this kind of observations poses strong requirements. Such measurements could be useful to obtain a fast estimate of the magnitude of a strong event.

The requirements for the observation of deformation associated with volcanic processes are very similar to that of post-seismic deformation. In general, continuous measurements are needed, with a latency of no more than a few minutes. Gravity changes should be measured by at least one campaign a year.

In the case of landslides, the speed of motion may vary by several orders of magnitude, from motions of millimetres per year to metres per second. Since the speed of the motion varies with time a monitoring as continuous as possible is required with, in many cases, mm-level accuracy.

Table 4.3-3: Requirements for the parameters for geohazard observation.

Application	*Accuracy*	*Frequency*	*Latency*	*Frame*	*Reproduc.*
Tectonic loading, inter-seismic deformation	~ 1 mm ~ 1 mm/a	months to years	post-processing	national to global	years to decades
Co-seismic deformation	~ 1 mm	once	n/a	local to regional	decades
Post-seismic deformation	~ 1 mm/a	0.1 – 0.01 Hz	minutes	local to regional	decades
Dynamic deformation	~ 1 mm	1 – 10 Hz	minutes	global	years
Ground deformation	1-5 mm	0.1 – 0.01 Hz	minutes	local	decades
Gravity variation	1 μGal	months to years	post-processing	local	decades
Volcanoes and landslides	~ 1 mm/a	hours to days	hours to days	local	n/a

Both ground-based and satellite-based techniques are used to measure ground displacements and monitor deformation. Increasingly, GPS networks, whether regional or local, are the core of deformation monitoring, especially over large areas. The global geodetic infrastructure is provided by a combination of GPS, Very Long Baseline Interferometry (VLBI), and Satellite Laser Ranging (SLR), which together form the basis for the precise International Terrestrial Reference System (ITRS). Dense regional networks, such as the Plate Boundary Observatory (PBO) network in the USA and the similar GPS Earth Observation Network (GeoNet) in Japan, already exist and demonstrate the value of such systems. They offer high accuracy and continuous observation, but they require the installation and maintenance of permanent stations and provide monitoring only at installation points. Although GPS networks are in place at a number of volcanoes, older techniques, including tilt, levelling, Electronic Distance Measurement (EDM), gravimetry or strain measurements are still performed in many active volcanic areas and successfully provide complementary information.

For volcano, landslide and earthquake deformation monitoring it may be of crucial importance to obtain surface deformation with a high spatial resolution and accuracy (and not just individual points an in the case of, e.g., GIS). Interferometric Synthetic Aperture Radar (InSAR) is nowadays a powerful technique to complement other observing techniques (see next section) in this domain.

Although in most of the cases it is enough to measure the relative deformation associated with geohazards, an absolute reference frame is fundamental for the coordination of efforts. Seismically active areas, as well as volcanoes, are often monitored by different countries or institutions, therefore the need for a common reference system to allow the integration and comparability of different results. Similarly, a key question is the accessibility of the data. Measurement campaigns and instrumentation are commonly financed by public funds. For this reason, it seems logical that the resulting measurements should be validated and available for the general use after a reasonable period of time.

4.3.6 Man-Made Hazards

Soil subsidence is a major man-made hazard caused by groundwater, oil, and gas extraction as well as mining activities. Man-made 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, land- and rockslides due to the effects of roads, railroad tracks, tunnels and buildings on the ground stability.

Man-made hazards can lead to considerable damage of property, and in the case of landslides, induced earthquakes, and flooding, also to loss of life. Abundant examples of damage to buildings and roads in areas with excessive groundwater extraction or the lowering of the groundwater level for mining purposes have demonstrated the potential hazards.

Man-made geohazards (subsidence, earthquakes, land- and rockslides) are associated with surface deformations which can be monitored with GPS/GNSS and InSAR. Precarious rocks and areas of potentially instable ground cause recurrently disasters in many countries, often after human interference with the topography. In many areas, steep hill sides are potentially a thread for the people living at the base of these slopes or infrastructure built at the bottom of such hills. In many areas, slow landslides pose a problem, too.

In knowingly instable areas, networks of campaign-type or permanent GPS/GNSS stations can be used to indicate a change in the motion and thus indicate a potentially perilous 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 is expected to play a leading role in the detection of geohazards and the monitoring of hazardous areas. InSAR has been successfully applied to, e.g., mapping the co-seismic displacements, deformations at volcanoes, silent landslides and man-made subsidence. In particular, the combination of permanent GPS stations with InSAR is expected to improve the resulting time series of deformation considerably.

In coastal areas, man-made subsidence can combine with local sea level changes and constitute a severe threat to the coastal population and infrastructure. For example, 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. In the city of Venice and the Lagoon, pumping of groundwater during the first half of the 20th century led to significant man-made subsidence, which was superposed on a natural subsidence of the lagoon due to tectonic and sediment processes. There, InSAR in combination with GPS allows the monitoring of the present-day subsidence, revealing a large spatial variability in subsidence caused by natural processes and still on-going man-made processes.

The monitoring of man-made 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.

4.3.7 Climate Monitoring and Weather Predictions

The Earth's atmosphere and ionosphere significantly influence the propagation of radio waves. This fact degrades the performance of Global Satellite Navigation Systems (GNSS), but offers also a unique potential for a precise and permanent all-weather monitoring of properties of the neutral and ionized part of the Earth's atmosphere on a global scale. This potential which allows various applications in weather forecast, climate research and space weather monitoring is currently more and more recognized by atmospheric scientists.

Global and regional densified ground networks form, together with constellations of GNSS-receivers aboard LEO satellites, already a geodetically based observing system for the Earth's atmosphere/ionosphere. Fig. 4.3.7.1 gives an overview of the various GNSS-based remote sensing techniques. These are: space-based GNSS radio occultation/reflectometry aboard LEO satellites, ground-based determination of the vertically integrated water vapour (Integrated Water Vapour Profile - IWVP) and the Total Electron Content (TEC) using global and regional densified GNSS ground networks, scatterometry and topside ionosphere monitoring.

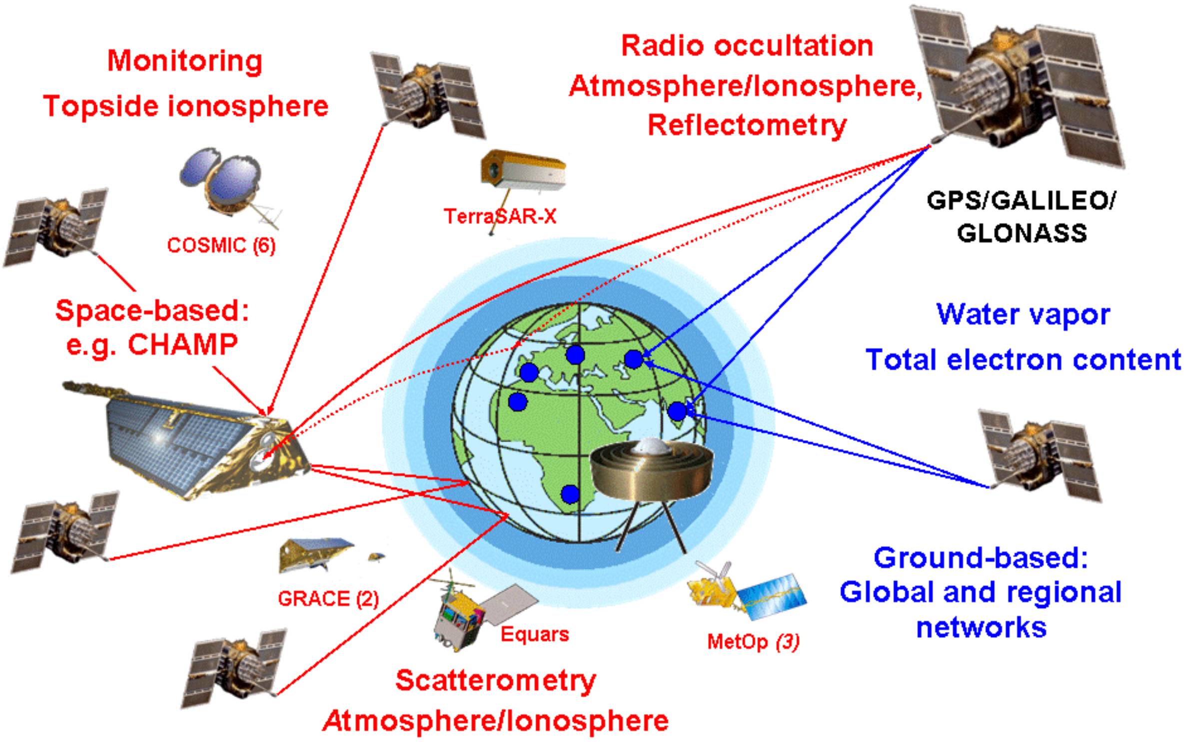


Fig. 4.3.7.1: Components of a geodetic based system for precise remote sensing of the Earth's atmosphere and ionosphere on a global scale. The system consists of global and regional densified networks of GNSS receivers and a constellation of LEO satellites with GNSS receivers aboard (from Wickert et al., 2006).

Ground-based techniques have a longer tradition compared to space-based (e.g. Davies, 1980 or Bevis et al., 1992) and are operationally applied to monitor IWVP and TEC (see, e.g., Jakowski et al., 2005; Gendt et al., 2004). Currently ground station data of the global IGS network and several national networks are used for an operational derivation of the vertical integrated parameters with accuracies of, e.g., ~1 mm for the vertical integrated water vapor. In many cases near-real time provision of the analysis products is demonstrated, which fulfils already the requirement of max. 1-2 h latency for the assimilation to regional weather forecasts (e.g. Gendt et al., 2004). Various impact studies demonstrated already positive influence on regional weather forecasts (e.g. Reigber et al., 2002).

Precondition for the application of space-based techniques is the existence of appropriate satellite configurations with specified GNSS receivers aboard. Before 2006 only the German CHAMP satellite provided GNSS occultation data continuously (~200 globally distributed profiles per day), supplemented since 2006 by GRACE occultations (see, e.g., Wickert et al., 2005). The situation significantly improved by the launch of the six COSMIC/FORMOSAT-3 (launch in April 2006; see, e.g. Lee et al., 2000) and the first Metop satellite (launch in October 2006). As a consequence, the number of operationally available occultation measurements increased significantly to ~2000 measurements daily.

Occultation data provide information on the vertical structure of atmospheric and ionospheric parameters, as, e.g. refractivity, temperature, water vapor or electron density on a global scale and are therefore perfectly suited to provide input information for the improvement of global weather forecasts, as base for climate change studies and to monitor space weather effects (Kursinski et al., 1997).

The high quality and information content of the occultation data was proven by first impact studies to improve global numeric weather forecasts at the Met Office and the ECMWF (e.g., Healy and Thepaut, 2006). Despite of the fact that a fairly small number of CHAMP observations was available per assimilation cycle a clearly positive effect could be proven on the forecasts. These results are extremely remarkable, because, e.g. for the ECMWF study, in parallel to the low number of ~80 global CHAMP measurements more than 3 million other data were assimilated in 12 h. Consequently a low number of measurements generated large impact, which proves their potential for significant improvements of numerical weather predictions. The requirement for the occultation data to be assimilated is set by the WMO guidelines, which demand a maximum delay of 1-4 h for global forecasts (WMO TD No. 913, SAT-21, 28/9/1998).

Major advantages of the GNSS radio occultation technique for the detection of climate trends in relation to other remote sensing methods are: self-calibrating technique, global and evenly distributed coverage of the measurements, high vertical resolution and weather-independence. GNSS radio occultation is capable to monitor atmospheric temperature trends of ~0.1 K/decade, which is equal or smaller than the expected trends due to the increase of greenhouse gases, which range from +0.1 K/decade in the troposphere to -0.5 K/decade in the upper stratosphere (Hoeg et al., 1995).

An overview of the application of space-based GNSS ionosphere sounding techniques is given by Jakowski et al. (2005). The authors focus on ionosphere radio occultations and the top-side ionosphere imaging using the navigation data from CHAMP.

Other innovative GNSS techniques for atmosphere/ionosphere remote sensing are based on the detection and analysis of GNSS signals reflected from sea or ice surfaces. They allow for the calibration-free determination of sea level changes (relevant for climate change detection) and significant wave heights. The ocean wave spectra can be correlated with wind velocities and directions (e.g., Komjathy et al., 2000). The application of reflected GNSS signals for ocean altimetry was first discussed by Martin-Neira (1993) and demonstrated since then within a number of aircraft and balloon experiments using dedicated GNSS receivers (see e.g. Garrison et al., 2002). Another potential application of GNSS reflections is the derivation of the ionospheric delay in altimeter measurements from satellites. These data can, e.g., be assimilated into global ionospheric models (see, e.g., Katzberg and Garrison, 1996). Signatures of reflected components were also detected in GNSS radio occultation data from GPS/MET and CHAMP (e.g. Beyerle et al., 2002), atmospheric properties at the location of the reflection point were derived, as, e.g., specific humidity (GNSS-Reflectometry).

It can be concluded that GNSS reflectometry/scatterometry has a great potential for a global monitoring of sea surfaces and also of atmospheric/ionospheric properties.

4.3.8 Control of Processes and Positioning

Highly accurate positioning of sensors, for example for airborne gravimetry and hydrographic surveys, requires 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, it also requires 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 oil fields 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, geo-databases 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 over many years to come. Even without assuming 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 for example in agriculture, construction work and maintenance. For all these applications, a high accuracy of 10 cm (for most agricultural applications) down to 1 cm (for snow clearing) and even sub-centimeter (for construction work) is required in real time. Currently, for all these applications, local augmentation systems have been set up. However, improved satellite orbits and clocks made available in real time will allow to base many of these applications on GNSS and *ad hoc* positioning (also called precise point positioning: PPP).

4.3.9 Monitoring of Infrastructure

Increasingly, GPS combined with the IGS products (denoted here as 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 man-made subsidence, volcanic eruptions) , 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 unanimously and the optimal reference is a regional or even global network.

Experience with oil platforms shows that user requirements for monitoring of such infrastructure are of the order of 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 bridges; however, here the tolerable latency may be much lower.

One task in monitoring the motion of oil and gas platforms is the measurement of the settlement of the platform into the supporting ground, where a long-term stability of the order of 1 mm/yr is required over several decades. 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 PPP, velocities can be determined on the basis of a moving window. For that, requirements in terms of velocity are on the order of a few mm/yr on time scales of months to years.

4.3.10 GEO and IGOS-P

The main purpose of the Intergovernmental Group on Earth Observation (GEO), which integrates about 70 member countries and 50 participating organizations, is the implementation of the Global Earth Observation System of Systems (GEOSS) with the vision to realize a future wherein decisions and actions for the benefit of humankind are informed by coordinated, comprehensive and sustained Earth observations and information. IAG is a participating organization, and GEO has included in its Work Plan for 2007-2009 its specific Task AR-07-03 "Ensure the availability of accurate, consistent, homogeneous, long-term stable, global geodetic reference frames as a mandatory framework and the metrological basis for Earth observations."

The work to be performed in this task is described as follows:

- User requirement coordination: Establish a comprehensive GEOSS database of user requirements concerning georeferencing and geodetic reference frames by identifying, describing and establishing links to relevant user communities in the nine societal benefit areas and conducing appropriate surveys. This includes the individual steps:
    - Identify relevant user groups in the societal benefit areas, including groups of users relevant for several benefit areas, and create a matrix of users, groups of users and benefit areas.
    - Identify and quantify the requirements of the nine benefit areas with respect to georeferencing and access to a long-term stable reference frame.
    - Facilitate an assessment of the current status and future requirements for the geodetic reference frames and geodetic observations with particular focus on the needs of the nine benefit areas.
    - Identify user-oriented capacity building needs within the different user groups with respect to reference frames.
    - Establish links between representatives of the different user groups within the nine benefit areas and an appropriate expert team to coordinate georeferencing and reference frame issues across these areas.
- Georeferencing: Ensure the availability of appropriate global geodetic reference frames for GEOSS. This includes the individual steps:
    - Identify steps towards ensuring consistent, high-accuracy, homogeneous, and long-term stable global geodetic reference frames for Earth observation and the observing systems contributing to GEOSS.
    - Advocate the continuous support of the global geodetic infrastructure required for the maintenance and development of the global geodetic reference frames at an appropriate level.
    - Critically assess the sustainability of the global geodetic infrastructure and the Services, which are currently based on: the voluntary commitments of a large number of national agencies, research institutions, and individuals, and consider alternative organizational models, including an intergovernmental framework for the maintenance of the geodetic reference frames, which would support the transition to fully operational reference frames.
    - Consider the potential of regional organizations to address reference frame related challenges in their regions and to stimulate cross-disciplinary solutions.

- Promote the establishment of sufficient geodetic infrastructure in regions currently lacking such infrastructure, particularly in Africa and parts of Asia and Latin America.
- Improve the accessibility and applicability of the geodetic reference frames for all GEOSS components.

The output and deliverables are defined as:

- To prepare a strategy report on “The Global Geodetic Observing System: Meeting the Requirements of a Global Society on a Changing Planet in 2020” (denoted as GGOS 2020) as input to the GEO Plenary.
- The definition of the GGOS Data Portal to be based on user requirements and to be designed as an important link to the identified user groups.
- To organize a Workshop on this topic.

The Integrated Global Observing Strategy (IGOS) seeks to provide a comprehensive framework to harmonize the common interests of the major space-based and in-situ systems for global observation of the Earth. It is being developed as an overarching strategy for conducting observations relating to climate and atmosphere, oceans and coasts, the land surface and the Earth's interior. IGOS strives to build upon the strategies of existing international global observing programmes, and upon current achievements. It seeks to improve observing capacity and deliver observations in a cost-effective and timely fashion. It may be characterized as follows:

- IGOS is a strategic planning process, involving a number of partners, that links research, long-term monitoring and operational programmes, as well as data producers and users, in a structure that helps determine observation gaps and identify the resources to fill observation needs.
- IGOS is a framework for decisions and resource allocation by individual funding agencies, providing governments with improved understanding of the need for global observations through the presentation of an overarching view of current system capabilities and limitations - thereby helping to reduce unnecessary duplication of observations.
- IGOS focuses primarily on the observing aspects of the process of providing environmental information for decision-making.
- IGOS is intended to cover all forms of data collection concerning the physical, chemical, biological and human environment including the associated impacts.
- IGOS is based on the recognition that data collection must be user driven, leading to results which will increase scientific understanding and guide early warning, policy-setting and decision-making for sustainable development and environmental protection.
- IGOS provides opportunities for capacity building and assisting countries to obtain maximum benefit from the total set of observations.

IGOS includes at present five Themes: (1) Global Carbon Cycle, (2) Geohazards, (3) Ocean, (4) Water Cycle, and (5) Atmosphere Chemistry. Other themes are under preparation. In order to integrate geodetic aspects another theme “Dynamic Earth” has been proposed but not yet appoved.

The IGOS Partnership (IGOS-P) brings together the efforts of a number of international bodies concerned with the observational component of global environmental issues, both from a research and a long-term operational programme perspective. GGOS is a partner of IGOS-P and is integrating its work into IGOS. Steps are being taken to strengthen joint initiatives with governmental organizations and international bodies.

4.4 Summary of User Requirements

The current and likely future accuracy requirements for access to positions in a terrestrial reference frame are summarized in Table 4.4-1. 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 *ad hoc* positioning. *Real time positioning* constitutes the first category (UC1). For these users, the most extreme accuracy requirements are expected to be considerably lower than 10 cm and in some cases even below 1 cm. 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 millimetres or better on intra-annual time scales. For long-term monitoring tasks, 1 mm/yr or better in stability seems to be a critical boundary both for scientific and non-scientific tasks. This number also applies to collection of geo-databases, 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 4.4-2. Presently, GPS&IGS satisfies 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 physical center of mass of the Earth system. Moreover, too many and uncoordinated changes in the IGS tracking network with respect to number of stations, hardware, software, processing strategy, and modeling algorithms 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 user category, 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, but also the rapid IGS products and the limited accuracy of the ultra-rapid IGS products leave a considerable share of this user category in the need of local or regional augmentation systems.

While UR1 and partly UR2 can be met by local to wide-area augmentation systems, the UR3 and UR4 requirements depend crucially on the quality of the ITRF and the available products. Moreover, achieving UR1 and UR2 through a Signal-in-Space Only system would considerably increase the areas of applications and provide significant economic advantages.

Table 4.4-1: URs for access to position. Reproduc. 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***	***Frame***	***Reproduc.***
Surveying with PPP	3d coord. velocity	10 to 50 mm 1 mm/yr	days n/a	national	decades
Monitoring	3d coord. velocity	< 10 mm < 10 mm/yr	days weeks	local local	decades decades
Control of processes	horizontal	10 to 100 mm	seconds to minutes	local	decades
Construction	3d	> 10 mm	seconds to minutes	local	months to years
Numerical weather prediction	IPWV	1-5 kg/m2	5-30 minutes	global	decades
Climate variations	IPWV	1 kg/m2	1-2 months	global	decades
Scientific studies	3d coord. velocity	< 10 mm < 1 mm/yr	n/a n/a	global global	decades decades
Earth observations	3d coord. velocity	< 10 mm < 1 mm/yr	days n/a	global global	decades decades

Table 4.4-2: Overview of latency and accuracy requirements of main user categories.

Class	***Requi.***	***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	< 1mm/yr

5 Assessment of Existing Components

5.1 Reference Frames and Earth Orientation Parameters (EOP)

5.1.1 Introduction and Objectives

A key geodetic contribution to both the three Global Observing Systems (GCOS, GTOS, GOOS) and initiatives like the European Global Monitoring for Environment and Security (GMES) is an accurate, reliable, long-term stable, and easily accessible reference system. Many emerging scientific as well as non-scientific high-accuracy applications require a unique, technique-independent reference frame. As outlined in Chapter 4, the user requirements for the accuracy, the integrity, the long-term stability, the tolerable latency, and update rates of the terrestrial reference frame are very much dependent on the particular application. In summary it can be stated that the overall requirements for the reference frame products are extremely high in order to fulfil all the user needs for the broad spectrum of applications. Such a reference frame can only be maintained and made available through a Global Geodetic Observing System (GGOS), which has been established by the International Association of Geodesy (IAG) in 2003. A major contribution to GGOS-related activities comes from European participants and, therefore, the EPIGGOS (European Partners In GGOS) consortium formed in 2004 will have an important role in the full implementation of GGOS. The GAGOS project is based on the expertise of the EPIGGOS community.

The assessment report on WP1.1 focuses on reference frames and on Earth orientation parameters (EOP). The International Earth Rotation and Reference Systems Service (IERS) is responsible for the establishment and maintenance of the reference frames. The core IERS products comprise the International Terrestrial Reference Frame (ITRF), the International Celestial Reference Frame (ICRF), and the Earth Orientation Parameters (EOP). The primary contributing space geodetic observation techniques are Very Long Baseline Interferometry (VLBI), Satellite and Lunar Laser Ranging (SLR/LLR), the Global Positioning System (GPS) and the Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS). In the last years services have been established by the IAG to coordinate the in-situ networks and data analysis for the different observation techniques (International GNSS Service, IGS; International Laser Ranging Service, ILRS; International VLBI Service for Geodesy and Astrometry, IVS; International DORIS Service, IDS).

Most of the cooperation within all these services is based on voluntary commitments of governmental and non-governmental institutions. Fluctuations in the contributions due to changes in the funding situation severely affect the long-term stability of the reference frames and, consequently, the accuracy of the geodetic-geophysical parameters that provide the basis for the observation and monitoring of the Earth system. Moreover, in order to reliably detect slow changes in the Earth system (e.g., global sea level change), the long-term stability is crucial. The assessment report will address this peculiar situation, identify shortcomings regarding the current structure and will make recommendations for future improvements. Existing observation networks (e.g., European parts of IGS, ILRS, IVS, IDS, EUREF, EPN, ECGN, national and research networks) have been rated to identify gaps and overlaps in geometry, lags in data flow and coordination. Furthermore emphasis has been put on unnecessary duplication of observations and to spot resources to fill observation needs.

Similar investigations were carried out with respect to the services' analysis centres, associated analysis and combination centres, and the resulting information and their access to obtain maximum benefit from the total set of observations. Moreover the review of the current state concerning geodetic reference frames taking into account the user requirements will provide the basis for the forward planning of the Global Geodetic Observing System.

In the first part of the assessment we focus on global reference frames and the EOP including the corresponding technique services and institutions involved. In the second part we address the regional reference frames in Europe and focus on the observation networks, the data analysis procedures and geodetic products for the users. Remaining deficiencies, gaps and overlaps will then be identified in Chapter 6 and proposals for future improvements will be made in Chapter 7.

5.1.2 Global Reference Frames and Earth Orientation Parameters (EOP)

5.1.2.1 International Earth Rotation and Reference Systems Service (IERS)

The IERS is responsible for the establishment and maintenance of the reference frames. The IERS products comprise the International Terrestrial Reference Frame (ITRF), the International Celestial Reference Frame (ICRF), the Earth Orientation Parameters (EOP), the global geophysical fluids, and the standards and constants given in the IERS Conventions.

Up to now, the IERS core products (ITRF, ICRF, EOP) are generated separately and almost independently of each other by the responsible Product Centres, leading to inconsistencies among them. The discrepancies are not only observed between techniques but also between various analysis centres of the same technique. Furthermore, the input data provided by various analysis centres must be consistent concerning modelling and parameterisation. This requires the adoption of common standards and models according to the most recent set of conventions, the IERS Conventions 2003 (McCarthy and Petit, 2004), which is currently not always fulfilled by the different processing software packages in use by the contributing analysis centres.

The IERS Product Centres perform their combinations primarily on the solution level. This strategy may lead to deformed results if individual solutions with bad or not clearly reported constraints are included, as it was the case, e.g., for some of the ITRF2000 contributions. This means that there are clear deficiencies in the space geodetic solutions and in the present IERS product generation, which have to be overcome by a rigorous combination of station coordinates, EOP and quasar coordinates. Towards this aim, the IERS Combination Pilot Project (CPP) has been initiated in 2004 (as a follow-on project of the SINEX Combination Campaign) to develop suitable methods for a rigorous combination of the IERS products, and to prepare the product generation on a weekly basis. The general scope and the objectives of the CPP are presented in Rothacher et al. (2006).

During the CPP and within the IERS Working Group on Combination it was recognized that the weekly SINEX solutions now routinely generated by the Technique Centres (e.g., IGS, ILRS, IVS) are not sufficient to generate combined inter-technique solutions over longer time periods. The most recent IERS realization of the terrestrial reference frame, the ITRF2000, does also not fulfil all the needs for the CPP, and thus a refined TRF realization is essential for the quality of the weekly rigorous combination of space geodetic observations. In December 2004 a call for long time series of "weekly" solutions for the new ITRF2005 and a supplement of the CPP was released.

5.1.2.2 International Terrestrial Reference Frame (ITRF)

The IERS is in charge of defining, realizing and promoting the International Terrestrial Reference System (ITRS). Realizations of the ITRS are produced by the IERS ITRS Centre (the former IERS ITRF section) hosted at the Institute Géographique National (IGN), Paris, under the name International Terrestrial Reference Frame (ITRF). More information can be obtained at the web page http://lareg.ensg.fr/itrf. The ITRF comprises a set of physical points on the Earth's surface with precisely determined positions and velocities in a specific coordinate system attached to the ITRS. The definition of the ITRS and the geophysical models to be used for its realization, the ITRF, are specified in the IERS Conventions (McCarthy & Petit, 2004). The procedure up to ITRF2000 was to combine individual TRF solutions provided by IERS analysis centres of the individual space geodetic techniques: VLBI, SLR/LLR, GPS and DORIS. There is a close link to the objectives and activities of the IAG Sub-Commission 1.2 "Global reference frames" (see Boucher, 2005).

Since 1988, a series of ten ITRF's was compiled by IGN, from ITRF88 to ITRF2000. The most recent IERS realization, the ITRF2000, consists of the positions and velocities of about 800 stations located at approximately 500 sites (Altamimi et al., 2002; Boucher et al., 2004). The input data for the ITRF2000 computation were multi-year solutions of different space geodetic techniques containing station positions and velocities with their full variance-covariance matrices in the Solution INdependent EXchange format (SINEX) for space geodesy. The combination strategy applied at IGN is based on minimally constrained solutions by simultaneously estimating transformation parameters of each individual solution w.r.t. the combined frame together with the station positions and velocities. The ITRF2000 has been computed in 2000 based on solutions of the space geodetic techniques available at that time. Since then almost five years of additional data have become available, new sites have joined the global network, the processing strategies and models have been improved and some station positions and velocities are no longer valid because of geophysical or man-made events (e.g., earthquakes, equipment changes, etc.).

Within the re-organized IERS structure, the ITRS Centre is supplemented by ITRS Combination Centres, which were included as new IERS components to ensure redundancy for the ITRF computations and to allow for a decisive validation of the combination results. Three ITRS Combination Centres are established at Deutsches Geodätisches Forschungsinstitut (DGFI), Institute Géographique National (IGN), and National Resources Canada (NRCan). They are responsible for performing the combination of space geodetic solutions to derive the ITRS products. According to the IERS Terms of Reference (http://www.iers.org/about/tor) the input data are now be provided by the services, i.e., the IGS, ILRS, IVS and IDS.

In its function as an ITRS Combination Centre DGFI has computed a terrestrial reference frame realization 2003 based on multi-year VLBI, SLR, GPS and DORIS solutions with station positions and velocities. The combination methodology, which is based on the level of unconstrained normal equations and the results of the TRF realization 2003 are presented e.g., in Angermann et al. (2004), Drewes et al. (2006). The performed TRF computations provide valuable results to assess the current accuracy of the terrestrial reference frame, to identify remaining deficiencies and to enhance the combination methodology. A comparison of the DGFI solution to ITRF2000 can be considered as a first "quasi-independent" quality control and external TRF accuracy evaluation. Fig. 5.1.2.1 shows the horizontal station velocities of the DGFI solution compared to ITRF2000. There is in general a good agreement between both TRF realizations. However, for some stations significant differences exist, and it should be noted that the DGFI solution contains less sites than ITRF2000, since stations with short data time spans (e.g. < 1 yr) were excluded, which do not allow an accurate and reliable velocity estimation. The results of this comparison show, for example, that for about 60 % of all 369 common stations the spherical (3-dimensional) differences in positions and velocities are below 1 cm and 2.5 mm/yr, respectively. However, there are more than 30 stations (about 10 %) with position and velocity differences greater than 5 cm and 1 cm/yr, respectively, which is not tolerable for a precise reference frame.

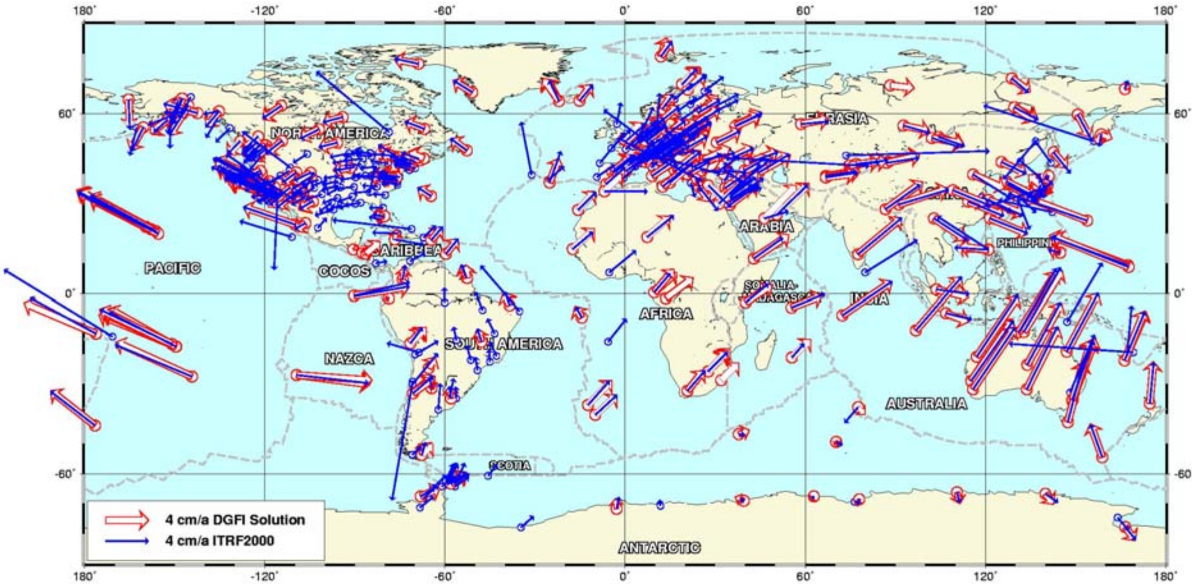


Fig. 5.1.2.1*:* Horizontal station velocities of ITRF2000 compared to DGFI solution TRF2003.

Taking into account the deficiencies of current ITRF realizations and the new developments concerning the combination methodology a call for long time series of "weekly" SINEX files for ITRF2005 and a supplementation of the IERS Combination Pilot Project was released by the IERS in December 2004. The ITRF2005 is based on the combination of time series of station positions and EOP. Weekly or (daily VLBI) contributions allow for a better monitoring of non-linear motions and other kinds of discontinuities in the time series. The ITRS Combination Centres, namely DGFI, IGN, and NRCan, coordinated by the ITRS Centre (IGN), are performing the computations for the ITRF2005 solution.

5.1.2.3 International Celestial Reference Frame (ICRF)

According to the recommendations of the IAU the IERS has the responsibility of monitoring the International Celestial Reference System (ICRS) and of maintaining its realization, the ICRF. The ICRS Centre of the IERS and the IVS carry out these activities jointly. The Observatoire de Paris and the U.S. Naval Observatory run the ICRS Centre jointly. More information may be obtained at the web page http://www.iers.org/iers/pc/icrs. A realization of the ICRS consists of a set of precise coordinates of extragalactic radio sources. The objects in the frame are divided into three subsets: “defining”, “candidate”, and “other” sources (McCarthy and Petit, 2004).

A first realization of the ICRF was performed in 1995 by a global single analysis of the available VLBI observations. It consists of equatorial coordinates of 608 extragalactic radio sources derived from about 1.6 million observations accumulated by a worldwide network in the time span 1979-1995 (Ma et al., 1998). The alignment of the Hipparcos Catalogue to the ICRF was realized with a standard error of ±0.6 mas for the orientation at epoch 1991.25 and ±0.25 mas/yr for the spin (Kovalevsky, 1997). Following the maintenance process, which characterizes the ICRS, an extension of the frame, ICRF-Ext.1 was constructed by using additional VLBI data until April 1999. The list and coordinates of the defining sources were not changed from the first realization of the ICRS (although it was found that some of them showed discrepant positions). The coordinates and errors of the candidates and other sources were refined and 59 new sources were added. The total number of objects in the ICRF-Ext.1 is 667. A second extension ICRF-Ext.2 contains about 1.2 million additional observations from approximately 400 sessions between May 1999 and May 2002 obtained from both geodetic and astronomic observation programmes (Fey, 2004).

Since the current ICRF was generated, VLBI modelling and estimations, data quality, source position stability analysis, and supporting observing programs have improved markedly (Ma, 2004). Furthermore, there are developing and potential applications in the area of space navigation, Earth orientation monitoring and optical astronomy from space that would benefit from a refined ICRF with enhanced accuracy, stability and spatial distribution. The limitations of the ICRF are the error floor (related to the modelling, estimation, and data imperfections), the defining sources (too sparse, unevenly distributed spatially, insufficient stable in retrospect), and data distribution (overall sparseness of sources and particular deficiency in the southern hemisphere), so that there is an urgent need for the production of a new ICRF realization in the near future, which then will be based on a combination of different VLBI solutions to ensure redundancy and quality control.

A working group of the IAG Subcommission 1.4 “Interaction of Celestial and Terrestrial Reference Frame” was formed to investigate the systematic errors in the ICRF because of the impact on Earth orientation parameters and indirectly on the satellite celestial reference frame (Zhu et al., 2005). Recently, at DGFI a VLBI solution with simultaneous estimation of celestial coordinates of the radio sources (CRF), station positions and velocities (TRF), and the full set of EOP was computed with the VLBI software OCCAM 6.0 (Tesmer et al., 2004). Assuming that this VLBI solution is free of systematic errors the results indicate that there are inconsistencies between the ICRF-Ext.1, the (VLBI part of) ITRF2000, and the IERS C04 (Angermann et al., 2006), which need to be further investigated.

5.1.2.4 Earth Orientation Parameters (EOP)

The Earth Orientation Parameters (EOP) provide the permanent tie between the ICRF and the ITRF. They describe the orientation of the Celestial Ephemeris Pole in the terrestrial system and in the celestial system (polar coordinates, x,y; celestial pole offsets $d\psi$, $d\varepsilon$) and the rotation angle of the Earth around this axis (UT1-UTC), as a function of time. According to the IERS Terms of Reference, the Earth Orientation Centre, hosted at Paris Observatory, is responsible for monitoring the EOP including long-term consistency, publications for time dissemination and leap second announcements (Gambis et al., 2005). A general presentation of the EOP, operational activities and analyses are provided at the web site http://hpiers.obspm.org. The Earth Orientation Centre makes different products available to users: long-term and operational series of polar motion, Universal Time (UT1), Length of Day (LOD), and celestial pole offsets. The EOP are determined as combined solutions of the analysis centres of the different techniques, i.e., VLBI, SLR GPS and DORIS. Various solutions are computed at the Earth Orientation Centre: long-term solution (IERS C01), normal values at five and one-day intervals (IERS C02 and C03) and the operational smoothed solution Bulletin B at one-day intervals published monthly and providing EOP with a delay of 30 days with respect to the date of publication. Bulletin B is updated in an operational mode in the IERS C04, which is computed twice a week. A description of Bulletin B is available at the IERS Explanatory Supplement for Bulletin A and B. Since formal uncertainties reported by the contributors are often under-estimated, they are calibrated by a statistical assessment using the Allan Variance Analysis in order to reflect the real quality of the data. This procedure leads to an optimal weighting of the individual series entering the combinations (Gambis, 2004). Recently the algorithms and software allowing to compute C04 series have been considerably improved. The new version is based on combined smoothing (Vondrak and Cepek, 2000).

Until now, the core IERS products (ITRF, ICRF, EOP) are computed (combined) separately by different product centres. Consequently, the results are not consistent, e.g., different ITRF realizations produce offsets and drifts in the EOP series (Rothacher, 2000). The results of the IERS Analysis Campaign to align EOPs to ITRF2000/ICRF reveal that significant biases exist between EOP series (Dill and Rothacher, 2003; Gambis and Bizouard, 2003; Nothnagel et al., 2003). It was found that there are obviously systematic differences in the reference frames realized by different techniques resulting in offsets and drifts in individual EOP series. We used the VLBI solution computed at DGFI with simultaneous estimation of station positions and velocities (TRF), celestial coordinates of the radio sources (CRF), and the full set of EOP (Tesmer et al., 2004) for a comparison with the IERS C04 series. The results indicate that inconsistencies, such as offsets (a rotation of station positions), drifts (a rotation of station velocities) and periodic effects (especially for the early years up to 1990) are obvious and vary over the entire period of 20 years (Angermann et al., 2006).

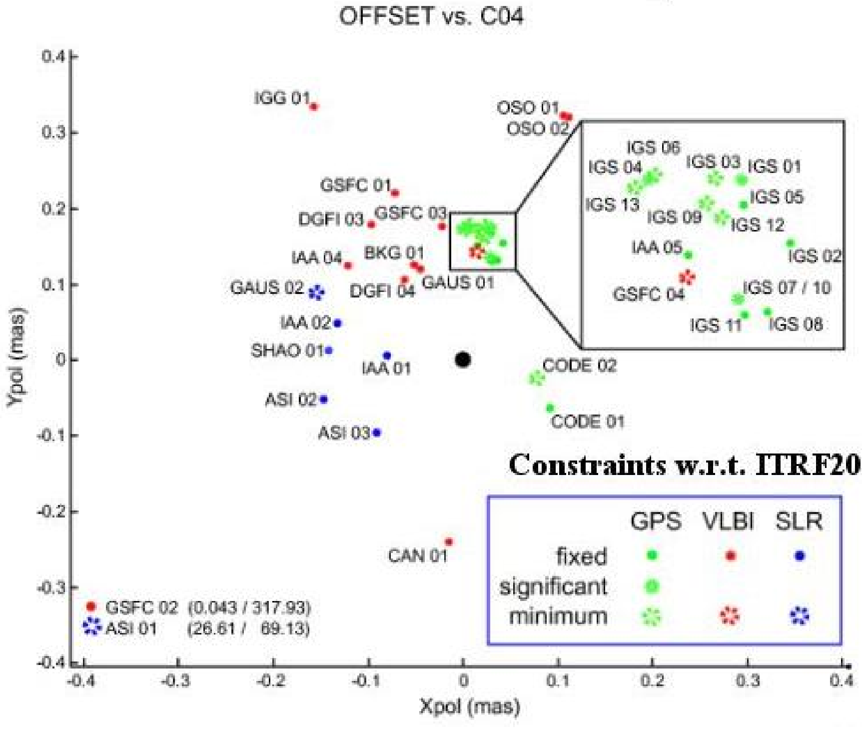


Fig.5.1.2.2: Results of the EOP Alignment Campaign (Dill and Rothacher, 2003).

5.1.3 Technique Services - Observation Networks and Data Analysis

Over the last decade, the organisational development within international space geodesy has been inspired by the success of the International GNSS Service (IGS), which was established by IAG in 1994. The success of the IGS stimulated the establishment of similar services for the other space geodetic observation techniques, namely the International Laser Ranging Service (ILRS) in 1998, the International VLBI Service for Geodesy and Astronomy (IVS) in 1999, and the International DORIS Service (IDS) in 2004. The organisational structure is similar for each of these services and comprises various components, such as a Governing Board, Tracking Stations and Sub-networks, Operations Centres, Global and Regional Data Centres, Analysis and Associate Analysis Centres, Central Bureau, and Working Groups. The organisational background of these services is based on an international collaboration of organisations and institutions based on voluntary commitment and the best efforts of the contributors. Below we assess the current status of the individual services mentioned above and summarize thereby also the contributions of the European partners.

5.1.3.1 International GNSS Service (IGS)

The IGS (formerly known as International GPS Service) represents the GNSS (GPS, GLONASS, and Galileo). It was established by IAG in 1994 and was approved as a member of the Federation of Astronomical and Geophysical Data Analysis Services (FAGS). The IGS structure (see IGS web page at http://igscb.jpl.nasa.gov) has served as a model for the ILRS, IVS and now IDS. The IGS global network, which consisted of about 30 GPS stations in 1994, extended to about 350 stations at present (Fig. 5.1.3.1). The stations are globally well distributed with some densification areas, e.g., in Europe and Southern California. The network feeds the observation data into a hierarchy of Data Centres (local, regional, “operational” and global). They are processed with low latency by a number of Analysis Centres using highly automated software and procedures.

The IGS products comprise precise satellite orbits, station and satellite clocks, station positions and velocities, EOP, troposphere parameters, and ionosphere maps. Furthermore consolidated real-time (predicted) satellite orbit and clock solutions are available to the users continuously for the full GPS constellation. Three types of GPS ephemeris, clock and earth orientation solutions are computed: (1) The final combinations are available with a latency of 12 days; (2) the Rapid product is available with approximately 17 hours latency; (3) the UltraRapid combinations are released four times each day and contain 48 hours worth of orbits, the first half computed from observations and the second half predicted.

Subsets of IGS stations feature additional instrumentation or capabilities that allows them to contribute to other IGS products and working group activities (e.g., reference frames, troposphere, precise orbits for Low Earth Orbiters (LEO), low-latency products) as well as IGS pilot projects, such as the Tide Gauge Benchmark Monitoring Pilot Project (TIGA-PP).

The data of the IGS global network are routinely analysed by 10 analysis centres (CODE, ESOC, GFZ, JPL, NOAA, NRCan, SIO, USNO, MIT, GOP-RIGTC). Furthermore 19 Regional Network Associate Analysis Centres (RNAACs) are computing also on a weekly basis regional solutions (e.g., EUREF, see below) for the densification of the terrestrial reference frame. Two Global Network Associate Analysis Centres (GNAACs) combine these regional solutions with the global solutions for the densification of the global reference frame. In addition NRCan combines sets of station coordinates, velocities, EOPs, and apparent geo-centre motions provided by the IGS analysis centres to produce the IGS official combined station position and EOP solutions. The weekly combined station coordinates are accumulated in a multi-year solution (Ferland, 2002). Besides this, NRCan has recombined the GPS solutions back to 1996, which serve as input for the IERS Combination Pilot Project and for the computation of the ITRF2005. The IGS analysis coordinator is G. Gendt (GFZ).

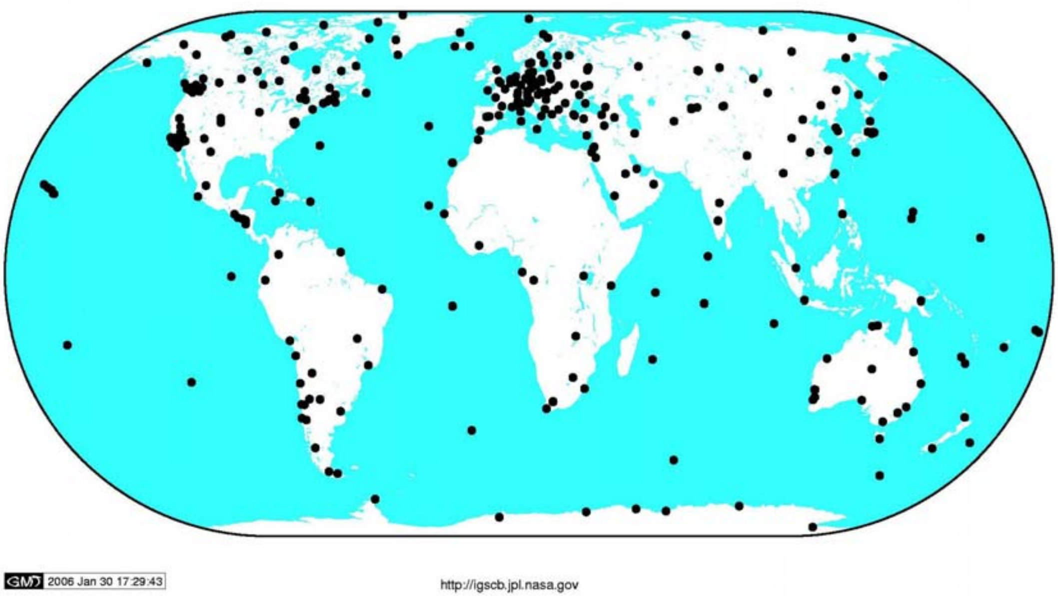


Fig. 5.1.3.1: IGS station network (Source: IGS Web page at http://igscb.jpl.nasa.gov).

The European contributions to the IGS comprise, among others:

- About 45% of the EUREF Network stations contribute also to the IGS;
- 1 (of 4) IGS Global Data Centre (IGN);
- 1 (of 5) Regional Data Centres (BKG);
- 7 (of 16) Operational Data Centres (CNES, DUT, ESA, GFZ, ASI, KMS, SK);
- 4 (of 10) Analysis Centres (CODE, ESOC, GFZ, GOP-RIGTC);
- 14 (of 18) Regional Network Associate Analysis Centres (e.g., EUREF and SIRGAS);
- Significant contributions to the IGS Working Group Activities and Pilot Projects.

5.1.3.2 International Laser Ranging Service (ILRS)

The ILRS (see http://ilrs.gsfc.nasa.gov) was established in 1998 as a service within IAG to support programs in geodetic, geophysical and lunar research activities and to provide data products to the IERS in support of its prime objectives. The ILRS accomplishes its mission through seven components, comprising the Governing Board, Tracking Stations and Sub-networks, Operations Centres, Global and Regional Data Centres, Analysis and Associate Analysis Centres, Central Bureau, Permanent and Temporary Working Groups. More information is given in the ILRS web page and relevant publications (Pearlman et al., 2005).

The SLR station network consists presently of 29 tracking stations, which are typically associated with one of the three regional sub-networks: National Aeronautics and Space Administration (NASA), European Laser Network (EUROLAS), or the Western Pacific Laser Tracking Network (WPLTN). As shown in Fig. 5.1.3.2, the spatial distribution of SLR stations is not optimal; in particular there are only few stations on the Southern hemisphere. Furthermore the data quality and quantity is relatively poor for some of these stations. As the operation of an SLR station is rather expensive and also requires quite a lot of manpower, there are ongoing discussions about the funding. On the other hand, SLR is extremely important for the establishment of GGOS, as this technique provides the origin and scale for the ITRF and the long time series of observations (> 25 years) is fundamental to ensure the long-term stability of the reference frame and to study secular phenomena.

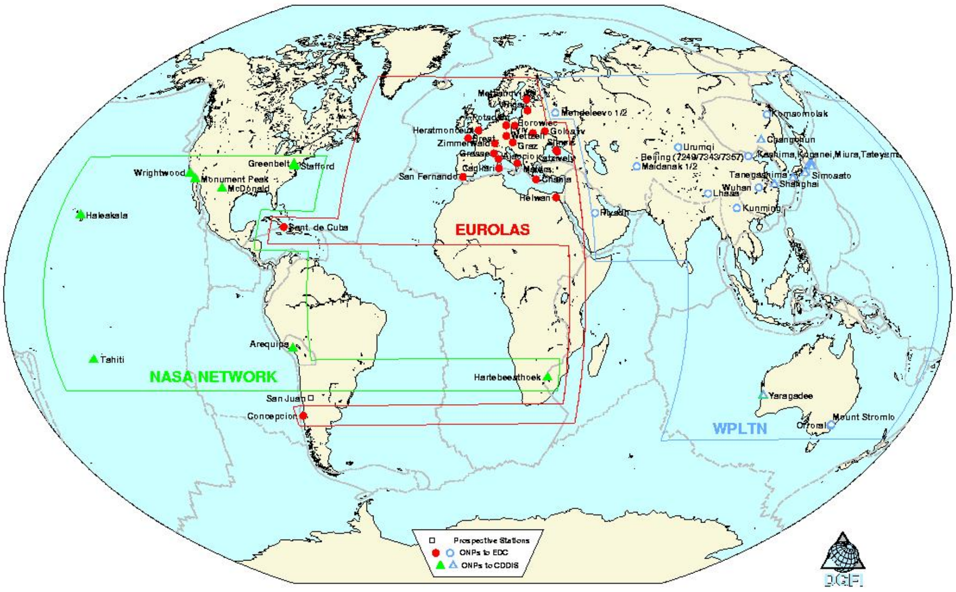


Fig. 5.1.3.2: SLR station network (Source: EUROLAS Data Centre, DGFI).

The ILRS analysis activities, which are coordinated by the ILRS Analysis Working Group (Chair: R. Noomen, DEOS, The Netherlands), made significant progress through a number of pilot projects and the benchmarking of software and analysis procedures in use by various analysis groups. Since 2004 official combined ILRS products on EOP and station positions are produced on a weekly basis. The latency of the products is several days (< 10 days). Real-time or near-real time products are not provided by the ILRS. At present, six analysis centres are nominated as official ILRS Analysis Centres: ASI (Agencia Spatiale Italiano, Italy), BKG (Bundesamt für Kartographie und Geodäsie, Germany), DGFI, GFZ, JCET (Joint Center for Earth Systems Technology, USA), and NFGS (National Environment Research Council, NERC, Space Geodesy Facility, UK). Furthermore there are two official ILRS Combination Centres: ASI (primary), and DGFI (backup). Besides the routine delivery of the weekly ILRS products the ILRS has re-processed the data back to the year 1993, which serve as input for the IERS Combination Pilot Project and for the computation of the ITRF2005.

The European contributions to the ILRS comprise, among others:

- European Laser Network (EUROLAS): 11 SLR stations (Borowiec, Conception, Graz, Herstmonceux, Matera, Potsdam, Riga, San Fernando, Simeiz, Wettzell, Zimmerwald)
- EUROLAS Data Centre (EDC) at DGFI as one of the two global SLR data centres (the second one is CDDIS at NASA).
- ILRS Analysis Centres (ASI, BKG, DGFI, GFZ, NFSG)
- ILRS Combination Centres (ASI, DGFI)
- 8 ILRS Governing Board members from Europe; Chair: W. Gurtner, (Switzerland)
- Significant contributions to the ILRS Working Group Activities

5.1.3.3 International VLBI Service for Geodesy and Astrometry (IVS)

The IVS (see http://ivscc.nasa.gsfc.gov) has been established in 1999 as a service of the IAG to support VLBI programs for geodetic, geophysical and astronomical work on reference systems, Earth science research, and operational activities. In 2000, the IVS was also recognized as a service of the International Astronomical Union (IAU) and was tasked to contribute to the maintenance of the ICRF (Resolution B1.1 of IAU XXIV General Assembly, 2000). Furthermore, IVS was approved as a member of the Federation of Astronomical and Geophysical Data Analysis Services (FAGS) in 2001.

IVS is an international collaboration of organizations, which operate to support VLBI components. Altogether IVS consists of 73 permanent components, representing 37 institutions in 17 countries. The goals of IVS are realized through seven types of components, which include network stations (29), operational centres (3), correlators (6), data centres (6), analysis centres (21), technology development centres (7) and a coordination centre (1). The geographical distribution of these components is displayed in Fig. 5.1.3.3. In addition to its components, IVS comprises the Directing Board, associate members, corresponding members, the network coordinator, the analysis coordinator and the technology coordinator.

Fig. 5.1.3.3: Map of IVS components (http://ivscc.gsfc.nasa.gov).

In order to meet the service requirements best, IVS has made a review and an evaluation of the products and the respective observing programs. As a result, the new and improved IVS observing program was established at the beginning of 2002, which results in an increase in the number of observation days by roughly 30%. The evolution of observing programs is still going on. Nevertheless problems are the relatively sparse VLBI observation network (especially in the Southern hemisphere) and the fact, that typically only 4-6 telescopes observe simultaneously within one daily session, and the station configuration often changes from one session to the next. IVS provides official products for ICRF, ITRF and EOP. VLBI realizes the ICRF and has the unique capability for the determination of the complete set of EOP including polar motion, UT1, and nutation corrections.

The IVS data analysis is coordinated by the IVS Analysis Working Group (Chair: A. Nothnagel, GIUB, Germany). Altogether 7 full analysis centres and 14 associate analysis centres contribute to the IVS data analysis (see http://ivscc.gsfc.nasa.gov). The IVS Combination Centre at GIUB combines the individual VLBI solutions into official IVS products (see Nothnagel and Steinfort, 2002). At present the VLBI data is recorded on tapes or hard discs and they are delivered by ordinary mail. Thus the VLBI session data can only be analysed with a delay of several days (or even weeks) after observation, which has to be considered for the generation of the IVS products. The submission via Internet (e-VLBI) is in the development phase due to the huge amount of data. Besides the routine delivery of the official IVS products the IVS has re-processed the data back to the year 1984, which serve as input for the IERS Combination Pilot Project and for the computation of the ITRF2005.

The European contribution to IVS comprise, among others:

- 12 VLBI Network stations are operated by European Institutions: O Higgins, TIGO and Wettzell (BKG, Germany); Medicina and Noto (Instituto Radioastronomia, Italy); Matera (Agenzia Spatiale Italania, Italy); Ny Alesund (Norwegian Mapping Authority, Norway); Svetloe and Zelenchukskaya (Institute of Applied Astronomy, Russia); Yebes (Institute Geografico Nacional, Spain); Onsala (Chalmers University of Technology, Sweden);
- 1 Correlator: Astro/Geo Correlator at MPI (GIUB and BKG);
- 4 Data Centres: Paris Observatory, BKG Leipzig, CNR Italy, GeoDAF Italy;
- 12 IVS Analysis Centres: Institute of Geodesy and Geophysics (Austria); Observatoire Paris and Observatoire de Bordeaux (France); DGFI and GIUB-BKG (Germany); Istituto di Radioastronomia CNR and Centro di Geodesia Spaziale CGS (Italy); Norwegian Defence Research Establishment (Norway); Institute of Applied Astronomy and Astronomical Institute of St. Petersburg University (Russia); Chalmers University of Technology (Sweden); Astronomical Observatory Kiev (Ukraine);
- 7 (of the 16) Directing Board Members are from Europe, Chair: W. Schlüter (BKG);
- Significant contributions to the IVS Working Groups.

5.1.3.4 International DORIS Service (IDS)

DORIS has been developed by the Centre National d'Etudes Spatiales (CNES) in conjunction with the Institut Géographique National (IGN) and the Groupe de Recherche de Géodesie Spatiale (GRGS). A proof of concept for the IDS was conducted through a pilot phase until the establishment of the International DORIS Experiment in 1999 by the IAG. The IDS has begun formally on July 1, 2003 after the IAG official approval at the IUGG General Assembly in Sapporo. The primary objective of the IDS is to provide a service to support, through DORIS data and data products, geodetic and geophysical research activities.

The IDS collects, archives and distributes DORIS observation data sets of sufficient accuracy to satisfy the objectives of a wide range of applications and experimentations. The structure of the IDS is similar to that of the other technique services. It comprises various components, such as the satellites carrying a DORIS receiver, the network of tracking stations, Data Centres, Analysis Centres, Analysis Coordinator, Working Groups, Central Bureau, Governing Board. The tracking network consists of about 60 homogeneously distributed stations

(Fig. 5.1.3.4), which provide a good data coverage for orbit determination. The Central Bureau (CB) produces/stores/maintains basic information on the DORIS system, including various standard models (satellites, receivers, signal, reference frames, etc). The observational data and products, formats and analysis descriptions are stored at two global Data Centres (DC) located at IGN/LAREG (France) and GSFC/CDDIS (USA).

The Analysis Coordinator provides information about the analysis strategies and models, and analyses of the products of the Analysis Centres at IGN/LAREG web page (see http://lareg.ensg.ign.fr/IDS/), referring to CB and DC information on the data and modelling. Currently there are 6 Analysis Centres (CNES, CSR, IGN/JPL, INASAN, LEGOS/CLS, SSALTO) and another 6 Analysis Centre may contribute in the future. Weekly DORIS solutions with station positions and EOP are routinely provided. Besides this, three IDS Analysis Centres (IGN/JPL, INASAN, LEGOS/CLS) have reprocessed the DORIS data back to 1993 and provided weekly solutions (positions and EOP), which serve as input for the IERS Combination Pilot Project and for the computation of the ITRF2005. Until now, no official combined DORIS solutions are provided by the IDS.

The European contribution to IDS comprise, among others:

- DORIS has been developed in France by CNES in conjunction with IGN and GRGS;
- Operation of DORIS Network stations;
- IGN/LAREG global Data Centre (France);
- 5 IDS Analysis Centres in Europe: CNES, LEGOS/CLS, SSALTO (France); INASAN (Russia); IGN/JPL (France/USA);
- 7 (of the 16) Directing Board Members from Europe, Chair: G. Tavernier (CNES);
- Significant contributions to the IVS Working Groups.

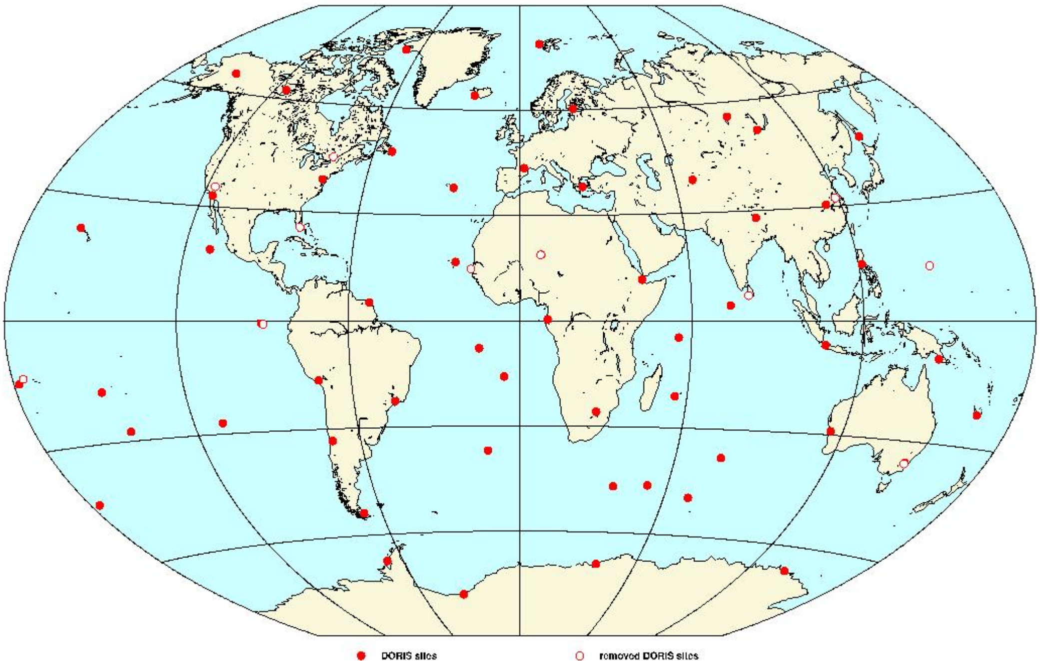


Fig. 5.1.3.4: DORIS station network**.**

5.1.3.5 Integration of Different Space Techniques - Co-location Sites and Local Ties

The space geodetic observation techniques (e.g., GNSS, VLBI, SLR, DORIS) contribute in a different and unique way to the determination of geodetic parameters (e.g., site positions and velocities, EOP, atmosphere parameters, gravity field coefficients) and each of these techniques has its strengths and weaknesses concerning the determination of various parameters (e.g., Rothacher, 2000; Angermann, 2002). Thus it is an important goal to make optimal use of the specific properties of the different techniques, and to identify remaining biases between them, which can be considered as one of the major limiting factors concerning today's accuracy of space geodetic solutions.

Co-location sites (Fig. 5.1.3.5) and local ties (intra-site vectors) are key elements to integrate and combine the technique-specific solutions into a common reference frame. Both, the current situation regarding geographical distribution of co-location sites and the accuracy of local ties are not satisfying. The ITRF2000 results (see Altamimi et al., 2002; Boucher et al., 2004) and the DGFI combination results (see Angermann et al., 2004, Krügel and Angermann, 2005) indicate that there are several erroneous local ties. The discrepancies between local ties and coordinates determined by the space geodetic techniques are unacceptably large in too many cases. Reasons are manifold, e.g., uncertainties of the space geodetic solutions and unresolved systematic biases between them, local site effects, small remaining datum inconsistencies between techniques and "real" errors in local tie measurements. Thus spatially well-distributed co-location sites and accurate local ties are an essential requirement to fully exploit the unique capabilities and individual strengths of the different space geodetic techniques, and to identify remaining technique-specific systematic effects.

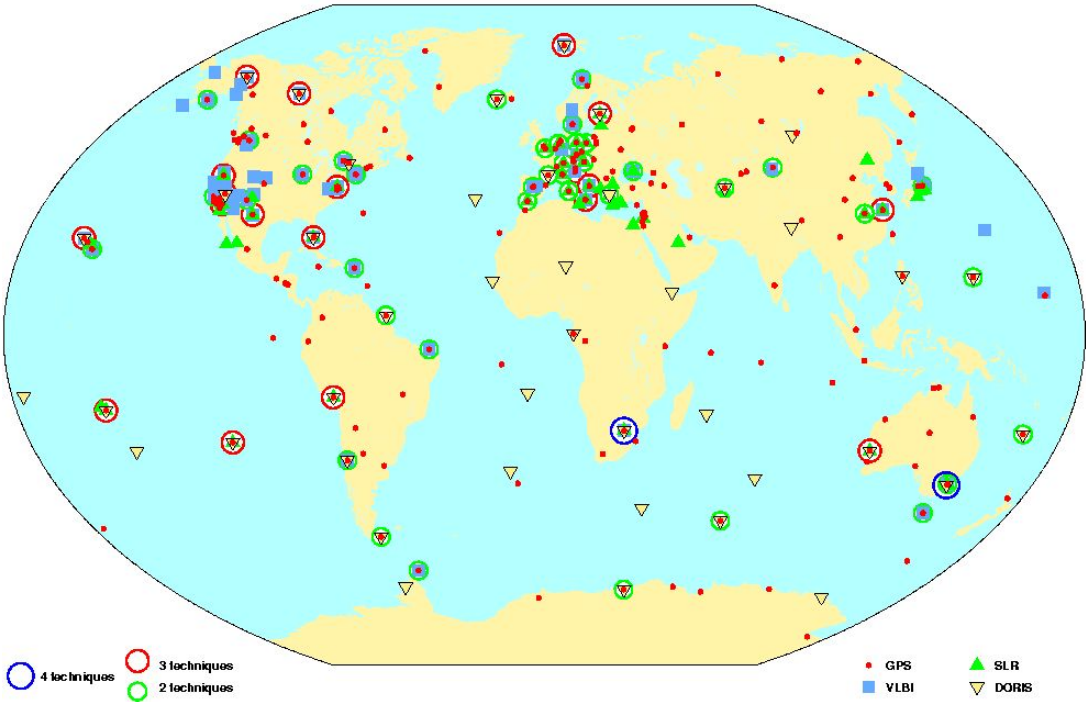


Fig. 5.1.3.5: Co-location sites with two, three and four co-located observing techniques. (Source: Angermann et al. 2004).

As common parameters of the different space geodetic techniques the station velocities at co-location sites and the EOP (and probably also troposphere parameters) represent additional ties to integrate the technique-specific networks into a unique datum. A common adjustment of the ITRF and EOP is in progress by the ITRS Combination Centres and some specific studies concentrated on this subject (e.g., Ray et al., 2005). However this field is not very well understood yet and the integration of different techniques on the satellite level has not been addressed sufficiently, too.

5.1.4 European Reference Frame - EUREF

5.1.4.1 Overview

EUREF is the IAG Reference Frame Sub-Commission for Europe, integrated into the Sub-Commission (SC) 1.3 "Regional Reference Frames", under Commission 1 "Reference Frames", following the implementation of the new IAG structure at the IUGG General Assembly held in Sapporo, 2003. The SC-1.3 consists of six sub-parts, which are the SC-1.3a "Reference Frame for Europe (EUREF)", SC-1.3b "Reference Frame for South and Central America (SIRGAS)", SC-1.3c "Reference Frame for North America (NREF)", SC-1.3d "Reference Frame for Africa (AFREF), SC-1.3e "Reference Frame for South East Asia and Pacific", and SC-13.f "Reference Frame for Antarctica" (see Drewes and Hornik, 2005). The Sub-Commission EUREF was founded in 1987 at the IUGG General Assembly held in Vancouver.

The mission of EUREF is the definition, realization and maintenance of the European Reference Systems, in close cooperation with the IAG components (Services, Commissions, and Inter-Commission Projects) and EuroGeographics, the consortium of the National Mapping and Cadastre Agencies (NMCA) in Europe. The main objective is to provide the geodetic infrastructure for multinational projects requiring precise georeferencing (e.g., three-dimensional and time-dependent positioning, geodynamics, precise navigation, engineering, geo-information). The Terms of Reference (ToR), which were adopted at the annual symposium held in Bratislava (June 2004), contain the description of EUREF, its objectives, activities, organisation and the rules for membership according to the general rules expressed in the Statutes and By-laws of IUGG and IAG (see http://www.euref-iag.net/html/Overview_of_EUREF_Terms_of_reference.html). The organisational structures of EUREF are shown in Fig. 5.1.4.1.

EUREF has been developing a set of activities related to the establishment and maintenance of the European Terrestrial Reference System (ETRS89) and the European Vertical Reference System (EVRS2000). A key instrument in maintaining the ETRS89 is the European Permanent Network (EPN), covering the European continent, with stations that continuously track GPS/GLONASS satellites with high accuracy. The European Commission recommends to adopt ETRS89 as the geodetic datum for geo-referenced information and to promote the use of ETRS89 within member states. ETRS89 has been adopted by Eurocontrol and its adaption by the NMCA is an ongoing activity of EuroGeographics.

The forum, where activities are discussed and decisions are taken is the annual symposium, organized since the EUREF foundation in 1987. The last symposium has been attended by more than 120 participants coming from more than 30 member countries in Europe. Current activities are governed by the Technical Working Group (http://www.euref-iag.net/html/twg.html). The main working fields of the TWG in the recent time include the terms of reference, the EPN with its Central Bureau and Analysis Centres contributing to various projects, the ETRS89, the EVRS2000, the European velocity field, the European Combined Geodetic Network (ECGN), the United European Levelling Network (UELN), various research projects (e.g., troposphere project, real-time activities, GPS meteorology) and national networks.

The results of EUREF are available in the annual symposia proceedings. Besides the presented papers, the proceedings contain the resolutions and documentation for some of the most important activities and data base maintenance.

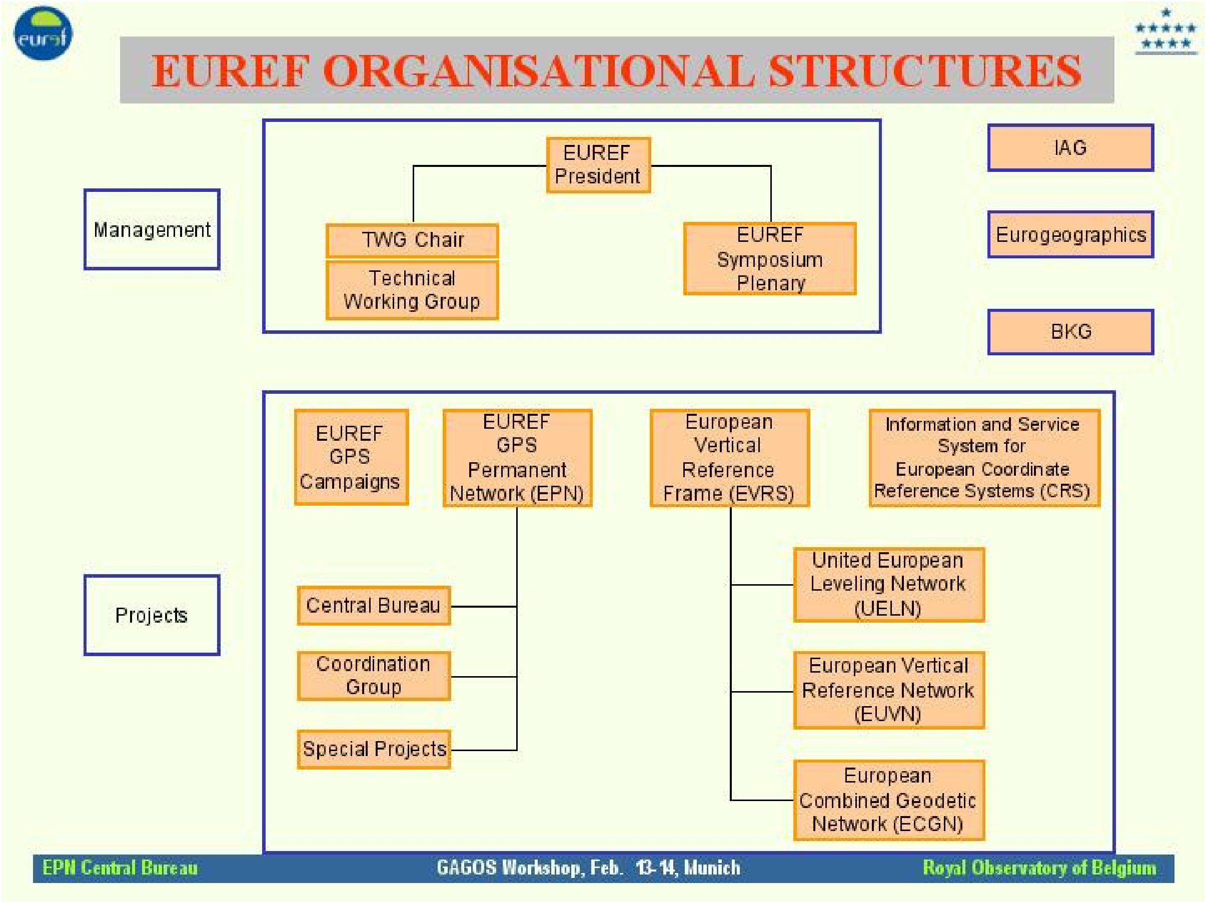


Fig. 5.1.4.1: EUREF Organisational Structures (Source: Bruyninx et al. 2006).

5.1.4.2 EUREF Permanent Network (EPN)

The EUREF Permanent Network (EPN) is a network of continuously operating GNSS stations, primarily installed for reference frame maintenance. At present, the EPN consists of more than 180 stations (status: 2006), which are operated by 130 contributing agencies covering 30 European countries (see Fig. 5.1.4.2). About 45% of the EPN stations also submit data to the IGS, and thus provide the link of the European reference frame to the ITRF. The majority of the stations (about 76%) are providing hourly data. This so-called near-real time network supports meteorological and space weather applications. Almost 20 of the EPN stations contribute to the TIGA (Tide Gauge Benchmark Monitoring) Pilot Project of the IGS. The real-time core network is in progress. It consists currently of 28 EUREF-IP stations and 4 IGS real-time stations. Furthermore, a selected set of EPN stations belongs also to the kinematic European Combined Geodetic Network (ECGN).

The procedure for becoming an EPN station has been completely revised. The new procedure is active since December 2003, and can be downloaded via the EPN Central Bureau (CB) web site at http://www.epncb.oma.be. The most important change concerns the new requirement to submit a commitment letter guaranteeing that the station will be operated according to EPN guidelines for a minimal duration of 5 years. In addition, the guidelines for

EPN Stations and Operation Centres have also been reviewed. New guidelines were issued mainly in order to improve the data flow within the EPN and to guarantee the availability of the EPN data. This is achieved be making available the data to two regional Data Centres: BKG (Germany) and OLG (Austria).

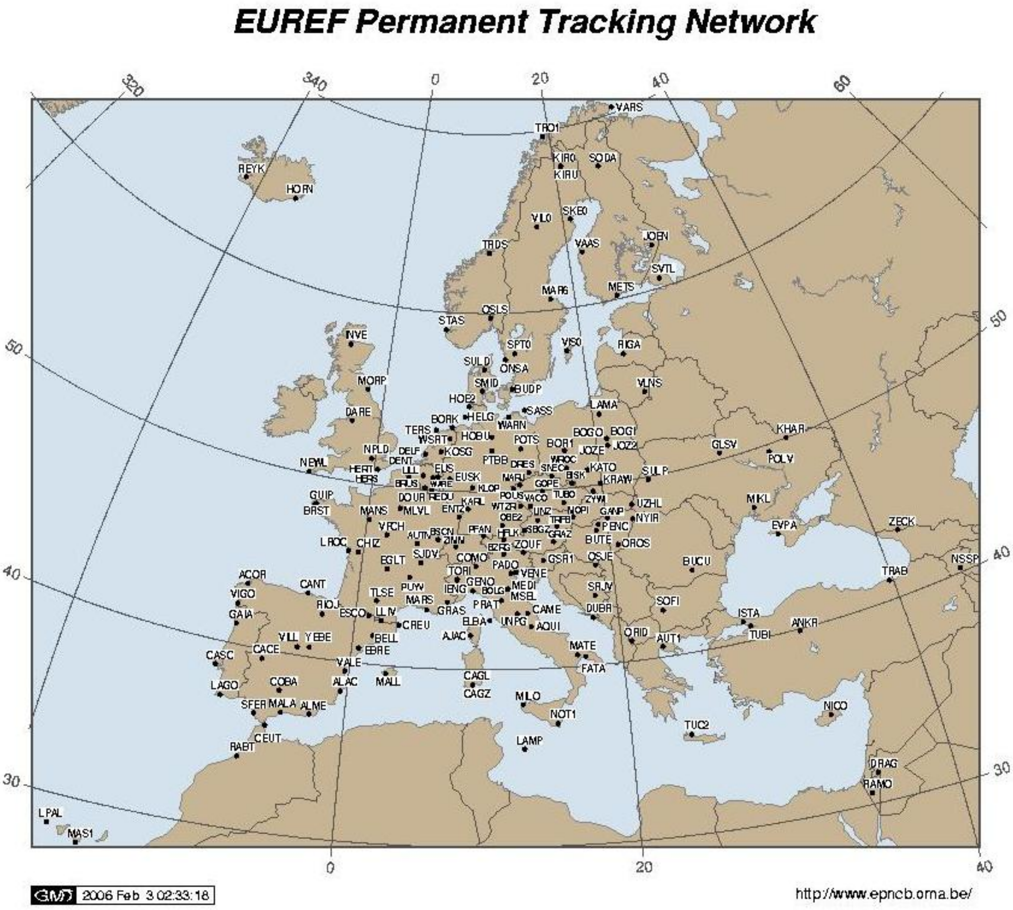


Fig. 5.1.4.2: Stations of the European Permanent Tracking Network (http://www.epncb.oma.de).

The EPN CB web site has been recently updated showing the results of the monitoring of the long-term quality of the GNSS observations. As a complement to the “Station latency reports” that are monthly distributed via EUREF mail, some graphics were added at the EPN CB web page showing the delay of each hourly data file. The EPN CB makes also available standard coordinate time series for the sake of monitoring the station coordinates. These time series provide valuable information to detect possible problems that can occur (e.g., instrumentation changes, environmental effects). Since May 2004, these coordinate time series are computed using the CATREF software, which has been developed by Z. Altamimi from IGN France. For a large number of EPN stations discontinuities in the coordinate time series can be observed, which are often caused by equipment changes, changes in the processing strategy or reference frame realizations (Fig. 5.1.4.3).

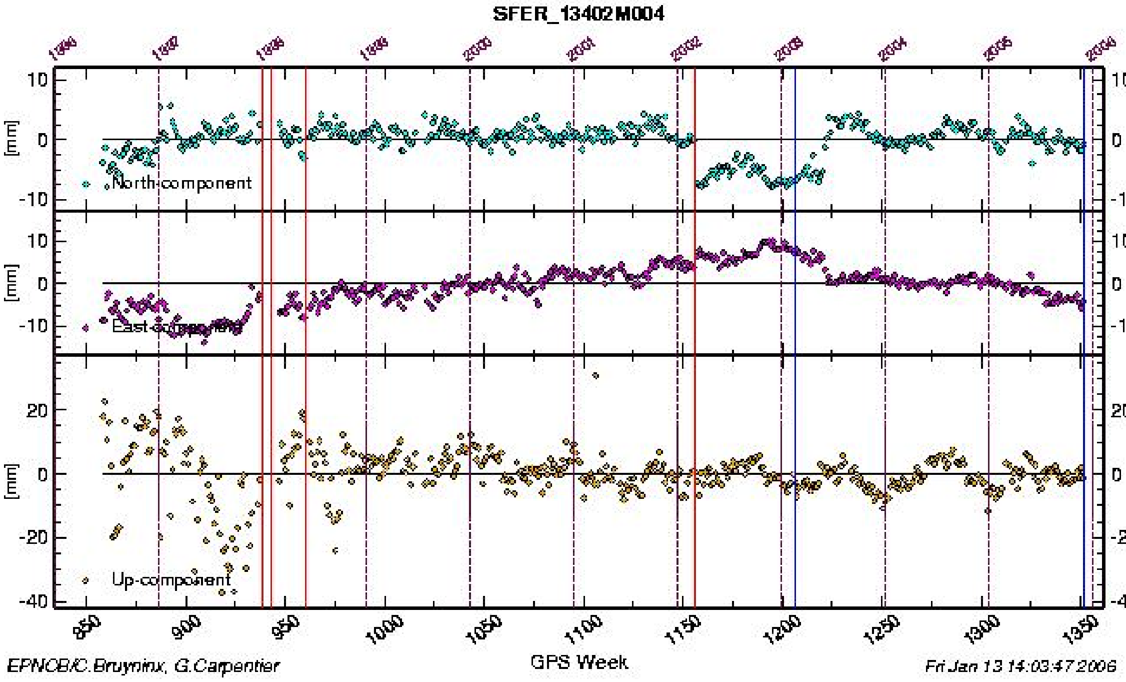
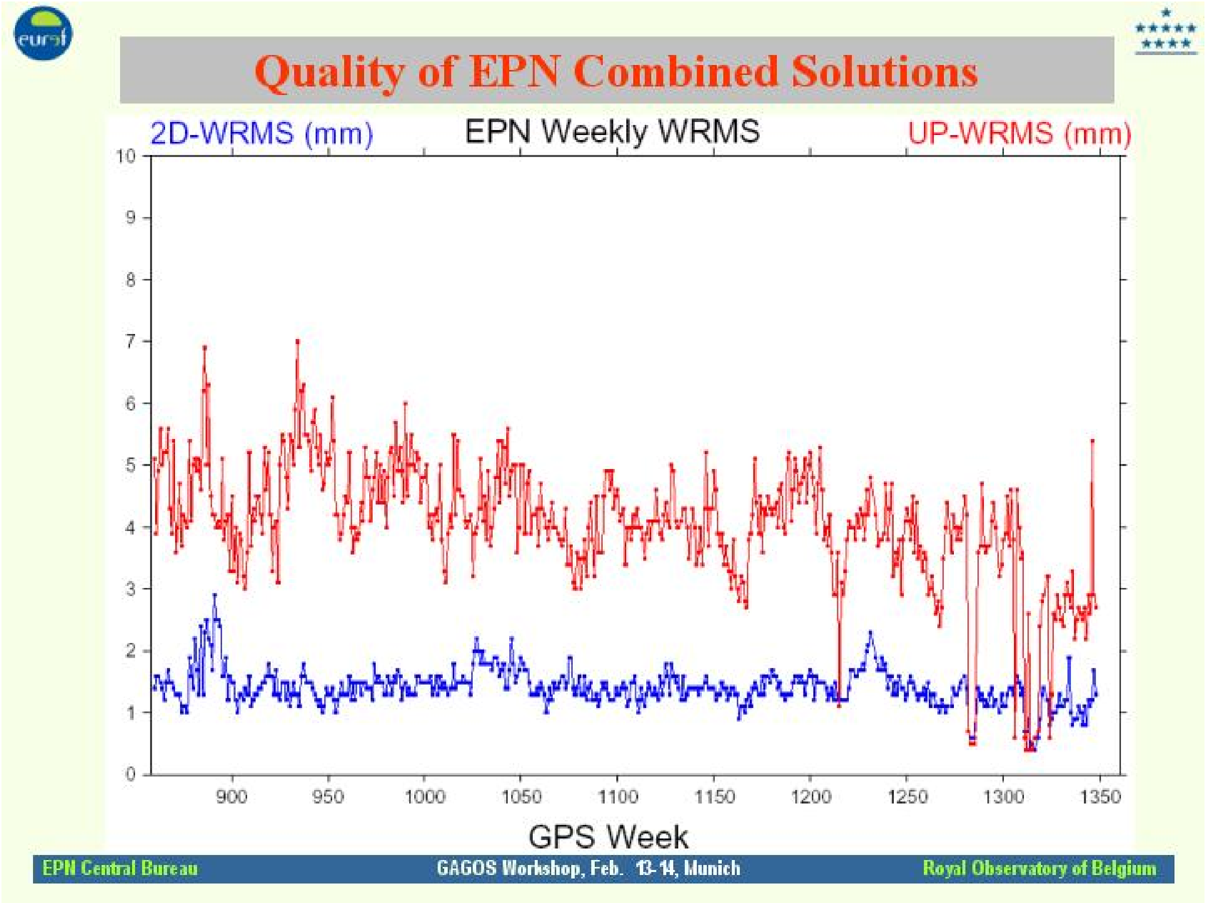


Fig. 5.1.4.3: Position time series for San Fernando (SFER), Spain (**http://www.epncb.oma.be**).

5.1.4.3 EPN Data Analysis and Products

In order to optimise the data processing within the EUREF network, the principle of distributed processing is used. In this approach the European permanent network is divided into sub-networks, which are separately processed by different EPN Local Analysis Centres (LAC's). The EPN Combination Centre is responsible for combining the EPN sub-network solutions into one European solution submitted to IGS. Since GPS week 1020 (July 1999), BKG located at Frankfurt (Germany) took over this responsibility. Before that time, the Astronomical Institute of the University of Bern (Switzerland) was acting as Combination Centre. The resulting free-network solutions (official EUREF combined solution) are made available as SINEX files to the IGS Global Network Associate Analysis Centres (GNAAC). The EPN Network Coordinator (C. Bruyninx, Belgium) is in charge of the distribution of the stations to the LAC's. Each EPN station is analysed by at least 3 LAC's. The EPN Analysis Coordinator (H. Habrich, BKG) computes the EUREF combined solutions. The consistency between the contributing sub-network solutions is verified through the calculation of a 7–parameter transformation between each LAC solution and the combined solution. If an individual solution differs more than 5 mm in the horizontal or 10 mm in the height component, respectively, it is rejected from the combination. The consistency could be improved in comparison to previous solutions (e.g., Habrich, 2003). The quality of the combined solutions is now in the order of 1-2 mm horizontally and about 5 mm for the height (see Fig. 5.1.4.4). Finally, the EPN combined solutions are tied to the ITRF by applying minimum constraints (since 2005). Before 2005 this was done in the form of constrained solutions.



Quality of EPN Combined Solutions

EPN Central Bureau GAGOS Workshop, Feb. 13-14, Munich Royal Observatory of Belgium

Fig. 5.1.4.4: Quality of EPN combined solutions (Source: Bruyninx et al. 2006).

The LAC's all process a sub-network out of the EUREF Permanent Network following the rules and guidelines as set up by the International GNSS Service and supplemented by the EUREF Technical Working Group. They submit weekly free network solutions (SINEX format) to the EPN Regional Data Centre BKG. Most of the LAC’s are using the Bernese GPS software, except two LAC’s: ASI uses Microcosm and DEO uses GIPSY/OASIS. The 16 LAC’s are:

- ASI, The Centro di Geodesia Spaziale "G. Colombo", Matera, Italy;
- BEK, Bayerische Kommission für die Internationale Erdmessung of the Bavaria Academy of Sciences and Humanities, Munich, Germany;
- BKG, Bundesamt für Kartographie und Geodäsie, Germany;
- COE, The Centre for Orbit Determination in Europe (CODE), Astronomical Institute of the University of Bern, Switzerland;
- DEO, Delft Institute for Earth-Oriented Space Research, Delft, The Netherlands;
- GOP, The Geodetic Observatory Pecny, Pecny, Czech Republic;
- IGE, The Instituto Geográfico Nacional de España, Spain;
- IGN, The Institut Géographique National, France
- LPT, The Bundesamt für Landestopographie, Wabern, Switzerland
- NKG, The Nordic Geodetic Commission GPS data Analysis Center, Chalmers University of Technology and Onsalo Space Observatory, Sweden;
- OLG, The Institute for Space Research (ISR/ASS), Graz, Austria
- ROB, The Royal Observatory of Belgium, Brussels, Belgium;
- SGO, The FOMI Satellite Geodetic Observatory, Budapest, Hungary;
- SUT, The Slovak University of Technology, Bratislava, Slovakia;

- UPA, The University of Padova, Padova, Italy;
- WUT, The Warsaw University of Technology, Warsaw, Poland.

The weekly combined time series are used for monitoring the EPN site performance and consequently the coordinate time series of each EPN site. In 2000, the special project (SP) “EPN Time Series Monitoring” has been created to deal with this specific task (Kenyeres and Bruyninx, 2004).

The EPN products include weekly station positions of the EPN stations obtained from the combined solution of the 16 contributing LAC’s. A “rapid” solution with 1-hourly tropospheric zenith path delays contributes to the IGS combination. Another product is the EPN sub-network solution as contribution to the IGS Project TIGA. These products are updated weekly and the latency is about 4 weeks. Furthermore, a monthly updated cumulative solution with station positions and velocities tied to the ITRF is provided regularily. As part of recent ITRF realizations (e.g., ITRF2000), also station positions and velocities of the EPN stations are provided by the ITRS Centre with a latency of a few years.

5.1.4.4 European Terrestrial Reference System (ETRS89)

The ETRS89 is being adopted as the official system for geo-referencing by several organisations and most European countries. A network of geodetic reference sites determined at national and multi-national level by GPS campaigns achieves the establishment and maintenance of the European Reference Frame. The ETRS89 definition stipulates that its realizations should be co-moving with the rigid part of the Eurasian tectonic plate and should be consistent with the ITRS at epoch 1989.0. ITRS and ETRS89 are conceptually identical, differing by conventional transformation formula.

Up to 2001, the motion of the rigid Eurasian plate was realized by the geophysical model NUVEL-1A-NNR (DeMets, 1994). In the case of the ITRF2000 computation a new rotation vector has been computed for Europe based on 19 selected ITRF stations with high geodetic quality (Altamimi and Boucher, 2002), which differs significantly from the geophysical model (Kierulf et al., 2003). It has to be considered, that both models do not take into account intra-plate deformations.

The EUREF TWG has initiated a project to establish a Dense European Velocity Field (DEVF) whose main objective is to ensure the long-term maintenance of the ETRS89 (Altamimi, 2004). As a contribution to this DEVF project, EPN weekly combined solutions are analysed, by stacking the corresponding time series, provided in SINEX format. Using CATREF software (IGN, France), the datum definition is implemented with minimum constraints over a set of high-quality EPN sites.

In the near future, it is intended to make station positions and velocities of the EPN, expressed in the ETRS89, available to the users. This cumulative solution will be updated regularly and will be used as a backbone of the DEVF. The intention is also, to include weekly solutions of national and local permanent networks as available from the national authorities.

5.1.4.5 European Combined Geodetic Network (ECGN)

The European Combined Geodetic Network (ECGN) is a kinematic network for the integration of time series of spatial/geometric observations (GNSS – GPS/GLONASS and in the future Galileo), gravity field related observations and parameters (precise levelling, tide gauge records, gravity observations, Earth and ocean tides), and supplementary information (meteorological parameters, surrounding information of the stations, e.g. eccentricities and ground water level). The objectives of ECGN as Integrated European Reference System for spatial reference and gravity are:

- Maintenance of the terrestrial reference system with long-term stability with an accuracy of 10^{-9} for Europe, especially for the height component;
- In-situ combination of geometric positioning (GNSS) with physical height and other Earth gravity parameters at 1 cm accuracy level;
- Modelling the impact of time-dependent parameters of the solid Earth on the Earth's gravity field, the atmosphere, the oceans, the hydrosphere for different applications of positioning;
- Integration of the spatial and height reference system into the Earth's gravity field parameter estimation;
- Modelling of gravity field components to validate the gravity field missions CHAMP, GRACE, GOCE.
- Contribution to the IAG project GGOS and platform for further geo-components (GMES, GEOSS, GGOS).

The first call for participation in the project was directed to the implementation of the ECGN stations. These stations include the observation techniques GNSS, gravity (super conducting gravimeter and/or absolute gravimeter), levelling connections to nodal points of the United European Levelling Network (UELN) and meteorological parameters. As a result of this first call a total of 50 ECGN stations (8 core stations, 42 stations with the "ok-status") were selected. From the 74 originally proposed stations 7 were identified as candidates and 17 as proposed stations. More information about the current status and the distribution of ECGN stations is shown in Ihde et al. (2005). Standards and guidelines for the ECGN stations were prepared for each main observation technique (GNSS, gravity measurements, levelling, tide gauge). They include details about the execution of the measurements, the expected accuracy as well as information on the collection of data (see Ihde et al., 2005). At an ECGN station the observation points of different techniques should be located in close proximity. According to the conditions each observation technique has its own marker and one marker will be selected as the primary reference. Local ties to this marker need to be defined according to the ECGN standards for local tie determination. It was decided that the intended 2nd call focussing on the methodology and data analysis has to be postponed because first of all the currently available extent of information for the ECGN stations and their quality has to be improved (e.g., metadata forms, availability of measurements, data policy, re-analysis of GPS observations, etc.) in order to reach the goals of this project.

5.1.4.6 European Research Networks and Projects

An "EPN Special Project on coordinate time series analysis" has been created in 2000 (Kenyeres and Bruyninx, 2004). The goal is the identification, interpretation and elimination of offsets and outliers present in the EPN coordinate time series in order to estimate reliable coordinates and velocities and consequently maintain a high-quality kinematic reference network. Any change in any station component (including the environment) can lead to an inconsistency in the time series which is then visible as an offset, outlier or change in the coordinate repeatability or even a change of the apparent station velocity. These effects commonly degrade the quality of the estimated parameters in terms of biases or higher uncertainties, and can be considered as the major limiting factor concerning today's accuracy.

Main causes are, e.g., equipment changes, antenna malfunctioning, annual effects, tectonic activity, processing strategy changes, changes in the ITRS realizations. The final purpose of the investigation was the creation of station problem files, which include the estimated coordinates offset values and the most critical outlier periods. These tables include about 50 offset values and some 80 outlier periods. The tables are freely available and offered for the use in geodesy and geokinematics. In addition, improved EPN coordinate time series are displayed at the EPN CB web site at http://www.epncb.oma.be.

In June 2001, the EPN Special Project "Troposphere Parameter Estimation" started its practical work. The project meanwhile comprises about 150 EPN sites analysed by 16 LACs (Söhne and Weber, 2004). The main purpose of the data analysis in the field of positioning is the improvement of the height component. The results yield one Zenith Total Delay (ZTD) parameter per hour, which are compared among the LACs. Moreover comparisons between GPS and VLBI estimates of the IVS are performed.

Another field of interest is atmospheric research. Therefore the activity "GPS Meteorology in Europe – COST716, EUMETNET, and EUREF" has been initiated. The main interest is the benefit for both geodesy and meteorology in common activities for atmospheric research. GPS meteorology is based on a voluntary network for near real-time exchange of GPS data with the goal of numerical weather prediction and climate monitoring and research. The COST716 project has been started in March 2001 and has been finished in 2004. Altogether 428 stations participated in the activities analysed by 10 operational Analysis Centres (ACRI, ASI, BKG, IEEC, GFZ, GOPE, LPT, NKG, NKGS, and SGN), see http://www.knmi.nl/samenw/cost716). EUMETNET is a network of 20 European Meteorological Services (see http://www.eumetnet.eu.org). The EUMETNET GPS programme comprises to ensure continuity of the European atmospheric research network, promotes cost/benefit sharing between parties, liaisons with the geodetic community (data providers and processing centres), establishes data processing policies, promotes applications and provides support and documentation.

In June 2002, the IAG Sub-commission for Europe (EUREF) adopted a resolution to disseminate differential corrections in RTCM format via Internet for DGPS positioning and navigation purposes. The EPN intends to add an Ntrip-based real-time component to its so far post-processing oriented services. These issues are investigated and developed within the "EUREF – IP Pilot Project" (Weber and Gonzales-Martesanz, 2005). EUREF-IP Ntrip Broadcaster Implementation is available now in BKG, FGI, FÖMI, GURS, IGNE, Swisstopo. As a practical application a successful EUREF-IP Ntrip Driving Test has been performed in Finland over a distance of 18 km.

5.1.4.7 National Networks in Europe

The liaison with EuroGeographics, the consortium of the National Mapping and Cadastre Agencies (NMCA) in Europe, continues through its Expert Group on Geodesy (ExGG). The main link between EuroGeographics and EUREF is the definition and maintenance of a common reference system for Europe providing accurate transformation parameters and procedures for the national systems (see http://www.eurogeographics.org/eng/01_about.asp).

Today, EUREF has been adapted by 26 countries: Armenia, Austria, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Great Britain, Hungary, Italy, Latvia, Lithuania, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland, and Turkey. The status concerning observation networks, data analysis procedures, and the participation in diverse EUREF components and projects differs considerably for the contributing countries. In general each of the nations contributes with few stations to the EPN, which is important to transform the national reference frame into ETRS89. In addition the national authorities operate national permanent stations for various purposes (e.g., monitoring of the national reference frame, contribution to various projects), and GPS campaigns were carried out for a densification of the national networks. In general the reference epochs for the realizations of the national reference frames in the ETRS89 system are not consistent for the European countries. An overall description of the current status for all the national networks, and the data analysis procedures would exceed the scope of this assessment report. Details are reported in the corresponding national reports, which are published in the Annual EUREF Symposia Proceedings.

5.1.5 Summary of Reference Frame Products

International Terrestrial Reference Frame: The latest realization is the ITRF2000, comprising about 800 stations located on 500 sites. For about half of the stations the accuracy for the positions is better than 1 cm and better than 3 mm/yr for the velocities. For about 20% of the stations the standard deviations for the velocities exceeds 1 cm/yr, which is not tolerable for a precise reference frame. These poorly observed stations have to be excluded from future ITRF realizations. Currently, the computation of a new realization is in progress by the ITRS Combination Centres. This ITRF2005 solution is based on the combination of time series solutions with station positions and EOP. Updated ITRF realizations are normally provided every few years with a latency of 1-3 years. The time period from ITRF2000 to ITRF2005 is larger, since the IERS has been reorganized and the ITRF2005 computation is based on a completely new strategy, which also had to be implemented by the Technique Services (IGS, ILRS, IVS, IDS) to provide the input data in the form of time series solutions with station positions and EOP.

International Celestial Reference Frame: A first realization of the ICRF was derived in 1995 from about 1.6 million observations in the time span 1979-1995. Following the ICRF maintenance process, the ICRF-Ext.1 was constructed by using additional data until April 1999. A second extension ICRF-Ext.2 contains about 1.2 million additional observations from approximately 400 sessions between May 1999 and May 2002. For various reasons, there is an urgent need for the production of a new ICRF realization in the near future.

Earth Orientation Parameter: Various solutions are computed at the Earth Orientation Centre: long-term solution (IERS C01), normal values at five and one-day intervals (IERS C02 and C03) and the operational smoothed solution Bulletin B at one-day intervals published monthly and providing EOP with a delay of 30 days with respect to the date of publication. Bulletin B is updated in an operational mode in the IERS C04, which is computed twice a week. Until now, the EOP solutions are computed separately from the terrestrial reference frame. Consequently, the results are not consistent and significant biases between different EOP series do exist. The new ITRF2005 solution is for the first time a common adjustment of the terrestrial reference frame and EOP, and will ensure consistency between both product types.

Time series solutions: Intra-technique combined time series solutions with station positions and EOP are routinely generated by the IGS and the ILRS with a time delay of 1-2 weeks. The IVS generates routinely combined daily session solutions with positons and EOP with a latency of up to a few months. Until now, no intra-technique combined time series solutions are provided by the IDS. These time series solutions generated from one technique only, can be affected by technique-specific biases and should not be provided to the users as final product for geodynamic interpretations. Until now, inter-technique combined time series solutions are not generated routinely. The development and implementation of suitable methods for the weekly inter-technique combination to generate consistent IERS products is the aim of the IERS Combination Pilot Project, which has been initiated in 2004.

European reference frame products: The stations of the European Permanent Network (EPN) are routinely analysed by 16 LACs on a weekly basis and combined to generate the official combined weekly EUREF solutions with station positions. These products are updated weekly and the latency is about 4 weeks. Furthermore, a "rapid" solution with 1-hourly tropospheric zenith path delays contributes to the IGS combination. Another product is the EPN sub-network solution as contribution to the IGS Project TIGA. These products are also updated weekly with a latency of about 4 weeks. In addition, a monthly updated cumulative solution with station positions and velocities tied to the ITRF is provided regularly. As part of recent ITRF realizations (e.g., ITRF2000), also station positions and velocities of the EPN stations are provided by the ITRS Centre with a latency of a few years.

5.2 Earth Physical Shape and Gravity Field

5.2.1 Introduction and Objectives

The Earth's physical shape – the geoid – determined by the Earth's gravity field is a key quantity to enhance the knowledge of the Earth's mass distribution and redistribution as an indispensable prerequisite for the exploration of geodynamic convective and climatologically driven processes within the Earth system, as well as for applications in surveying and navigation. Vice versa, the results of the accurate determination of the static and the time-variable components of the Earth's gravity field and the geoid will provide significant contributions to the establishment of GGOS as well as to the goals of GMES. In this chapter we first briefly review the context for an accurate determination of the Earth's physical shape and gravity field and its links to GMES. In sections 5.2.2-5.2.3 an assessment of the existing space-borne-, airborne- and ground-based observational systems and of the existing infrastructure for modelling and monitoring the gravity field at different spatial and temporal scales will be given. A focus is set on the identification of deficiencies and gaps of the existing observational systems in view of current research fields as well as potential future applications and developing user needs.

Context of the Determination of the Earth's Gravity Field and Geoid

From the view point of practical applications in surveying and navigation the fundamental role is driven today by the wide-spread and ever evolving use of accurate Global Navigation Satellite Systems (GNSS) such as the US GPS, the Russian GLONASS or the to-be established European GALILEO system. In addition to the purpose of precise orbit determination of Earth-orbiting satellites, the key problem is to integrate the purely geometric results for the point-positioning from the GNSS data into existing physically-technically relevant reference systems. In particular to relate geometric heights determined from GNSS into practically relevant physical heights, which e.g. allow for the derivation of the direction of the flow of water, one needs the gravity-based geoid surface as accurate reference surface. In order to fully exploit our days accuracies for GNSS-based geometric heights at ± 1cm and better, over several hundred kilometres and longer, the geoid needs to be known with a comparable accuracy. Since at this level of accuracy the GNSS positioning is also sensitive to geophysical and climatologically-induced deformations of the Earth's surface the tiny temporal variations of the gravity field and the geoid, respectively, need to be known as well. A prominent example in this field is the so-called GPS-levelling based on height determination from GPS data and the geoid instead of the time- and cost-consuming levelling using terrestrial instrumentation including terrestrial gravimetry. Besides its capability of surveying larger areas in a time- and cost-efficient manner, GPS-levelling also offers the opportunity of unifying existing but, due to various reasons, inconsistent regional/national height systems. Another important example is the definition of a globally uniform height datum via a global and precise geoid which is needed for the determination of the mean sea level from altimeter mission data such as ENVISAT, JASON-1, ERS-2, TOPEX/POSEIDON and others.

In view of scientific applications the principle importance of the Earth's gravity field and the geoid is attributed to the basic correlation between the structure of the Earth's gravity and a spatio-temporal varying mass distribution of a dynamic Earth. In this way the gravity field and its potential surface, the geoid, can be regarded as a mirror reflecting mass distribution and mass transport within the Earth system (compare Fig. 5.2.1.1). Vice versa, an accurate determination of the gravity field including its temporal changes – together with simultaneous measurements of the Earth's deformation, its revolution in space as well as other remote sensing and geophysical data – allow for the quantitative determination of the underlying mass redistribution and its change in time. This is an indispensable quantity for the understanding and modelling of ongoing geodynamic and climatologically-driven processes, such as post-glacial rebound (PGR) in former ice-covered areas (e.g. Fennoscandia, Northern Canada) giving insight into lateral variations of the Earth's mantle viscosity, mass transport due to the global hydrological cycle, mass and heat flux of the surface and bottom currents in the world oceans or changes in the ice mass balance of the polar ice sheets and related variations in the global mean sea level. As ultimate goal, a consistent and continuous description of the spatio-temporal varying mass distribution of the Earth with accurate gravity measurements as a key observable, will lead to a deeper knowledge of the highly dynamic Earth system, which will contribute significantly to the development of sustainable strategies to safeguard the human habitat for future generations.

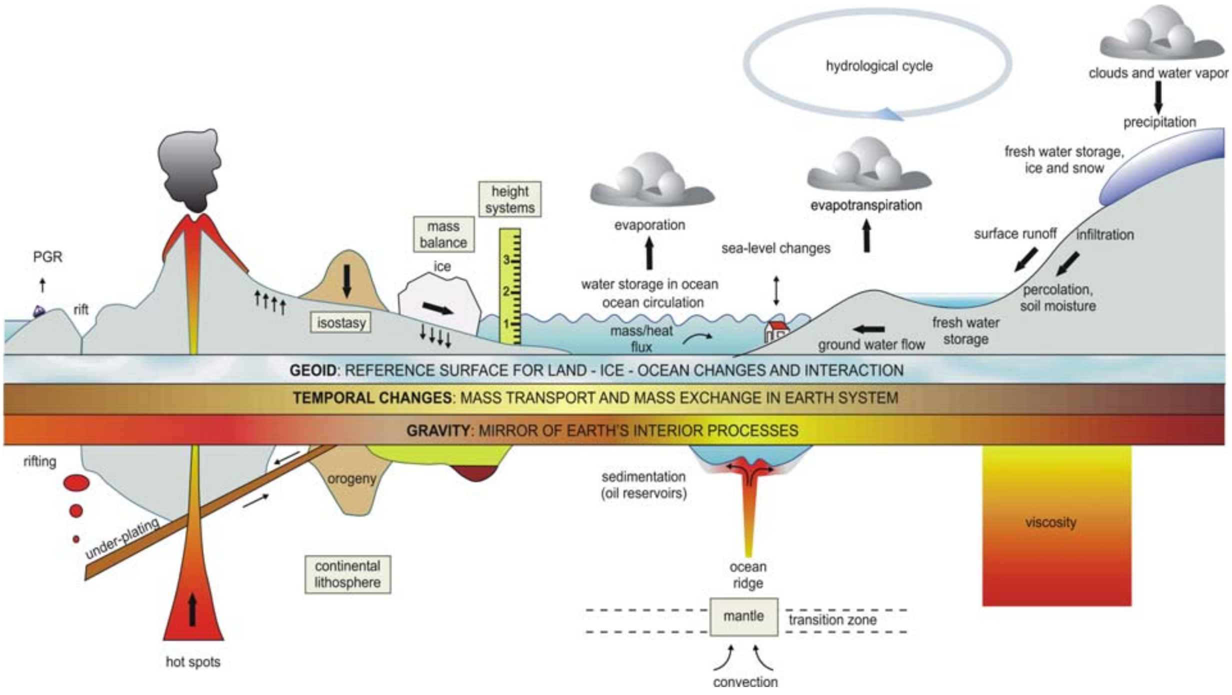


Fig. 5.2.1.1: The interrelation of gravity, gravity variations, mass transport and distribution (Ilk et al., 2005).

This principle relevance of the accurate determination of the Earth's gravity has been emphasized in various reports such as the US National Research Council report "Satellite Gravity and the Geosphere, Contributions to the Study of the Solid Earth and Its Fluid Envelope" (NRC, 1997) or "Scientific Objectives for Future Geopotential Missions" (ESA, 2003) and is fully acknowledged by the realization of the modern gravity satellite missions CHAMP, GRACE and GOCE as well as international and national research programmes (e.g. the priority research programme "Mass Transport and Mass Distribution in the Earth System" (Ilk et al. 2005) by the German Research Foundation (DFG)).

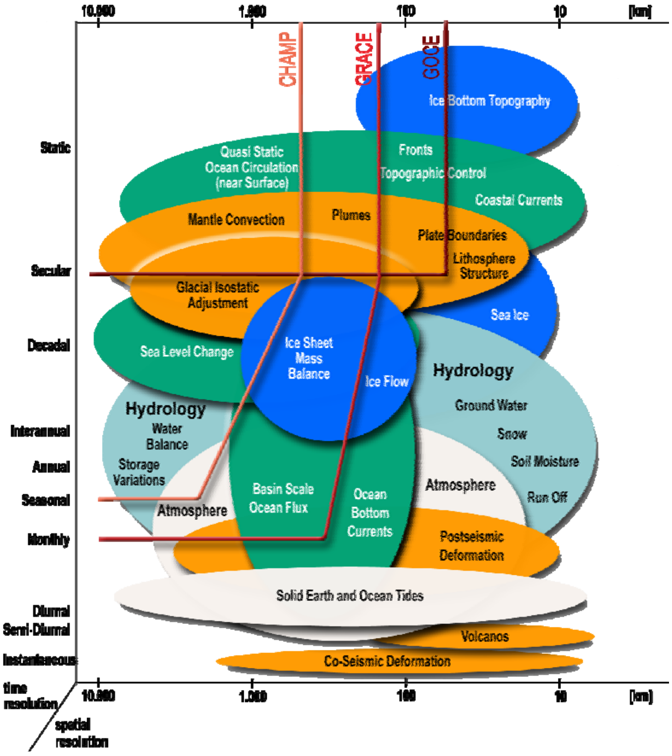
Links to GMES Tasks

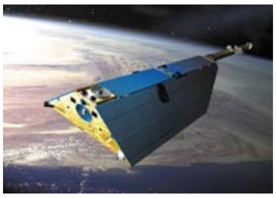
The European Union initiative "Global Monitoring for Environment and Security (GMES)" will enable decision-makers in Europe to gather, interpret and use data and information in support of sustainable development policies (COM, 2004). In this context existing and future gravity observing systems will contribute in a very basic way to the following fields:

- The establishment of consistent, physically-technically relevant geodetic reference systems along with the accurate determination of the Earth's geometry and rotation from geodetic observations in the frame work of the establishment of GGOS as a prerequisite for modern applications of GNSS data in surveying and navigation, and
- to allow for a consistent derivation of Earth system related quantities necessary to deepen the knowledge of geodynamical and climatologically driven processes which are of fundamental socio-economic interest (e.g. variations in the mean sea level, ice mass changes, the global hydrological water cycle, mass and heat flux in the global oceans and their interactions).

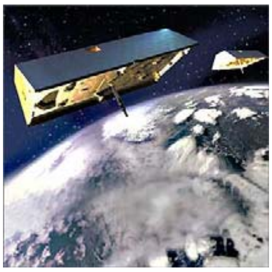
5.2.2 Space-Based Systems

Space-based systems are indispensable instruments for the determination of the global gravity field and have been used since more than 30 years for the computation of global gravity models. However, despite some significant improvements in the observation technology and an increasing number of satellites, the knowledge of the Earth's gravity field improved only gradually and remained restricted to long wavelength features of the field (Reigber et al, 2005). Only the marine geoid could be resolved with higher accuracy using satellite altimetry data. Improvements with respect to spatial resolution over continents could be obtained from terrestrial and airborne-based data. However, due to heterogeneities of and larger gaps in the available data the advances were not thorough in terms of homogeneity and accuracy of the gravity models. The derivation of time-variable gravity signals at spatial and temporal scales relevant to the applications addressed in the previous section (compare Fig. 5.2.1.1) was restricted too, since only few parameters of the conventional mathematical representation of the gravity field could be determined from existing observational data such as ground-based Satellite Laser Ranging data (SLR). The main reasons originate from general restrictions in the sensitivity of the missions with satellite altitude, insufficient measurement accuracy, sparse tracking data coverage and difficulties to model non-gravitational forces such as air drag or solar radiation pressure. The situation changed dramatically with the advent of the modern, dedicated gravity missions CHAMP (Reigber et al., 1999) and GRACE (Tapley et al., 2004a) and will further improve with the soon to be launched ESA mission GOCE (ESA, 1999).

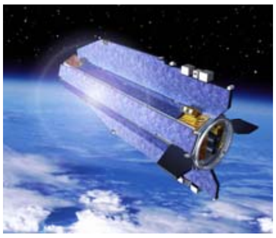




CHAMP
Launch: July 2000
Concept: h/l-SST
http://www.gfz-potsdam.de/champ/
http://www.dlr.de/champ



GRACE
Launch: March 2002
Concept: l/l-SST
http://www.gfz-potsdam.de/grace/
http://www.csr.utexas.edu/grace/



GOCE
Launch: Feb. 28, 2007
Concetp: SGG
http://www.esa.int/export/esaLP//goce.html
http://www.goce-projektbuero.de

Fig. 5.2.2.1: Spatial and temporal scales of geoid signals associated to solid earth (orange), ocean (green), ice (dark blue) and continental hydrology (light blue) processes. The red lines show the spatial and temporal resolution limits of CHAMP, GRACE and GOCE mission (Ilk et al., 2005).

The Modern Satellite Gravity Missions CHAMP, GRACE and GOCE

CHAMP, GRACE and GOCE are based on advanced gravity observation techniques such as the Satellite-to-Satellite Tracking (SST, CHAMP and GRACE) concept and the satellite gravity gradiometry (SGG, GOCE). In case of SST the key observables are measurements of the intersatellite distance (range) or its change (range-rate) between pairs of satellites. This observation type has a significantly higher sensitivity to the gravity signals at satellite altitude than the conventional ground-based satellite data. Two different methods can be distinguished:

a) The high-low SST (h/l-SST), i.e., the measurement of SST data between a high- and low-orbiting satellite (LEO) and

b) the low-low SST (l/l-SST), i.e. the measurement of SST between a pair of low-orbiting spacecrafts.

Due to the stronger attenuation of the gravity signal for the high-orbiter the h/l-SST improves only the resolution of long wavelength features while the l/l-SST gives access to medium and short wavelengths. In case of high measurement accuracy and a low LEO altitude the l/l-SST is currently considered the key technology for the observation of the time-variable gravity field (compare Fig. 5.2.2.1). The CHAMP satellite is based on the h/l-SST concept only, while GRACE combines the h/l- and l/l-SST. The h/l-SST link is established for both missions by flying a geodetic GPS receiver onboard the LEO satellites and using the GPS signals to precisely determine the satellites' trajectories. To reduce the effect of non-conservative forces capacitive 3d accelerometers are precisely located at the satellite's center of gravity measuring non-gravitational accelerations like air drag and solar radiation pressure. The instrumentation is completed by sets of star cameras to derive an accurate absolute and relative orientation of the satellites in the celestial reference system.

In case of GOCE the key instrument is a gradiometer, i.e., a 3d constellation of ultra-precise 3d accelerometers which directly observe the second derivatives of the gravity potential. These observations are in particular sensitive to the short wavelengths thus allowing for an improved recovery of small features of the static gravity field. Due to limitations in the sensitivity of the gradiometer measurements to time-variable gravity changes at long to medium wavelengths and the projected short observation period resulting from a necessarily low orbit at about 250 km the SGG concept is not expected to contribute to the determination of the time-variable gravity field (compare Fig. 5.2.2.1).

Along with their dedicated instrumentation the missions have highly inclined, almost circular orbits to obtain a sufficient spatial coverage over the entire Earth (CHAMP 89°, GRACE 89.5°, GOCE to be 87.5°) and low initial altitude above the Earth's surface (CHAMP 450 km, GRACE 500 km and GOCE ~ 250 km) to counteract the damping of the signal of the Earth's gravity field with increasing orbital height.

Due to the different spatial and temporal sensitivity of the missions the three concepts h/l-SST, l/l-SST and SGG are regarded complementary for the determination of the Earth's gravity field. In the sequel the assessment is split into the determination of a mean, quasi-static gravity field model and the computation of gravity field variations in time.

Mean Field Models

The need for a precise mean field is twofold:

(1) satellite-only models from CHAMP, GRACE and in future GOCE shall provide the best available geoid for use as a reference surface for the determination of the sea surface topography from satellite altimetry data for oceanographic modelling.

(2) spatially even higher resolving models compiled from the satellite data and surface data given by terrestrial gravimetry, aerogravimetry and altimetry will be needed for GNSS-based surveying (determination of physical heights) as well as in geophysical applications (geotectonic/geodynamic interpretation and modeling).

Figure 5.2.2.2 depicts the gain in the spatial resolution of the mean field from the pre-CHAMP era via gravity models derived solely from CHAMP and GRACE data to the expected resolution from the GOCE mission.

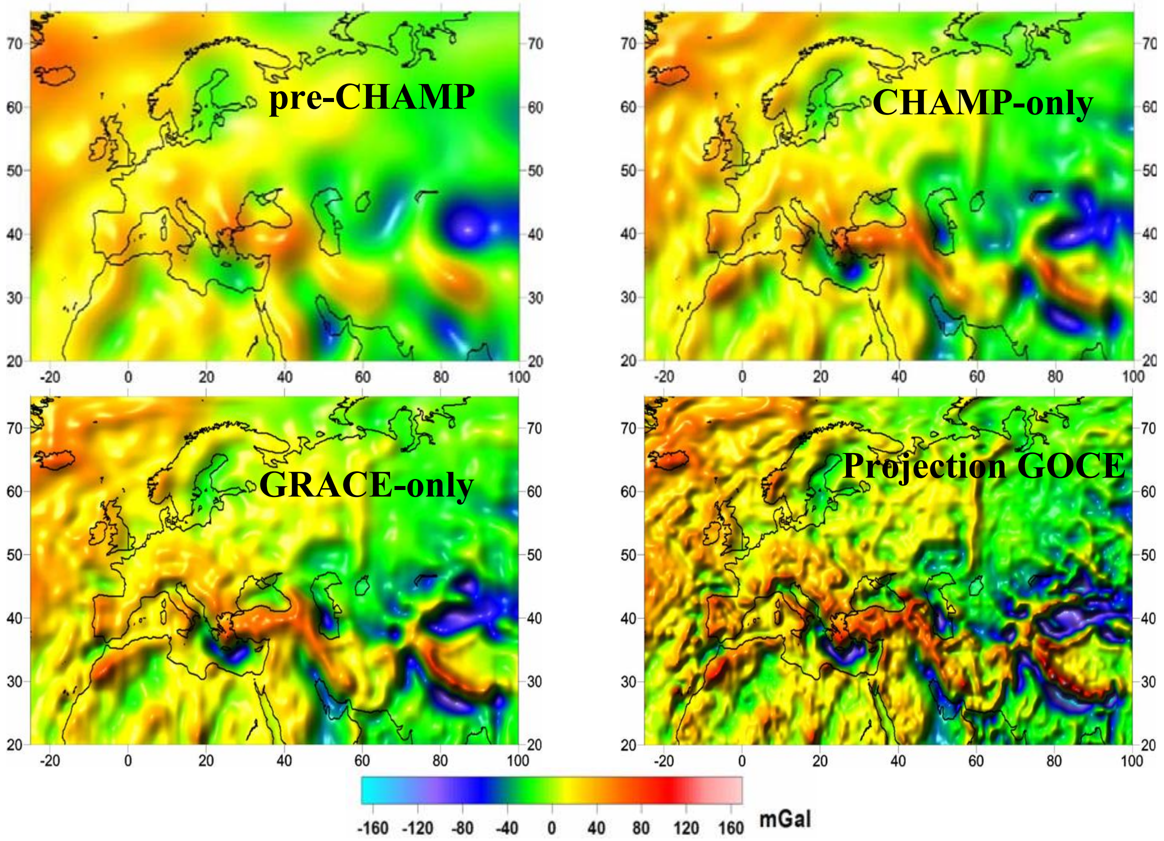


Fig. 5.2.2.2: Development of the spatial resolution of static global gravity field models from geodetic satellite data of the (pre-CHAMP era (i.e. GRIM5-S1GRIM5-S1, Biancale et al. 2000 model), to CHAMP (EIGEN-CHAMP03S, Reigber et al., 2004a), to GRACE (EIGEN-GRACE02S, Reigber et al., 2004b) and the expected resolution with GOCE. Displayed are the deviations of gravity with respect to mean values (gravity anomalies). Units are mGals, where 1 mGal = 10^{-5} m/s².

The gain in resolution and accuracy for the geoid is illustrated in Fig. 5.2.2.3 in the spectral domain as a function of the spatial half-wavelength. It can be seen that with GRACE the minimal resolvable half-wavelength has dropped from about 300 - 200 km of pre-CHAMP era satellite-only models like GRIM5-S1 (Biancale et al., 2000) or EGM96S (Lemoine et al.,

1998) to about 150 km (EIGEN-GRACE02S, Reigber et al. 2004b). The amplitude of the accumulated geoid error at this half-wavelength has decreased below 50 cm to about one third of the value of the pre-CHAMP era models. The currently achieved performance for the recovery of the mean field with respect to specific values relevant for applications in practical and scientific applications is shown in Table 5.2-1. Comparisons in the space domain to independent terrestrial and altimetric-derived surface gravity data confirm the strength and homogeneity of the novel satellite-based gravity models (see Table 5.2-2). Although there are inhomogeneities of the terrestrial and altimetric-derived surface gravity data with respect to spatial distribution (gaps) and accuracy and the obtained values do not reflect the true outer accuracy of the satellite-based models, the overall tremendous gain becomes evident.

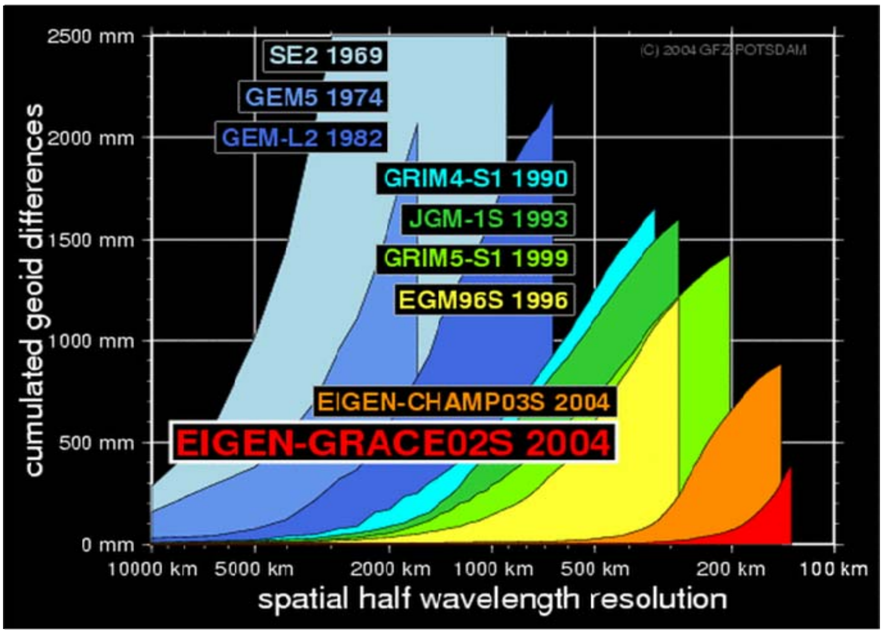


Fig. 5.2.2.3: Development of spatial scales of geoid signals from satellite-based global gravity models. EIGEN-CHAMP03S is a CHAMP-only model from 33 months of CHAMP data. EIGEN-GRACE02S is a GRACE-only model from 111 days of GRACE data.

Table 5.2-1: Mean gravity field recovery: geoid (cm) and gravity anomaly (mGal) accuracy vs. resolution (λ/2 pixel side length). Shown are the already achieved results for CHAMP and GRACE and the expected accuracy (by pre-launch simulations) of all three missions. For CHAMP and GRACE the expected improvements are due to advances in data processing and the decreasing orbit altitude.

Mission	**achieved geoid/gravity/resolution**	**expected**
CHAMP (33 months)	10 cm / 1 mGal / 350 km 1 cm / 0.02 mGal / 650 km	factor 1.5 improvement wrt. currently achieved
GRACE (110 days)	10 cm / 1 mGal / 200 km 1 cm / 0.02 mGal / 330 km	factor 5 improvement wrt. currently achieved
GOCE	-	2 cm / 1 mGal / 100 km

Table 5.2-2: Comparison of satellite-only geopotential models with altimeter-derived geoid heights (N, 'CLS01 minus ECCO' oceanic geoid) and gravity anomalies (Δg, NIMA marine gravity anomalies) for a grid spacing of 5° x 5° and 2.5 ° x 2.5 °. Values are rms – root mean square of difference about mean

	rms(dN)		**rms (dΔg)**	
Model	**5° x 5°**	**2.5° x 2.5°**	**5° x 5°**	**2.5° x 2.5°**
GRIM5-S1 (pre-CHAMP)	44 cm	76 cm	2.00 mGal	5.40 mGal
EIGEN-CHAMP03S	15 cm	30 cm	0.48 mGal	3.23 mGal
EIGEN-GRACE02S	14 cm	16 cm	0.28 mGal	1.25 mGal

To illustrate the relevance of these recent developments for applications, the determination of the dynamic sea surface topography is shown in Fig. 5.2.2.4 as one major example. The ocean dynamic topography is due to ocean current systems like the Gulf stream in the North Atlantic, the Kuroshio stream in the Northern Pacific or the Antarctic Circumpolar Current. This knowledge is of ultimate importance for the understanding of these surface circulations including the mass and heat fluxes therein, being a major quantity in numerical models of the world's climate. It is determined independently from oceanographic data from the difference of the instantaneous surface of the oceans observed by satellite altimetry and the precise geoid derived e.g. from GRACE. The geoid represents the reference surface of an ocean without currents while the sea surface from altimeter data represents the dynamic ocean surface, thus the difference gives a quantitative measure for the current dynamics. Fig. 5.2.2.4 (left) depicts the incomplete determination of the ocean dynamic topography from a satellite-only model prior to CHAMP/GRACE and on the right the results based on a GRACE-only derived geoid.

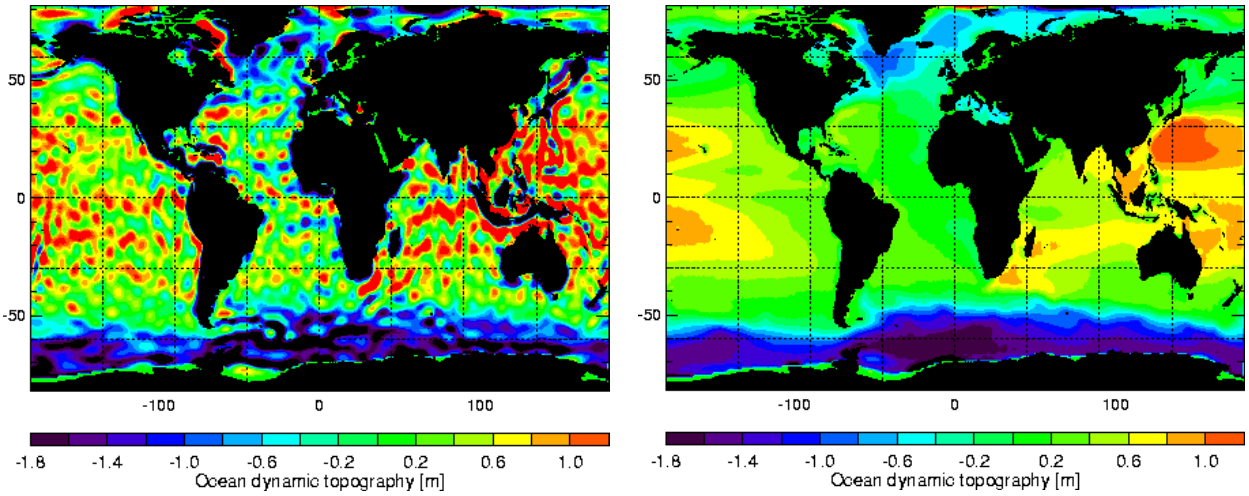


Fig. 5.2.2.4: Left: Ocean dynamic topography from satellite altimetry and the geoid of a pre-CHAMP era gravity model (EGM96S, Lemoine et al., 1998) and the geoid from a GRACE-only gravity model (right, EIGEN-GRACE02S, Reigber et al., 2004b). The sea surface heights from altimeter data have been processed at GFZ Potsdam.

Temporal Gravity Field Variations

The determination of time-variable gravity signals at the required spatial resolution (compare Fig. 5.2.2.1) is at the moment only possible from GRACE-based gravity models. At present various groups worldwide including the CHAMP/GRACE-Science Data System (SDS) team at GFZ Potsdam are routinely computing global gravity models with a monthly resolution from monthly batches of GRACE data. The evolution of the obtained time series with respect to the mean static model gives access to temporal variations of the Earth's gravity field. These time series have commenced intensive investigations in various Earth system related sciences such as e.g. hydrology (changes in the continental water storage, e.g. Tapley et al., 2004b), oceanography (e.g. Tapley et al., 2003, Kanzow et al.,2005, Han et al. 2005) and glaciology (changes in the polar ice sheets, e.g. Velicogna et al. (2004)). As examples results for hydrology and oceanography are presented in the sequel.

Figure 5.2.2.5 (left) depicts the change of the geoid surface derived from monthly GRACE-only gravity models due to variations in the distribution of the continental water storage between May and August 2003. The expected geoid variations based on water storage maps from a state-of-the-art global hydrology model (WGHM, Döll et al. 2003) are shown on the right of Fig. 5.2.2.5. Both data sets have been smoothed using a spatial averaging function (Gaussian kernel) with a filter radius of 500 km. From the comparison it can be seen that GRACE clearly traces changes in the water storage in the world's largest drainage basins such as the Amazon in South America, Niger and Congo in Africa, the Ganges in India or the Lena/Ob in Siberia. The observed discrepancies in amplitude between the GRACE results and the predicted values from the hydrology model have been expected, since global hydrology model are known to underestimate the water storage change at these global scales. Apart from residual GRACE modeling errors visible as stripes in Fig. 5.2.2.5 (left) (and which probably also influence the estimate of the amplitude of the mass variations), this result clearly indicates limitations of state-of-the-art hydrological modeling of the global water storages and the potential contributions of the GRACE mission in this field. Since changes in the continental water storage are closely interrelated with water transport in the oceans and atmosphere, GRACE-based estimates of the continental water mass will significantly contribute to the understanding and modeling of the global water cycle.

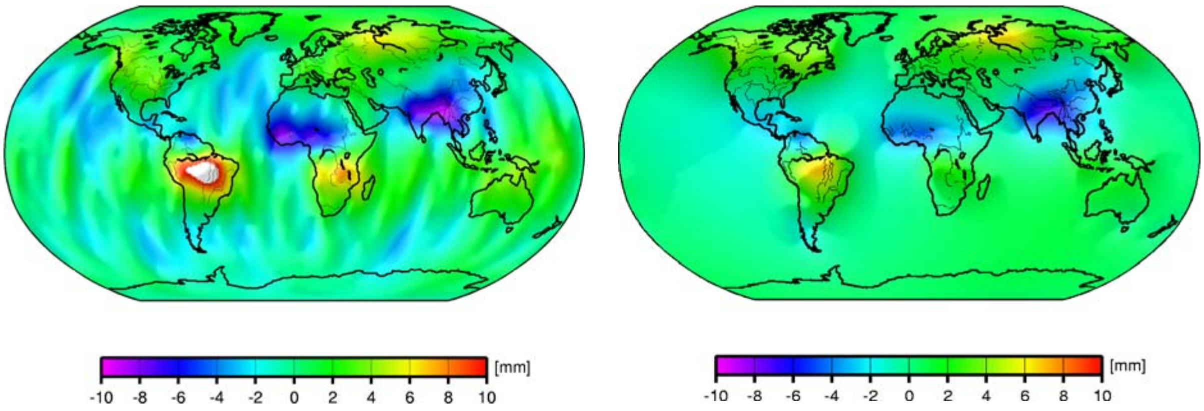


Fig. 5.2.2.5: Geographical distribution of changes of the geoid surface in millimeter between the months May and August 2003 observed by GRACE (left) and predicted from the WGHM (Döll et al. 2003) hydrology model. Both data sets have been smoothed using the Gaussian averaging function for an averaging radius of 500 km.

As an example in oceanographic applications Fig. 5.2.2.5 depicts results for the ocean bottom pressure variation in the North Atlantic observed by GRACE and from the independent global ocean circulation model ECCO (Stammer et al. 2003) for 2.5 years (update from Kanzow et al. (2005)). Global measurements of the ocean bottom pressure are an important quantity to understand and model oceanic mass redistributions due to deep ocean currents being a fundamental part of the global ocean circulation system. Compared to the hydrological mass redistributions variations in the ocean bottom pressure are about one order of magnitude smaller (1-3 millimeter amplitude for geoid height variations) and are still difficult to be detected by GRACE. However, as indicated by Fig. 5.2.2.5 the general pattern of seasonal large-scale variations is already traceable in monthly GRACE-only solutions.

In general the actual performance of the GRACE-based time-variable gravity is difficult to assess since no independent global data set of comparable strength and homogeneity exists. With respect to hydrology the minimal spatial resolution of present state GRACE-only gravity models globally lies at or above 500 km half-wavelength, but may be even smaller in larger drainage basins with large water storage changes (e.g. the Amazon or the Ganges). For applications in oceanography the spatial resolution is much smaller – around 1000 km half-wavelength – due to the significantly weaker signals to be observed there and a larger impact of residual systematic modeling errors in the GRACE solutions. Table 5.2-3 shows the estimated accuracies for mass variations from a recent time series of monthly GRACE-only models in terms the height of an equivalent water column (Schmidt et al. 2005).

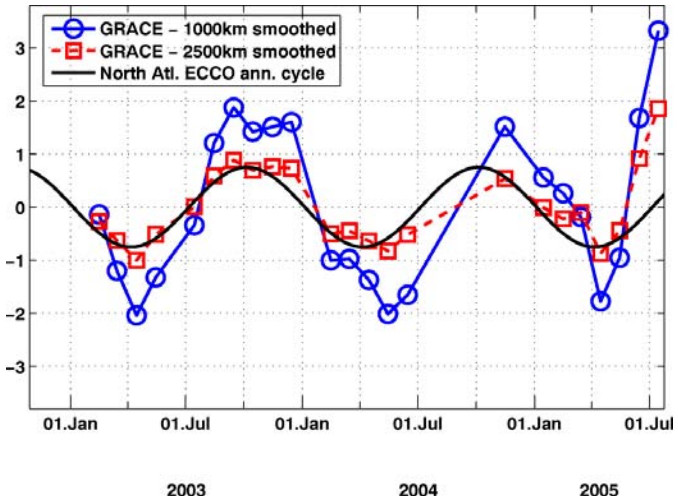


Fig. 5.2.2.6: Seasonal evolution of the ocean bottom pressure signal in the North Atlantic in mbar from GRACE and from the independent ocean circulation model ECCO (solid line). Estimates from GRACE are averaged using the Gaussian filtering functions for a 1000 km (circles) and a 2500 km (squares) radius

Table 5.2-3: Estimated accuracy of GRACE temporal gravity field recovery in terms of the height of an equivalent water column (Schmidt et al. 2005)

Estimated accuracy of monthly GRACE-only models				
half wavelength [km]	1500	1000	750	500
water column [cm]	0.9	1.5	2.1	3.7

Ground Infrastructure for Space-Based Systems

In the context of the determination and observation of the Earth's gravity field via space-, airborne- and ground-based systems diverse infrastructure for modelling (including provision of quality assessed gravity models and/or gravity data) and monitoring the gravitational field has developed in national and international efforts in the past. In the following, prominent institutions, groups, cooperations and consortiums with respect to the three systems are summarized.

For the space-based systems the Science Data Systems (SDS) of modern gravity missions CHAMP, GRACE and GOCE can be considered as the currently most developed institutions with respect to the modelling of the Earth's gravity field (including provision of quality assessed gravity models and/or gravity data) as well as a routinely monitoring of the field. The SDS described below, are assisted by international science teams which use the gravity model products provided by the SDS in their scientific application which along with the research gives an assessment of the products. Other groups of the science teams are working on methodological issues in the context of an improved modelling and recovery of the Earth's gravity field.

CHAMP and GRACE Science Data Systems and GOCE High-level Processing Facility

The operational processing of CHAMP and GRACE mission data is performed in Science Data Systems (SDS) which are part of the CHAMP and GRACE mission ground segments. The ground segment supplement is the Mission Operation System operated by the German Space Operation Center in Oberpaffenhofen being responsible for the monitoring of satellite function, operation of receiving and transmit stations and the raw data center (RDC). For near-real-time processing of GPS occultation data the prime receiving stations in Weilheim and Neustrelitz are completed by a polar receiving station in Ny Alesund installed and operated by GFZ Potsdam. While the CHAMP SDS is managed by GFZ exclusively, the GRACE SDS was installed and is operated in a joint effort between the University of Texas Center for Space Research (UTCSR), the Jet Propulsion Laboratory (JPL) and GFZ Potsdam based on CHAMP heritage (Watkins et al., 2000).

The SDS regularly receives the Level-0 raw instrument data (GPS, K-band, star camera, accelerometer, and housekeeping data) from the RDC and applies all calibration factors which are necessary to convert the binary encoded onboard measurements to engineering units (Level-1A). Then the data are correctly time tagged and the sampling rate is reduced. Resulting Level-1B products are then used to derive the CHAMP and GRACE Level-2 gravity field solutions. To take into account short-term atmospheric and oceanic mass variations the GRACE SDS also calculates on a routine basis "de-aliasing" Level-1B products based on ECMWF meteorological data (Flechtner et al, 2006).

The CHAMP and GRACE products are then provided to the international user community using the Integrated System and Data Center (ISDC) at GFZ and the Physical Oceanography Distributed Active Archive Center (PO.DAAC) at JPL.

The high-level processing of data from ESA's future GOCE mission will be performed within the GOCE High-level Processing Facility (HPF), which is currently under development by 10 leading European institutions (TU Munich, GFZ Potsdam, University

Copenhagen, SRON, TU Delft, TU Bonn, University Bern, CNES, Politechnico di Milano, and TU Graz) united in the European GOCE Gravity Consortium (EGG-C) (Figure 5.2.5.2).

The Central Processing Facility (CPF) located in SRON (The Netherlands) regularly receives the Level-1 instrument data from the Payload Data Segment and distributes the data over 5 Sub-processing Facilities (SPFs) of the HPF which have the following tasks

- SPF3000 (SRON, TU Delft, University Copenhagen, TU Munich): instrument data pre-processing and external calibration.
- SPF4000 (TU Delft, University Bern, TU Munich): Computation of kinematic and reduced dynamic GOCE orbits.
- SPF5000 (CNES, GFZ): precise scientific GOCE orbits and determination of the Earth gravity field model by means of the direct approach based on the classical brute force technique considering the data as belonging to the space-time domain and using numerical integration of the LEO satellite orbits.
- SPF6000 (TU Graz, TU Bonn, TU Munich): precise scientific GOCE orbits and determination of the Earth gravity field model by means of the time-wise approach considering the data as belonging to the time domain and using the energy conservation technique.
- SPF7000 (Politechnico di Milano, University Copenhagen): precise scientific orbits and determination of the Earth gravity field model by means of the space-wise approach considering the data as belonging to the space domain and using the energy conservation and fast spherical collocation technique.

These intermediate Level-2 products are then delivered to the SPF8000 (TU Munich, TU Delft) for final validation, final Level-2 product generation (precise scientific orbits, gravity field model, gridded values of geoid heights, gravity anomalies and deflections of the vertical) and delivery to ESA for distribution to the international user community.

The latency of the different CHAMP, GRACE and GOCE gravity related products is shown in the following Table.

Table 5.2-4: Latency of CHAMP, GRACE and GOCE gravity related products (in days).

Product	CHAMP	GRACE	GOCE
Level-0 raw data	0.5	0.5	TBC
Level-1 instrument data		11	2 – 7
Level-2 gravity field products		60	ESA's decision

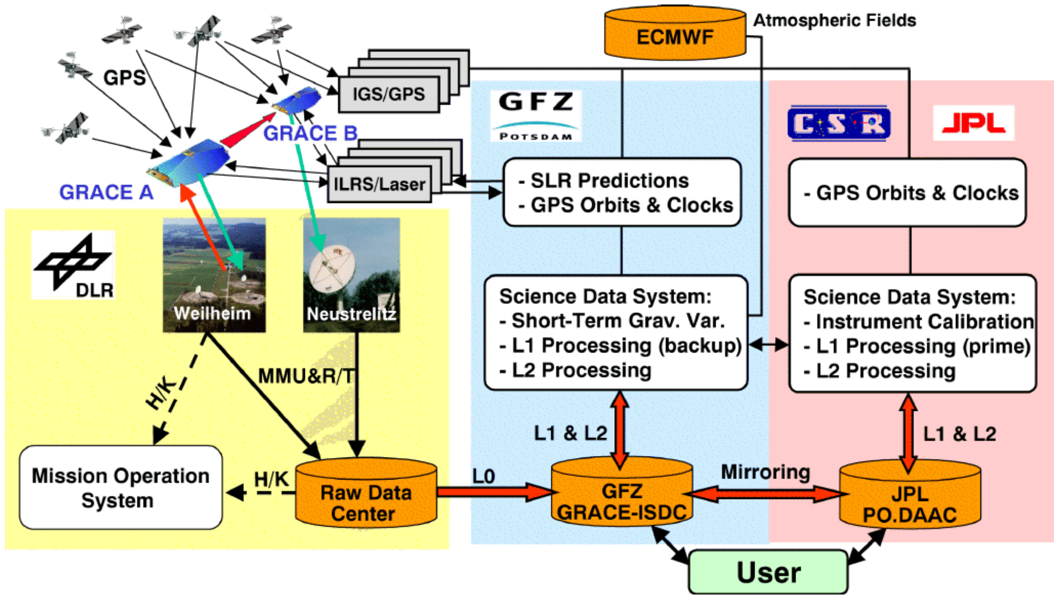


Fig. 5.2.2.7: Schematic illustration of the GRACE ground segment including the data/information flow.

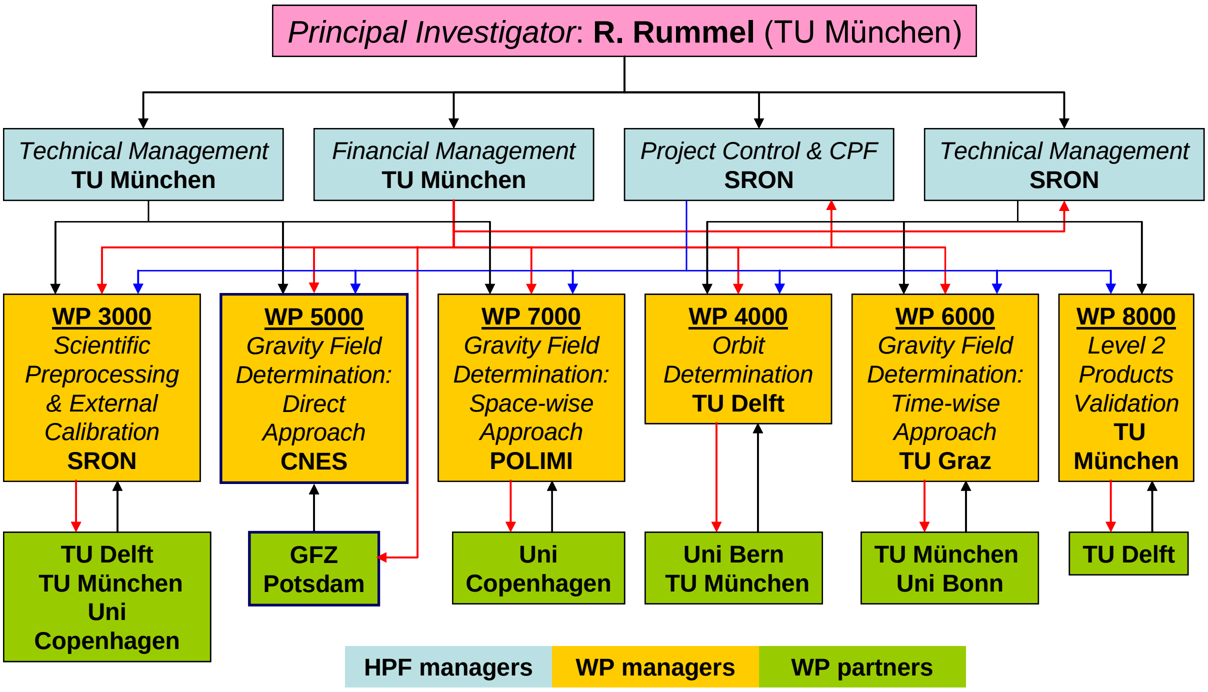


Fig. 5.2.2.8: Schematic illustration of the GOCE HPF.

5.2.3 Airborne Systems

The airborne gravimetry determines the location-dependent variation of the vertical component (scalar gravimetry) or the three components (vector gravimetry) of the gravity vector. A scalar airborne gravimetry system consists of two sets of instruments: a) the airborne gravimeter on a moving platform that measures the total effects of gravity including the disturbing part due to the aircraft motion and b) the high precision positioning system (kinematic differential GPS also in combination with an inertial navigation system (INS) and/or laser altimeter) which allows the determination of the three-dimensional positions and accelerations of the aircraft. From this data the disturbing part can be calculated and subtracted from the gravimeter data.

For scientific applications in scalar gravimetry the upgraded LaCoste&Romberg Air/Sea and the Bodenseewerke KSS31 (mainly used for shipborne applications) Air/Sea gravimeter are mostly used. A new development of an airborne gravimeter is made by Canadian Micro Gravity Company.

The scientific goals of airborne gravimetry can be derived from the knowledge of the location-dependent variations of the gravity vector. Examples are:

- Geoid determination: Airborne gravimetry can fill the gap in spatial resolution in the gravity field models determined from satellites (GRACE) between about 100 and 5km, especially in coastal regions
- Determination of gravity anomalies for exploration of mineral resources
- Determination of temporal and spatial variations, e.g., observations in tectonically active areas.

The performance of an airborne gravimetry system with the Lacoste & Romberg Gravimeter under good flight conditions (small turbulences) is:

- Gravity resolution: 1 µgal
- Spatial resolution: 5 km

Fig. 5.2.3.1: Lacoste & Romberg Sea/Airborne Gravimeter

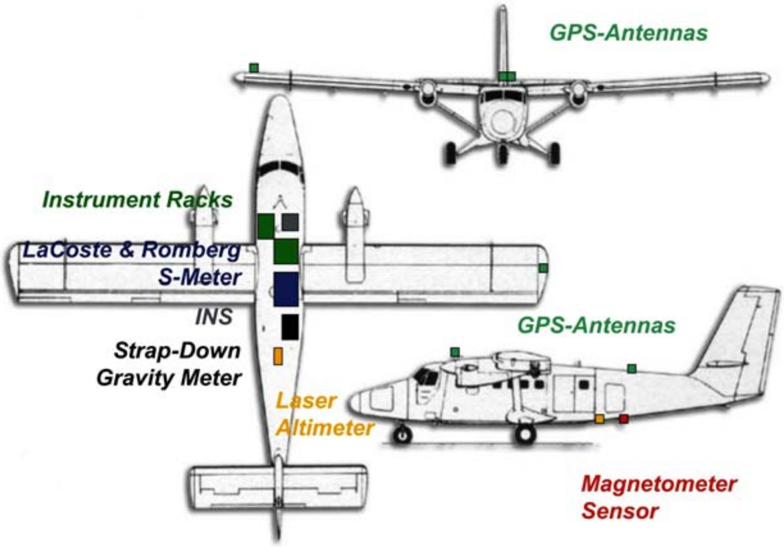


Fig. 5.2.3.2: Components of an airborne gravimetry system in an aircraft (e.g. Cessna)

An example for airborne applications is shown in Fig. 5.2.3.3.

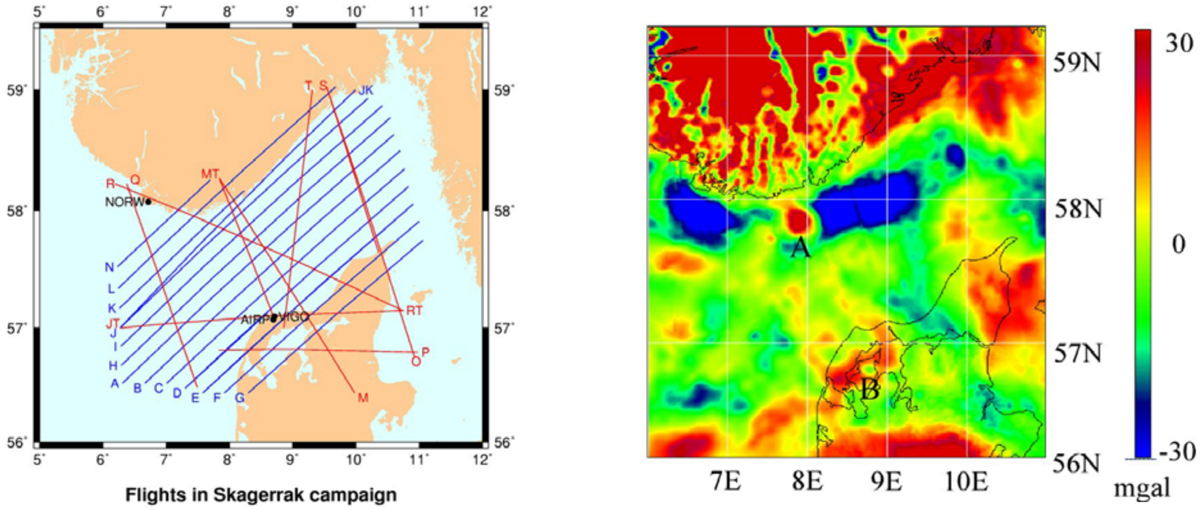


Fig. 5.2.3.3: Results of the AGMASCO campaign in Skagerrak area: a) flight profile, b) gravity anomalies in Skagerrak area (A = buried volcano, B = salt dome)

The vector gravimetry uses three accelerometers of an inertial navigation system which replace the gravimeter in the airborne system. The accuracy of these systems (strap-down gravimeter) has not yet the quality of the scalar gravimeters.

The airborne gravity data and the appropriate GPS, INS or altimeter data including the analysis results are not stored in a central data base. These data are only available to the campaign manager and cooperating groups.

5.2.4 Ground-based Systems

5.2.4.1 Absolute Gravimeter

Absolute gravimeters measure the absolute value of the vertical gravity vector. The most recent developments are the Micro-g LaCoste' FG5 and A10 Gravimeters with the parameters:

FG5: Accuracy: 2µgal, Repeatability: 1µgal
A10: Accuracy: 10µgal, Repeatability: 10µgal

<u>Applications:</u>

- Gravity reference station determinations
- Establishing relative gravity network control points
- Calibration of superconducting or other high-precision relative gravimeters
- Detection of vertical crustal motion
- Complementary verification of displacements measured with GPS and VLBI
- Determination of the geoid
- Volcanic magma flow monitoring
- Postglacial rebound studies
- Water table monitoring in deep and/or multiple aquifers
- Mineral

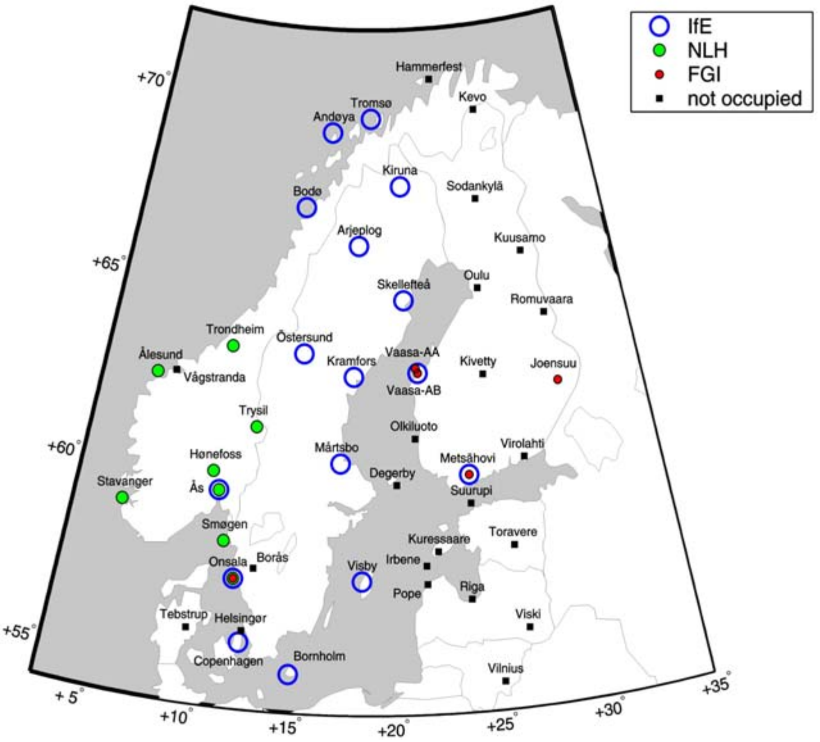


Fig. 5.2.4.1: Observed absolute gravity stations in 2004 occupied by the absolute gravimeters FG5-220 (IfE), FG5-221 (FGI), FG5-226 (UMB).

An example for absolute gravimeter observations is shown in Fig. 5.2.4.1 for the determination of the Fennoscandian land uplift.

The absolute gravimeter data have been sent to BGI Toulouse, where different data sets are available. Nowadays, the data are typically distributed by the project managers of absolute gravity measurements.

5.2.4.2 Relative Gravimeter

Relative gravimeters measure temporal gravity field variations. Two kinds of applications are important:

a) Continuous measurements at one site (observatory measurements) for the determination of surface gravity effects.

Table 5.2-5 summarizes the main global surface gravity effects that the SG records. All these effects are included in the raw gravity data. Depending on the SG site, additional local effects mainly caused by the hydrosphere and local secular gravity variations from postglacial rebound, post seismic deformation, crustal deformation in tectonically active zones etc. Measuring and analysing these effects are tasks coordinated by the "Global Geodynamic Project" (GGP). GGP is also coordinating a network 20 worldwide-distributed stations equipped with Superconducting Gravimeters, in operation since July 1997, using a similar hardware and the same procedures for data acquisition.

Table 5.2-5: Global surface gravity effects.

Period range	Physical source	Gravity effect
0.1 s – 10 s	Micro seismic (natural or man made) noise	up to ~10 µgal
0.1 s – 100 s	Earthquakes	up to ~1 mgal
1 min – 1 hr	Earth's free oscillation	< 1 µgal
4 hr – 8 hr	Slichter modes	< 0.01 ngal
6 hr – 1 yr	Body tides	up to ~300 µgal
6 hr – 1 yr	Tidal ocean loading	up to ~10 µgal
hr - yr	Non-tidal ocean loading	up to ~1 µgal
~430 day (~15 deg/h)	Earth's Nearly Diurnal Free Wobble (NDFW)	
min – yr	Atmospheric pressure variations	up to ~20 µgal (~0.3 µal/hPa)
min – yr	Groundwater variations	~1-10 µgal/m
~ 435 day	Polar motion	up to ~10 µgal

b) Temporary measurements at different sites (field measurements) for the determination of gravity anomalies, e.g., for:
    - Monitoring of gravity changes in geodynamic research areas
    - Densification of national gravity reference networks
    - Provision of dense networks of gravity data to improve regional geoids

Superconducting Gravimeters

The Superconducting Gravimeter (SG) is an integrating sensor measuring gravity variations associated with mass redistributions of various sources in its near and far surrounding. The Gravity Sensing Unit (GSU) consists of a sphere (test mass) which is loosely suspended by a very stable magnetic field, realised by a persistent current in superconducting field coils. The GSU is inside a dewar filled with liquid helium and kept at a temperature of 4.2 K (controlled to a few µK). A negative feedback technique provides an additional force to hold the sphere in zero position. The feedback voltage is a linear function of the measured gravity variation.

Fig. 5.2.4.2: Superconducting Gravimeter

The Superconducting Gravimeter performance is shown in Table 5.2-6. The SG is characterized by a resolution better than 1 ngal (10-11 m/s^2) for a period range from seconds to years with a linear transfer function and a linear drift rate of about 3 µgal/yr. The new instruments do not need liquid helium refilling. In a closed circuit the helium gas is liquefied by a compressor. The dual-sphere SG has the same parameters for each sensor as the single-sphere SG. Additionally the dual-sphere system measures the gravity gradient with a resolution of about 0.5 µgal/m (5 Eötvös). The high precision and the low drift of the instrument allow the investigation of the whole tidal and non-tidal frequency band.

Table 5.2-6: SG parameters

Resolution ADC (24bit)	10^{-12} ms^{-2}
Resolution gravity	>10^{-11} ms^{-2}
Period range	10 s – yrs
Measurement range	0.001 ngal to 1.5 mgal
Accuracy calibration factor	0.2% ~0.05 µgal/Volt
Gravity phase shift (standard)	8.6s (0.035 deg/cpd)
Gravity filter corner frequency (standard)	61.5 mHz
Drift rate	~ 3 µgal/yr

Applications:

- Short- and long-period tidal monitoring and modelling of earth inelasticity
- Volcano monitoring
- Sea level monitoring at sites near to the ocean
- Long-term crustal motion

- Validation of satellite-derived (e.g. GRACE) gravity variations and the combination of ground- and space-based measurements
- Ground water table measurements
- Measurements at geodetic reference stations in combination with GPS and laser telemetry (SLR and LLR)
- Reference station for a network of absolute gravity sites (to correlate and remove environmental effects)
- Continuous gravity measurements at selected sites (e.g. tectonically active areas) in combination with GPS measurements for differentiation between mass and elevation changes
- Post-seismic deformation
- Any location where long -term continuous gravity measurements are required

Fig. 5.2.4.3 shows an example of gravity variations derived from SG, GRACE and the hydrological model H96 at the site Metsahovi in Finland.

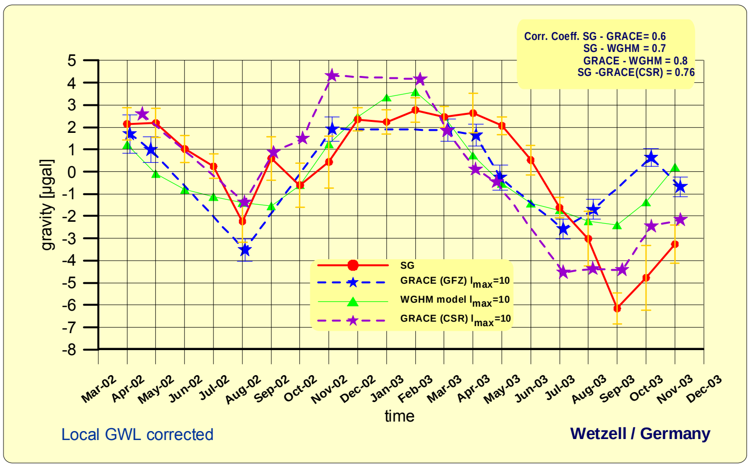


Fig. 5.2.4.3: Comparison of gravity variations derived from SG, GRACE and the hydrological model H96 at the site Metsahovi, Finland.

The SG gravity network covers now 20 stations. Their locations are shown in Fig. 5.2.4.4. The SG data and collected environmental data are stored in the Global Geodynamic Project (GGP) Information System and Data Center (http://ggp.gfz-potsdam.de/). It started operation in 1997. The data are stored in a standard format and can be downloaded. Additionally, information about the data and instruments (station description and instrumental parameters) is available. Beside the raw data, corrected data (corrected for spikes, offsets and data gaps) are maintained in the data base.

Gravity data from other relative gravity measurements are available at the International Center for Earth Tides (ICET) Brussels http://www.astro.oma.be/ICET/.

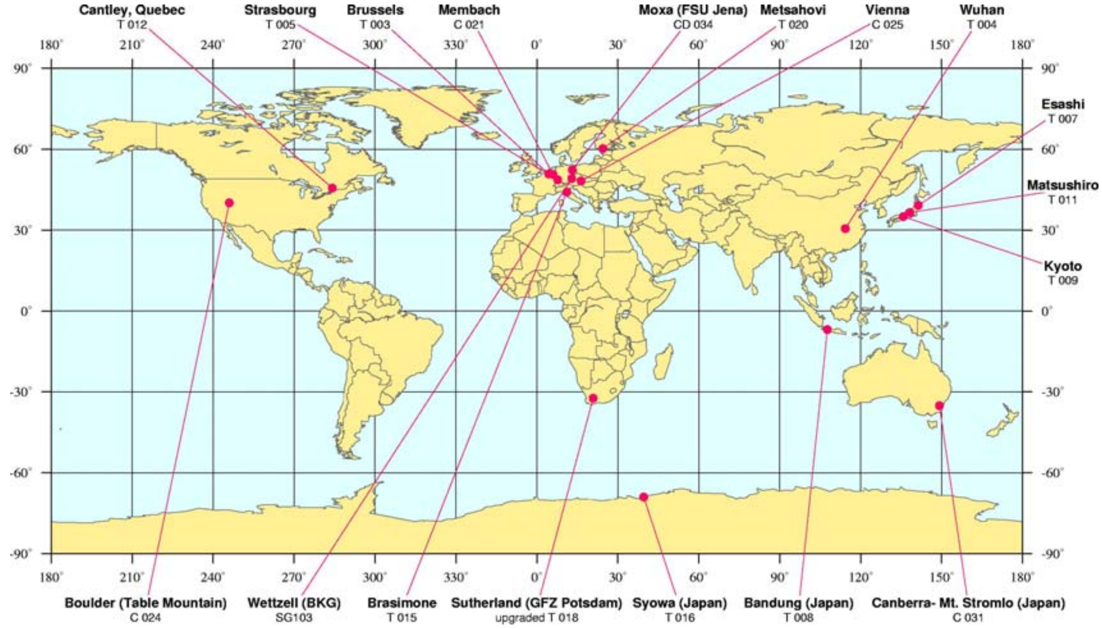


Fig. 5.2.4.4: Network of Superconducting Gravimeters.

Lacoste & Romberg and Sintrex Autograv Gravimeters

These gravimeters have a resolution below 1 µgal and an accuracy between 1 and 10 µgal. They are mainly used as field instruments for tasks according to b).

5.3 Infrastructure for Geohazards

5.3.1 Introduction and Objectives

Geohazards such as earthquakes, volcanic eruptions and landslides inflict an enormous cost on society. According to the United Nations Environment Program (UNEP), more than 26,000 have died in volcanic disasters between 1975 and 2000 and earthquakes caused more than 460,000 fatalities during the same period. Only in 1994, landslides in Bolivia affected 165,000 people. For every life lost, many more are injured, or lose their homes or livelihoods. In addition, geohazards can damage or even destroy infrastructure at great expenses, with dramatic consequences especially for developing countries.

The United Nations (UN) has established that the total costs of natural disasters as a whole have raised 10 fold in the past 40 years. The principal driver is the increase in human population and a consequent increase in the intensity of development in hazardous areas, such as on steeper slopes and along coastal zones. Geohazards therefore pose an increasing risk to society that can only be reduced by developing a better understanding of the occurrence and behaviour of the hazard events. Two different approaches are established in geohazard investigations: (1) *Monitoring, rapid information and early warning*: Modern society requires access to rapid and accurate information, with the goal of monitoring geohazard occurrence, improving disaster preparedness and mitigation, providing an accurate picture of the expected damage, coordinating interventions and steering emergency management. (2) *Assessment of hazard and risk*: Minimization of the loss of life, property damage, and social and economic disruption due to geohazards events depends on reliable estimates of hazard (the probability of event occurrence), to serve as basis for improved building design and construction, emergency response plans, the protection of critical infrastructures, land use planning and strategies for sustainable development.

Geohazards are driven directly by geological processes involving ground deformation and mass transfer. For this reason, there is an obvious and crucial contribution from Geodesy to the study of geohazards. However, the use of geodetic techniques for the study of geohazards is often *ad hoc*, and observations and methods are used that were not originally thought for the purpose. On the following, we will introduce the three different geohazards considered in this project (earthquakes, volcanoes and landslides) and give an overview of the current use of geodetic methods applied to their study. We will describe the most common applications as well as the most up-to-date and less spread techniques and their limitations.

5.3.2 Earthquakes

Earthquakes are probably the most devastating and frequent of all the geological hazards. The United States Geological Survey (USGS) National Earthquake Information Center (NEIC) reports that, every year, seismic networks around the world record some 12,000 to 14,000 earthquakes. Events of magnitude 5 or more, from which important damage can be expected, add up to about 1,500 per year. The extensive distribution of plate boundaries and associated fault zones, in comparison to the more localised occurrence of volcanoes, means that the number of countries at risk is higher. There is also a marked difference in the effects that earthquakes have in developed and developing countries. Fatalities caused by the Northridge (1994, M 6.7) and Kobe (1995, M 6.5) earthquakes were relatively low (57 and 5,500, respectively), but the economic costs to the USA and Japan were huge, estimated at $40 billion and $100 billion respectively. In contrast, the larger earthquakes that struck Izmit (1999, M 7.4) and Gujarat (2001, M 7.8) produced death tolls of roughly 17,000 and 20,000, respectively. This enormous loss of life was largely a consequence of poor building construction practices. Whilst the dollar estimates of damage for these latter earthquakes may be lower than for Northridge and Kobe, their impact on the economies of Turkey and India was no less devastating.

Earthquakes are a sensible threat for many countries in Europe, particularly for those around the Mediterranean Sea. Early warning systems, based on real-time automated analysis of ground motion measurements, can have an important role in reducing the negative impact of catastrophic events on densely populated areas and, particularly, in mitigating the damage to strategic structures and lifelines. Europe is covered by high-quality seismic networks (Fig. 5.3.2.1), managed by national and by European agencies, including some local networks designed for seismic early warning around Bucharest, Cairo, Istanbul and Naples, respectively.

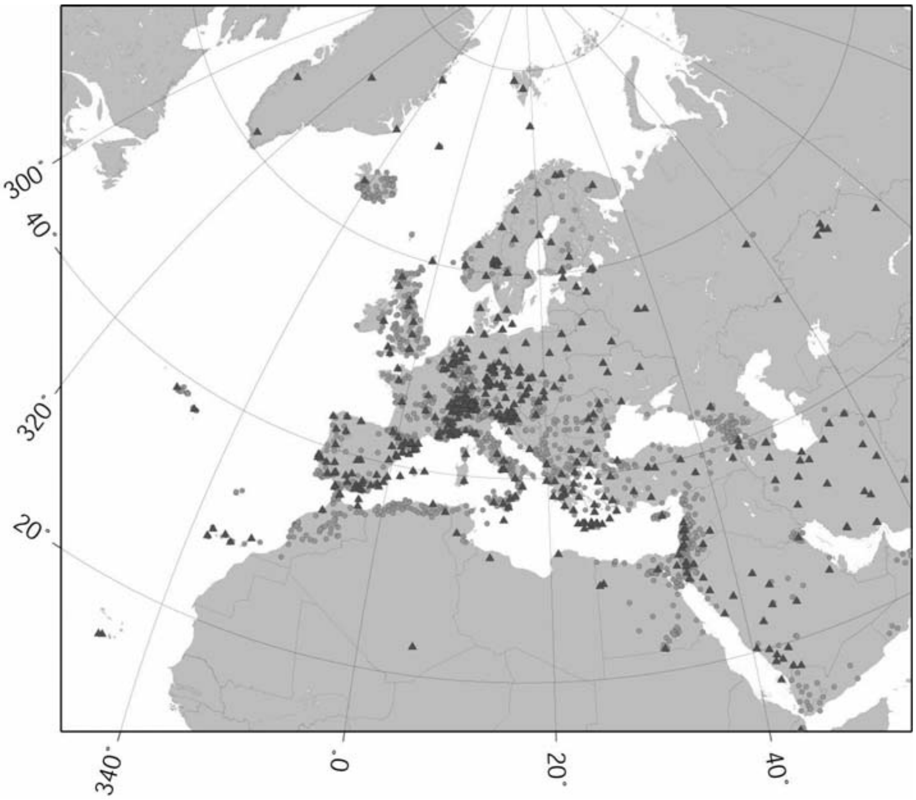


Fig. 5.3.2.1: Short-period (gray circles) and broadband (black triangles) seismic stations in Europe (status April 1, 2003).

In the frame of the SESAME project (Seismotectonics and Seismic Hazard Assessment of the Mediterranean Basin), the coordination and correlation of seismological activities lead to a common seismotectonic zonation and seismic hazard assessment in the Mediterranean area. This project integrated data from geological evidence (prehistoric record of paleoseismic activity, geomorphology, rates of crustal deformation from land and space geodesy, geodynamic modelling) to supplement the historical record of seismicity and build a statistical model of seismogenic sources to reproduce the historical record of seismicity (location in space and time, frequency-size distribution). The SESAME strategy was the integration and coordination of the regional programs operating in the Mediterranean. The final product from the SESAME project was the peak ground acceleration map of the Mediterranean Basin reproduced in Fig. 5.3.2.2 (Jimenez et al., 2003).

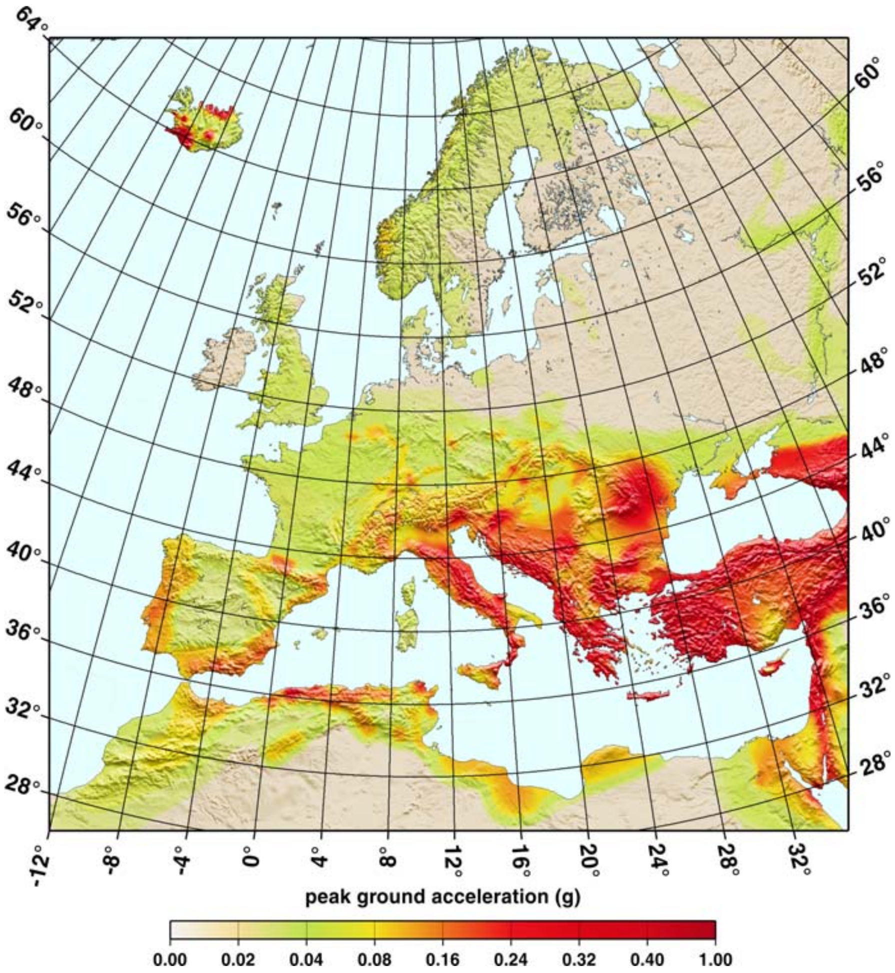


Fig. 5.3.2.2: SESAME peak ground acceleration map of the Mediterranean Basin (Jimenez et al., 2003).

As far as Geodesy is concerned, there are two characteristic features of earthquakes that are relevant. First of all, the epicentres of large earthquakes are usually located along known seismically active zones, although the disruptive effects of an earthquake may extend over areas hundreds of kilometres away. Although it is possible to monitor seismically active areas or faults that are known to have ruptured in the past, there is no possibility to monitor earthquakes themselves. A second important feature is that earthquakes usually produce a noticeable lateral or vertical displacement where the active fault intersects the surface. Similarly, a steady deformation takes place during the inter-seismic phase of the earthquake cycle, which can be measured with the appropriate techniques.

The scientific monitoring and research of seismically active areas requires all data available, in particular from seismicity, intensity, strain, Digital Elevation Models (DEM), soil type, moisture conditions, infrastructure and population. Seismological networks are the most important source for information, but some features can be complementary studied by means of geodetic recordings. Measurements of the deformation on the surface have been repeatedly used to derive the extent of the rupture, as well as the slip distribution on it (see Fig. 5.3.2.3), which are parameters that do not necessarily correlate with the magnitude or distribution of seismicity. Also, the study of the time development of the deformation has proven useful to identify post-seismic processes like viscoelastic relaxation, after-slip or poroelastic rebound. This documentation and interpretation of the ground motions and deformation that constitute the earthquake itself is still an object of scientific interest.

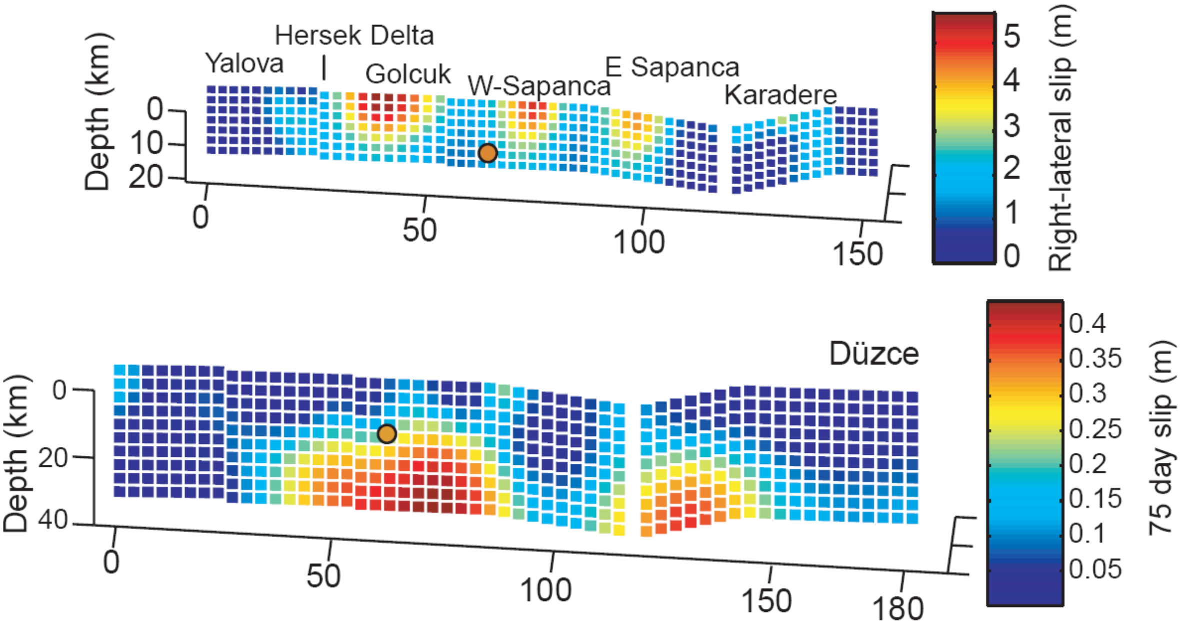


Fig. 5.3.2.3: Co- and post-seismic slip distribution on the 1999 Izmit rupture surface as derived from GPS observations (Reilinger et al., 2000).

Earthquake-related parameters that are the subject of Geodesy include ground strain accumulation and relative crustal displacement associated to tectonic processes. Also, possible links between earthquakes and changes in the Earth's gravitational field are being researched actively at the present time. Satellite missions to monitor changes in the Earth's gravitational field, such as GRACE, CHAMP and GOCE may elucidate the link between deeper tectonic processes and the geohazards.

For two decades satellite laser ranging and very long baseline interferometry have been used to monitor strain and crustal motion, respectively, in the vicinity of active faults. These are a direct and valuable input to models of earthquake risk. These techniques have since been superseded by GPS as rapid development of receivers has made it possible to install them in dense networks to monitor large areas. Using these arrays, it is possible to improve maps of known faults, detect possible unknown faults, and locate areas on these faults which are locked and therefore susceptible to sudden rupture. The most required earthquake hazard geodetic observation is the characterisation of baseline topography and ongoing horizontal and vertical deformation. Relative displacements along faults are typically measured after the earthquake, but deployment of permanent, continuously recording GPS networks can provide a more complete picture of pre-, co- and post-seismic displacement. An example for this is the Plate Boundary Observatory (PBO) project (see Fig. 5.3.2.4).

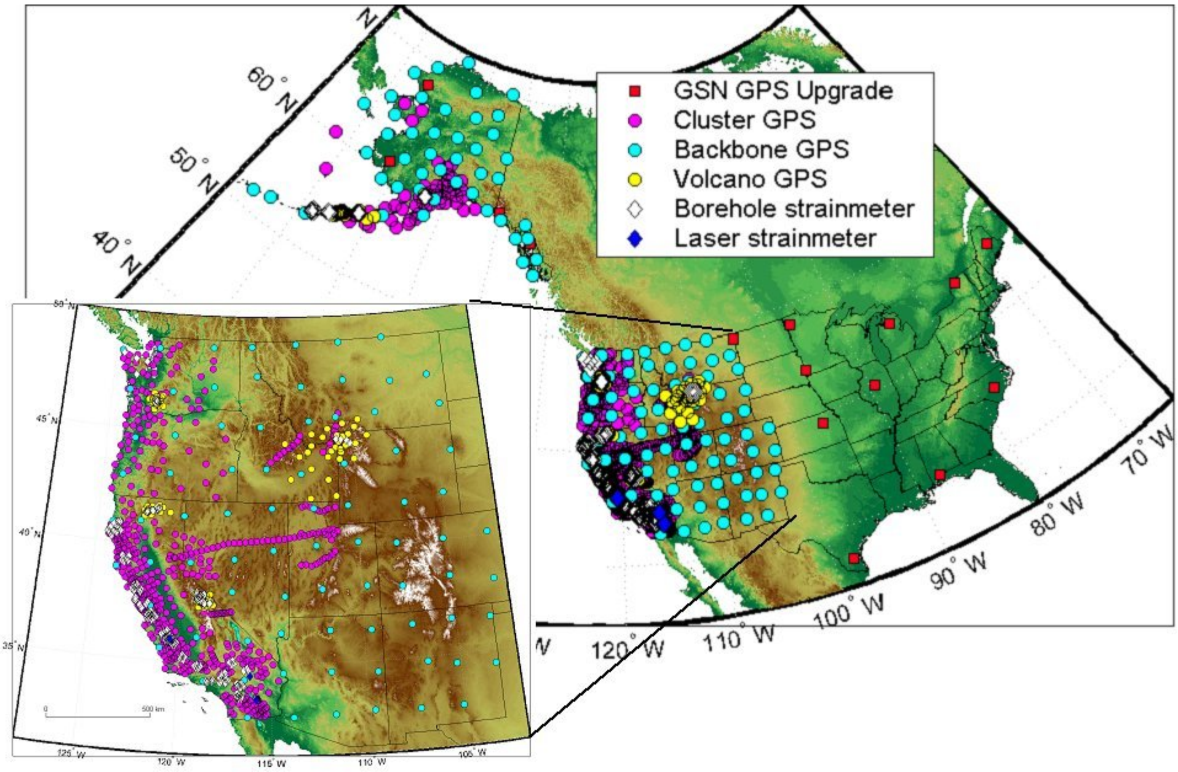


Fig. 5.3.2.4: Stations of the Plate Boundary Observatory (PBO) network.

In recent years, Synthetic Aperture Radar Interferometry (InSAR) has demonstrated the ability to map line-of-sight ground motions, and work is underway to develop hybrid InSAR technologies to supplement or even replace GPS networks. Although InSAR is mainly a space technique, it allows for the use of in-situ man-made radar reflectors, so there is an in-situ segment for this technology. InSAR holds increasing utility for the mapping of seismic ground deformation. By using InSAR to study pre-, co- and post-seismic deformations, the technique contributes to the spatial understanding of fault mechanism dynamics and strain. InSAR is also useful to identify the deformation extent and event mechanism, as well as to estimate damage in built environments, since the latter correlates with ground displacement. The use of InSAR across all the main active faults can help to document continuous strain and identify locked segments of major faults. These data, coupled with other geodetic, hydrologic and geophysical data, can help scientists to understand how the crust deforms in inter-seismic periods. This will, in turn, form the basis for refined seismic probability forecasts.

An interferometric image represents the phase difference between the reflected signals in two SAR images obtained from similar positions in space. In case of space-borne SAR the images are acquired from repeat pass orbits. For the European ENVISAT, for example, the standard orbital repeat interval is 35 days. For the recently launched ALOS's the recurrent period is 46 days, but when a disaster occurs it can observe any point on the Earth (except for polar regions) within 2 days. The phase differences between two repeat-pass images result from topography and from changes in the line-of-sight distance (range) to the radar due to displacement of the surface or change in the atmospheric propagation path length. It is important to note that in all InSAR techniques results on their own do not de-couple horizontal from vertical displacements. The technique also becomes progressively less sensitive if the vector of displacement nears that of the satellite track. For these reasons, until multi-view angle satellite constellations will exist, InSAR techniques are likely to be largely supplemental to other ground-based monitoring systems.

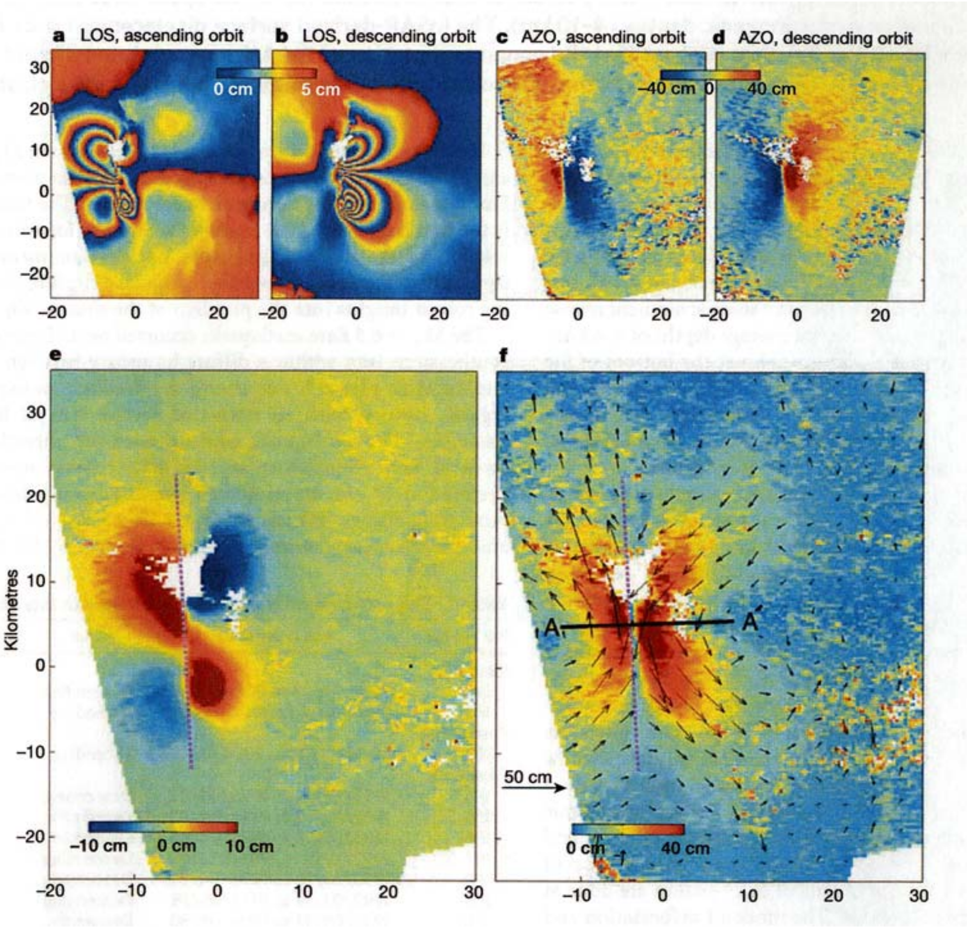


Fig. 5.3.2.5: Coseismic deformation caused by the Bam earthquake as imaged by the Envisat ASAR data (Fialko et al., 2005).

Though InSAR has a remarkable capability, system and process constraints complicate a routine or global application. There have been, however, noticeable developments with the study of naturally occurring and man-made SAR signal reflector arrays in two hybrid techniques called Permanent Scatterer InSAR (PSInSAR), and Corner Reflector InSAR (CRInSAR) respectively. The three complementary InSAR techniques together, in combination with an appropriate SAR data acquisition strategy, promise an economic substitute or supplement for expensive ground-based GPS and laser-ranging networks in many circumstances:

Conventional InSAR: This technique can deliver spectacular measurements of the large-scale ground deformations associated with main earthquake events, provided the temporal separation and horizontal baseline between the two SAR scenes used are kept within appropriate limits. Many examples exist. Such results on their own offer unique input to strain models and support the understanding of fault mechanisms, and have even been successfully used for the verification of insurance claims. Though usually applicable to the main co-seismic event (Fig. 5.3.2.5), and so is perhaps a ‘response’ technique, the deformation information can provide valuable understanding of fault mechanisms and thus input to forecast models in the mitigation phase. However, conventional InSAR is not considered a tool for the measurement of the millimetre-scale motions associated with interseismic activity; the displacement resolution of the technique becomes degraded by temporal decorrelation and/or atmospheric heterogeneity resulting in phase ambiguites of similar orders of magnitude as the ground displacements anticipated.

Corner reflector InSAR: This technique involves the placement of man-made radar reflectors (Fig. 5.3.2.6), against which precise, sub-centimetre measurements of displacement can be measured over time. CRInSAR is appropriate for the motion monitoring of specific structures (dams, bridges, power stations, etc) or more localised areas at risk The attraction of using corner reflectors is their positional stability, zero maintenance requirement and, in particular, their persisting high coherence over the time-spans needed to detect tectonic motion. However, the technique is invasive and there can be issues of reflector security on the ground.

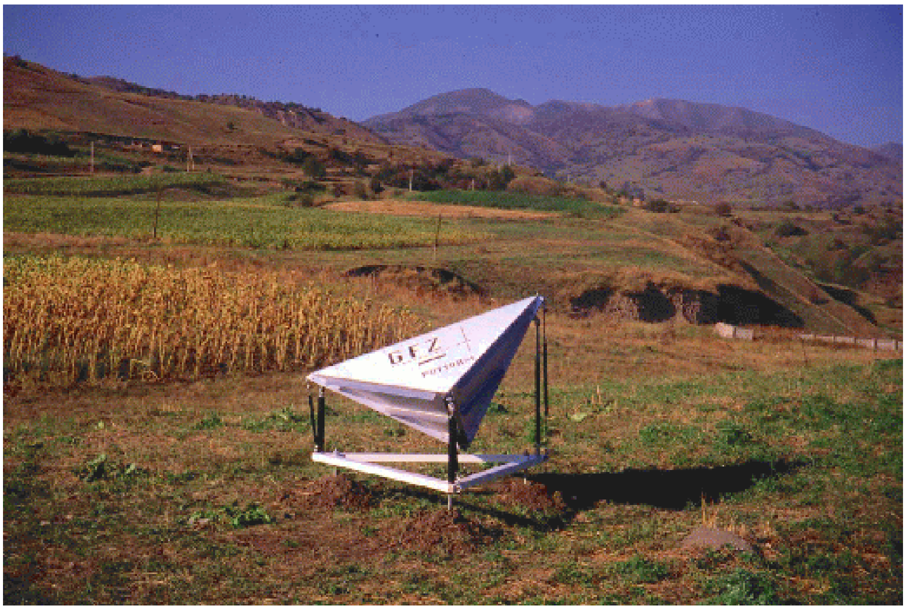


Fig. 5.3.2.6: Corner Reflector in Southern Kyrgyzstan supporting interferometric analysis of ERS-1/2 SAR data.

Permanent scatterer InSAR: This technique involves the processing of more than 30 interferograms over the same place to identify a network of temporally-stable, highly reflective ground features – permanent scatterers (Fig. 5.3.2.7). The phase history of each scatterer is then extracted to provide interpolated maps of average annual ground motions, or more importantly, the motion history, up to 9 years (length of SAR data archive), of each individual scatterer, thus providing a 'virtual' GPS network with 'instant' history. Due to the relatively high density of scatterers that occur in built environments (a few hundred per square kilometre) and the large number of atmosphere samples (SAR scenes) used, the heterogeneity of the atmosphere can be accurately modelled so that measurements of sub-millimetre accuracy can be calculated. A limitation of PSInSAR is the lack of control over precise scatterer location, but with the densities obtained in built environments this is not considered an issue for the mapping of interseismic ground motions.

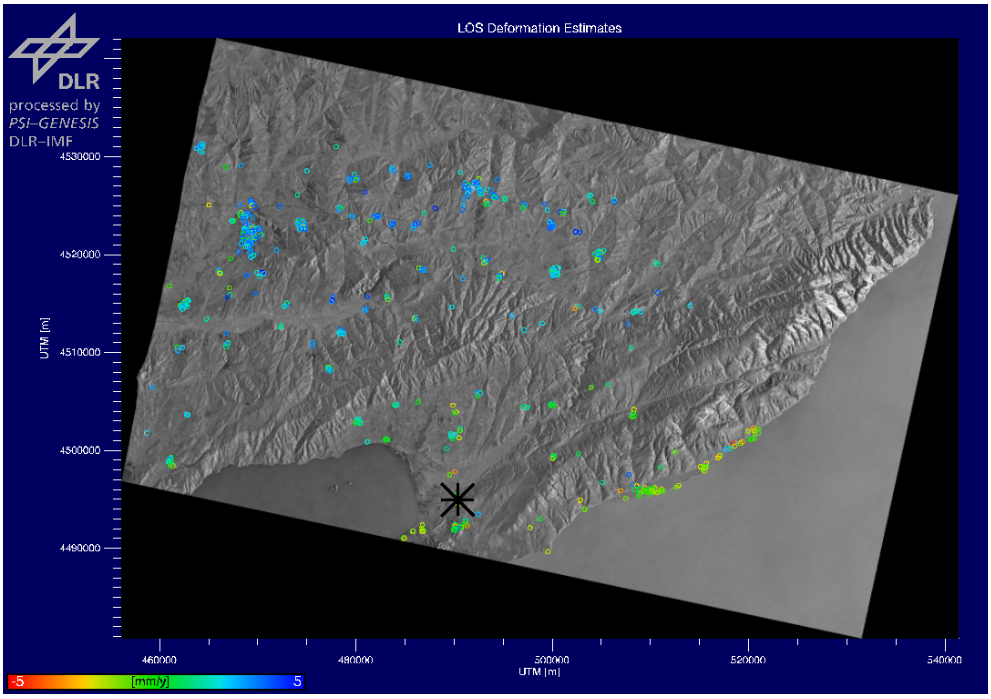


Fig. 5.3.2.7: Permanent scatterers around the Ganos fault, Western Turkey (Motagh, pers. comm.).

None of the three InSAR techniques on their own offer a complete solution to the monitoring of co- and interseismic ground motions. Each technique has its own advantages and disadvantages. The degraded resolution of conventional InSAR renders the technique more appropriate to the mapping of larger scale displacements in terms of both magnitude and coverage, in other words it is more appropriate to the measurement of main earthquake events. Given sufficient repeat SAR data, the sub-millimetre accuracy of PSInSAR does represent an effective tool for the measurement of interseismic ground motions. However, the PSInSAR model makes assumptions about the atmosphere that might not be true from one urban conurbation to another (within the same SAR frame) that might be separated, for example, by 25km of non-scattering, rural farmland. Interpolating PS results between such large distances could be misleading. Depending on the density of scatterers, PSInSAR is more appropriate to the monitoring of contiguously developed areas. The advantage of CRInSAR is that the target against which measurements are made can be sited exactly where required - across a bridge, around a dam, along a pipeline, across a fault. Because of the invasive nature of CRInSAR and the costs associated with the manufacture and deployment of reflectors, CRInSAR is considered more appropriate to localised installation.

5.3.3 Volcanoes

During the last decades, there has been a notable improvement in the interpretation of signs of volcanic unrest by volcano scientists. However, important aspects of volcanic activity remain poorly understood. Many active volcanoes in inhabited areas are inadequately monitored. Furthermore, the increase in population worldwide means that both the number of people and the value of infrastructure sited close to active volcanoes are increasing. Recent examples include: fast-moving lava flows at Nyiragongo (Congo) killed over 70 people in 1977; El Chichon volcano (Mexico), which was completely unmonitored, killed 1800 people in 1982 and devastated the surrounding area for a decade; landslides and lahars occurred in

1998 at Casita volcano in Nicaragua and swept over the towns of El Porvenir and Rolando Rodriguez, killing more than 2000 people. Modern instrumentation and volcano monitoring techniques lead to a number of successful eruption warnings, saving thousands of lives, e.g. at Mount St. Helens (1980), Pinatubo (1991), or Montserrat (1997). However, in many cases forecasting and warning of volcanic activity remains difficult. For instance, Nyiragongo was identified as a Decade Volcano under the UN-sponsored International Decade for Natural Disaster Reduction (IDNDR). Nevertheless, the January 2002 eruption of Nyiragongo killed 147 people. Evidence for increased exposure to volcanic hazards includes a steady increase in the number of eruptions causing fatalities over the last 500 years.

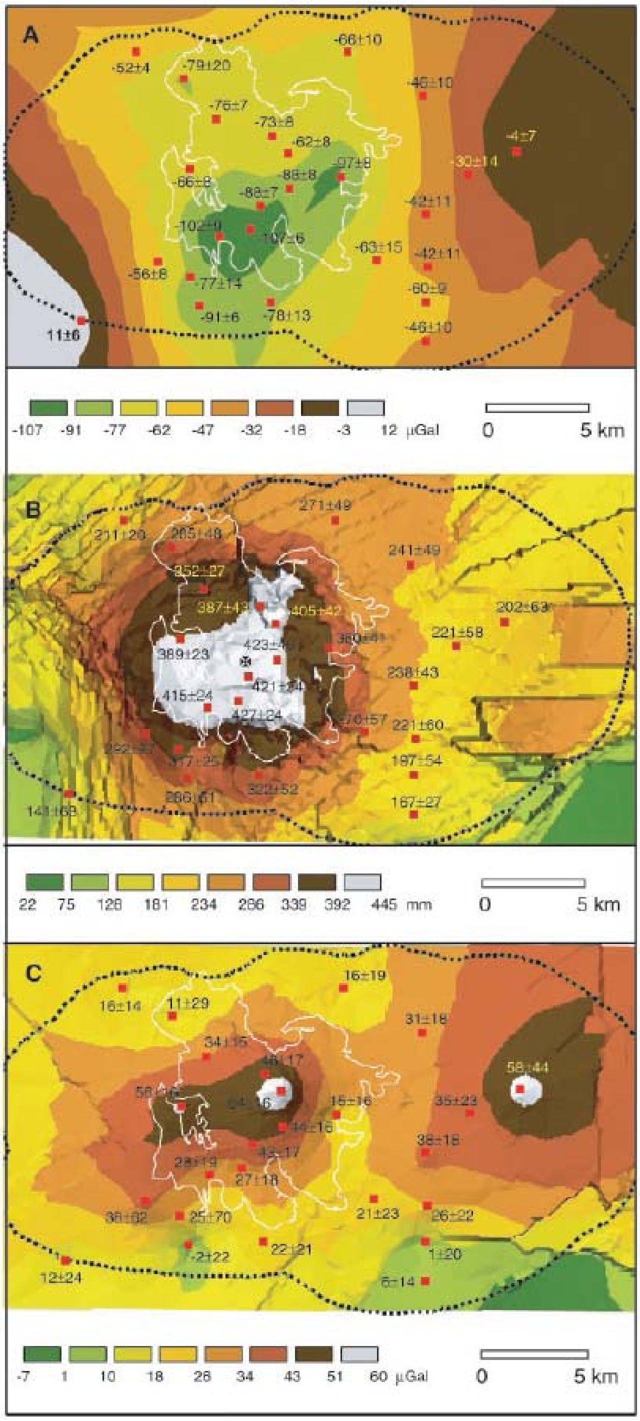


Fig. 5.3.3.1: (A) Gravity changes (in microgals) in Long Valley caldera from July 1982 to July 1998. (B) Uplift at Long Valley caldera between 1982 and 1998. (C) Residual gravity changes in Long Valley caldera from July 1982 to July 1998. (Battaglia et al., 1999).

What the study and monitoring of volcanic activity need in detail is dictated by the nature of volcanoes and volcanic eruptions. Global historical eruption catalogues show that about seventy-five percent of the most explosive and hazardous eruptions since 1800 occurred at volcanoes that had no previous historical eruptions. This means that identifying the potentially dangerous volcanoes requires monitoring also of the less active ones. Volcanoes usually give some warning of impending eruptions, the signals of which are detectable if appropriate monitoring is being carried out. This contrasts with earthquakes and landslides, where detailed location and times of events cannot be predicted. Finally, eruptions leave traces in the geologic record, allowing reconstruction of the eruptive history (frequency, type of eruption, size of eruptions, ages of eruptions, etc) of a volcano. This may give some indication of what the next eruption at a given volcano could be like.

Recent geodetic research has shown that volcanoes can steadily inflate, presumably because new magma is rising. To distinguish between inflation caused by magmatic intrusion and inflation caused by pressurisation of a geothermal system, the monitoring of changes in gravity at the same location can have important implications (Fig. 5.3.3.1). For instance, of much concern was the detected uplift at the Italian volcanic field Campi Flegrei in the eighties. Reevaluation of deformation and gravity data now suggests that magma played only a very minor role. This example shows that various datasets need to be combined for reliable forecasts and sound geologic interpretation.

There are two distinct circumstances in which volcanologists monitor activity at volcanoes: (1) unrest at a volcano that has been dormant, but which may be preparing to erupt and (2) activity at a volcano during an eruption, particularly a long-term eruption with spurts of accelerated activity or pauses (as at Kilauea, or Etna, or the slow dome-building eruptions of Montserrat or Unzen). In the first instance, the volcano will erupt only if there is renewed influx of magma from deep within the Earth. Magma movement triggers earthquakes and tremor, hence the widespread use of seismic networks as the monitoring method of first resort. Satellite monitoring can come into play only when the magma is near enough to the surface to produce surface deformation, or enhanced heat flow or gas emissions. At this later stage of reawakening, volcanologists need all the information they can get to evaluate the probability of an eruption.

Volcano monitoring data includes seismicity, deformation, microgravity, thermal and gas data, which can be measured at the ground or by air or space and be collected in real-time. Seismicity, deformation and gravity changes provide the earliest assessments for movement of magma toward the surface and then in the near-surface environment. However, volcano-related seismic signals can be variable, and require much experience in interpretation. Digital Elevation Models (DEM) and physical models may help predicting the distribution of mass flows such as pyroclastic flows or lahars, so as to identify areas of both high risk and no danger. The availability of accurate geologic and infrastructure maps, as well as high resolution DEMs is the central part for a successful volcano monitoring program and hazard evaluation. Thermal and gas emissions may also precede activity, but some techniques, such as acoustic flow monitoring require an actual eruption event in progress. To monitor deformation it is necessary to properly display and survey deformation networks to monitor tilt, expansion or contraction.

An important aspect in volcano hazard prediction is the ability of detecting ground deformation above accumulating magma reservoirs. Such data allows inferring the volume change and pressure increase under volcanoes, but also allows more detailed analysis of other data such as gravity or gas sampling. Horizontal and vertical deformation can be measured using different techniques that have their advantages and disadvantages. EDM and GPS are classical tools to measure ground displacements, and such information can be either continuously transmitted or obtained by appropriate measurement campaigns. InSAR is an additional powerful tool for the background monitoring of volcanoes, allowing spatial information on the (near vertical) line of sight (Fig. 5.3.3.2). However, limited spatial and temporal availability of satellite data means that, for most proximal hazards, it is used mainly as supplemental information for ongoing eruptions, and post-disaster assessment in mitigation and prevention of future disasters. With new satellites, further developments in stereo viewing, and the availability of aperture radar wavelengths long enough for interferometric processing in vegetated areas, InSAR applications are likely to expand significantly in the near future.

There are two key difficulties in trying to develop satellite systems for better volcano monitoring. The first is that volcanic eruptions are comparatively rare. For example, the high-resolution ASTER system has a revisit time of 16 days at the longer wavelengths, which makes it difficult to capture any but the longest eruptions. As a matter of fact, there are no satellite systems in place that were designed specifically for volcano monitoring, and tools initially developed for other purposes need to be used. However sensors needed for detecting and evaluating other hazards (wildfire detection and tracking, detecting deformation fields associated with earthquakes, landslide imaging and assessment) would also serve to monitor volcanic phenomena.

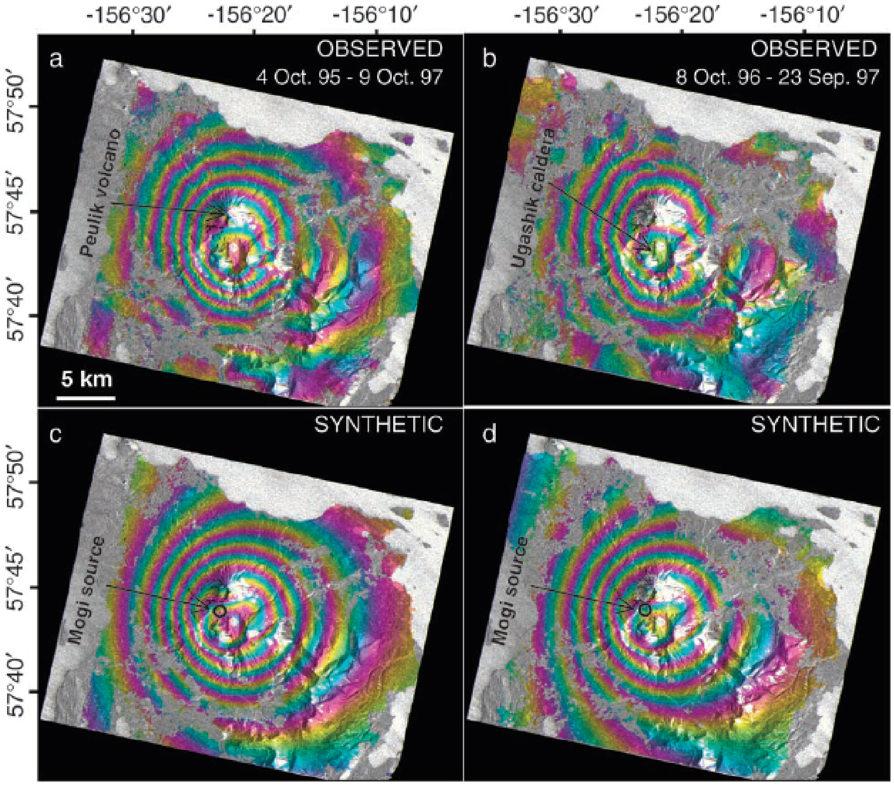


Fig. 5.3.3.2: Topography-removed interferograms (observed and synthetic) for the Mount Peulik volcano. Each fringe (full colour cycle) represents 2.83 cm of range change between the ground and the satellite (Lu et al., 2002).

Recent and ongoing experience at trying to monitor the topography and deformation of the eruption at Soufriere Hills Volcano, Montserrat (1995-99) has shown some of the benefits and limits of the currently available SAR data. The operational need for mapping the changing topography during dome growth is clear and a frequency of about once a week would be adequate. Equivalent deformation measurement intervals needed are a few weeks. However, the topographic surface of the lava dome itself, which is a key observational target, is too dynamic to capture using the technique, even with the 1-day separation of ERS-1/-2 interferograms.

Space-borne differential InSAR has proved to be an excellent new source of deformation information on some volcanoes. However, we have as yet no experience in using InSAR to predict anything about a pending eruption. Another difficulty is that the magnitude of the signal can be low, and noise high, particularly where vegetation is abundant. Volcanoes in the tropics are the greatest challenge in this regard. The longer wavelength of L-band radar relative to C-band allows better phase retrievals from forested areas (Fig. 5.3.3.3), but there is no L-band satellite currently available, except for the Japanese ALOS satellite, currently on its test phase.

The situation will improve as the next generation of space-borne SAR satellites is launched. These will bring multi-frequency, polarization and angle data to bear on the problem. However, all of these platforms will have long (tens of days) repeat times, giving little direct improvement in the ability to respond rapidly to a new eruption. Also the problem of tropospheric noise from variable water vapour contents has no clear solution in sight. In the longer term the volcanological community should be arguing for (1) space-borne single-pass interferometric radar to capture new topography, and (2) repeat-pass L-band radar, to generate a long time series of surface motion data, but with an event response mode with a tasking lead-time of hours to a day or two and complementary tropospheric water vapour mapping. InSAR monitoring of deformation at volcanoes has much the same observational requirements as that for monitoring deformation associated with earthquakes, so that improvements directed at one hazard will support monitoring of another.

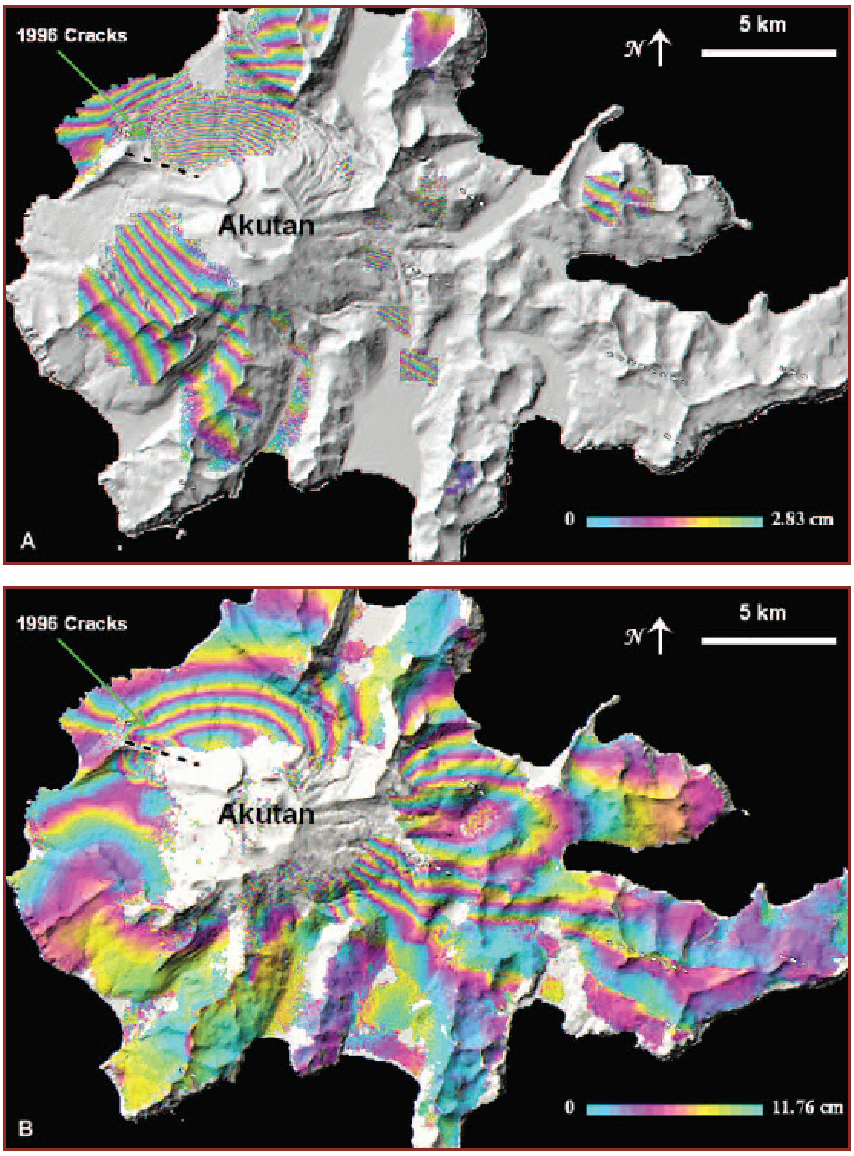


Fig. 5.3.3.3: Different coherence provided by C-band ERS (Lu et al., 2000, top) and L-band JERS (Rykhus et al., 2002) data interferograms at the Akutan volcano.

5.3.4 Landslides

The term landslide denotes "the movement of a mass of rock, debris or earth down the slope". In addition to this definition it can be stated that the movement occurs when the shear stress exceeds the shear strength of the material. The analysis of a possible increase of the shear stress and/or decrease of the shear strength of the material is integral to fully understanding landslide mechanics and applying the most appropriate remedial measures.

Landslides are observable through surface deformations and displacements. Its destructive effect on the population is greatest in developing countries, where there is an average of a thousand deaths per year caused by landslides, but even in developed countries deaths are in the hundreds. Economic losses are largest in developed countries. Landslides commonly occur with other major natural disasters such as earthquakes, volcanic activity and floods caused by heavy rainfall. Each type of earthquake induced landslide occurs in various geological environments, ranging from steep rock slopes to gentle slopes with unconsolidated sediments. Damage from landslides and other ground failures have sometimes exceeded damage directly related to earthquakes. In many cases, expanded development and human activities, such as modified slopes and deforestation, can increase the incidence of landslide disasters. World population growth, consequent intensive land use on steep slopes and in coastal zones, increased needs for water, oil, gas and minerals extraction and the potential increase in triggering events like major storms due to global climate change will all serve to increase the occurrence of these hazards.

Landslide triggers are either natural factors, such as extreme rainstorms, prolonged wet periods, and earthquakes, or factors related to human activity like mining, excavations and blasting. There are preparatory factors, which predispose a given area to failures, including natural and induced changes in land cover and land use, presence of soil and physical characteristics, hydrology, and geological conditions, including weathering status.

Landslides vary enormously in their distribution in space and time, the amounts of energy produced during the activity and especially in size. This means that the resulting surface deformation or displacement varies considerably from one type of instability to another. Individual landslides are local landscape phenomena. Data about site-specific conditions must be available in order to associate the identified deformation or displacement patterns with causative factors and hence model zones of different degrees of susceptibility to the specific type of ground instability.

For the mitigation of landslide hazards, there is a need for data on landslide inventory, DEMs, deformation (to the ground and critical infrastructure), hydrology, geology, soils, geophysical, geotechnical, climatic, seismic zonation maps, land cover, land use, historical archives and relevant human activities, all of them at the appropriate scales.

Better understanding is needed of the patterns of motion before, during and after events. The speed of motion ranges from millimetres per year, which can be effectively monitored rather than requiring a forecast, to metres per second, which represents a catastrophic event that does need forecasting. The speed of these motions changes with time and it is possible that such changes are precursors to the more significant events. InSAR may allow slow, small-scale motion to be observed systematically for coherent targets. Field instrumentation to monitor ongoing deformation is essential, as well as the development of satellite-based monitoring that can be applied to targets that may decorrelate over small time-intervals, like landslides.

Ground-based interferometers may be a solution for monitoring landslides, because of their high temporal frequency. The main advantages are continuous monitoring, optimal illumination geometry, flexibility and the possibility to remotely monitor landslides up to a distance of about a kilometre, the latter being especially important when landslide sites are not easily accessible with traditional instruments. These systems also offer two-dimensional images, and can provide cost-effective solutions for specific sites, where the system can be properly installed and long-term monitoring properly established.

The most required ground instability hazard observations are for deformation with high accuracy and frequency (horizontal and vertical). For this, a GPS network of stations continuously transmitting or reoccupied as necessary should exist. Important information can also be extracted from satellite, airborne and ground-based SAR interferometry at various wavelengths, as well as from other surveys, e.g., levelling, laser scanning (terrestrial and airborne), aerial photography and high-resolution stereo satellite data or borehole inclinometers. In the case of a crisis, additional GPS stations should be set up as needed to capture deformation, or the existing ones more frequent occupied if data was not continuously transmitted, which also applies to other ground-based instrumentation.

There are two important constraints for the application of InSAR to slope motion monitoring: (1) InSAR measures only displacements in slant range (the axis perpendicular to flight direction), so that the component of the velocity vector in flight direction cannot be measured, and (2) InSAR can only map the motion at characteristic temporal and spatial scales, related to the spatial resolution of the sensor and the repeat interval of imaging. Typical scales for ERS interferometry application to landslide movements are millimetres to centimetres per month (with 35-day repeat-pass images) down to millimetres to centimetres per year (with approximately annual time spans). Faster landslides could only be studied during special orbital repeat configurations of ERS in previous years, such as the Tandem Phase or the 3-day repeat cycle during the Commissioning Phase and the Ice Phase of ERS-1 during a few months of 1992, 1993 and 1994. With the resolution of ERS (9.6 m in slant range, 6.5 m across track, 5.6 cm wavelength) the minimum horizontal dimension of a landslide for area-extended interferometric analysis, which can be applied with a single image pair, is about two-hundred meters across- and along-track. Future SARs with higher resolution (Radarsat-2) will enable the mapping of smaller slides. With the Permanent Scatterer Technique the movement of small objects (down to about one square meter) can be monitored, as discussed below.

Due to the typical SAR repeat orbits of the order of 30 days, InSAR is mainly suitable for monitoring very slow movements of slopes and individual objects, and for mapping of subsidence. Thus it is able to fulfil specific information needs for landslide monitoring, complementary to other information sources. The main advantage over conventional techniques is the possibility of very precise displacement measurements over large areas at reasonable costs, thus being an excellent tool for reconnaissance.

The difficulties associated with the interpretation of EO data can require a high level of user knowledge in remote sensing systems. Characterizing form, size, causative and triggering factors, pre-monitory signs, mechanisms, and post-failure evolution will require both ground-truth knowledge and advanced technical skills in remote sensing processing. Although any InSAR sensed deformation is potentially of interest to an engineering geologist or geotechnical engineer, in the case of landslides or unstable slope areas, a change detection in both vertical and horizontal distances is needed to evaluate landslide mechanisms (the monitoring of a horizontal component of movement is often critical for hazard assessments). Furthermore, some other phenomena such as subsidence (e.g., caused by natural processes such as compaction, thawing, or man-made), settlement or subsidence of engineering structures, (e.g., caused by compression), shrink and swell of some geological materials, need to be taken into account to correctly interpret the significance of the ground deformation one might be detecting from EO data.

It follows that, in general, the information obtained from InSAR (or other EO) methods will need to be correlated with ground data and detailed survey controls in order to be correctly evaluated and to provide reliable and relevant information to a disaster management community or to engineering geologists and geotechnical engineers. In short, at present the InSAR methods could be viewed as the complementary data source with respect to those acquired through ground-based observations and in-situ surveying. They will be especially attractive where no other data sources are available by providing initial (potentially wide-area) assessments of ground deformation susceptibility. Detailed slope and motion maps produced from InSAR techniques can assist in more accurate slope stability studies. When the conditions are correct, SAR interferometry is a useful tool for detecting and monitoring mass movement and thus is able to contribute to the assessment and mitigation of landslide hazards.

5.4 Man-made Problems

5.4.1 Introduction

Traditionally, geodesy has served society with the provision of a reference frame for a wide range of practical application 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. The fairly recent advent of space-geodetic techniques has brought about a rapid development in global geodesy, particularly during the last decade. Based on space-geodetic techniques, a global geodetic reference frame can now be maintained with a stability of millimeters per year. Together with the Global Navigation Satellite Systems (GNSS), the global geodetic reference frame is now accessible anywhere on Earth adhoc with an accuracy of down to 1 cm. As a consequence, national and regional reference frames depend today crucially on the global reference frame and the global space-geodetic techniques that provide access to this frame.

On the user side, this technological development has stimulated new applications demanding for 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 more or less 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 2005] estimated that uses of the geodetic reference frame contribute 6 % to 9 % of the Gross Value Added (GVA). This fraction is very likely going to increase in the future: In particular, the emerging combination of broadband communication, geo-reference databases and easily accessible accurate positioning can be expected to facilitate many new applications and services, which will transform the society and lead to an increasing dependency on the geodetic foundation, i.e. the geodetic reference frame including easy access to this frame in form of accurate positions.

In the frame 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 and to assess the adequacy of the observing system to meet these requirements. The EU-funded project Assessing and forward planning of the Geodetic and Geohazards Observing Systems for GMES applications (GAGOS) has the ultimate goal to give recommendations on how to improve the geodetic and geohazards observing systems in order to serve better the needs of a wide range of users with both scientific and non-scientific applications. One focus is on geodetic monitoring of large infrastructure and potential hazards associated with human activities.

A first step towards an assessment of the existing observing system is the compilation of a comprehensive set of user requirements. 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 to address with highest priority. The GAGOS project is expected to produce as its final output recommendations, particularly towards the European Commission, of steps that would help to close gaps in the observing system.

Driven by the rapid development of new space-geodetic techniques, leading on the one side to a transition, if not a revolution, in the geodetic methods, and on the other site 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 during 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 two of the questions to be answered by GAGOS.

In the frame of the adhoc Group on Earth Observations (GEO) and the Global Monitoring for Environment and Security (GMES) programme 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 from space-geodetic observing systems and the main products derived from these. Therefore, based on existing documents and experience of the project participants, a preliminary set of requirements for the application of space-geodetic techniques to the monitoring of large infrastructure and areas with potential man-made hazards caused by subsidence, ground instabilities or failure of man-made infrastructure has been compiled. Here, we give a brief summary of these requirements.

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.

The last three decades have seen an increase in accuracy of the space-geodetic techniques of more than three orders of magnitude. Today, these techniques provide a global reference frame of unprecedented accuracy and stability as well as highly accurate observations of crucial parameters related to changes in the Earth's geometry, rotation and gravitational field.

Increasingly, access to highly accurate geodetic positions is demanded for many scientific and non-scientific 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 and adhoc access to highly accurate 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 GPS and the coming Galileo are, in principle, able to provide such positions relative to a unique, global reference frame adhoc, i.e. without simultaneous measurements at 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 and to describe the surface velocity field well enough to fully exploit the potential efficiency of adhoc positioning.

5.4.2 Global and National Geodetic Reference Frames

In a modern, high-technology society, the requirements for precise positioning and survey 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 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 off-shore 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. Similarly, risks associated with instabilities of soil and rocks or processes related to volcanism require increasingly monitoring as both infrastructure and population are increasing in endangered areas. Aviation and marine traffic require accurate and timely updating of their position in order to avoid accidences, and the geo-data bases used in creating the 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 geo-referenced 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, which poses extremely high requirements on the global reference frame. 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 better than 0.5 mm/yr. For global studies, the relation between geocenter and reference frame needs to be known with an accuracy of down to 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.

Many of the mentioned tasks require a stable reference frame that allows the determination of coordinates with millimeter accuracy and a reproducibility of several decades. In particular, the global and 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.

Currently, the best global terrestrial reference frame is the International Terrestrial Reference Frame (ITRF), which is maintained under the umbrella of the International Association of Geodesy (IAG) by the International Earth Rotation and Reference Systems Service (IERS). 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 of far more than 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. This dynamic nature of the solid Earth complicates the determination and maintenance of a stable reference frame considerably. In order to meet the increasing requirements and to allow for full exploitation of the economic advantages of adhoc positioning, national reference frames have to be linked to the ITRF as the best maintained and most accurate global reference frame. For most non-scientific 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 off-shore 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 non-scientific 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 International GNSS Service (IGS), which initially served the needs of many scientific applications. The excellent service provided by IGS to scientific and increasingly non-scientific 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 experience with applications of IGS products over the last 10 years forms an excellent basis to assess future user requirements.

5.4.3 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 a 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. For a surveying method that measures coordinates relative to neighboring markers of the national geodetic reference frame it is sufficient that the coordinates of these points can be kept fixed. The markers have to have coordinates with sufficient precision, and the deformations in the reference frame have to 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 be able 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, the relative precision over short distances is important. For surveys of larger areas and across country borders, the accuracy is more important.

The requirements for the reference frame also depend on the 'observation method'. For most surveying, adhoc 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 adhoc 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 of 1 mm/yr introduces already an error of 1 cm in adhoc positions over 10 years. In some regions, plate tectonic models provide a first order approximation to the horizontal velocity field. 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 in most areas.

The choice of the observation methods determines to what extent the 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 adhoc 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.

5.4.4 Man-made Hazards

Soil subsidence is a major man-made hazard caused by groundwater, oil, and gas extraction as well as mining activities. Man-made 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, land- and rock slides due to the effects of roads, railroad tracks, tunnels and buildings on the ground stability.

Man-made hazards can lead to considerable damage of property, and in the case of landslides, induced earthquakes, and flooding, also to loss of life. Abundant examples of damage to buildings and roads in areas with excessive groundwater extraction or the lowering of the groundwater level for mining purposes have demonstrated the potential hazards.

Man-made geohazards (subsidence, earthquakes, land- and rock slides) are associated with surface deformations which can be monitored with GPS/GNSS and InSAR. Precarious rocks and areas of potentially instable ground cause disasters recurrently in many countries, often after human interference with the topography. In many areas, step hill sides are potentially a thread for the people living at the base of these slopes or infrastructure build at the bottom of such hills. In many areas, slow landslides pose a problem, too.

In knowingly instable areas, networks of campaign-type or permanent GPS/GNSS stations can be used to indicate a change in the motion and thus indicate a potentially perilous situation. However, the recurrence period of land- and rock slides can be very large and in many areas, the risk is not obvious. The Interferometry Synthetic Aperture Radar (InSAR) is an emerging technology, which allows the determination of surface deformation with high spatial resolution and accuracy in many regions. InSAR is expected to play a leading role in the detection of geohazards and the monitoring of hazardous areas. InSAR has been successfully applied to e.g. mapping the co-seismic displacements, deformations at volcanoes, silent landslides and man-made subsidence. In particular, the combination of permanent GPS stations with InSAR is expected to improve the resulting time series of deformation considerably.

In coastal areas, man-made subsidence can combine with local sea level changes and constitute a severe threat to the coastal population and infrastructure. For example, 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. In the city of Venice and the Lagoon, pumping of groundwater during the first half of the 20th century led to significant man-made subsidence, which was superposed on a natural subsidence of the lagoon due to tectonic and sediment-processes. There, InSAR in combination with GPS allows the monitoring of the present-day subsidence, revealing a large spatial variability in subsidence caused by natural processes and still on-going man-made processes.

The monitoring of man-made 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.

5.4.5 Monitoring of Infrastructure

Increasingly, GPS combined with the IGS products (denoted here as 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 man-made subsidence, volcanic eruptions), 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 unanimously and the optimal reference is a regional or global network.

Experience with oil platforms shows that user requirements for monitoring of such infrastructure are of the order of 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 bridges; however, here the tolerable latency may be much lower.

One task in monitoring the motion of oil and gas platforms is the measurement of the settlement of the platform into the supporting ground, where a long-term stability of the order of 1 mm/yr is required over several decades. 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 PPP, velocities can be determined on the basis of a moving window. For that, requirements in terms of velocity are on the order of a few mm/yr on time scales of months to years.

5.4.6 Control of Processes and Positioning

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, geo-databases are collected at a rate that has increased by several orders of magnitude over the last few decades. The database collected today can be expected to be in use over many years to come. 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 for example in agriculture, construction work and maintenance. For all these applications, a high accuracy of 10 cm (for most agricultural applications) down to 1 cm (for snow clearing) and even sub-centimeter (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 to base many of these applications on GNSS and adhoc positioning.

5.5 Data Acquisition

5.5.1 Geometric Data and Products

This section summarises the state-of-the-art concerning the IAG Services for the geometric space techniques (i.e., IGS, ILRS, IVS and IDS) and the IERS for making available the products for the ITRF, ICRF and the EOP. Each of the geometric IAG Services utilizes a similar structure for the flow of information, data, and products from the observing stations to the user community. The major components are the network stations, Data Centers, Analysis and Combination Centers.

Networks of tracking stations transmit data through various levels of data centers to reach the service analysis and combination centers, and finally the user community. The time delay concerning the transmission of the data is different for the geometric services. Currently, GNSS and laser ranging stations are required to transmit data on a daily basis (although most stations send on an hourly basis), at a minimum to the operational data centers. VLBI data are shipped from the network stations to a correlator on disk packs (with a delay of a few days); in some cases however, the data are electronically transferred via high-speed networks (e-VLBI). Since VLBI observations are organized in sessions, the data transmission follows a session schedule. DORIS stations uplink data to the DORIS receiver on-board the observed satellite, thus making installations in more remote areas possible. DORIS-equipped satellites then download these data to the DORIS satellite control center for transmission to IDS data centers.

Each Service (starting with the IGS) established a hierarchy of data centers to distribute data from the network of tracking stations: Operational, Regional and Global Data Centers.

Operational Data Centers serve as a direct interface to the network stations (or correlators in the VLBI case), connecting the remote sites, downloading the data, and archiving the raw station data. Regional Data Centers gather data from various Operational Data Centers and maintain an archive for users interested in stations of a particular region. In order to reduce communication traffic, the Regional Data Centers are used to collect data from several Operational Data Centers before transmitting them to Global Data Centers. The Global Data Centers are the data source for the Analysis Centers and the user community. Operational and Regional Data Centers transmit data to these Global Data Centers where they are then available on-line for ftp/web download.

The data are utilized by the Service Analysis and Combination Centers to create a range of products, which are then transmitted to the Global Data Centers for public distribution. Standards, both technique-specific and cross-techniques, in data and product generation must be utilized througout all levels in each of the Services. Each Service has to develop its products using standard models and algorithms to ensure consistency over time. Data are currently archived in technique-specific formats (e.g., RINEX for GNSS), however, products derived from the different techniques are moving toward common formats across data types (e.g., SINEX for station positions and Earth Orientation Parameters, SP3 for satellite orbits).

The products of the IERS comprise the International Terrestrial Reference Frame (ITRF), the International Celestial Reference Frame (ICRF) and the Earth Orientation Parameters (EOP). ITRF realizations are provided by the ITRS Product Center every one to four years with a time delay in the order of one year. The latest realization, the ITRF2005, contains data until the end of 2005 and was available in October 2006. ICRF-Ext.1 was constructed by using VLBI data until April 1999. A second extension ICRF-Ext.2 contains additional observations from about 400 sessions between May 1999 and May 2002 (Fey, 2004). The time frequency for updating the ICRF realizations is several years. The Earth Orientation Centre makes different products available to users: long-term and operational series of polar motion, Universal Time (UT1), Length of Day (LOD), and celestial pole offsets. Various solutions are computed by the Earth Orientation Centre: long-term solution (IERS C01), normal values at five and one-day intervals (IESR C02 and C03) and the operational smoothed solution Bulletin B at one-day intervals published monthly and providing EOP with a delay of 30 days with respect to the date of publication. Bulletin B is updated in an operational mode in the IERS C04, which is computed twice a week.

A new IERS Data and Information System has been implemented at the IERS Central Bureau at “Bundesamt für Kartographie and Geodesy (BKG, Frankfurt a.M., Germany)” and is running in the operational mode since the end of 2005. The new system presents information related to the IERS and to the topics of Earth Rotation and Reference Systems. As the central access point to all products of the various IERS Products Centers it provides tools for search within the products (data and publications), to work with the products and to download the products.

5.5.2 Gravimetric Data and Products

The International Gravity Field Service (IGFS) is a unified "umbrella" service of the International Association of Geodesy (IAG), which basically coordinates collection, validation, archiving and dissemination of gravity field related data and models. There are five IGFS Centres each one providing a specific service function:

- BGI - International Gravity Bureau - collection, archiving and distribution of gravity data
- IGeS - International Geoid Service - collection and distribution of geoid models, geoid schools
- ICET - International Center for Earth Tides - collection and archiving of global earth tide data
- ICGEM - International Centre for Global Earth Models - distribution of satellite and surface spherical harmonic models
- IDEMS - International DEM Service - Global Digital Terrain Models

Unfortunately, surface gravity data is not in general public. National gravity activities are often in the responsibility of military organisations. Extensive gravity networks or airborne gravity campaigns are observed by commercial companies for the purpose of geophysical prospecting. Thus, many organisations contribute data to the BGI holdings, but prohibit any re-distribution – according to their restrictive data policy. For dedicated geoid computations some research institutes (e.g., Institut für Erdmessung, University Hannover) maintain their own gravity data bases and are supposed to have more complete data holdings than BGI. GETECH, a commercial company, outsourced from Leeds University research school is known for its comprehensive global gravity and magnetic data holdings. It mainly addresses the requirements of companies involved in geophysical prospecting. The U.S. National Geospatial-Intelligence Agency (NGA) compiles a global data set of mean gravity anomalies with a resolution of 5'×5'. Anomalies over ocean surfaces have been generated by research institutes by means of satellite altimetry data and are available to the public. The land data however is compiled by many different sources and about 46% of the land data is proprietary.

The ICGEM is hosted by the GeoForschungsZentrum Potsdam and provides a dedicated service allowing to access global gravity field models, to visualize gravity field models, their time variations and their differences to other models. Moreover, the web interface allows for calculating different functionals of the gravity field models, e.g. geoid surfaces. Options allow defining the reference ellipsoid, the tide system, and the desired grid resolution. In this way, un-experienced users are served rather well and the risk to derive a geoid surface affected, e.g., by a wrong tide system is minimized. The decision, however, which gravity field model is best suited for a specific application is not easy and could be improved by metadata associated to the gravity field solutions and the provision of the systematic differences between different gravity field models. For the experienced users it is desirable to get detailed information on the processing standards applied to generate the gravity field model of their choice. The ICGEM compilation is limited to global gravity field models. Regional or national geoid computations have the potential to provide an even better spatial resolution, and are compiled by IGeS. Again, only a few of those regional models are public.

The preparation and analysis of gravimetric data and the computation for new gravity field models are typical post-processing activities requiring extensive resources and computation time. Therefore there are up to now no efforts for a near real-time service. The necessary data flow is realized as requirements arise. The publication of new space-based gravity field models are scheduled by the science teams of the dedicated gravity missions CHAMP, GRACE, and (later on) GOCE. Regional geoids are published irregularly, depending on national projects.

5.5.3 Databases for Geohazards

Many essential databases and archives already exist for selected geohazards data. The Smithsonian Global Volcanism Project and its monthly bulletin are the archive of record for volcanic activity, worldwide. The USGS NEIC maintains on-line files of major earthquakes, with some supporting descriptive material, but it does not include full descriptions of all related data and events. There is nothing comparable for ground instability hazards. Similar international initiatives for developing a global landslide database for the collection, storage and dissemination of landslide information have not yet been organised, although the International Consortium on Landslides formed after the Kyoto summit in 2002 may support this in the longer term. Examples of other relevant databases include IRIS, the global archive for seismic records supported by the US National Science Foundation, which makes data freely available to participating institutions and investigators, and the International GNSS Service (IGS), which has provided valuable scientific data and products to users since 1994. The University NAVSTAR Consortium (UNAVCO) also serves the GPS data user community. The EROS Data Center of the USGS archives all Landsat and ASTER data, as well as other airborne and EO data streams, and similar archives exist at the various space agencies for other relevant EO data such as ERS and RadarSat.

Earthquakes are recorded today in the larger European region by over 1,700 short period and 380 broadband permanent seismic stations (Fig. 5.3.2.1), operated by nearly 100 networks and observatories. Access to seismological infrastructures, data and products by scientists and operators is largely achieved by remote access to the data centres collecting, archiving and processing the data. Presently, the European infrastructures for seismology are ORFEUS (Observatories and Research Facilities for European Seismology; serving since 1987 as European centre for the research community) and the EMSC (European-Mediterranean Seismological Centre; founded in 1976 to collect earthquake parameters and to provide rapid warning). To upgrade the inter-operability of the European seismological infrastructure the EU funded project NERIS (Network of Research Infrastructures for European Seismology) will start in April 2006.

Earthquake early warning is the provision of timely and effective information, through identified institutions, that allow individuals, exposed to a hazard, to take action in order to avoid or reduce their risk and prepare for effective response. A seismic early warning system for Europe (SAFER) with the test areas Athens, Bucharest, Cairo, Istanbul, and Naples will be established in the next years under guidance of the seismological community.

The existence of such databases facilitates the development of software for integration of the different streams of geohazard data. Integration aims to create a richer data product that contains the strengths, but overcomes the weaknesses, of each contributing dataset. Examples include the integration of 3-D point observations of topographic change from GPS, which are continuous in time but limited in spatial extent, with InSAR measurements which cover wide areas but are not continuous in time and only available in the radar’s line of sight.

5.5.4 Spatial Data Infrastructure and User Interface

Geodesy contributes in innumerable ways to the functioning of modern society. While the contribution of geodesy is essential to define the infrastructure underlying many of the functions of modern society, it is not necessarily well known or understood by most people outside the geodetic community. This infrastructure is known as Spatial Data Infrastructure

(SDI), and geodesy is the tool which defines the SDI. Due to the globalization and interoperability requirements, (geo-) spatial data and positioning are increasingly required with respect to a global reference frame.

In Europe the SDI program is known as the Infrastructure for Spatial Information in Europe (INSPIRE). Awareness has been growing at the national (e.g., GDI-DE in Germany) and EU level regarding the need for quality geo-referenced information. While SDI initiatives are much more than just reference frames and coordinates, there is a trend towards ever higher accuracies in the SDI. This means that a corresponding improvement in the accuracy of the geodetic infrastructure generally one order of magnitude higher is required. The SDI can be visualised as many layers of spatial information resting on a strong geodetic foundation. Hence this foundation must be defined and maintained on a high level of integrity. Any crustal motion impacts the realization of the national reference frame, and must therefore be monitored so that a valid 4-D reference system can always be reconstructed. Furthermore, all geospatial data sets must be referenced to the correct 4-D reference frame or datum. The transformations between different data must be defined to the appropriate level of accuracy. Finally, the quality and integrity of the associated high-accuracy techniques (e.g., GNSS, VLBI, SLR) must be consistent and quantifiable if the crucial connection between geopositioning and SDI is to be maintained for the benefit of so many applications (e.g., navigation, engineering, surveying, mapping, early warning, emergency management, infomability, management of and access to natural resources, monitoring the environment and improving predictability).

The user interface is a very important component to give access to observations, products and information to users at various levels and to achieve a maximum benefit for the scientific community and in society in general. The new IERS Data and Information System (see 5.5.1) may serve as an example for the present status in this field. The new system is running since 2005 at BKG in Frankfurt, Germany and provides information related to the IERS and to the topics of Earth Rotation and Reference Systems.

The concept of the dynamic and database-driven IERS Data and Information System is based on the application of the eXtensible Markup Language (XML) and the generation and administration of ISO standardised metadata. XML can be regarded as the future standard format for data and information exchange over the web. Using XML the heterogeneous products of the IERS in their various formats can be consistently described based on one common markup language. Moreover, despite their originally heterogeneous formats all products can now be merged easily for further investigations. From these data files extended metadata are extracted and stored in the data base for search and for the description of the available data sets. Additionally, the metadata can be explored by international metadata information systems to enlarge the user community of the IERS products. The web pages to present the available product versions and the associated information like the metadata have to be created automatically from the information stored in the data base. The system has to be completed by an Administration Tool providing all necessary instruments to maintain the data and information. Important features that need to be improved include the visualisation of products and information and explanation on data, products and geodetic techniques.

6 Deficiencies and Gaps

6.1 Reference Frames and Earth Orientation Parameters (EOP)

a) Global Reference Frames and EOP

Organisational background: The current organisational background for the global geodetic observation system consists of a number of mainly science-driven IAG services, which are all based on voluntary commitments and best efforts of the contributors, which are mainly national institutes and organisations. Although considerable improvements concerning observation networks, data analysis procedures, combination of different observation techniques, and the computation of global reference frame products could be achieved during the last years, the global geodetic infrastructure is suffering from reduced funding and increasingly sparse resources. In order to ensure the required accuracy and long-term consistency of the global reference frames the international geodetic infrastructure needs to be improved and a significant contribution of European organisations is essential.

Observation networks: The current definition of the IERS network does not fully satisfy accuracy, reliability and homogeneity requirements of a precise reference frame. The tracking network operated under the coordination of the IGS appears to be sufficient with respect to the number of stations, although some regions (e.g., Africa) are not well covered and especially concerning the station operations (e.g., standards, instrumentation, data latency) improvements are necessary. The ILRS network has been subject to funding problems and as a consequence some stations stopped operation. The number and in particular the spatial distribution of SLR is not sufficient and furthermore there are several stations with poor data quantity and quality. The long-term operation of the European Laser network (EUROLAS) must be guaranteed and the establishment of more SLR stations especially in the Southern hemisphere is essential, as SLR is important to realize the origin and scale of the terrestrial reference frame. Also in the case of VLBI the spatial distribution of stations is not optimal and typically only 4-6 telescopes observe simultaneously within one VLBI session, and the station configuration often changes from one session to the other. The DORIS network is homogenously distributed over the globe, but the monumentation for the beacons needs to be improved for many stations to allow precise point positioning. Furthermore the focus should be on high data quality, availability and very short latency to fulfil the needs for near real-time applications.

Integration of techniques: High quality co-location sites are important to integrate the different techniques and to ensure long-term stability of the reference frame. Both, the current situation regarding geographical distribution of these so-called fundamental stations and the accuracy of local ties are not sufficient. Each SLR and VLBI station should be co-located with GPS, which is currently not the case. All missing and questionable ties should be re-surveyed with highest priority, and then the other ties should follow. The local ties should be provided with full variance-covariance matrix with an accuracy of 1 mm. The high experience of the European institutions for the establishment and maintenance of fundamental stations (e.g., Wettzell) should be used to improve the overall situation. Furthermore, all the common parameters of the different techniques (e.g., station velocities, EOP, troposphere parameters) should be studied and possibly included in the integration.

Another issue that needs to be addressed in much more detail is the integration of different techniques on the satellite level.

Data analysis and combination: The data analysis procedures applied by the analysis centres must be consistent concerning modelling and parameterisation. This requires the adoption of common standards and models according to the most recent set of conventions (e.g., McCarthy and Petit, 2004), which is currently not always fulfilled in the different processing software packages. During the last years the software systems, models and processing strategies have improved continuously. To achieve consistent results it is necessary to re-process all the data with the latest software version, state-of-the-art models and the same strategy. This is, in particular in the case of GPS, a tremendous effort, which has not been achieved within the IGS. Thus the IGS time series solutions are affected by changes due to inconsistent software, models and processing strategies. Although significant progress has been achieved concerning the intra- and inter-technique combination of space geodetic observations, there are clear deficiencies and the combination methodologies still need to be refined for the generation of highly precise and self-consistent combined products. In this context also the user requirements concerning the latency of the global reference frame products should be considered accordingly. Furthermore, remaining biases between the different techniques need to be removed to the highest possible extent and their influence on the combined solution must be minimized.

Global reference frame products: Currently, the global reference frame products (ITRF, EOP, ICRF) are computed separately by the responsible IERS Product Centers, which leads to inconsistencies among them. Therefore, it is essential to develop rigorous combination methods for the generation of the IERS products, in order to ensure consistent reference frame results. As a first step towards this aim the IERS Combination Pilot Project has been initiated. Furthermore, the very high accuracy, which has been reached for the space geodetic observation techniques, is not fully reflected in current ITRF realizations. Major deficiencies are still remaining systematic errors (biases) between techniques, and non-linear site motions (e.g., seismic effects, seasonal signals, equipment changes) that were not considered in past ITRF realizations with positions and constant velocities. These non-linear site motions are detectable from a time series analysis of “weekly” solutions. Future ITRF realizations should be based on time series solutions and should also include seasonal variations. Furthermore, a high long-term stability better than 1 mm/yr on decadal to 50 years time scale should be achieved (e.g., for monitoring global sea level changes). As these ITRF realizations will become available with a time delay of 1-2 years, it is very important to provide also products in near real-time, which are a pre-requisite for the monitoring and detection of changes in the Earth’s system. For this purpose it is essential to develop suitable methods for the combination of time series solutions on a weekly basis to compute precise and reliable near-real-time products (e.g., precise station positions, EOP).

Availability of products: Global reference frame products are available with a latency of a few years. The update rates are also in the order of a few years. Time series solutions with station positions and EOP are provided by the Technique Services routinely with a time delay of 1-2 weeks (IGS, ILRS), and a latency of up to a few months by the IVS. The IDS does not provide combined time series solutions at present. As the time series solutions provided by the services are derived from one space technique only, the solutions may be affected by technique-specific biases. Until now, inter-technique combined time series solutions are not provided on a routinely basis. It is also very important that near real-time procedures will be developed, to contribute to the monitoring and detection of changes in the Earth’s system.

Furthermore the quality control procedures and the availability of the products need to be improved. So far mainly internal users of the space geodetic community are more or less familiar with the different product types. For external users (e.g., from other scientific disciplines or non-scientific users) it is difficult to find the best suitable products for their specific applications and to get all the necessary information they need. Thus there is an urgent need to improve the data information system for providing reference frame products to the users (see 5.5).

b) European Reference Frame (EUREF)

Observation stations: The EUREF permanent network (EPN) consists presently of more than 180 stations, and about 15 new stations join the network each year. A major problem is that for a number of EPN stations several equipment changes have been performed, which very often produce significant jumps in the position time series solutions. To account for all these changes a thorough time series analysis and a clear documentation of all these events is essential. In order to ensure long-term consistency it is important to improve this situation and to adopt the IGS standards for the operation of EPN stations. In addition to the EPN stations, the European countries should further increase their contribution to the in-situ networks of the other space techniques (e.g., SLR, VLBI, DORIS) and to fill gaps in networks of the ILRS, IVS and IDS and to improve the situation concerning high-quality co-location sites.

Data analysis and combination: Within EUREF, 16 Local Analysis Centres (LACs) are computing sub-network solutions, which are then combined to obtain the final EUREF solution. Although common standards and procedures are defined for the EUREF data analysis, the analysis procedures and the models used by the different LACs are not fully consistent among each other, which may lead to deformed results. This holds in particular for the two LACs which use other software packages than the Bernese GPS Software. To achieve consistent results to the highest possible extent it is strongly recommended that all LACs should use the same software, namely Bernese. For the combination of the sub-network solutions it is important to ensure, that all the applied constraints are documented correctly, so that they can be removed completely before the combination. Otherwise the constraints (which may be applied differently by different analysis centres) may lead to deformations in the combined solution. Another important issue is, that the processing strategies, models and the global reference frame have been updated from time to time, which led to jumps in the time series solutions. Thus it is required to perform a complete re-processing and re-combination of the weekly EUREF solutions to achieve consistent results.

European Reference System ETRS89: The ETRS89 is defined in such a way, that it is co-moving with the rigid part of the Eurasian tectonic plate and should be consistent with the ITRS at epoch 1989.0. Intra-plate motions, which for example exist in the Mediterranean Area (deformation zones) and in Scandinavia (post-glacial rebound) are not considered. In the Mediterranean Area station velocities differ by up to 4 cm/yr from the “stable” Eurasian motion, which leads to an error in the station coordinates of more than 70 cm (for observations performed 17 years after 1989.0). Furthermore post-glacial rebound in Scandinavia affects primarily the height component with up to 1 cm/yr, which should be introduced by geophysical models in the velocity model. Thus the computation of a plate kinematic and deformation model should be done on the basis of the space geodetic observations.

Research projects: The establishment of the European Combined Geodetic Network (ECGN) is an important contribution of the European countries to IAG's Global Geodetic Observing System (GGOS). So far the major focus was on the implementation of the ECGN network (1st call). It is also important that activities concerning the methodology and combined analysis of the ECGN data will be addressed in more detail. In various research projects it has been demonstrated that geodesy can provide important contributions to atmospheric research, which should be continued and further extended. The EUREF-IP project aims towards near real-time positioning. These activities should be continued with highest priority to satisfy the user requirements for near real-time applications.

National networks and transformations: Concerning the national networks the status for the different countries is very different and should be homogenized to the highest possible extent to ensure consistency among the national reference frames. Also the reference epochs for the realizations of the national reference frames in the ETRS89 system are partly different for the European countries. It is essential to provide consistent reference frame results for all countries in Europe (and over the world) to serve as the basis for a unique geoinformation system. For most suryeying 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 networks. In order to transform time-dependent ITRF coordinates to national coordinates, a detailed knowledge of the velocity field of the Earth's surface with an accuracy better than 1 mm/yr is required (an error of 1 mm/yr introduces already an error of 1 cm in positions over 10 years). As intra-plate deformations easily reach (or exceed) the 1 cm/yr level, present-day plate kinematic and deformation models based on space geodetic data must be developed. An example for such a model is APKIM, which has been developed at DGFI (e.g., Drewes, 1998).

6.2 Earth Physical Shape and Gravity Field

In spite of the fascinating achievements in the field of global monitoring of the Earth gravity field in past years primarily due to the new dedicated satellite missions (CHAMP, GRACE), the requirements defined in Tables 4.3-1 and 4.3-2 imposed on the determination of the static and time-variable gravity field signals have not been reached as yet. In the first place this is due to insufficient or reduced funding. Additionally, some technological, organisational and methodological difficulties still influence the accuracy, homogeneity, consistency und continuity of the results unfavourably. The main shortcomings are briefly outlined in the following.

6.2.1 Space-based Recovery of the Earth Gravity Field

The main concern is that there still does not exist a consistent plan and a secured financial support for sufficient future dedicated gravity field satellite missions, necessary for an uninterrupted monitoring of the temporal variations of the gravity field which is of utmost importance for the reliable detection of global change phenomena, but also for the improved modelling of the static gravity field. If a GRACE-type follow-on mission is not ready on time, i.e., before the decommissioning of the GRACE satellite pair, data gaps will emerge, making it difficult to bridge the missing time period and to connect the GRACE-era and the post-GRACE observations of the temporal variations of the Earth gravity field in order to obtain a consistent long-term time series for the detection of trends.

Technical difficulties which led to the postponement of the GOCE mission as a complementary technique to GRACE postpone the improved recovery of smaller features by the satellite-only static gravity field solutions and therewith both the improvement of the consistent unified global vertical reference frame and of the definition of the mean sea surface topography necessary for the oceanic general circulation models. Such technical difficulties, which can emerge in some form in the realization of other space missions as well, point at the same time to the necessity of planning and implementing new and especially follow-on missions on time, if possible with an adequate overlap.

In spite of the revolutionary achievements brought by CHAMP and GRACE missions, it should be noted that the anticipated baseline accuracy of the GRACE mission has not been achieved as yet. This might be partly due to the accuracy limits of the inter-satellite measurements based on a K-band link, which will in some future missions probably be replaced by an optical one. However, this cannot solve all problems, since a part of the inaccuracies comes from the deficiencies of the physical background models (in the first place of the atmosphere and ocean circulation models, but also for instance of the deficiencies of the ocean tidal models in the shallow-sea regions). These background models, the so-called dealiasing products, are inevitable in the process of the gravity field recovery from the low-low satellite-to-satellite (SST) observations. It should be noted that the improvement of the physical background models is an iterative process. Just the global solutions for the time variable gravity field derived from GRACE observations contributed essentially to the detection of the deficiencies in the background models. Hence, any deficiencies (e.g., discontinuity) in the monitoring of the Earth gravity field from space postpone an improvement of the background physical models as well, which in turn has an unfavourable influence on the accuracy of the monitoring of the Earth gravity field from space.

An obvious shortcoming of the space-based techniques for the monitoring of the Earth gravity field from space are polar gaps. This deficiency can presently be only partly compensated by combining these techniques with airborne, marine and terrestrial ones.

Satellite-only models for the Earth gravity field, especially monthly (or even shorter, like 10-days) solutions, which represent time variations of this field, still contain a considerable portion of noise, visible in the form of well known stripe-features. In recent years there were remarkable successful efforts in removing them by taking into account the nature of correlated GRACE observation errors. However, the decorrelation techniques developed as far aim at postprocessing of the time series of gravity field solutions delivered by the processing centres. A direct integration of the decorrelation techniques into the gravity recovery processing itself was not realized as yet.

6.2.2 Airborne and Marine Observations of the Earth Gravity Field

Airborne and marine gravimetry can considerably densify and improve the static global Earth gravity field modelling by combining the regional gravity data with the global gravity field models derived from satellite missions. In contrast to a relatively good global coverage of the shipborne gravity data, adequate airborne surveys of many inaccessible areas of the globe, especially the Amazon, mountainous regions, large parts of Africa, coastal regions, and especially Antarctica, are still rather incomplete.

Another present shortcoming is that the already existing data from many airborne surveys are currently classified or proprietary.

In contrast to the continuous observations of the time variations of the Earth gravity field realized by space techniques or on terrestrial permanent ground stations, an airborne gravity survey of some region with a comparable continuity does not seem to be realistic.

6.2.3 Terrestrial Observations of the Earth Gravity Field

The spatial coverage of terrestrial data is very inhomogeneous. This holds both for the data obtained by means of the absolute and relative gravimetry and applies both to the data collected in sporadic campaigns and to continuous registration of permanent stations of the Global Geodynamics Project (GGP).

The big majority of the sites of the Global Geodynamics Project (running superconducting gravimeters) is located in Europe and Japan leaving huge gaps in the global coverage of the Earth. Moreover, several stations ceased their operation in past years.

In order to extract the secular signal from terrestrial observations, high-frequency variations caused by solid-Earth and ocean loading tides, polar motion, atmospheric and hydrological loading have to be corrected for. With the exception of hydrological loading this can be usually done with sufficient accuracy by using available physical models. In order to correct the recordings for the influence of local hydrological loading additional equipment for the acquisition of the necessary data at and in the vicinity of the station is necessary, which is not available in most cases.

The gravity anomaly measured by a gravimeter is the sum of the effects due to the vertical motion of the gravimeter through the unperturbed gravity field and the contribution from mass changes in the vicinity of the gravimeter. In order to separate these two effects, gravimeters need to be collocated with geometric instruments such as a GNSS receiver, which is often not the case.

Both, in order to calibrate the Superconducting Gravimeters (SG) and to monitor the continuous gravity changes during, and in between, the observations of Absolute Gravimeters (AG) it is necessary to perform intercomparisons between the SG and AG instruments, which is not always the case.

An additional shortcoming is that a considerable part of the existing terrestrial gravity data is currently classified or proprietary, and hence not available to the general community.

6.3 Geohazards

Critical gaps exist in: the provision of detailed, global topographic data, hazard inventories and geoscience maps; continuity of the C- and especially L-Band radar interferometry that are needed to observe surface deformation under varying vegetation cover; density and coverage of local GPS and seismic networks; accessibility of relevant databases; adequacy of models and data integration; and the integration of the geohazards community.

Deformation monitoring is required for all the geohazards and at many scales. Over the last decade, two new methods (GPS and SAR differential interferometry) have emerged that allow us to quantify even small displacements over wide areas. These are already the methods of choice for monitoring seismic zones. They are gradually integrating and replacing the traditional ground-based systems for determining horizontal and vertical displacements and tilt that were developed for monitoring deformation at volcanoes. InSAR is being used in a pre-operational system to monitor subsidence in Europe. In the case of GPS, we can obtain precise, long-term measurements of topographic change, whether in regions of high interest (e.g., southern California, with the SCIGN network) or globally (the IGS network). The main limitation is that the high-density networks needed for hazards monitoring exist only locally. A major challenge for the integration of local GPS data globally, and the integration of GPS data with older, heritage deformation data sets, is the spreading of formats and established archives, plus limited accessibility for the different kinds of deformation data.

Satellite radar differential interferometry provides the capability to map past and ongoing crustal displacements, day or night, in all weather and over wide areas. The CEOS DMSG Report concluded that building up long time series of radar images over sensitive locations would enable more systematic exploitation of multi-interferometric techniques. Their wider application to displacement monitoring is limited by inadequate temporal resolution; a lack of coherent data due to the radar frequency at which observations are currently made, the difficulty of resolving line-of-sight measurements into three dimensions, and insufficient mission continuity. The most frequent observation was achieved during ERS's Tandem Mission, when it was shown to be possible to monitor even certain types of landslides using InSAR. This was based on a 1-day revisit interval, whereas SAR satellites typically have revisit interval in the order of 1 month.

Development has also been limited by the relative inability of existing (C-band) systems to produce information over unconsolidated or vegetated natural surfaces. L-band InSAR has been shown to be applicable over a wider variety of natural land surfaces than C-band during the now-completed JERS mission. The recent report from the Solid Earth Science Working Group (SESWG) “Living on a Restless Planet” also emphasises the relevance of L-band SAR for differential interferometry over natural surfaces. Filling this gap in observations might be feasible using the forthcoming PALSAR, the proposed TerraSAR-L systems or the recently launcher ALOS satellite.

At either wavelength, there is an urgent need for long-term continuity of observations. The phenomena to be observed are often slow but continuous, and their successful monitoring can only be achieved with decades of satellite data. Other requirements are that the orbit and satellite design be optimised for this application, be tasked specifically with interferometry in mind, in order to provide sufficient frequency of observation and have sufficient look directions to resolve motion in three dimensions. More generic missions have been used to great effect in research mode but they involve compromises in spatial, spectral and temporal resolution that limit the utility of these observations for operational geohazard mitigation in general and long-term monitoring in particular.

At a basic level databases exist for most types of Earth Observations, often as part of a processing and archive facility, and for many ground-based measurements, as part of particular organisations' data management strategies. The gaps that exist relate to the visibility and fitness for purpose of these data stores. The requirement is for much more than storage within a single organisation. Databases are needed with a high visibility within the geohazards community, which facilitate the transfer of data, information and knowledge between different types of users in different countries. Interoperability of databases is crucial, as geohazards require multidisciplinary research. The heterogeneous nature of existing databases can be an obstacle to the progress of our understanding of the geohazards mechanisms. This leads to the need for the creation and population of international geohazards databases.

A good example of what is required is provided by the evolving World Organisation of Volcano Observatories database. Similar initiatives are needed for all the geohazards. Such databases should contain both, baseline data and the output of monitoring activities, including relevant ground-based data from geoscience organisations and also data from existing satellite archives. The data in them should be calibrated, validated, put into a standard format and quality assured prior to databasing. Mechanisms are needed to facilitate the rapid and smooth transfer of data from the space agencies to the scientists monitoring geohazards and of information from the scientists to the users.

Integration of data acquired at different resolutions, with different accuracies and geometric characteristics and from different observation systems, still needs a major effort from the scientific community. For example, the techniques needed to monitor crustal deformation and surface displacements include both, satellite-supported InSAR and ground-based monitoring, with GPS monitoring combining elements of both. The methods are complementary: ground-based monitoring can provide a record of deformation at a specific point on the ground that is continuous in time, while InSAR gives us periodic measurements of the areal distribution of displacement over wide areas. Both are needed in an operational monitoring scenario and they can also be used to cross-validate the observed deformation, increasing confidence in both individual results. But, in the main, the integrated use of ground and satellite data is generally limited to intercomparisons and data calibration.

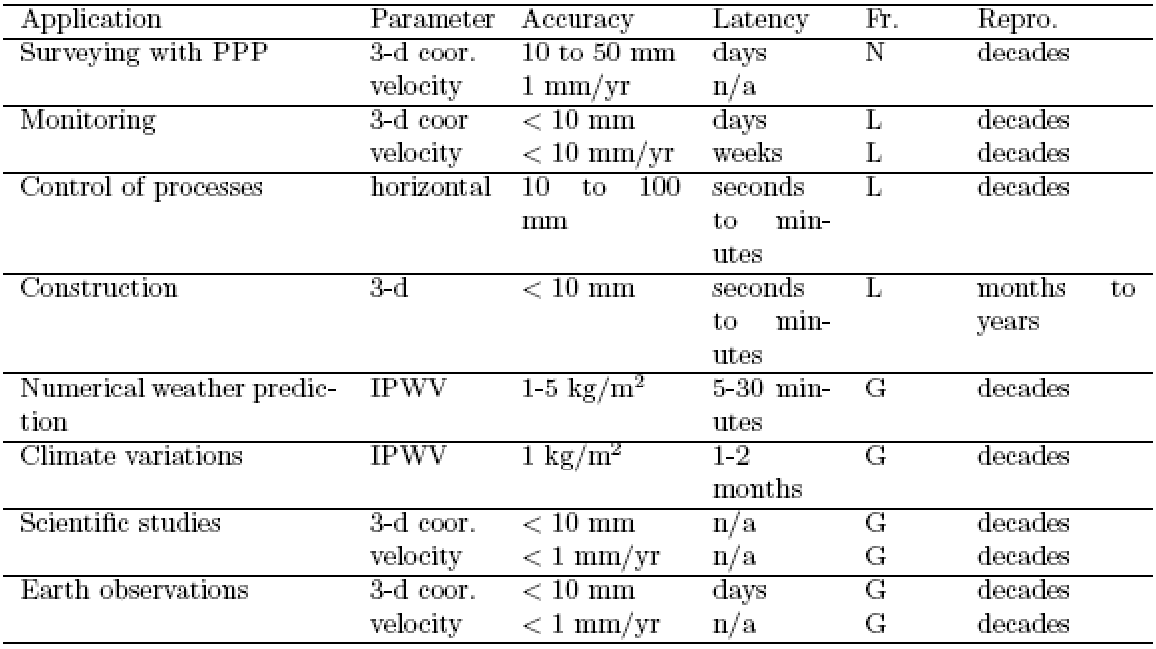
One of the most formidable obstacles to effective global monitoring of geohazards is that activities occur at an enormous range of time scales. Explosive eruptions may be over in a few hours to a few days, while pyroclastic flows and lahars can move at metres or tens of metres per second. Even the largest earthquakes are over in minutes. Landslides may be rapid, catastrophic events on similar time scales to eruptions. For rapid events, scientists are dependent on monitoring networks already in place, geostationary satellites (which can take an image every 5-15 minutes), strategically placed time-lapse or video cameras, or observers in aircraft, to capture details of the events. One scientific challenge, then, is that effective EO monitoring will require either a range of higher resolution sensors on geostationary satellites, or larger constellations of low-Earth-orbiting (LEO) satellites than currently exist.

Other events are far slower: eruptions can last for decades, like the current long-lived eruptions at Montserrat (1995-present), Popocatepetl (1995-present), Etna (1991-3 and 1995-present) and Kilauea (1983-present). Regional subsidence can be a slow, relentless process occurring over similar timescales. For these events, the need for continual monitoring becomes very expensive, whether it is ground-based or uses satellite observations. Improved monitoring and archiving of long-lived events will help establish which parameters are most useful, in order to make long-term monitoring as efficient as possible. There is also the issue of the long repose time between large events. About 60 of the world’s 1500 potentially active volcanoes erupt in any given year, and most erupt only once a century or less frequently. There is a similar long repose time between extremely large earthquakes at any one location.

6.4 Man-made Problems

The current and likely future accuracy requirements for access to positions in a terrestrial reference frame are summarized in Table 6.4-1. 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.

Table 6.4-1: URs for access to position (cf. Plag 2006). 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 PPP	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
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

Using the acceptable latency as independent parameter, we can identify three main user categories (UC) for high accuracy applications requiring or benefiting from ad hoc positioning. Real time positioning constitutes the first category (UC1). For these users, the most extreme accuracy requirements are expected to be considerably lower than 10 cm and in some cases even below 1 cm. 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 intra annual time scales. For long-term monitoring tasks, 1 mm/yr or better in stability seems to be a critical boundary both for scientific and non-scientific tasks. This number also applies to collection of geo-databases, which are to be maintained over time scales of several decades.

Table 6.4-2: Overview of latency and accuracy requirements of main user categories (cf. Plag 2006).

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

Depending on the time scale, we see the latency and accuracy requirements for high accuracy applications summarized in Table 6.4-2. Presently, GPS&IGS satisfies 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 physical center of mass of the Earth system. 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 user category, 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 user category in the need of local or regional augmentation systems.

While UR1 and partly UR2 can be met by local to wide-area augmentation systems, the UR3 and UR4 requirements depend crucially on the quality of ITRF and the available products. Moreover, achieving UR1 and UR2 through a Signal-in-Space Only system would considerably increase the areas of applications and provide significant economic advantages.

6.5 Data Acquisition and User Interface

The deficiencies and gaps are reviewed for the following components:

Infrastructure for network stations: The time delay for the transmission of the data from the network stations to the operational data centers is not satisfying for many applications (e.g., weather forecast, early warning systems). Furthermore the procedures for checking the downloaded data need to be improved.

Data Centers: The data flow between the Operational, Regional and Global Data Centers do not satisfy the requirements for a near real-time generation of the products. An efficient access and storage of the data, a reduction of the traffic on the Internet, as well as the level of redundancy allowing for security of the data holdings is not optimal.

Analysis and Combination Centers: The standards and models applied by different analysis centers are not fully unified leading to inconsistencies in the derived products. This holds for both, the analysis centers of the same techniques and across techniques. The analysis and combination procedures often require long processing times and are thus not suitable for near real-time applications.

Product generation: The reference frame products, the International Terrestrial Reference Frame and the International Celestial Reference Frame are available with a delay of about a few years (for the ITRF) and several years (for the ICRF). Real-time and near real-time applications (such as weather forecasting, tsunami early warning systems) require low-latency product delivery, which is not yet achieved.

Spatial Data Infrastructure and User Interface: There are ongoing developments concerning the Spatial Data Infrastructure, however there are still a number of deficiencies and gaps to satisfy all the needs of a modern society. Furthermore, the geodetic contributions for many applications (e.g., navigation, engineering, surveying, mapping, early warning, emergency management, informability, management of and access to natural resources, monitoring the environment and improving predictability) are not well known for users outside the geodetic community. There are still a number of deficiencies and gaps (e.g., access to the data, description of the data and products, visualisation of products) that need to be improved.

7 Forward Planning of a Geodetic and Geohazards Observing System and Recommendations

7.1 Introduction and Objective

When planning a Geodetic and Geohazards Observing System and considering the implementation of such a system for the monitoring of the Earth system with geodetic and geophysical methods and with a high spatial and temporal resolution, this cannot be done independently of the major activities that are in progress in this field. The most recent developments that are crucial to the issues discussed here, are the Global Geodetic Observing System (GGOS) of the International Association of Geodesy (IAG) and the Global Earth Observing System of Systems (GEOSS) of the Group on Earth Observation (GEO). The European initiative GMES may be considered the European contribution to GEO and the GEOSS. The planning concerning a geodetic and geohazards observing system should therefore take into account the developments of GGOS as a part of GEOSS.

In this Chapter 7 we will start with the overall design and characteristics of such a geodetic and geohazards observing system and then describe in the following the various components of this system and their perspective for the future. Recommendations will be given on which actions and measures are most important to improve the present situation and fill gaps in the field of geodetic and geohazard monitoring infrastructure and organization. In view of the considerable contribution of the European community to these activities, GMES should have a special interest to address the points mentioned in this chapter.

7.2 Overall System Design

The philosophy behind the overall design of the observing system is given in Figure 7.2.1. On the left-hand side the various geodetic and geophysical observation techniques are displayed. They allow the monitoring of the three major pillars of space geodesy, namely the geometry and deformation of the Earth (including the oceans), the orientation and rotation of the Earth and the Earth gravity field and its temporal variations. These pillars again contain valuable information about the various components of the Earth system on the right-hand side. Starting from right to left, on the other hand, accurate models of the processes in the Earth system will help to get a better interpretation of the phenomena visible in variations of geometry, Earth rotation and the gravity field and to identify deficiences and gaps in the measurement techniques. This will motivate the design and realization of new innovative observation technologies. Because the various observation techniques are complementary in many aspects they should be combined, to the extent, into one consistent and efficient system, making use of the strengths of the individual instruments. On the right-hand side, in analogy to the combination issue on the left-hand side, the interaction between the individual components of the Earth system have to be understood and the corresponding processes have to be modelled to improve our ability to eventually precisely and reliably predict both, the future long-term trends in and the short-term behaviour of the Earth system.

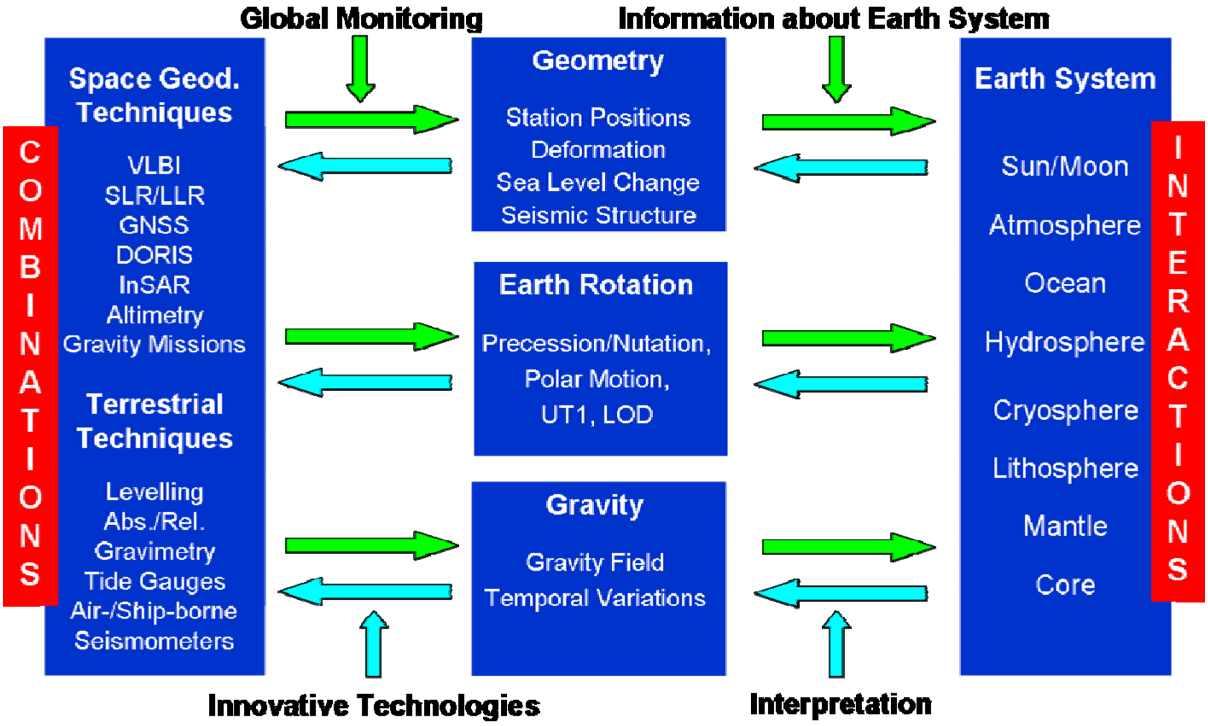


Fig. 7.2.1: Measuring and Modelling the Earth System

It is clear that the observing system should be designed in such a way that it meets the specifications summarized in Chapter 4. In view of the demanding requirements, only the integration of a multitude of sensors and instruments into one global observing system, where all the instruments will work together like one extremely complex sensor, will reach the goals. In order to function as a big Earth observatory for the benefit of science and society, the observing system has to encompass not only global terrestrial networks of observatories and space missions devoted to geodetic Earth observation, but also communication infrastructure, analysis centers, coordinating centers, and internet portals (requiring hardware, software and manpower).

The following four important parts should be considered in the design of the geodetic and geohazards observing system:

- **Instrumentation:** global, regional and local terrestrial networks of observatories and Earth observing satellites.
- **Data Infrastructure:** data transfer, communication links, data management and archiving systems, data and product dissemination centers, web portals, etc.
- **User Interface and Portal:** a unique access point for all products and observations with a database of relevant metadata according to international standards.
- **Data Analysis, Integration and Modelling:** complete and consistent data processing chains ranging from the acquisition and processing of vast amounts of observational data to the consistent integration and assimilation of these observations into complex numerical models of the Earth system.

These four components will be described in more details in the next sections.

7.3 Instrumentation

In order to meet the monitoring requirements and needs of science and society concerning accuracy, timeliness, and spatial and temporal resolution, the observing system has to consist of a variety of different instruments, not only on ground but also in space, in the air and on the oceans. The individual parts of the overall system are linked to each other by co-location of instruments at the same site on Earth or on the same satellite in space. This co-location of instruments and sensors is extremely important to establish a common, high-precision reference frame, for the consistency and accuracy of the system and for the integration of the individual sensors into a system that acts like one large and complex "instrument".

7.3.1 Ground-Based Infrastructure

This component of the observing system consists of all the terrestrial networks of geodetic and geophysical ground stations contributing to the terrestrial reference frame realization and maintenance and to the Earth monitoring:

- The global network of VLBI radio telescopes coordinated by the IVS
- The global network of SLR/LLR stations of the ILRS
- The global network of GNSS stations of the IGS
- The global network of DORIS stations coordinated by the IDS
- The global network of superconducting gravimeters comprised in the GGP and the global network of sites occupied episodically with absolute gravimeters
- The global network of tide gauge stations coordinated by the Intergovernmental Oceanographic Commission (IOC)
- The global network of geodetic timing stations
- The global network of seismic stations

Core Network of Co-Location Sites: The core of the terrestrial global observation network should be a set of about 40 globally well-distributed core stations, where all the major geodetic observation techniques (and a variety of additional sensors) are co-located. These stations realize the links between the different instrument types on a global scale. The co-location of the different techniques allows not only the integration of the individual technique-specific networks into a unique terrestrial reference frame (ITRF) but also the assessment of the observation quality and accuracy and the mutual validation of the results. For this, the local ties between the instruments of the individual space geodetic techniques would have to be exactly known. A network of such core stations is mandatory to realize, maintain and monitor the global reference frame with an accuracy of 1 mm or below for decades. A prerequisite for these connections between the techniques

> **Recommendation 01:** In the next 5-10 years a global network of about 40 core sites should be established with a homogeneous global distribution.

> **Recommendation 02:** The local ties between the space geodetic techniques should be measured continuously and automatically at global core sites.

Let us mention here, for the sensor networks of importance in the context of this report, the most important steps to be taken to improve the monitoring capabilities.

Global VLBI Network of the IVS: At present the IVS is not capable to perform VLBI observations for geodesy in a continuous mode, 7 days a week and 365 days a year. For space and planetary missions, e.g., however, the rotation angle of the Earth has to be known very well in real-time to point the radio telescopes to the correct location in space. The IVS therefore plans to aim for a global VLBI network with about 40 sites, each site equipped with one or, even better, two small-antenna observing systems and connections to high-speed network links. A group of antennas directly connected to the correlator via high-speed networks will provide the possibility of real-time or near real-time processing of the data and to produce EOP products in a matter of hours.

> **Recommendation 03:** To enable continuous VLBI observations a network of about 40 VLBI sites is required.

Global SLR/LLR Network of the ILRS: The size of the SLR/LLR network should be such, that it can meet the requirement of a 1-mm stability of the origin and the scale of the global reference frame over time periods of decades (e.g. to allow an accurate monitoring sea level change with altimetry). According to the plans of the ILRS, the stations will be equipped with fourth generation laser systems with repetition rates of 100-1000 Hz, with increased sensitivity of the detectors, shorter dead-times between events, very automated or autonomous operations, and real-time data flow to the data and analysis centers.

> **Recommendation 04:** To reach the requirement of a reference frame stabiliy of 1 mm or below over decades, a network of 30-40 improved SLR/LLR stations should be established.

Global GNSS Network of the IGS: The GNSS network of the future will be a real multi-purpose observation network that will support the following applications:

- the reference frame realization, monitoring and maintenance
- the densification of the network of core stations and the basis for regional densifications of the global reference frame
- time and frequency transfer between time laboratories equipped with GNSS receivers
- the monitoring of global plate tectonics and deformation phenomena (loading, etc.)
- the monitoring of the displacements after and during an earthquake (GNSS seismology, that is, observing the seismic waves with 20-50 Hz sampling rates) to give additional information to determine earthquake magnitudes and rupture processes
- the connection of tide gauges to the global reference frame through co-location
- and for ground-based atmospheric sounding (troposphere and ionosphere)

The following steps will be important to allow for applications mentioned above:

- Installation of GNSS receivers tracking the GNSS satellites of all the systems (GPS, GLONASS, GALILEO, COMPASS, …)
- Homogeneous global distribution of sites, densely covering all major tectonic plates, so that the deformation in the global reference frame caused by a large earthquake can be determined in near real-time
- All core sites should be equipped with at least three GNSS receivers and antennas to allow for equipment change without loss of accuracy (mutual calibration of the antenna phase center variations)
- Real-time data communication links and the support for high-rate data collection (20-100 Hz)

> **Recommendation 05:** The global GNSS stations should install receivers that allow the tracking of the satellites of all relevant GNSS systems.
>
> **Recommendation 06:** All global core sites should be equipped with at least three GNSS receivers and antennas
>
> **Recommendation 07:** The global GNSS stations should be equipped with real-time data communication and should be tracking with at 1-10 Hz or higher. Analysis centers should strive to process the real-time data in (near) real-time for near real-time reference frame monitoring and earthquake magnitude determination.

The global IGS network will be the reference frame for the regional and local densification for various geodetic and geohazards monitoring efforts (Earthquake and volcano monitoring, tsunami early warning systems, InSAR support, atmospheric sounding, …).

Global DORIS Network of the IDS: A new generation of DORIS beacons will be installed at all the DORIS sites, most of them connected to atomic clocks. Remote management and control of the DORIS sites is envisaged.

Gravimeter Network: In order to derive time series of gravimetric measurements that improve the monitoring of the Earth system on a global level, a network of about 30-40 should be set up. To the extent possible, these sites should be identical with the 40 core sites. Each of these stations should eventually consist of a super-conducting and an absolute gravimeter, both continously measuring the gravitational acceleration and its change with time.

> **Recommendation 08:** To the extent possible the 40 core sites should be equipped with superconducting and absolute gravimeters to allow for the combination of gravimetric and geometric data (loading, geocenter).

Global Seismic Networks: The global seismic network is constantly growing, especially due to the establishment of tsunami early warning systems, where seismometer network is a crucial component. As many of these seismometers as possible should also be equipped with a GNSS receiver to allow for a combined determination of earthquake magnitudes together with seismological data.

> **Recommendation 09:** To the extent possible, the global seismic network should be equipped with GNSS receivers for a combined analysis and earthquake magnitude and rupture process estimation.

7.3.2 Space-Based Infrastructure

GNSS Satellites: In a few years the GLONASS will have a full constellation of satellites again. GALILEO will probably become operational around 2013 with an additional 30 satellites and the Chinese government is also planning a 30-satellite GNSS called COMPASS-2. Other nations like India or Brazil will eventually follow as well, since the GNSS are step by step going to be as important an infrastructure as railway tracks, highways, oil and gas pipelines, or high voltage power lines. Therefore, approximately 120 GNSS satellites will be available around 2013 or shortly after. This will once more open up a new dimension in global positioning and navigation applications, also for Earth monitoring and geohazards early warning systems. The IGS should have the goal to generate consistent GNSS products for all the available systems and the ground network should support this by installing GNSS receivers that are capable to track the satellites of all these systems simultaneously.

> **Recommendation 10:** Global GNSS products should be made consistent for all relevant GNSS systems (especially satellite clocks and orbits),

Satellite Missions for Earth Observation: Satellite missions are an extremely important component for the monitoring of the Earth system and the detection of hazards. Satellites have the big advantage that they collect data homogeneously and consistently over the Earth surface, typically covering most of the Earth surface. They also allow the collection of data that cannot be recorded at the Earth's surface. These satellites are nowadays equipped with a multitude of sensors and instruments and thus enable the monitioring of the land, ocean and ice surfaces as well as the Earth gravity field and its temporal variations. The potential and impact of satellite missions on Earth observation will increase considerably due to the fact that (1) more and more satellite constellations instead of individual satellites will be launched increasing the temporal and spatial resolution of the data and (2) satellites will be flown in formations thus allowing to form large observing instruments composed of sensors on more than one satellite.

Chains of Satellite Missions: Due to the importance of the satellite component for the observation of geodetic/ geophysical parameters of the Earth (e.g., the gravity field and its temporal variations) the monitoring should not end with the end of a dedicated mission but has to be continued with follow-on missions establishing a chain of missions (as in the case of the altimetry missions TOPEX, Jason- 1, Jason-2, and ERS-1, ERS-2, Envisat, etc.). Such chains of satellite missions are crucial for monitoring the Earth system over long time periods and for the detection of long-term trends and changes in the Earth system.

> **Recommendation 11:** Chains of satellite missions should be established for successful Earth observation missions (gravity, InSAR, altimetry, atmospheric sounding) to ensure long-term stable time series of geodetic/geophysical observations for gobal change research.

Gravity Field Missions: This is especially true for the gravity field missions allowing the monitoring of highly relevant mass transport phenomena like the water cycle in large river basins, melting of ice sheets in Antarctica and Greenland and the associated sea level change, as well as in the ocean current systems. ESA's future GOCE mission will lead to another huge improvement in the resolution and accuracy of the Earth static gravity field and of our knowledge of the oceanic current systems. GOCE will also mark an important step toward a more accurate unified global vertical reference frame. In view of these developments it is clear that present and future gravity field missions have to play a crucial role in a global geodetic observing system. An uninterrupted monitoring of the temporal variations of the gravity field is of utmost importance for climate research and global change phenomena, i.e., the reliable detection of small trends in the gravity field due to sea level rise, the melting of ice sheets and changes in the ocean current systems. To avoid any gaps in the time series – GRACE may last till 2013 – a GRACE follow-on mission with only minor design changes is mandatory, because the development of new technologies may require several years and, thus, might not be ready before the decommissioning of the GRACE pair. On the longer run, innovative instrumentation (e.g., optical inter-satellite links, optical clocks in space, etc.) may improve the accuracy of satellite measurements by 2-3 orders of magnitude.

> **Recommendation 12:** An uninterrupted monitoring of the temporal variations of the gravity field is of utmost importance for climate research and global change phenomena. A GRACE follow-on mission should therefore be realized before the present GRACE pair fails in orbit.
>
> **Recommendation 13**: Around the years 2016-2018 a new gravity mission with innovative instrumentation (optical inter-satellite link, optical clocks, …) should be ready for launch.

InSAR Missions: Complementary to other space-based geodetic observations, which produce temporally smooth, but spatially discontinuous point measurements of surface motions, InSAR observations produce spatially continuous images of the deformation of the Earth's surface. The need for improved coverage of the Earth's surface is obvious, particularly for geohazards and Earth sciences. Due to the difficulties encountered with C-band InSAR in vegetated areas, the relevance of L-band InSAR for differential interferometry over natural surfaces should be emphasized. In the US the mission DESDynI, an L-band InSAR and laser altimetry mission, will be launched in the 2010-2013 time frame. DESDynI will measure surface and ice sheet deformation for understanding natural hazards and climate and vegetation structure for ecosystem health. This gap in the monitoring should also be addressed by the GMES. To improve temporal and spatial coverage, constellations of satellites are required. By 2020 we anticipate a constellation of InSAR satellites with contributions from the US, Europe, Brazil, Taiwan, and Japan. A coordinated constellation of InSAR satellites will enable multi-baseline observations for the determination of topography and vegetation structure. The constellation will also allow for more frequent observations at particular locations, enabling more rapid response to events such as earthquakes, volcanoes, and landslides, as well as a better determination of time dependent phenomena.

> **Recommendation 14:** Europe should consider an L-band InSAR mission or a cooperation with NASA in the DESDynI mission to get access to satellite data that is very important for geohazards monitoring.

Co-location on Satellites: In view of the difficulties to exactly measure (with 1-mm accuracy) – all around the world – the local ties between different instruments installed at the same location on ground, co-location of instruments on satellites should be encouraged as a compementary set of links between the observation techniques This will also help to mutually validate quantities measured by more than one instrument type and to combine the various measurements, e.g., to separate the individual contributions of different processes in the Earth system to the measured quantity. Therefore, all GNSS satellites should be equipped with laser retro-reflector arrays. In addition, satellite missions should be designed to co-locate the various observation techniques (GNSS, SLR, VLBI and DORIS).onboard satellites with very high accuracy.

> **Recommendation 15:** A future satellite mission should be designed that co-locates all the major space geodetic observation instruments onboard a satellite to improve the global terrestrial reference frame (ties between the techniques).

New Technologies: The recent progress in various areas of satellite technology has been extremely fast and triggers the design of new satellite mission concepts. The most important new concepts are the design of micro- or even nano-satellites (a fraction of the present costs for a satellite mission), constellations with a large number of satellites to increase the temporal and spatial resolution and the timeliness of products. In the near future, constellations of 10-100 satellites will become feasible and affordable. Formation flying as another interesting aspect adds to new dimensions compared to conventional missions, namely the possibility of inter-satellite measurements and the integration of several satellites to form one large instrument.

> **Recommendation 16:** New technological concepts like constellations of micro- or nano-satellites or formation flying should be studied for future Earth Observation satellite missions.

7.3.3 Airborne and Shipborne Infrastructure

Airborne and sea surface data with their higher spatial resolution (compared to satellite data) are very important to assess the quality and accuracy of satellite or ground-based data. They help to get more detailed information about the processes considered. Although the main focus of GMES may be on global aspects of Earth monitoring, most of the natural hazards are rather regional or local in nature. Airborne and shipborne instruments should therefore supplement the space- and ground-based sensor networks.

As an interesting example, airborne and shipborne gravimetry illustrate of how our knowledge of the global Earth gravity field from satellite missions can be densified and improved with airborne and shipborne sensors. The regional gravity data is combined with the global gravity field models from satellites to get the high-frequency part of the field.

7.4 Data Infrastructure

The Global Geodetic Observiong System (GGOS) and most of the IAG Services, on which a considerable part of a geodetic and geohazards observing system would be based, already have a data system infrastructure in place to support the users of the respective service. The infrastructure used by the individual IAG Services for the flow of information, data and products from the observing stations to the user community is very similar. The same is true for the services of the seismological community. Network stations continuously track and transmit data using predetermined schedules, data centers interface to stations and users, perform data quality checks and data conversion, and archive data and products for analysis center and users, and analysis centers that generate higher level products.

Satellite Communications: In general the data flow, including redundancy and checks etc., is well-established in all the services. When striving for a much more homogeneous coverage of the Earth with core sites or technique-specific sites in remote areas to improve the global products, especially the global reference frame, much more emphasis will have to be put on satellite communication technologies. As satellite communication links become cheaper and cheaper this might be the technology of the future. Thinking of the challenges of a near real-time or real-time monitoring system (which is especially essential for geohazards, early warning systems, etc), the communication procedures setup nowadays are certainly not sufficient. Real-time data flows (e.g., NTRIP for GNSS or e-VLBI for VLBI) have to be established to allow for the real-time detection of natural or man-made hazards.

> **Recommendation 17:** Satellite communication technologies should be pushed to allow for the data transfer from countries with otherwise bad communication technologies.
>
> **Recommendation 18:** Real-time or near real-time data flow should become the standard in the various geodetic and geohazards services. Formats for real-time data transfer have to be defined for these flows.

Inter-Satellite Communications: With micro- and nano-satellites becoming more and more powerful and with satellite constellations and formation flying concepts becoming reality, a near real-time monitoring of the Earth is in view as well. However, only geostationary satellite or inter-satellite communications will allow the data transfer to the Earth, to the data and analysis centers for the data analysis in due time. Therefore, the development of such innovative communication technologies has to start now.

> **Recommendation 19:** Inter-satellite and geostationary satellite communication links should be developed for the geodetic/geophysical services.

Data Volumes Measured in Petabytes: It is to be expected that the data sampling rates of the space geodetic techniques will increase significantly over the next few years. Instead of 30 GPS satellites about 100 GNSS satellites will be observed and sampling rates of 50-100 Hz might become an issue, because they will allow the monitoring of seismic events themselves or rapid scintillations in the ionosphere. Imaging satellites like TerraSAR-X, TanDEM-X or EnMAP are or will record data measured in petabytes. The data infrastructure that is capable to handle such huge amounts of data has not yet been designed nor developed. First steps in this direction have to be initiated now.

> **Recommendation 20:** Data infrastructure that is capable to handle extreme quantities of data (petabytes) have to be developed.

7.5 User Interface and Portal

For a large user community, as in the case of the geodetic and geohazards communities, GMES or GEO with many links to other disciplines and fields, the setup of a user interface for the access of all the relevant information, that is of importance to the communities and their inter-linked disciplines as well as to the general public interested in the topic, is a necessity but also a challenging task. Such a user interface should consist of three parts:

- a database, which mainly contains information, meta information and catalogues, and facilitates access to observations and products provided by the various IAG and geohazards services
- a web portal, which will be an unique access point for all products and information made available
- a clearinghouse for geodesy and geohazards, which will allow to search for information related to all aspects of these fields

In the frame work of the GEOSS, these type of concepts are now designed and established. It is very important that the geodetic and geohazards community are part of these developments and get linked to the corresponding data infrastructure and have their own influence on the standards and conventions to be agreed upon. All the data and products available through the IAG Services and corresponding services in the geohazards community should become visible in the GEOSS architecture. The European part might also be bundled in a corresponding GMES user interface, portal and clearing house as a lower hierarchical level.

> **Recommendation 21:** The geodetic and geohazards communities and their data portals should be closely linked with the GEOSS (and GMES) data infrastructure.

7.6 Data Analysis and Integration

In this section the emphasis is on the fact that nowadays the analysis of the data and the integration of a variety of sensor types is a very complex and demanding task. The major points to be addressed when aiming at a thorough integration of the different observation techniques are the following:

Standards and Conventions: Having in mind the multi-technique, multi-component and multi-parameter nature of GGOS, a big effort will have to be put into the realization of the required consistency of processing startegies, geodetic and geophysical models and standards across all components of the envisaged observing system. Only a consistent set of products will allow for a meaningful interpretation of the various time series of quantities obtained by the geodetic/geophysical sensors.

> **Recommendation 22:** The geodetic and geohazards communities should ensure that their products are highly consistent and follow the same set of standards and models.

Redundancy and Reliability: To obtain redundant and reliable products of the observing system more than one, better a few analysis center should be available for all the major tasks and each of the primary product types. Comparisons (and combination) of the products of the individual analysis centers will lead to fast progress and improvements in the quality and reliability of the products (due to friendly competition among analysis centers). This concept of friendly competition is nicely illustrated by the very successful activities of the IGS and the other IAG services.

> **Recommendation 23:** The primary products of a geodetic/geohazards service should be generated by more than one analysis center and should be compared (and combined) between analysis centers.

Homogeneous Reprocessing: In addition, the analysis centers have to be able to reprocess all the data of the relevant observation techniques within a reasonable amount of time to ensure that long, homogeneous, consistent and high-accuracy time series of geodetic and geophysical parameters can be obtained to allow the establishment of a long-term highly stable global reference frame and to detect critical trends and anomalies in the time evolution of the time series. The importance of such a capability is emphasized by the following examples: ESA recently decided to finance the reprocessing of all the ESA satellite altimetry data available and the IGS initiated a special reprocessing project for the consistent re-analysis of the global GNSS data set of the last 14 years.

> **Recommendation 24:** The IAG and geohazards services should be able to reprocess all their global data sets within a reasonable time frame.

Combination of Geometry and Gravimetry: Currently the IERS is working on a rigorous combination of the geometric products (site coordinates, EOPs, quasar coordinates, …) . Much progress has been achieved, but there are still significant deficiences in the consistency of the products as outlined in Chapter 6. It is the goal of the IERS and GGOS to combine all the parameters common to more than one observation technique to obtain full consistency and strength. Especially this should lead to a consistent set of products for ITRF, ICRF, and all the EOP.

> **Recommendation 25:** A lot of effort should be put into the development of a rigorous combination of all the space geodetic techniques including all their common parameters.

The combination of geometry with gravity is even more demanding. The International Gravity Field Service (IGFS) has only recently been established. But such a combination, if opbtained, will only lead to more consistent products but also to a better understanding of the various geodynamic and geophysical processes visible in coupled deformation and gravity changes.

> **Recommendation 26:** The combination of geometric and gravimetric data in a consistent way is of utmost importance for the correct interpretation and understanding of the geodynamic/geophysical processes.

Combination of InSAR and GNSS: As mentioned already above, the InSAR technique, providing spatially continuous images of the deformation of the Earth surface is very much complementary to the GNSS ground measurements that produce temporally smooth but spatially discontinuous, point measurements. A combination of both techniques is, therefore, very beneficial and should be strengthened. Geodtic networks are providing control points for the SAR images but also corrections for tropospheric (and ionospheric) refraction to improve the interferograms.

> **Recommendation 27:** The synergies between GNSS and InSAR observations should more efficiently be exploited.

Combination of GNSS and Seimology: The deformation caused by a large earthquake can be accurately measured by GNSS receivers. An accurate knowledge of the displacements in the vicinity and surroundings of the earthquake epicentre gives information about the characteristics of the earthquake that is complementary to that of seismometers and is very valuable for the estimation of the earthquake magnitude and the rupture process, especially in the case of large earthquakes. In addition, with modern GNSS receivers the deformation caused by the earthquake waves themselves can be determined by tracking the GNSS satellites with a sampling rate of 20-50 Hz. A combination with the corresponding seismic data should be done. Therefore, GNSS antennas and seismometers should, to the extent possible, be co-located, especially in areas that are prone to earthquakes.

> **Recommendation 28:** Co-locations of GNSS stations with seismometers for earthquake monitoring should be stressed and realized.

Complete Processing Chains: For a geodetic and geohazards observing system it cannot be enough to collect and record huge amounts of observation data. Complete processing chains have to be established from the collection of the raw data and the processing of the large amounts of observational data to the consistent integration and assimilation of these observations into complex numerical models of the Earth system. To detect and identify natural disasters in due time, these chains should also support the near real-time or even real-time processing of the data. The establishment of a tsunami early warning system (e.g., the German Indonesian Tsunami Early Warning System (GITEWS)) can be seen as a challenging example, where a real-time or near real-time monitoring is of crucial importance for the success of the system. In this example the integration of various sensors (seismometers, ocean bottom pressure sensors, GPS buoys, GPS land stations, tide gauges, etc.) into one c0mplex system is vital as well.

> **Recommendation 29:** Operational and fully automated processing chains should be established for Earth system and geohazards monitoring.

Finally, the major outcome of the observing system should be a set of highly accurate, consistent and long-term stable products as the geodetic/geophyiscal contribution to the observation and monitoring of the Earth system (i.e., to GMES, GEOSS, IGOS-P and other international and regional initiatives). All the product accuracies should reach the order of about 10^{-9} (as the ratio of the errors to the absolute values of the measured quantities). This has to be true also for the consistency between the various porducts of such an integrated observing system.

7.7 Organizational Issues

Probably the most critical issue concerning the organization of the various IAG Services and the operation of a geodetic and geohazards observing system is the fact, that to a large extent these services are based on the same principle of voluntary commitment and best effort as e.g. GEOSS. The experience of the successful IAG Services shows that this principle requires a high degree of redundancy, and at the same time is problematic for providing a uniform global coverage of ground- and space-based infrastructure. In particular for reference frame maintenance, large spatial gaps and temporal variations in the monitoring infrastructure (including changes in the polyhedron through new and disappearing stations) cause temporal inhomogeneities and degradations of accuracy. Similarly, it is difficult to realize a continous series of satellite missions (e.g. gravity or InSAR missions) to allow for a long-term monitoring of the Earth system.

GMES is certainly one place, where such critical issues in the global geodetic and geohazards monitoring infrastructure should discussed and most probably are.

> **Recommendation 30:** The financing of the crucial operational aspects of the geodetic and geophysical global observing networks and the establishment and maintenance of the terrestrial reference frame (ITRF) should be put on a more solid basis.

Despite the importance of the ITRF for highly accurate monitoring of relevant Earth system parameters, up to date no formal integration of the underlying geodetic observing networks into the G3OS has taken place. However, the current development in the community responsible for determining and maintaining the ITRF towards a high-level integration on global scale opens also for an integration of the important reference frame issue into the Earth Observing Systems. The weight of the European contribution to this community constitutes a special obligation for GMES to address this issue.

> **Recommendation 31:** The ITRF should be recognized by GEO (and GMES) as the terrestrial reference frame that gives the basis for all Earth observation.

In the quest to become the leading knowledge-based society, the current contribution of European institutions to the ITRF is an important contribution. Combining geo-referenced databases, broad-band communication capacities and the possibility to determine highly accurate positions ad hoc will have a profound effect not only on global Earth system monitoring for sustainable development but also on a large number of service for the security of the society such as disaster warning, assessment of natural hazards risks, estimation of post-hazards damages, rescue aids and many other application.

8 Conclusions

The overall goals of the GAGOS project were (1) to assess the present situation of two major components of the Earth observing system, namely the global geodetic and the global geohazards observing systems of relevance for GMES (Global Monitoring for Environment and Security), (2) to identify deficiencies and gaps by comparing the status quo with the requirements of the scientific and societal users, and (3) to perform a forward planning for an improved global geodetic and geohazards observing system including recommendations for such improvements. Thereby the following fields were addressed:

- Terrestrial reference frame and Earth orientation parameters,
- Earth physical shape and gravity field,
- Geohazards,
- Man-made problems and monitoring of infrastructure,
- Data acquisition, data flow, data archiving and data information management.

The conclusions related to the chapters 3 to 7 of this document are:

Earth observations and geodesy: The increasing accuracy of space geodetic observations, the extension of space techniques, and the enormous achievements in data processing led to a significant expansion of the objectives of geodetic research. As an Earth science the objectives of geodesy have extended to the observation and analysis of phenomena and effects of processes in the Earth system. The principle of geodetic observations and parameter estimation as well as the elements of the Earth System are outlined before discussing the complex interrelations between Earth signals and geodetic parameters. The new challenge is the combination of heterogeneous but extremely precise geometric and gravimetric data in a common consistent procedure, which has to be adapted to a physical model matching as closely as possible reality, in order to allow geophysical analysis and interpretation. The rigorous integration of precise observations by combination requires a consistency of measurements, constants, models, reference systems, processing methods and estimated parameters. Only if compatability is guaranteed we can provide reliable results that fulfil the high requirements for the representation of the complex phenomena and effects in the Earth system.

Requirements for a Geodetic and Geohazard Observation System: A basic requirement for a correct representation of the properties and processes of the System Earth is the integration of all elements and all observation data. If the individual elements are modeled separately, the estimated parameters may be incorrect due to the effects of signals from other elements, which were not modelled. If the elements of the Earth system are modeled by one observation type only, the properties and processes may be represented incompletely or wrong, because important information from other measurements is missing. Incomplete integration holds the risk to interprete unmodelled effects as geophysical signal. There are also specific requirements from various applications, which were addressed in chapter 4. These geo-scientific applications include climatologically induced mass transports, geodynamics, surveying, navigation and real-time positioning, contribution to geohazards, climate monitoring and weather predictions, monitoring of infrastructure, as well as GEO and IGOS-P related applications. Finally, the latency and accuracy requirements of main user categories were summarized for the various applications.

Assessment of existing components: The present situation concerning existing components was assessed in chapter 5. This assessment was performed for the reference frame products, such as the International Terrestrial Reference Frame (ITRF), the International Celestial Reference Frame (ICRF), the Earth Orientation Parameters, and the European Reference Frame. The same was done for the second field “Earth physical shape and gravity field”. In this field the assessment was performed for space-based systems including the modern satellite gravity field missions (CHAMP, GRACE, GOCE) and ground-based systems. The infrastructure for geohazards was assessed for earthquakes, volcanoes and landslides followed by an assessment for man-made problems and monitoring of infrastructure. Concerning data acquisitation, data flow, data archiving and data information management the assessment was performed for geometric data and products, gravimetric data and products, databases for geohazards, spatial data infrastructure and the user interface.

Deficiencies and gaps: Taking into account the requirements for a global geodetic and geohazard observing system and the status quo of the existing components, deficiencies and gaps were identified. This was done for the global and regional reference frames and for the Earth orientation parameters. Thereby aspects, such as the organizational background, the observation networks, integration of techniques, data analysis and combination as well as the availability of products were addressed. In the field of Earth physical shape and gravity the deficiencies and gaps were identified concerning the space-based recovery, the airborne and marine observations, and the terrestrial observations of the Earth gravity field. Deficiencies and gaps were also identified for the three other fields, such as geohazards, man-made problems, data acquisition and user interface.

Forward planning of a Geodetic and Geohazard Observing System and recommendations: In order to close the deficiencies and gaps of the existing components a planning for a future, improved geodetic and geohazard observing system was performed. This was done for the following components: Overall design of such an observation system, ground-based infrastructure, space-based infrastructure, airborne and shipborne infrastructure, data analysis, integration and modeling, data management and user interface, and organizational issues. As a result of this study, about 30 recommendations for an improved global geodetic and geohazard observing system were given in chapter 7. Finally, it should be underlined that the forward planning and the recommendations focus on improvements which will provide a sound basis to serve applications within GMES and to provide significant European contributions to GGOS, GEO and IGOS-P.

On the international level, IAG is working on the scope and realisation of the Global Geodetic Observing System (GGOS), a planning to be very soon published by a reference document, called GGOS2020 (Plag et al., 2008). This document describes the future GGOS as an observing system in the year 2020. Many findings of the present study will have to be taken into account in the GGOS design. This way, the European GAGOS-activities will have an important role in the full implementation of GGOS.

9 References, Acronyms

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9.2 Acronyms and URLs

ALOS	Advanced Land Observing Satellite (Japanese satellite mission)
AFREF	Reference Frame for Africa
ASI	Agencia Spatiale Italiano, Italy
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
BEK	Bayerische Kommission für die Internationale Erdmessung of the Bavaria Academy of Science, Munich, Germany
BKG	Bundesamt für Kartographie und Geodäsie, Germany
CB	Central Bureau
CDDIS	Crustal Dynamics Data Information System
CEOS	Committee on Earth Observation Satellites
CGS	Centro di Geodesia Spaziale, Matera, Italy
CHAMP	CHAllenging Mini-satellite Payload
CLS	Collecte Localisation Satellites (www.cls.fr)
CLS	Collecte, Localisation, Satellites
CNES	Centre National d'Etudes Spatiales
CNR	Istituto di Radioastronomia, Italy
CODE	Center for Orbit Determination in Europe, Astronomical Institute of the University of Bern, Switzerland

COST716	GPS Meteorology in Europe
COSMIC	Constellation Observing System for Meteorology, Ionosphere & Climate
CPP	Combination Pilot Project
CRF	Celestial Reference Frame
CRInSAR	Corner Reflector InSAR
CSR	Center for Space Research, The University of Texas at Austin
DC	Data Centre
DEM	Digital Elevation Model
DEO	Delft Institute for Earth-Oriented Space Research, Delft, The Netherlands
DEVF	Dense European Velocity Field
DFG	German Research Foundation
DGFI	Deutsches Geodätisches Forschungsinstitut
DGPS	Differential GPS
DMSG	ad hoc Disaster Management Support Group
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite
DUT	EPN data centre at Delft Institute of Technology, Delft, The Netherlands
EC	European Commission
ECCO	Estimating the Circulation and Climate of the Ocean
ECGN	European Combined Geodetic Network
ECMWF	European Center for Medium Weather Forecast
EDC	EUROLAS Data Centre
EDM	Electronic Distance Measurement
EGG-C	European GOCE Gravity Consortium
EGNOS	European Geostationary Navigation Overlay Service
EIGEN	European Improved Gravity models of the Earth from New techniques
EMSC	European-Mediterranean Seismological Centre
ENVISAT	ENVIronmental SATellite mission
EO	Earth Observation
EOP	Earth orientation parameters
EPIGGOS	European Partners In GGOS
EPN	European Permanent Network
EROS	Earth Resources Observation and Science
ERS	European Remote Sensing satellite
ESA	European Space Agency
ESOC	European Space Operations Center of ESA, Darmstadt, Germany
ETRS89	European Terrestrial Reference System
EUMETNET	conference of 19 European Meteorological Services
EUREF	European Reference Frame and IAG Sub-commission for Europe EUROLAS European Laser Network
EVRS	European Vertical Reference System
ExGG	NMCA Expert Group on Geodesy
FAGS	Federation of Astronomical and Geophysical Data Analysis Services
FGI	Finnish Geodetic Institute
FÖMI	Földmérési és Távérzékelési Intézet
FORMOSAT-3	see COSMIC
GAGOS	Assessing and forward planning of the Geodetic and Geohazards Observing Systems for GMES applications
GCOS	Global Climate Observing System
GEO	Group on Earth Observations
GeoDAF	Geodetic Data Archiving Facility, Italy

GeoNet	GPS Earth Observation Network (Japan)
GEOSS	Global Earth Observation System of Systems
GFZ	GeoForschungsZentrum Potsdam
GGOS	Global Geodetic Observing System
GIPSY/OASIS	GPS-Inferred Positioning SYstem and Orbit Analysis SImulation Software
GIUB	Geodetic Institute of Bonn University
GLONASS	Global Navigation Satellite System
GMES	Global Monitoring for Environment and Security
GNAAC	Global Network Associate Analysis Centres of IGS
GNSS	Global Navigation Satellite Systems
GOCE	Gravity field and steady-state Ocean Circulation Explorer
GOOS	Global Ocean Observing System
GOP	Geodetic Observatory Pecny, Pecny, Czech Republic
GOPE	Geodetic Observatory Pecny
GPS	Global Positioning System
GPS/MET	GPS Meteorology Satellite Mission
GRACE	Gravity Recovery and Climate Experiment
GRGS	Groupe de Recherche de Géodesie Spatiale
GSFC	Goddard Space Flight Center, Greenbelt, MD, US
GTOS	Global Terrestrial Observing System
GVA	Gross Value Added
HPF	High-level Processing Facility
IAG	International Association of Geodesy
IAU	International Astronomical Union
ICRF	International Celestial Reference Frame
ICRS	International Celestial Reference System
ICSU	International Council for Science
IDNDR	International Decade for Natural Disaster Reduction
IDS	International DORIS Service
IEEC	Institut d'Estudis Espacials de Catalunya, Spain
IERS	International Earth Rotation and Reference Systems Service
IGE	Instituto Geográfico Nacional de España, Spain
IGN	Institut Géographique National, Paris, France
IGNE	EPN data centre at Institut Géographique National, Paris
IGOS	Integrated Global Observing System
IGS	International GNSS Service
ILRS	International Laser Ranging Service
INASAN	INstitut AStronomii rossijskoj Akademii Nauk (Institut of Astronomy of the Russian Academy of Sciences), Moscow, Russia
InSAR	Interferometry Synthetic Aperture Radar
IOC	Intergovernmental Oceanographic Commission
IP	Internet Protocol
IRIS	global archive for seismic records supported by the US National Science Foundation
ISDC	Integrated System and Data Center
ITRF	International Terrestrial Reference Frame
ITRS	International Terrestrial Reference System
IUGG	International Union of Geodesy and Geophysics
IVS	International VLBI Service for Geodesy and Astrometry
IWVP	vertical integrated water vapor

JCET	Joint Center for Earth Systems Technology, US
JERS	Japanese Earth Resources Satellite program
JPL	Jet Propulsion Laboratory, Pasadena, US
KMS	Kort & Matrikelstyrelsen (National Survey and Catastre), Copenhagen, The Netherlands
LAC	EPN Local Analysis Centre
LAREG	Laboratoire de Recherches en Géodésie, Marne la Vallée, France
LEGOS	Laboratoire d'Etudes en Géophysique et Océanographie Spatiales, France
LEO	Low-Earth Orbiting satellite
LLR	Lunar Laser Ranging
LOD	Length of Day
LPT	Bundesamt für Landestopographie, Wabern, Switzerland
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Administration; US
NAVSTAR	Navigation Signal Timing and Ranging
NEIC	National Earthquake Information Center (US)
NERC	Space Geodesy Facility, UK
NERIS	Network of Research Infrastructures for European Seismology
NFGS	National Environment Research Council
NKG	Nordic Geodetic Commission (Statens Kartverk, Norway)
NKGS	Nordic Geodetic Commission (Onsala Space Observatory, Sweden)
NMCA	National Mapping and Cadastre Agencies in Europe
NOAA	National Oceanic & Atmospheric Administration, US
NRC	National Research Council
NRCan	National Resources Canada
NREF	Reference Frame for North America
Ntrip	Networked Transport of RTCM via Internet Protocol
OLG	Institute for Space Research, Graz, Austria
ORFEUS	Observatories and Research Facilities for European Seismology
PALSAR	Phased Array type L-band Synthetic Aperture Radar (radar antenna)
PBO	Plate Boundary Observatory network (US)
PO.DAAC	Physical Oceanography Distributed Active Archive Center
PS	Permanent Scatterer
PSInSAR	Permanent Scatterer InSAR
RIGTC	Research Institute of Geodesy, Topography and Cartography, Czech Republic
RINEX	Receiver Independent Exchange format
RNAAC	Regional Network Associate Analysis Centre
ROB	Royal Observatory of Belgium, Brussels, Belgium
RTCM	Radio Technical Commission for Maritime Services
SAFER	Seismic eArly warning For EuRope (EU FP6 proposal)
SAR	synthetic aperture radar
SCIGN	Southern California Integrated GPS Network, www.scign.org
SDS	Science Data System
SESAME	Seismotectonics and Seismic Hazard Assessment of the Mediterranean Basin
SESWG	Solid Earth Science Working Group
SGG	Satellite Gravity Gradiometry
SGN	Service de Geodesie et Nivellement (SGN) of IGN, France
SGO	FOMI Satellite Geodetic Observatory, Budapest, Hungary

SINEX	Solution INdependent EXchange format
SIO	Scripps Institution of Oceanography, La Jolla, US
SIRGAS	Sistema de Referencia Geocéntrico para las Américas
SK	Statens Kartverk, Norwegian Mapping Authority, Norway
SLR	Satellite Laser Ranging
SPS	Standard Positioning Service
SSALTO	altimetric and orbitography mission center
SST	Satellite-to-Satellite Tracking
SUT	Slovak University of Technology, Bratislava, Slovakia
TEC	total electron content (electron density)
TerraSAR-L	first European L-band SAR mission
TIGA-PP	Tide Gauge Benchmark Monitoring Pilot Project of IGS
TOPEX	ocean TOPography Experiment satellite mission
TRF	Terrestrial Reference Frame
TWG	EUREF Technical Working Group
UC	user categories
UELN	United European Levelling Network
UNAVCO	University NAVSTAR Consortium (US)
UNEP	United Nations Environment Program
UNESCO	United Nations Educational, Scientific and Cultural Organization
UPA	University of Padova, Padova, Italy
UR	user requirements
USGS	United States Geological Survey
USNO	US Naval Observatory, Washington, D.C., US
UT1	Universal Time
UTC	Universal Time Coordinated
VLBI	Very Long Baseline Interferometry
WMO	World Meteorological Organisation
WPLTN	Western Pacific Laser Tracking Network
WUT	Warsaw University of Technology, Poland
ZTD	Zenith Total Delay