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# Scientific objectives of current and future WEGENER activities

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## Abstract

The WEGENER group has promoted the development of scientific space-geodetic activities in the Mediterranean and in the European area for the last fifteen years and has contributed to the establishment of geodetic networks designed particularly for earth science research. WEGENER currently has three scientific objectives which are related to plate-boundary processes, sea-level and height changes, and postglacial rebound. In a full exploitation of the space-geodetic techniques, namely SLR, VLBI and GPS, the individual scientific projects do not only pursue these objectives but also contribute to improving and developing the observation techniques as well as the modelling theories. In the past, particularly SLR observations within WEGENER-MEDLAS have provided a fundamental contribution to determine

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the regional kinematics of the tectonic plates in the Mediterranean with high precision. With GPS, spatially denser site distributions are feasible, and in several WEGENER projects detailed studies of tectonically active areas were possible on the basis of repeated episodic GPS observations. Current projects associated with WEGENER are successful in separating crustal movements and absolute sea-level variations as well as in monitoring postglacial rebound. These tasks require high-precision height determinations, a problem central to all of the present WEGENER activities. In these projects, continuously occupied GPS sites are of increasing importance. Time series of heights observed with continuous GPS can be determined with a few centimeters RMS error thus enabling the reliable estimates of vertical rates over relatively short time intervals. Regional networks of continuous GPS sites are already providing results relevant, for example, for the study of postglacial rebound. The Mediterranean area is an extraordinary natural laboratory for the study of seismotectonic processes, and the wealth of observations acquired in previous WEGENER projects together with new space-geodetic observations will allow the test of geophysical hypotheses linking three-dimensional deformations of the Earth's surface to the dynamics of the Earth's interior. In particular, it is anticipated that WEGENER projects will aim at a test of the slab-detachment hypothesis. The complex investigations on sea-level fluctuations presently carried out at basin scale from the Strait of Gibraltar to the Black Sea make it possible to study the present and recent past interactions of ocean, atmosphere and solid Earth, as well as to develop appropriate models to assess future aspects.

*Keywords:* Space Geodesy; gravity; sea level; post-glacial rebound; African-Eurasian plate boundary; 3-D deformation of the Earth

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## 1. Introduction

The 'Working group of European Geoscientists for the Establishment of Networks for Earth-Science Research' (WEGENER) was established in the beginning of the 1980s as an inter-disciplinary group centered on the application of space-geodetic and other techniques to the study of geodynamics. A description of the evolution of WEGENER over the last one and a half decades is presented by Wilson (1998). In 1991, the 'WEGENER Project: Geodetic Investigations Related to the Kinematics and Dynamics of the African, Arabian and Eurasian Plates' was established as Special Commission SC6 of the International Association of Geodesy (IAG). It is the responsibility of WEGENER to organize parts of the international geodetic and geophysical community in a concerted effort to produce high-accuracy and coherent data and valuable results relevant to the three objectives defined below.

The present general study fields were basically worked out during meetings in 1990 and 1991 in response to NASA's 'Dynamics of the Solid Earth' (DOSE) Announcement of Opportunity and as a natural development of the scientific activities carried out by the WEGENER group in the course of NASA's Crustal Dynamics Project (CDP) which began in the early eighties.

After the initial period of growth in both the number of scientists involved or related to WEGENER activities and the geographical areas covered by projects carried out within its frame, WEGENER has been restructured in 1995 following the election by the IAG of a new president (S. Zerbini) and the formation of a new directing board. During the first meeting of the new board (Bologna, October 1995), the scientific objectives were reviewed and revised according to the most recent developments in the scientific areas of interest to the project.

Achieving the WEGENER scientific objectives relies very much upon the acquisition of high-accuracy data in the experiments. Therefore, it is a major concern of the group that the most appropriate techniques continue to be available or will be developed whenever possible. WEGENER is maintaining a close contact to the agencies and institutions responsible for the development and maintenance of the global space-geodetic networks in order to make them aware of the scientific needs and outcomes of the project which might have an influence on the general science policy trends.

The purpose of this paper is to clearly define the objectives, identify scientific hypotheses to be tested, and outline the approaches to be taken and the improvements needed to achieve these objectives. In that, the paper (1) outlines past results and current focus of three prominent areas of geosciences and (2) demonstrates to the wider scientific community the capabilities of space-geodetic techniques to provide useful constraints for the scientific problems in these fields. Moreover, the paper documents the width and interdisciplinarity required in empirical studies of geoscientific problems.

## 2. Scientific objectives of WEGENER: an overview

The present main objectives of WEGENER are: (1) to study the three-dimensional deformations and gravity along the African–Eurasian plate boundaries and in the adjacent deformation zones in order to contribute to a better understanding of the associated geodynamical processes; (2) to monitor the three-dimensional deformations in a large region centered around Fennoscandia in order to determine the magnitude and extent of the present-day postglacial rebound in that area, thereby extending our knowledge about the viscoelastic properties of the Earth; (3) to investigate height and sea-level variations in order to identify and separate the processes contributing to these variations.

In parallel to these objectives, the mutual improvements of the measurement techniques, the testing of new technological means and proposals for new missions, as well as the synthesizing of observable quantities and the inversion of the observations for geodynamically relevant parameters are parts of all the WEGENER activities. In combination, the three objectives make extensive use of the most advanced space-geodetic and gravity techniques to contribute to scientific fields associated with three-dimensional surface deformations, which are not only relevant to basic science but also have potentially significant economic and social benefits.

Plate boundaries are, in general, geographical areas associated with high risks of natural disasters. A principal key to understanding the plate boundary processes, including the driving forces, is a detailed knowledge of the kinematics and of the associated gravity changes. In particular, a synthesis of the structural information derived, for example, from seismic tomography and the present-day kinematics determined with the geodetic measurements will establish more strict or even novel constraints for geodynamical models of plate boundary processes. Moreover, these data contribute to the framework required for an assessment of natural hazard risks.

The present-day deformations and changes in gravity associated with the ongoing postglacial rebound are an important augmentation of the existing data-sets related to glacially induced deformations such as the Pleistocene and Holocene sea-level changes, secular polar motion, and secular changes of the low-degree geopotential. The interactions of glacial loads, crustal deformations and sea-level changes over the past 100 ka constitute crucial boundary conditions for paleo-climate models. The uncertainties in our knowledge of the rheology of the Earth's mantle are a basic limitation for the quality of, for example, reconstructed paleo-topographies or geophysically determined ice models. Such knowledge is required as input for paleo-climate reconstructions, and as such it is of utmost significance for the quality of paleo-climate reconstructions.

Sea-level variations and in particular secular changes of sea level play a prominent role in the climate-change discussion. Climate variability on time scales from decades to centuries is presently coming into focus but is not very well understood (see for example, Crowley and Kim, 1993; Rind and Overpeck, 1993). However, it is clear that at these time scales, the ocean is a major component of the climate system, and studying the sea-level variability will contribute to an improvement of our understanding of the relevant processes. Europe has coastal areas of considerable extent and ecological and economical value. Understanding sea-level variations on time scales of up to centuries is crucial for an integrated and sustainable management of coastal zones. The anticipated anthropogenic environmental changes are likely to induce significant changes in future sea levels, be it in the frequency of storm surges, tidal ranges or secular trends. Thus, the need to develop the capability of providing current rates and predicting future variations in sea level on local, regional and global scales is fully understood by the international scientific community, as is expressed in recently developed projects such as LOICZ (Holligan de Boois, 1993) and international activities of the IAPSO Commission on Mean Sea Level and Tides (Carter, 1994), the ILP (Fard, 1994), and the IOC-Euro-Gloss project (Baker et al., 1996).

Sea-level records longer than a decade originate exclusively from coastal tide gauges. To determine secular changes from such records is problematic, because tide gauges provide sea levels only related to a benchmark on land. In order to obtain absolute sea levels, crustal movements and sea-level variations have to be separated, which necessitates a monitoring of the crustal height variations. Thus, the height determination problem is closely related to the observation of coastal sea level. Moreover, in order to interpret correctly the observed height variations, crustal movements resulting from tectonic forces and postglacial rebound need to be known. This clearly demonstrates the synergistic nature of the three WEGENER objectives: the sea-level problem cannot be solved correctly without solving the two other problems attacked by the WEGENER activities.

In Section 3, we will first summarize the current status in monitoring three-dimensional deformations and gravity with respect to the various techniques and the time scales of the variations. Section 4 considers geodetic networks from the WEGENER perspective with special emphasis on the interactions between the WEGENER activities and the networks. The three main objectives are considered separately in Sections 5–7, each starting with a summary of the problem, then discussing scientific hypotheses to be tested, which might contribute to a better understanding of the problem, and, after a short description of ongoing projects, concluding with an identification of future approaches and activities apt to contribute to the objectives. The final section summarizes the current status related to the WEGENER objectives and outlines the major scientific developments to be expected for the near future.

## 3. Monitoring three-dimensional deformations and gravity

### *3.1. Space geodesy: techniques, organisations, and data products*

Space geodesy went through a remarkable development during its 35 years of existence. Three organisations dealing with space geodesy shall be mentioned briefly, namely the International Earth Rotation Service (IERS), the International GPS Service for Geodynamics (IGS), and the Commission on International Coordination of Space Techniques for Geodesy and Geodynamics (CSTG). The first two are service-type organizations, the last is a joint commission of the IAG and of COSPAR, the aim of which is to coordinate existing and stimulate new activities in the research involving space techniques. Very close links between the three organizations are required to guarantee a meaningful development in this area of research and application. More information concerning the IERS is given in the series of technical reports issued by the IERS, while Beutler et al. (1996) provide an overview of the IGS, and Beutler and Drewes (1996) discuss the current CSTG policy and important issues like the role of different space techniques today and in the future.

Whereas optical astrometry was the primary observational tool in the pioneer era, Satellite Laser Ranging (SLR) and Very Long Baseline Interferometry (VLBI) were the main contributors in the late seventies and in the eighties for high-accuracy tasks. The IERS Terrestrial Reference Frame (ITRF) up to the version ITRF92 almost uniquely relied on SLR and VLBI, and the IERS Celestial Reference Frame (ICRF) relies completely on the VLBI technique. Almost everything we know today about the Earth's geocenter and gravity field stems from the SLR observation technique. Since the end of the seventies until the early nineties the transformation parameters between the two systems ITRF and ICRF were also almost uniquely determined by VLBI and SLR.

In the late eighties and the early nineties a very powerful contributor to regional and global geodynamics — with the advantage of a low-cost terrestrial segment (as compared to both, VLBI and SLR) — came up in the form of the Global Positioning System (GPS). Particularly since the IGS started its operations in June 1992, GPS may be used in a very convenient and productive way for regional geodynamics projects. Today's IGS products are estimated to be accurate on the level of 10 cm for the satellite orbits, 0.1–0.2 ms for the pole positions $x$ and $y$, and 0.03 ms (time) in the length of day. This accuracy is comparable to those of VLBI and SLR. The IGS products allow a relative positioning in regions of continental (or even global) size with an accuracy of about 0.5 cm in the horizontal, and of about 1 cm in the vertical position with site occupation times of a few days provided there are some permanent IGS sites in the region of interest. Because IGS products of highest accuracy are available rather rapidly (11 days is the maximum delay) after the observations, there is indeed an almost unlimited number of scientific applications made possible through GPS. The availability of IGS products are of major importance for the WEGENER objectives.

It should be mentioned that recently other (than GPS) micro-wave satellite systems like DORIS, GLO-NASS, and PRARE started to contribute to regional and global geodynamics. It can be expected that more of these systems will be realised in the near future. Depending on the availability of the data, the Technology Committee of the WEGENER board will promote the integration of these systems in present and future activities within WEGENER.

Taking into account the achievements of these new systems, IERS progressively included GPS and then DORIS among the contributing techniques. Consequently, the ITRF92 solution included for the first time GPS contributions and ITRF94 included furthermore DORIS contributions. This greatly improved both the IERS network by giving it a substantially better geographical coverage and improving its reliability as well as the accuracy of the links between the frames underlying each technique.

It is nowadays widely recognized that the high-precision determination of particularly vertical crustal motion (as required, for example, in sea-level studies) requires a colocation of space-geodetic positioning methods and gravity. While the first techniques provide high-accuracy kinematic data, the variations of the gravity field provide information on the dynamics of the process (i.e., constraints on mass movements) as well as an extensive check on the vertical surface movements with a completely independent system. Several resolutions or conclusions of scientific bodies state in fact that "absolute gravity measurements should be made at all the space-geodetic primary stations (VLBI, SLR and GPS) and near as many individual tide gauges as possible" (Carter, 1994). The focus of attention is on absolute gravity because absolute gravimeters provide a powerful tool for studies of long-term changes of the gravity field. It should be stressed, however, that the spatial and short-term temporal variability of the gravity field needs to be monitored as well, which can be accomplished by using high-resolution relative gravimeters such as the superconducting ones.

### 3.2. Reference frames

The study of deformations requires the adoption of consistent reference systems. Therefore the precise definition and realization of such systems is a key element for those investigations. It is clear that the uncertainty of such realizations should be less than the level of the signals ascribed to the deformation processes. Though regional reference frames can be used, most of the time, a global system regarding the whole Earth is better. Such systems are in fact almost mandatory as soon as space techniques are used. The main kinematical characteristics are their origin, scale and orientation, as well as their time evolution. Such problems have already been investigated by groups which have produced global plate tectonic models (e.g. DeMets et al., 1990, 1994). Another recent example of such connections between reference frames and scientific results is the direct link between global sea-level variations derived from satellite radar altimetry and the secular scale change of the relevant terrestrial reference system.

Reference frames are also of physical interest as soon as they are clearly linked to the Earth as a massive deformable body. In particular, the link between its origin and the physical geocenter is of special interest. In addition, the motion in space of such a frame is also of major interest for global geodynamics (precession, nutation, Earth rotation).

As mentioned in Section 3.1, space-geodetic techniques such as VLBI, SLR and GPS provide high-accuracy three-dimensional station coordinates. Each of these techniques contributes to the definition of a terrestrial reference frame which might consist of the station coordinates at a given epoch and of the relevant station velocities. Recent comparisons of different individual solutions determined by using either SLR or VLBI data have demonstrated that the solutions agree at the subcentimeter level in the horizontal components and at the 20-mm level in the vertical one (Ray et al., 1991; Himwich et al., 1993; Watkins et al., 1994).

As already mentioned, since its creation in 1988 IERS has produced a series of terrestrial reference frames from a combination of all submitted solutions using the currently available space techniques. The definition of the system and its realizations are fully described in the IERS publications and specifically the IERS Conventions (McCarthy, 1996).

The most recent solution is ITRF94 (Boucher et al., 1996) which provides a set of positions and velocities for more than a hundred sites distributed over the globe and obtained by a combination of various single-technique solutions (4 VLBI, 2 SLR, 3 GPS, and 3 DORIS). The accuracy is estimated to be better than one centimeter for the best sites.

### *3.3. Current accuracies and limitations*

Based on space-geodetic methods, three-dimensional deformations can be monitored with a rapidly improving accuracy. In this section, a short summary of the status of the three most widely used techniques is given, namely GPS, SLR and VLBI. In addition, the status of absolute gravimetry is discussed.

#### *3.3.1. GPS*

The accuracies of coordinates, Earth Orientation Parameters (EOPs), etc. quoted in Section 3.1 so far apply to mean values over one or even several days. There are, however, indications (but not yet conclusive evidence) that the GPS will be as successful in giving a high sub-diurnal temporal resolution as it is in giving mean values.

For most scientific purposes, GPS is used as an interferometric technique, i.e. highest accuracies are achievable only if the difference of the original (phase) observables are analysed. The principles of observation and of processing are closely related to those of VLBI (radio-band of the electromagnetic spectrum, interferometric approach). VLBI is absolute in the sense that no orbits have to be modeled. Only station positions (and velocities), the effects of Earth rotation, and the tropospheric refraction have to be modeled by VLBI (once the celestial reference frame is fixed). Because some perturbing accelerations, in particular those related to radiation pressure, may not be known with sufficient accuracy (but have to be estimated instead), the GPS-derived LOD-values may even be biased due to correlations with the estimated radiation pressure parameters. Therefore, GPS (as every satellite geodetic technique) will always have to rely on VLBI for calibration purposes.

GPS and VLBI are making use of the radio-band of the electromagnetic spectrum. Both techniques are therefore fully exposed to the so-called wet tropospheric delay which is very difficult to predict on the accuracy level required. In both techniques the tropospheric delay has to be estimated. The models are getting more and more complex as they evolve from conventional time- and site-specific parameters to stochastic processes, from pure zenith-distance to zenith- and azimuth-dependent models. The more complex the model, the better the observable may be represented. On the other hand, the danger of correlations of troposphere parameters with other parameters is growing, too, with the complexity of the model. In GPS we know in particular that there are strong correlations between station heights and troposphere parameters (see Section 3.5). In this context SLR is an ideal calibration tool: SLR is working in the optical part of the spectrum, where the tropospheric delay may be modelled with an accuracy well below the centimeter level even with modest knowledge of the atmosphere surrounding a given observation site. Therefore, at this high-accuracy level GPS must rely on SLR as a calibration tool, for example, for the definition of a height datum or for the estimation of the geocenter. This calibration aspect will be of even greater importance if high time resolution is required, for example, when trying to model the sub-diurnal station motions or the sub-diurnal motion of the ephemeris pole on the Earth surface.

It is also predictable that GPS will be the working horse in all future regional geodynamics projects (see also Bevis et al., 1997). Thus, it is evident that this technique will play a central role in all future WEGENER projects. While currently a large fraction of GPS observations is still originating from campaigns with episodic occupations of sites, there is a clear trend towards more continuously operating GPS (CGPS) sites. Moreover, strategies for combining CGPS stations providing high temporal resolutions with spatially dense campaigns can be expected to be developed (e.g. Bevis et al., 1997).

#### *3.3.2. SLR*

The round trip time-of-flight of an ultra-short (a few picoseconds) laser pulse from a ground station to a satellite is certainly the most straightforward and accurate observable of all the competing space-geodetic techniques. In the best systems, systematic optical and electronic propagation delays in the instrumentation are usually assessed through colocation of two or more systems prior to deployment and then controlled at the few-millimeter level via frequent ground calibrations to well-surveyed targets. Fits of SLR normal point data around a short orbital arc generally have an RMS of 1 to 3 mm for the best systems, but performance varies widely within the existing global network of approximately 45 stations.

Of all the space-geodetic techniques, SLR suffers the least from propagation delay variabilities in the atmospheric channel. Compared to the microwave frequencies utilized by VLBI, GPS, DORIS and PRARE, SLR's optical frequencies are relatively insensitive to the two most dynamic (and hence least predictable) components of the atmospheric refraction delay, i.e. the ionosphere and water vapor distribution. Ions are too heavy and sluggish to respond to optical frequencies in the 300 to 900 terahertz range, and laser wavelengths are typically far from strong absorption features in the water vapor spectrum. Specifically, the effect of water vapor on laser ranges is roughly 70 times smaller than on microwave distance measurements (Hauser, 1989). Thus, the so-called 'dry' component of the atmosphere is the principal contributor to the propagation error in SLR, and subcentimeter atmospheric corrections can be applied relatively easily (for elevation angles greater than 20°) through onsite meteorological measurements and spherical shell models of the atmosphere (Degnan, 1993).

Another advantage of SLR is the simplicity and low cost of the space segment. Unlike microwave-based satellite systems which all require power, antenna structures, and occasional maneuvers to support these subsystems, SLR uses relatively inexpensive spherical satellites equipped with passive retroreflectors. Geodetic laser-ranged satellites, such as LAGEOS I and II and ETALON, are heavy and compact and placed in relatively high orbits (6000 to 20,000 km) to minimize the effects of drag and other nonconservative forces. Lower-altitude satellites of similar design (e.g. GFZ-1, Stella, and Starlette) are often used to provide better sampling of higher-order static gravity field components and the tidal part of the field. Furthermore, their simple spherical shapes allow any residual nonconservative force to be easily modelled.

The aforementioned three advantages — unambiguous data type, insensitivity to atmospheric variability, and simplified satellite force models — make SLR the preferred approach for determining the ITRF origin (geocenter) and scale (GM) as well as the terrestrial gravity field. Geocenter motions determined with LAGEOS observations have indicated annual and semi-annual signals of 2–4 mm amplitude (Watkins et al., 1995), and variations of the Earth's center of mass due to ocean tides can be resolved with sub-millimeter accuracy at some tidal frequencies. Estimates of GM have improved from 50 parts per billion (ppb) (Lerch et al., 1978) to 2 ppb (Ries et al., 1992). SLR also provides the highest absolute accuracy in determining station heights relative to the geocenter. Height estimates from the strongest SLR stations can be resolved to 2 mm using observations spanning eight years (Dunn et al., 1993). Furthermore, SLR is the only common tracking system for the three altimetric satellites currently measuring sea and ice surface height (i.e. ERS-1, ERS-2, and TOPEX/POSEIDON) and is expected to support future altimetry missions such as the U.S. Navy's GEOSAT Follow-on (GFO-1), TOPEX-2, and NASA's Geoscience Laser Altimeter System (GLAS).

On the negative side, SLR is not an all-weather technique, and the current global distribution of stations is far from optimum. Specifically, there are too few high-quality permanent stations in the Southern Hemisphere and Central Asia. From a WEGENER perspective, SLR coverage in central and southern Europe is good but the surrounding regions (i.e., Scandinavia, northern Africa, and Central Asia) are not well monitored by SLR. Some of these issues are currently addressed by relocating SLR systems.

### *3.3.3. VLBI*

While in the past the focus in VLBI was exclusively on horizontal movements, in the last few years the attention has also been drawn to the vertical component (see for example, Mitrovica et al., 1994a,b; Sovers, 1994; MacMillan and Gipson, 1994; VanDam and Herring, 1994). However, the error of this component is still about three times that of the horizontal ones, and significant effort is being devoted to reducing this error.

Limitations of VLBI accuracy, in particular for the vertical, are certainly due to tropospheric effects, but in some cases also 'modifications' of the atmospheric structure due to temperature variations have to be taken into account.

During 1994, the European network for VLBI was enlarged by including the stations of Crimea (Simeiz) and Ny-Alesund. The current accuracy for horizontal velocities in Europe obtained with VLBI is about 0.3 mm/a for the core network sites (Onsala, Wettzell, Madrid, Medicina, Matera, Noto and Effelsberg; see also Fig. 2), 1 mm/a for Ny-Alesund, and 2 mm/a for Crimea. For the vertical component, these figures are about three times larger for most stations, while for Ny-Alesund and Crimea they are probably four to five times larger at the moment.

#### *3.3.4. Gravity*

Absolute gravimeters measure the acceleration due to the gravity force of the Earth by studying the free fall of a mass in a vacuum. Space and time are directly measured by means of a laser interferometer and an high-precision time interval counter. The measurements are made with respect to metrological standards of space (iodine stabilized lasers) and time (rubidium frequency clocks). In this sense the measurement is absolute. It is worth noting that since the 'ruler' is based on atomic properties, the absolute technique is the only one suitable for long-term studies. Typically, some thousands (for free fall instruments) or one hundred (for rise and fall instruments) independent measurements are taken in one or two days measuring sessions. The standard deviation is normally of the order of 1–3 μGal. The main sources of errors are changes in the vacuum conditions, errors in the laser wavelengths and in the frequency standards, frequency-dependent errors in the electronic components, microseismicity and soil recoil effects. A recent intercomparison of eleven absolute gravimeters showed that a realistic overall error budget for a single gravimeter could be of the order of 3.2 μGal for a single session (Marson et al., 1995). This means that discrepancies between gravimeters of the order of 6–9 μGal could be expected (corresponding to about 20–30 mm in height). The detection of systematic errors or the measurement of their changes can be achieved by comparison with other absolute gravimeters and frequently repeated measurements at a reference station monitored by a superconducting gravimeter.

Absolute gravimetry is influenced by environmental effects such as: (1) solid Earth and ocean tides; (2) polar motion; (3) attraction and loading of atmospheric masses; (4) attraction and loading of ocean masses; (5) changes in water table and soil water content. Accurate mathematical models or direct measurements of the quantities which cannot be modelled have to be employed in order to remove these perturbing effects. A suitable solution for the improvement of the models, and eventually for the direct measurement of the environmental gravity effects, can be provided by the use of superconducting gravimeters. Ideally, a measuring site should be equipped with a permanently installed superconducting gravimeter, periodically colocated with an absolute one.

Absolute gravity applied to the determination of crustal deformations provides: (1) an independent control for vertical displacements and velocities determined by space-geodetic techniques; (2) information on the forces causing crustal deformations; (3) boundary conditions for the verification of crustal deformation models. In order to fulfil these tasks, secular gravity changes have to be measured with a precision of 0.5 μGal per year over decades. At the present level of precision (2 μGal), this could be achieved by semiannual measurements in 5 years.

### *3.4. Anticipated improvements of the measurements and corrections*

The repeatability of the space-geodetic measurements of surface positions or deformations is not only limited by the accuracy achievable for one sample of observations but also by the level of understanding of the geophysical signal at time scales comparable to the measurement duration required to obtain one sample. In this section we will first outline improvements on the measurement side and then, in the next section, turn to the problem of modelling short-period deformations that, if unmodelled, might reduce the repeatability or accuracy of the measurements.

#### *3.4.1. GPS*

The major improvements in high-accuracy applications of GPS probably will be due to (1) a better global coverage of the IGS network, (2) a better and (even) more reliable next generation of receivers and antennas (azimuth- and elevation-dependent phase center variations are still an important issue), and (3) several improvements in the modelling part.

It can be expected that a continued and intensive observation of the GPS satellites PRN5 and PRN6 with SLR (both satellites are equipped with a LASER reflector array) will help to break up some of the existing correlations (troposphere, station heights, antenna phase patterns). On the other hand it has to be mentioned that presently the 11-year solar cycle is at a minimum of its activity. This may lead to an overestimation of accuracy of precise positioning with the GPS because it is (1) easier for the receiver-internal software to maintain the phaselock (which means that fewer cycle slips occur) and (2) easier for the post-processing software to 'repair' the remaining cycle slips. However, the next generation of receivers may well be apt to cope in a better way with the challenges related to a highly dynamic ionosphere.

### *3.4.2. SLR*

Future improvements in the SLR data product are expected to come from several sources including: (1) a better geographic distribution of stations; (2) a more uniform performance (i.e. few-millimeter precision, subcentimeter accuracy, and high data yields) at these global sites; (3) the extended temporal coverage provided by fully automated stations; (4) improved handling of the atmospheric correction through the use of more sophisticated gradient models and/or the implementation of two-color ranging at selected sites; and (5) the deployment of a new generation of satellite targets designed to support millimeter accuracy ranging.

Efforts are already underway to transfer several Northern Hemisphere stations to French Polynesia, South Africa, Tunisia, and other Southern Hemisphere sites to provide a more balanced network in support of the ITRF. In addition, the three major SLR networks (NASA, EUROLAS, and WPLTN) are providing funds as well as technical consultation and support to improve the performance of SLR stations which are at important geographic locations but are not operating at an acceptable state-of-the-art level. New, state-of-the-art, high-precision SLR/LLR stations, such as the Matera Laser Ranging Observatory, being developed by the Italian Space Agency (Bianco and Varghese, 1994) are being colocated at fundamental stations in close vicinity of VLBI, GPS and PRARE geodetic stations, in order to provide a better connection between reference systems defined by concurrent techniques. New automated SLR stations, such as the SLR 2000 system being developed by NASA (Degnan, 1994; McGarry et al., 1996) and the Keystone stations being developed for use in Japanese geodetic monitoring, will greatly reduce the cost of SLR operations, provide round-the-clock tracking coverage, and allow SLR operations in remote areas (e.g. island sites) which have little or no technical infrastructure. Two-color laser ranging systems, which provide a direct measurement of the atmospheric refraction delay and promise 2 to 3 mm absolute range accuracies (Abshire and Gardner, 1985; Degnan, 1993), are already being field-tested in the United States, Europe, and Australia. Multi-color laser ranging to geodetic satellites, in addition to improved range accuracies, will contribute to a better understanding of the atmospheric refraction, which is currently the dominant error source in space-geodetic observational techniques. In the interim, the proliferation of global meteorological databases on the World Wide Web (WWW) permits the consideration and incorporation of more sophisticated atmospheric models which include the presence of horizontal gradients at individual single-color SLR sites. Finally, a new generation of geodetic satellites are being designed which preserve the narrow pulse-width of the laser (Degnan, 1993) and allow true millimeter-accuracy measurements. Experimental examples of these new target designs include the ADEOS Retroreflector in Space (ADEOS/RIS) experiment launched by Japan in August 1996 and the WPLS geodetic satellite launched by the Western Pacific Laser Tracking Network (WPLTN) in early 1997. The majority of the current SLR sites are colocated with GPS receivers of the IGS network. Combination solutions with the two data types have been reported as early as 1993 (Pavlis and Braatz, 1993).

### *3.4.3. VLBI*

Main improvements for VLBI are to be expected in the observing technique, where a better sky coverage and improved data quality due to a larger band available on several stations (Mark IV) are anticipated. Modelling of the troposphere is planned. Most stations of the VLBI network have now a permanent GPS receiver on site. Comparison of VLBI results with these continuous GPS observations and the use of the GPS-derived troposphere for VLBI solutions are likely to further improve the accuracy. Moreover, combined solutions of different techniques, including VLBI, shall be regularly computed in the future.

Concerning the European VLBI measurements, continuation of the present rate of six measurements per year are likely to improve the results particularly in the vertical. After almost five years of regular observations only for 1994 and 1995 six observations per year are available. Therefore, it is not yet clear whether apparent short-term variations are real motions or are attributable to some source of noise.

#### 3.4.4. Gravity

Over the last five decades, gravimetry has made an impressive progress. The precision of both absolute and relative measurements has been improved by almost three orders of magnitude to presently $10^{-9}$. A new concept of measuring the temporal variations of the gravity field by means of superconducting gravimeters has been introduced as well and this has allowed a continuous acquisition of the gravity signal at a given site with the impressive precision of $10^{-10}$. A similar trend cannot be expected for the next years. In terms of precision, gravimetry has reached a limit which will be difficult to overcome. The same is not true with respect to accuracy. Further studies and developments are required in the design of more accurate calibration techniques for superconducting gravimeters and in the reduction or even elimination of any drift. Absolute gravimeters still suffer from sources of potential systematic errors. Intercomparisons of instruments, frequent colocation of instruments of different types are powerful means to detect at least biases due to systematic errors. In this respect, the development of instruments based on different measuring concepts or techniques should be encouraged.

In order to detect the weak gravity signals associated with vertical crustal movement of the order of mm/yr, it is necessary to measure $g$ with a relatively high sampling rate over decades. This task puts serious constraints on the accuracy of the instruments to be used, as well as on the measurement strategy and on the modelling of perturbing effects. The low-frequency components can only be observed by an absolute gravimeter equipped with a laser stabilised on an iodine absorption cell (the only one theoretically free of drift), while the high-frequency part of the spectrum, which is very important for the modelling of environmental perturbing effects, can be observed by superconducting gravimeters. The design of a cost-effective measuring strategy which combines the two kinds of instruments will also be a challenging task for the future.

### 3.5. Modelling exogenic deformations and gravity variations

In most geodynamical applications of geodetic measurements, exogenic deformations and associated gravity variations are a significant source of noise. At periods of a day or less, Earth and ocean tides are major sources of exogenic deformations. At periods of days, storm surges induce vertical motion of several centimeters, however, with associated deformations restricted mainly to areas up to 100 km from the coast. For periods larger than a day and up to a year, atmospheric loading is dominant and may result in large signals (several centimeters) at certain locations and times, depending on climatological and meteorological conditions. Additionally, long-period tides contribute to the spectrum of surface deformation at the known tidal frequencies (fortnightly, monthly, semi-annual and annual).

#### 3.5.1. Earth and ocean tides

At any location on the Earth's surface, the deformations due to forces at tidal frequencies can be considered as the sum of the direct effect of solid Earth tides and secondary effects due to ocean tidal loading, nutation, and tidal variations of the Earth's orientation and rotation. The respective models that should be used in space-geodetic analyses are specified in the IERS Conventions (McCarthy, 1996). In principle, all the analysis centers in all space-geodetic techniques should use the algorithms given or recommended in this document. In practice, the situation is not as ideal as it could or should be particularly for the younger contributors like GPS, where the emphasis (especially at the beginning of the activities) had to be put on operational and not on modelling aspects. However, the situation is improving. The IERS Conventions are being observed more and more closely, and exceptions are made known by the analysis centers.

In general, the current algorithms are based on spherically symmetric models, which often are non-rotating. However, the theory for computing tides and other exogenic deformations for laterally heterogeneous Earth models is available (see for example, Wang, 1991; Plag et al., 1996), and as three-dimensional structural and compositional data (based, in particular, on seismic tomography) for the Earth become more reliable, the application of three-dimensional (3-D) Earth models in space-geodetic techniques is near to being feasible.

### *3.5.2. Atmospheric and non-tidal ocean loading*

Mass movements within the atmosphere and the ocean load and, consequently, deform the Earth. In the atmosphere, the pressure variations associated with mass movements have spatial scales ranging from a few hundred kilometers for tropical cyclones to a few thousand kilometers for continental anticyclones and typical time scales of a few days to a few weeks. In addition, large-scale variations are found at the seasonal time scale. The largest surface pressure variations are associated with weather patterns of 1000 to 2000 km, with increasing ranges towards higher latitudes.

Atmospheric and ocean loading mainly deforms the Earth in the vertical direction. Theoretical studies of deformations and gravity variations due to atmospheric loading based on half-space or spherically symmetric models (for example, Rabbel and Zschau, 1985; VanDam and Wahr, 1987; Merriam, 1992) suggest that maximum vertical displacements of more than 25 mm and 10 mm can be expected for daily and seasonal time scales, respectively, while horizontal displacements are typically only one-third to one-tenth of the vertical ones.

In recent years, several attempts have been made to identify the atmospheric loading signal in GPS, VLBI and SRL observations (see for example, VanDam et al., 1994; MacMillan and Gipson, 1994; Dunn et al., 1994). In most of these studies, the model calculations are based on a Green's function approach (Farrell, 1972), where the deformations are computed from a convolution of the surface mass density with the Green's function for a spherically symmetric, non-rotating, elastic and isotropic (SNREI) Earth model. The atmospheric loading is computed using the ECMWF or NMC gridded global meteorological data sets, which are based on the analysis of surface meteorological data. From these organisations data are now available in near real-time with temporal and spatial resolutions of down to 6 h and 2.5°, respectively.

According to VanDam et al. (1994), weekly averaged vertical station positions determined from continuous GPS observations can reach precisions of approximately 7 mm at the best sites. Thus, the atmospheric loading signal should be recorded in these station height variations. However, using a SNREI model, VanDam et al. (1994) find for most of the investigated stations about 65% of the modelled pressure load to be present in the GPS vertical positions. As sources for the remaining discrepancies between model and observations, they suggest, "(1) anisotropic effects in the Earth's loading response, (2) errors in the GPS estimates of tropospheric delay, (3) errors in the surface pressure data, or (4) annual signals in the time series of loading and station heights". Their first source should actually not be termed 'anisotropic'; it can be separated into effects due to lateral heterogeneities particularly in the lithosphere and upper mantle, and effects due to the largely unknown response of the ocean to atmospheric forcing. VanDam et al. (1994) emphasize the high correlation between local air pressure and the measured height variations, and, therefore, the second error source may originate from a partial assimilation of the deformations in the tropospheric delay. Related to the third error source it should be mentioned that the spatial resolution of the surface pressure data is low compared to the typical wavelength of the Earth's topography. Especially in mountainous areas, pressure determined from the grid poorly resembles the actual air pressure at a given topographic height, which represents the load on the crust. Moreover, the accuracy of the available gridded air pressure data is spatially highly variable depending on the availability of observations. In general, the accuracy is higher over land than over oceans. Over land, it is highest over Europe and North America and lowest over most of Asia, the former Soviet Union and the Indian subcontinent.

For VLBI, early attempts by VanDam and Wahr (1987) and Manabe et al. (1991) based on the Green's function approach failed to find a correlation between model displacements and observed vertical movements at VLBI stations. However, more recently, VanDam and Herring (1994) concluded that about 60% of the computed loading effect is present in the VLBI baseline length measurements. Using VLBI station air pressure, MacMillan and Gipson (1994) found a pressure sensitivity between 0 and $-0.6$ mm/mbar with a general trend to smaller sensitivities for stations near the coast, which would be expected from an inverted barometer response of the ocean to atmospheric loading. A simple loading model based on local approximations to the regional pressure field was found by Dunn et al. (1994) to make a significant contribution to the height signature observed at SLR stations.

### *3.6. Proposed activities*

As outlined in the previous section, the potential correlation of exogenic station-height variations and atmospheric effects particularly for GPS and VLBI might constitute a serious limitation for further improvements of the accuracies of these techniques. Therefore, a special programme should be initiated on studies of the atmospheric loading effect on the height component of site coordinates obtained by GPS. In these studies, a comparison between GPS- and SLR-determined station heights is mandatory for a separation of geophysical and tropospheric effects in GPS. The experiment currently being performed within the SELF II project (Zerbini, 1995) can be considered as a first example in this field. In this experiment, two GPS receivers are operating continuously at the Medicina reference site near Bologna, Italy, together with a cryogenic gravimeter periodically controlled by three absolute gravimeters. The experiment will be conducted for one year. The relevant high-accuracy atmospheric data are being collected on-site and from the regional meteorological service for a network of stations at distances of up to 70–80 km around the reference site. Additionally, a GPS receiver is observing continuously for one year at the Porto Corsini tide-gauge station near Rovenna, Italy, on the Adriatic Sea. The Porto Corsini site is also periodically checked with an absolute gravimeter.

Modelling the displacements due to atmospheric loading for laterally heterogeneous Earth models requires the implementation of the theory outlined in Plag et al. (1996), together with the setting up of a global 3-D model of the Earth's lithosphere and mantle. A 3-D model of the crust is now available with a spatial resolution of 5º (Mooney et al., 1998), while a 3-D mantle model can be based on results of global seismic tomography (e.g. Trampert and Woodhouse, 1996). As discussed by Plag et al. (1996), based on global GPS-measured atmospheric loading the 3-D Earth model could be iteratively improved.

As a result of such a programme, recommendations for position determinations in regions with different geomorphology or varying atmospheric and climate conditions could be given. Moreover, the programme should be aiming at a service supplying continuously the deformations due to atmospheric (and at a later stage, non-tidal ocean) loading, which could be directly utilized, for example, in the analyses of GPS observations.

## 4. Geodetic networks: the WEGENER perspective

Networks constitute the connection to the fundamental reference systems for all geodetic investigations and are therefore an essential tool for WEGENER activities. They are established at three levels of relevance for WEGENER. Efforts are made in each case to maintain the highest level of achievable accuracy and precision, in accordance with the objectives and requirements of the study being performed, the physical and logistical feasibility and the available funding. The three categories may be defined as: (1) global networks; (2) regional networks; (3) local networks. Individual measurements will always be made in relationship to one or another of these.

*Global networks* serve to define the International Terrestrial Reference Frame (ITRF) and establish the basis for connecting terrestrial networks (DORIS, GPS, SLR, VLBI etc.) to the Inertial Reference Frame and three-dimensional space. They are made up of permanent, continuously operated stations, many of which are occupied by more than one (colocated) observing system. Global networks build the framework into which all subsidiary networks need to be fitted. The individual stations are required to report their observations daily in accordance with internationally agreed standards to an international data collection agency. They therefore require a good infrastructure and need to have access to especially good communication facilities. The data are analysed continuously and the reported results are made available to the user communities at frequent intervals.

*Regional networks* comprise stations covering a restricted region of the Earth's surface, for example, the eastern Mediterranean or South-East Asia, which are under investigation. The individual stations may be permanently or repeatedly occupied, dependent on the availability of instrumentation, technical know-how, man-power and infrastructure. The connection to the global reference is established by a core of permanent stations within or on the fringes of the network making observations coincident with the periodic repeat measurements. Under well designed experimental conditions, this core controls the continuity of the observed phenomena from one observation period to the next.

*Local networks* serve to make detailed periodic or continuous recordings addressing specific geophysical questions particularly characteristic of the local area. In general, the observing systems will only be installed temporarily, but every effort is made to relate the observations to at least two reference stations of a global or regional network.

WEGENER has contributed, and will continue to contribute to each of the foregoing network types and exchanges data in accordance with well established international principles. The facilities offered by the Crustal Dynamics Data Information System (CDDIS), the IGS and the European SLR Data Centre (EDC) are used extensively both for data archiving and exchange purposes. Specifically, WEGENER members contribute a number of stations to the global networks (though this has never been an objective of the group), and they have initiated a number of regional and local studies. By doing so, WEGENER continues to demonstrate its basic philosophy of taking advantage of existing facilities and coordinating activities in consultation with other groups, to address problems jointly that no individual organisation could solve on its own.

### 4.1. Global networks

The results of the WEGENER investigations must ultimately be tied to a global reference frame in order to maximize the scientific contributions of the data. Each of the experimental techniques employed contributes something unique to the investigation, and one must be able to freely use all data types in the scientific analysis. This can only be accomplished if adequate networks of colocated stations are maintained and analyzed to provide the appropriate coordinate transformations for each space-geodetic technique (i.e. SLR, VLBI, GPS, GLONASS, DORIS, and PRARE, see Figs. 1–5).

VLBI is a purely geometric technique. It provides a unique link to the celestial reference frame and is capable of providing continuous and unambiguous measurements of the full suite of EOPs including nutation, precession, polar motion, LOD, and UT1. The competing satellite techniques are insensitive to nutation and precession (parameters which are not particularly relevant to the WEGENER science programme), whereas successful long-term monitoring of LOD and UT1 are ultimately limited by uncertainties in the satellite force models and require periodic updates from VLBI. Among EOPs, polar motion is somewhat unique in that it can be effectively monitored by all of the principal space-geodetic techniques. Variations in polar motion, LOD, and UT1 can signify large-scale movements of mass and/or exchanges of angular momentum between the solid Earth, ocean, and atmosphere systems.

As a geodetic tool, VLBI can provide relative station positions and velocities with a high precision unencumbered by a need for accurate satellite force models, but the resulting polyhedrons are totally decoupled from the geocenter by the very nature of the measurement. Satellite techniques, on the other hand, are sensitive to the geocenter. However, because VLBI is independent of the Earth's gravity field and its secular variations, it has the potential to provide an independent constraint on the scale of the global polyhedron, although VLBI scale stability may ultimately be limited by the quality of tropospheric modelling.

Accurate monitoring of station heights and vertical movement rates is crucial to the WEGENER scientific objectives. On a local or even regional scale, geocenter motion (real or instrumentally induced) can often be treated as a common-mode error with little or no impact on observed relative vertical positions and rates or the resulting scientific conclusions.

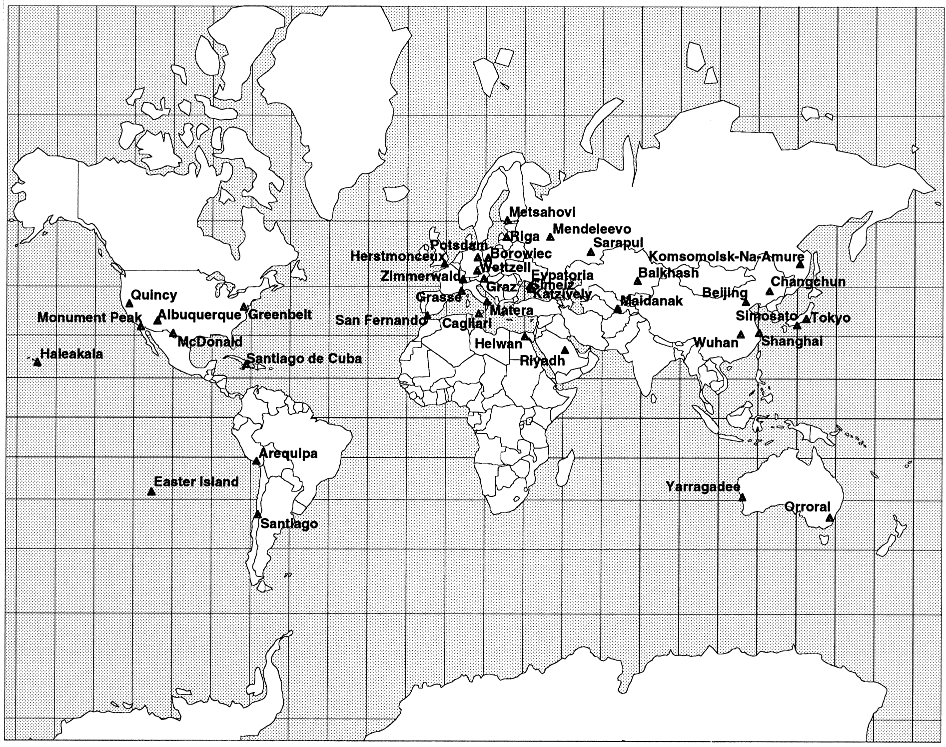

Fig. 1. Current global network of SLR stations.

However, without a properly constrained geocenter as provided by a global network of satellite tracking stations, measurement of absolute rates (e.g. of mean sea-level rise) would not be possible, and many observed phenomena could not be properly interpreted from a global perspective.

Satellite techniques are also the primary source of information on the intermediate- to long-wavelength terms of the gravity field (and hence the geoid) and their secular variations. Combined with spaceborne altimetry, satellite measurements can further refine the spatial resolution of the geoid over the open oceans and other large bodies of water, such as the Mediterranean, and reveal important topographic features on the ocean floor resulting from tectonic processes.

For reasons given in Section 3.3, SLR is best suited to define the origin (geocenter) and scale (GM) of the terrestrial reference frame, but the other satellite systems (GPS, GLONASS, DORIS, and PRARE) also sense the geocenter with varying degrees of accuracy. Over the past eight years, the University of Texas Center for Space Research (UTCSR) computations of the SLR geocenter, based on successive 15-day LAGEOS orbits, have been stable to better than 5 mm (RMS) in $X$ and $Y$ and better than 15 mm (RMS) in $Z$. Tidally coherent motions have been reported by Pavlis (1994) and are in good agreement with theoretical models based on TOPEX/Poseidon-tides (Schrama and Ray, 1994). Long-term secular changes in the lower-order zonal harmonics of the Earth's gravity field, as observed through SLR tracking of LAGEOS and other passive geodetic satellites, have long been correlated with geophysical processes such as postglacial uplift. Presently, SLR is the only tracking system common to the three ice and ocean altimetric missions presently in orbit — ERS-1 (SLR only), ERS-2 (SLR and PRARE) and TOPEX/POSEIDON (SLR and DORIS plus limited GPS). SLR therefore provides a crucial link between the geodetic and altimetric databases and permits all of the topographic

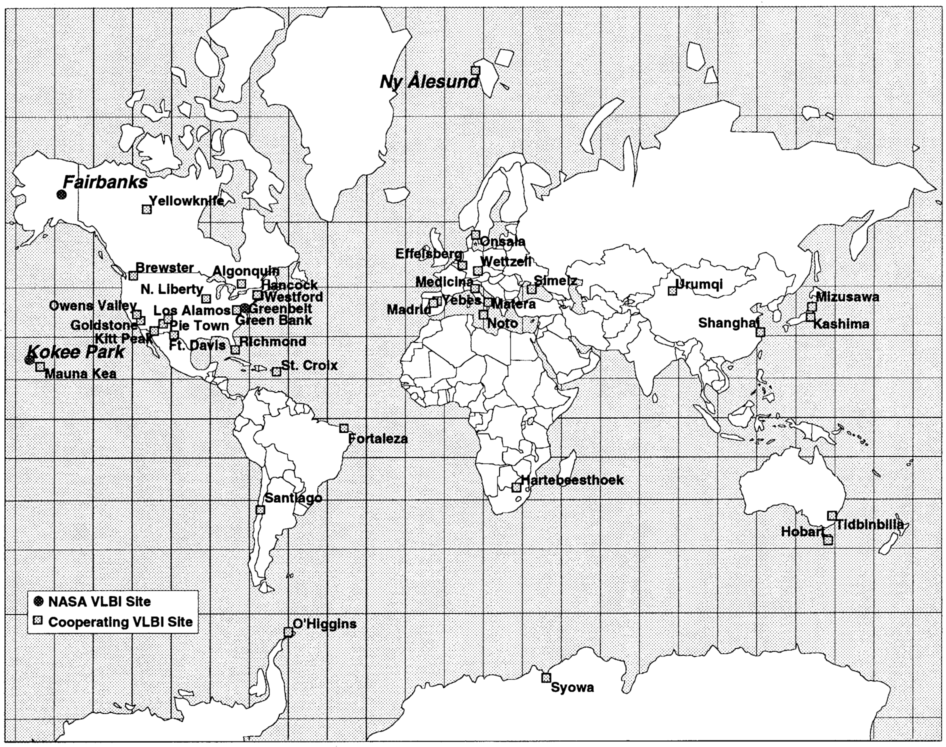

Fig. 2. Current global network of VLBI stations.

results to be expressed in a unified global reference frame. The subcentimeter absolute range accuracy of SLR combined with the relatively good global distributions of the GPS, DORIS, and PRARE ground networks (which are often colocated at SLR and VLBI sites) can provide high-quality orbits (few centimeter absolute accuracy) for altimeter missions, clearly an important component of the WEGENER sea-level initiative. The optical wavelengths used by SLR are also useful in calibrating out residual ionosphere and water vapor effects in the altimetry measurement and in monitoring long-term drifts in the instrumentation.

The relatively low-cost and high-precision relative positioning of GPS receivers permits the spatial densification required to study adequately the complex tectonic interactions between the Eurasian and surrounding plates, the details of uplift in Fennoscandia, and the integration of tide-gauge networks into the geodetic/altimetric dataset for mean sea-level studies. Through the auspices of the IGS, a global network of over 80 high-quality GPS receivers continuously monitors the transmissions from the nominal 24-satellite GPS constellation. Global IGS analysis centers produce and distribute daily and high-accuracy ephemerides for each of the satellites with a latency of about a week. Direct comparisons of these precise ephemerides with SLR measurements to the retroreflector-equipped GPS-35 and 36 satellites typically indicate a radial agreement to better than 10 cm as do the orbits computed by the various IGS Analysis Centers (Pavlis, 1995). The precise ephemerides and site positions obtained from the global analysis can then be used in the treatment of regional and local GPS networks. For optimum results, three or more global IGS sites are used to constrain the regional analysis, while three or more regional sites further constrain the local analysis. Colocation of the IGS global GPS receivers with the other space-geodetic techniques, combined with careful millimeter level local surveys between systems, allows the entire GPS network (global, regional, and local) to draw on the inherent, and often unique, strengths of the other space-geodetic tech-

Fig. 3. Current global network of permanent GPS stations supporting the IGS.

niques and aids in the identification, quantification, and correction of residual instrumentation or analysis errors.

### 4.2. Regional and local networks

An important aspect of WEGENER, being linked to one of the main scientific objectives of the project, is the investigation of horizontal and vertical crustal motions in the boundary region between the Eurasian, African and Arabian tectonic plates. This zone extends more than 5000 km in longitude from the Azores to the Caspian Sea, and 3000 km in latitude from the Caspian Sea to the Gulf of Aden. For a careful study of the kinematics of the entire region at the level of individual tectonic units, ideally continuous observations from an extremely dense geodetic network with a spacing of about 10–100 km would be required. The obvious technique to use is GPS, since it is the only 'affordable' technique capable to provide such dense coverage at present. Examples of medium-density networks can be found in Southern California in the US (Bock et al., 1993; Bock and Williams, 1997) and in Japan (Tsuji et al., 1995).

However, it is not feasible to cover the entire area with GPS. First of all this would be very costly because of the large number of receivers required (for a cost estimate, see Prescott, 1996a). Secondly, much of the area is covered with large sea and ocean basins where GPS points can only be established on a few islands. Finally, political problems and lack of an adequate infrastructure also make it difficult to establish a dense network in most of the remaining land areas.

Therefore, a distinction is made between regional networks and local networks. Regional networks may be considered as the first level of densification of the global network. Their function is to provide regional connections to the global reference frame and to monitor the evolution of medium-scale tectonic processes. Local networks primarily serve to study smaller areas in more detail, such as deformation zones near active faults.

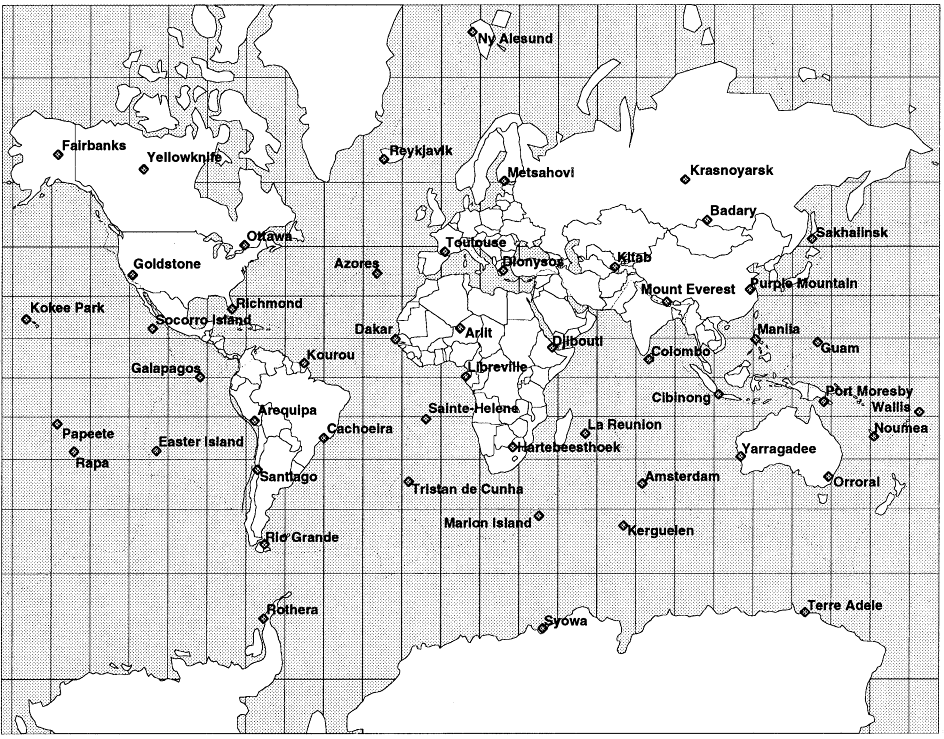

Fig. 4. Current global network of DORIS stations.

A good example of the first category is the WEGENER-MEDLAS network. It was established in the mid-eighties with mobile SLR (which was the only suitable technique at that time), to provide information on the overall tectonic motions in the eastern and central Mediterranean regions. Since the early nineties, it has also been observed with GPS and together, the observations of both techniques have resulted in an accurate kinematic model for this area (see e.g. Noomen et al., 1996). However, this was achieved on the basis of epoch-type campaigns. With this approach it is difficult to discriminate between continuous deformations and instantaneous displacements due to, for example, earthquakes. Also, the repeated installation (and removal) of equipment, which may also change between campaigns, bears the risk of introducing errors.

Therefore, regional networks, consisting of fixed, permanently operating systems are favoured. Ideally, such networks consist of evenly spaced stations at mutual distances of typically 250 km, fitted with standardized GPS equipment. To ensure a proper connection with the global reference frame, some of these stations should also be part of the global IGS network, in particular those colocated with other techniques such as SLR, VLBI, DORIS and PRARE.

In Europe, the core of such a network basically already exists. It consists of a relatively dense network of about 30 IGS stations, which are mainly located in the central part of Europe. Also, there is an initiative to increase the number of permanent stations as a contribution to the densification of IGS. This activity is coordinated by the EUREF subcommission of the IAG. In addition, in a growing number of countries, extensive networks of continuously operating GPS receivers have been or are currently being established for reference purposes (see Table 1). Still, the scope of these networks is too limited to serve all the scientific investigations of WEGENER. This is illustrated in Fig. 6, which shows the current network of permanent IGS stations in Europe and adjacent regions. As can be seen, the main problem is that there are almost no stations on the African continent and in Arabia. Therefore, one of the major tasks of

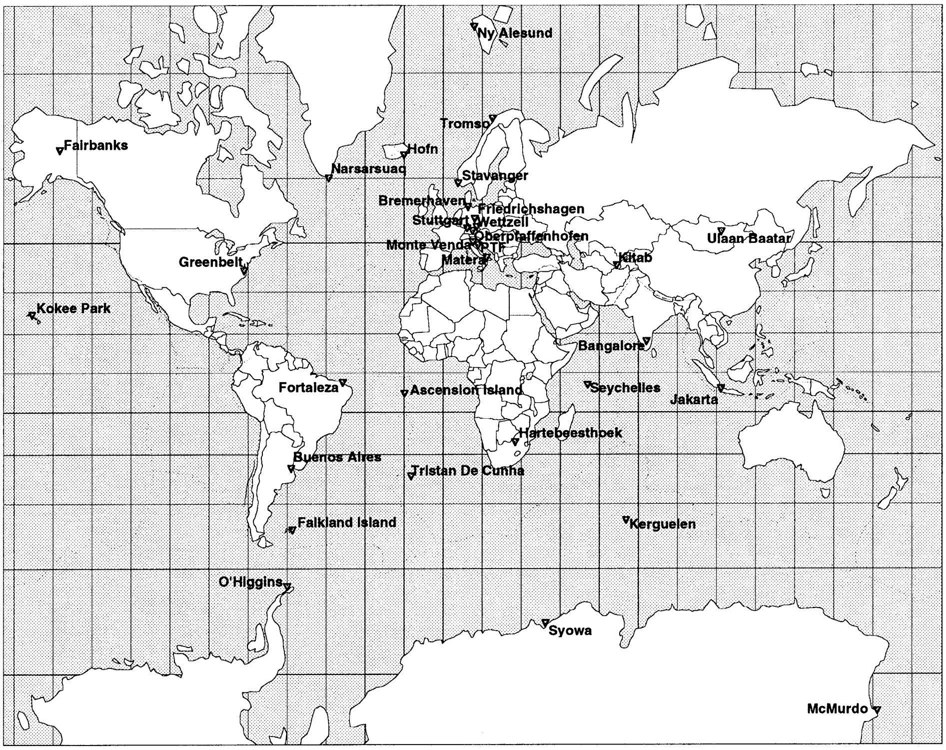

Fig. 5. Current global network of PRARE stations.

WEGENER should be to establish new permanent stations in these areas.

Other important scientific areas of investigation addressed by WEGENER are the postglacial rebound in Fennoscandia and sea-level fluctuations associated with climate change. To study these phenomena, dense regional networks of continuous stations are also required. For sea-level monitoring, many of these stations should be colocated with tidal stations.

Table 1
Some continuously operated GPS networks in Europe

| Network | Country/Region | Number of stations |
|---|---|---|
| SATREF | Norway | 11 |
| SWEPOS | Sweden | 20 |
| FINNNET | Finland | 12 |
| BIFROST | Scandinavia | 46 |
| GREF | Germany | ~50 |
| AGRS | Netherlands | 5 |
| | Belgium | 4 |
| | Italy (IGS) | 5 |

Both topics are primarily concerned with the vertical component and to a certain extent they are interrelated: vertical land motions manifest themselves as sea-level changes at tidal stations. As stated in the previous section, these studies require an accurate and stable vertical reference frame. Although GPS does not (yet) provide accurate height information in an absolute sense, it may well be used to study time variations and relative changes between stations in this component. The connection with an absolute global vertical reference frame can be provided by colocating a few points of the regional networks with SLR.

In Scandinavia, a relatively dense network of about 40 permanent GPS stations already exists (see e.g. Plag et al., 1998). They were primarily established for differential navigation purposes, but the data are also used to study postglacial rebound. There are plans to further expand the networks, in particular to colocate more points with tidal stations. A selection of the stations has been proposed as a contribution to the European Vertical Network (EUVN), which is being established to provide an accurate vertical European

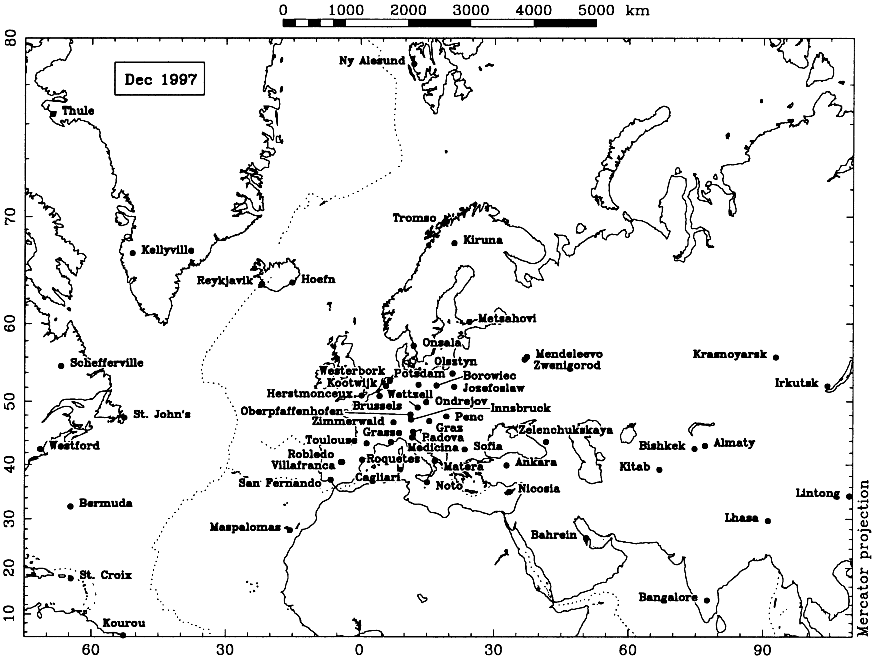

Fig. 6. Current network of IGS stations in Europe and adjacent regions.

reference frame. Still, although the current network covers the main uplift area quite well, more stations are needed in the surrounding regions (Baltic states, Denmark, UK) to extend the coverage to the margins. Furthermore, the connection with the global SLR network should be improved. The colocation sites in Europe are presently mainly concentrated in the mid-latitudes. Therefore, it would be quite useful to repeat the 1991 occupation of Tromsø in northern Norway with mobile SLR.

To study the relation between sea-level fluctuations in Europe and global sea-level change, again, an extensive network of permanent GPS stations colocated with tidal stations can provide significant information. At present, only a few of these stations are operational. There are several projects underway (Euro-GLOSS, EOSS) which aim at densifying the network of tidal stations colocated with GPS. However, it may still be necessary to establish more points, in particular in areas of special interest such as the Baltic and Caspian Seas. Until this has been realized, epoch-type campaigns such as those conducted in the frame of the SELF projects are necessary to get started.

Local networks are usually established in relatively small areas with the aim to study a very specific phenomenon. They often consist of some 30 to 80 points with a spacing of 20 to 50 km. In most cases these networks are observed during epoch-type campaigns which typically last between one and two weeks and which are repeated at one to two year intervals. GPS is ideally suited for this purpose and it has been successfully applied for many projects within the WEGENER area. In Table 2 an overview of the most important projects is presented. Sometimes it may be required to establish permanent networks for such local applications, in particular when discontinuous motions are expected. The only example within WEGENER at this moment is the Kephalonian Fault network. Currently, epoch campaigns remain necessary to further densify the networks and to study special localized phenomena. They also provide an useful alternative for regions where it is difficult to establish continuous stations. However, for a full exploitation of the capabilities of GPS, a combination of a number of CGPS sites with other episodically occupied GPS sites may turn out to be most appropriate. This approach is called the multimodal occupations strategy (MOST) by Bevis et al. (1997). A major task for the next years will

Table 2
GPS campaign-type networks in the WEGENER area; status of the table corresponds to mid-1996

| Project | Region | Number of stations | Number of occupations |
|---|---|---|---|
| GIG-91 | Europe | ~25 | 1 |
| WEGENER | Eastern Mediterr. | ~15 | 2 |
| EUREF | Western Europe | >150 | ~10 |
| SAGET | Central Europe | ~10 | 2 |
| W. ALPS | Western Alps | ~10 | 1 |
| BULGARIA | Bulgaria | 15 | 2 |
| CERGOP | Central Europe | 31+5 | 2+ |
| CRODYN | Croatia++ | 22 | 2 |
|  | E Turkey + Cauc. | ~80 | ~5 |
| NAFAS | Turkey (Mudurnu) | 31 | 5 |
| W-TURKEY | Western Turkey | 35 | 3 |
| MARMARA | Marmara Sea | ~55 | 3 |
| AEGEAN | Aegean | 29 | 3 |
| CENTR. GREECE | Central Greece | 66 | 4 |
| W-HELENIC ARC | SW Greece/SE Italy | 30 | 4 |
| WHAT-A-CAT | SW Greece/S Italy | 20–43 | 3+ |
| TANGO | Azores | ~15 | 4 |
| PEKA | Caucasus/Black Sea | ~20 | 2 |
| CATS | Pamir–Tienshan | >75 | >3 |
| BAIKAL | Baikal Sea | 13 | 1+1/2 |
| SELF | Mediterranean Sea | 28 | 2 |
| BSL | Baltic Sea | 35 (+12) | 2 |
| UKGAUGE | UK | 9–16 | 6 |
| EUROGAUGE | UK/France/Spain/Portugal | 16 | 2 |
| NEREF-MAREO | The Netherlands | 18 | 3 |

be to define the conditions for successful applications of MOST and to illuminate the strengths and limitations of this strategy.

### 4.3. Tide gauges

Several authors have pointed out that the relatively large interannual and decadal variability in sea level requires long records of 50 years and more if reliable estimates of (local) trends in mean sea level are to be determined (e.g. Pirazzoli, 1986; Warrick et al., 1996; Douglas, 1997). Moreover, only tide gauges with high-quality data and with a well documented history of the tide-gauge benchmarks (TGBM) that has been used as the local datum can provide reliable trends. Permanent GPS measurements at, or near, tide gauges now make it possible to measure the vertical crustal movement to an accuracy of ±1 mm/a with about five years of data. Therefore, this is an additional reason for concentrating the GPS and absolute gravity work at well established tide gauges, where the relative mean sea-level trend is already known to this or a better accuracy. On the global scale, there is a well known bias in the spatial distribution of mean sea-level information, with the majority of long sea-level records being from a limited number of areas on the Northern Hemisphere. The IOC GLOSS (Global sea-level observing system) network of tide gauges was initiated specifically to address this issue and to ensure that a better spatial distribution of high-quality sea-level data will be available in the longer term.

In Europe, there is a similar north–south bias in long sea-level records. For example, in the Mediterranean and Black Sea, all five tide gauges with more than 50 years of well-controlled sea-level data are exclusively located on the northern coasts: Port Tuapse, Bakar, Trieste, Genova and Marseille. On the Atlantic coast of the Iberian Peninsula, there are five appropriate tide gauges: Lagos, Cascais, Vigo, La Coruna and Santander (and Santa Cruz on Tenerife). Further north, Brest in France and five tide gauges around the UK are suitable. However, in the Netherlands there are nine tide gauges with very long records and for the countries around the Fennoscandian postglacial rebound and subsidence area (Denmark, Germany, Finland, Sweden and Norway) there are a large number of long tide-gauge records available with many of them having 80 years or more of data. In areas of coastal subsidence, such as the southern North Sea or the northern Adriatic, where coastal infrastructure and eco-systems are under threat, a higher density of modern geodetic measurements is clearly required. Even if the nearest suitably long tide-gauge record is a few hundred kilometers away, then this can be used (together with GPS and gravity measurements at the tide-gauge locations) to determine the regional absolute sea-level trend and the local GPS and gravity measurements can be used to find the spatial variability of the coastal subsidence, and hence the local relative sea-level trend required for coastal impact work.

The IOC-coordinated EUROGLOSS proposed a network of 135 tide gauges around the European coasts (Baker et al., 1996) in order to realize a more uniform coverage of high-quality tide gauges. In particular, this network will provide information on the spatial variability of mean sea-level trends.

### *4.4. What WEGENER needs from and may return to networks*

The present-day capabilities of space technology allow to perform geodetic observations with an accuracy which is significantly higher than typical deformations of the Earth's crust occurring on global to regional or even local scales. These observations provide, on the one hand, fundamental input to geophysical studies which deepen insight into, for example, the response of the solid Earth to different forces, its internal structure and density distribution. On the other hand, basic kinematic information is also supplied for the definition of the terrestrial reference system which is affected by geodynamical processes.

The realization of a reference system is done through a reference frame, that is, by means of a network (or polyhedron) of stations whose coordinates implicitly define a spatial coordinate system. The terrestrial reference system is produced through an ensemble of Cartesian station coordinates given at a certain arbitrary reference epoch and obtained by combining different space-geodetic observations such as SLR, VLBI and GPS. The deformations of the Earth's crust are taken into account, at least to the first order, by providing together with the station coordinates the associated velocity field deduced from long-term geodetic measurements. The connection between the fundamental polyhedron and the terrestrial system is given by the deformation of the station positions (Bock, 1996).

The area of interest to WEGENER encompasses a wide region from the Azores triple junction in the west to the Caspian Sea in the east, and from Fennoscandia in the north as far as to the northern border of the African plate in the south. In this area, networks of space-geodetic stations, both at regional and local scales, are already available for the realization of some of the scientific objectives. Others are presently being developed. These networks benefit from the existence of reference systems such as those produced by the IERS and IGS and will rely upon the realization of a dense reference frame which is reasonably uniform in distribution and quality, accurate (few mm) and readily accessible to GPS users such as that proposed by Blewitt et al. (1993). This reference frame could provide the kinematic boundary conditions for the WEGENER large-scale network and for the local networks dealing with specific problems of a more localized nature (Blewitt et al., 1995).

WEGENER is also concerned with the establishment and maintenance of a highly accurate vertical reference system. To this end, WEGENER supports the continuation and the development of the activities initiated by projects such as SELF I and II (Zerbini, 1995; Zerbini et al., 1996) and to be developed within MEDGLOSS. One of the results shall be the separation of the vertical crustal rates at the tide-gauge stations from sea-level variations which, at a regional scale, can differ significantly from the global trend. This is being accomplished by a combination of space and terrestrial techniques (absolute gravimetry). To properly accomplish this task, fiducial stations are needed, and for these WEGENER relies upon the IGS network and the IERS reference systems. In order to further contribute to the reliable definition of the vertical crustal rates WEGENER is also supporting long-term deployments (at least one year) of mobile SLR systems at Tromsø in Norway, for measurements of postglacial rebound, and Medicina in Italy for sea-level variation studies.

In turn, WEGENER provides a fundamental contribution to the reference frames and systems through, basically, two mechanisms. First, the large-scale SLR/VLBI/GPS network operating in the specific region supplies continuously high-accuracy observations which are being analyzed and interpreted within different WEGENER projects. Thus, WEGENER contributes to the definition of the reference frame by providing highly accurate solutions for the coordinates of the stations as well as a reliable velocity field necessary for the realization of the reference system. Second, numerous GPS projects, at local scales, are being carried out within WEGENER and they contribute, with campaign-type of observations, to realize a more uniform and dense IGS polyhedron. This could not possibly be realized otherwise, since the establishment of a very dense network of fixed stations is neither economically nor logistically feasible.

As regards this latter point, WEGENER, with the aim to achieve a better representation of the kinematics of the plates and platelets in the Mediterranean region and to contribute to a deeper understanding of the dynamic processes involved, is proposing to develop the following activities: (1) to densify the IGS network along the African/Eurasian/Arabian plate boundary by means of campaign-type of observations and solicit the installation of, at least, two to three permanent GPS stations on the northern African border; (2) to densify the existing GPS network on the Azores and to deploy, for a long occupation (1–2 years), one of the available mobile SLR systems; (3) to establish three to four fixed stations across the Strait of Gibraltar; (4) to establish a network in the Arabian Peninsula across the Red Sea; (5) to densify the existing network in the Caucasus and Caspian Sea; (6) to densify with 2–3 fixed stations, for a limited amount of time (1–2 years), and 30–40 stations with campaign-type of observations, the network between southern Italy and Greece.

## 5. The African–European collision zone

### 5.1. The geodynamic setting

The Alpine–Mediterranean region marks the broad transition zone between the African/Arabian and Eurasian plates (Fig. 7). In a generalized scheme the recent major tectonic processes occur within the large-scale kinematic framework of active sea-floor spreading in the Atlantic Ocean, the Red Sea/Gulf of Aden and northwest Indian Ocean. The higher spreading rate in the South Atlantic (40 mm/a) as compared to that in the North Atlantic (20 mm/a) leads to a gradual counterclockwise rotation of the African plate resulting in a north-northwestward-directed push against Eurasia, which in turn leads to a lithospheric shortening of 5 to 6 mm/a increasing to 40 mm/a in active subduction zones. With northwest–southeastward-oriented spreading in the North Atlantic the zone of the Eurasian/African plate contact in the Mediterranean is expected to be to a large extent under compression. Argus et al. (1989) have deduced a kinematic model in which the closure of the current plate motion circuit around the Azores triple junction has been enforced. This motion belongs to a large-scale plate boundary which predicts a right-lateral slip of about 4 mm/a across the Azores–Gibraltar fracture zone and a west-northwest convergence beneath the Gibraltar nappe in the Gulf of Cadiz.

Despite the overall shortening between Africa and Europe, the Alpine–Mediterranean region encompasses large sedimentary basins that have in the past and even now experienced major extension since the late Cenozoic, e.g. the western Mediterranean, Tyrrhenian, Aegean, and Pannonian basins (Dewey, 1988). The kinematic displacement field obtained so far for the central Mediterranean demonstrates the complex nature of the tectonics of the region (Albarello et al., 1995). In particular, this is illustrated by the presence of extensional tectonics in the Pantelleria Rift, the Sicily Channel, the Siracusa and Apulia escarpments which all lie along and close to the North African compressional boundary. These regional non-stationary plate boundary processes contribute significantly (of the order of a few cm/a) to the global-scale relative motion between Africa and Europe.

At the northeastern end of the African plate, the Arabian plate is separating from Africa (Nubia) in a NNE direction from the spreading center of the Red Sea, originally proposed by Drake and Girdler (1964), and from Somalia in a NE direction from the spreading center at the Gulf of Aden (Laughton et al.,

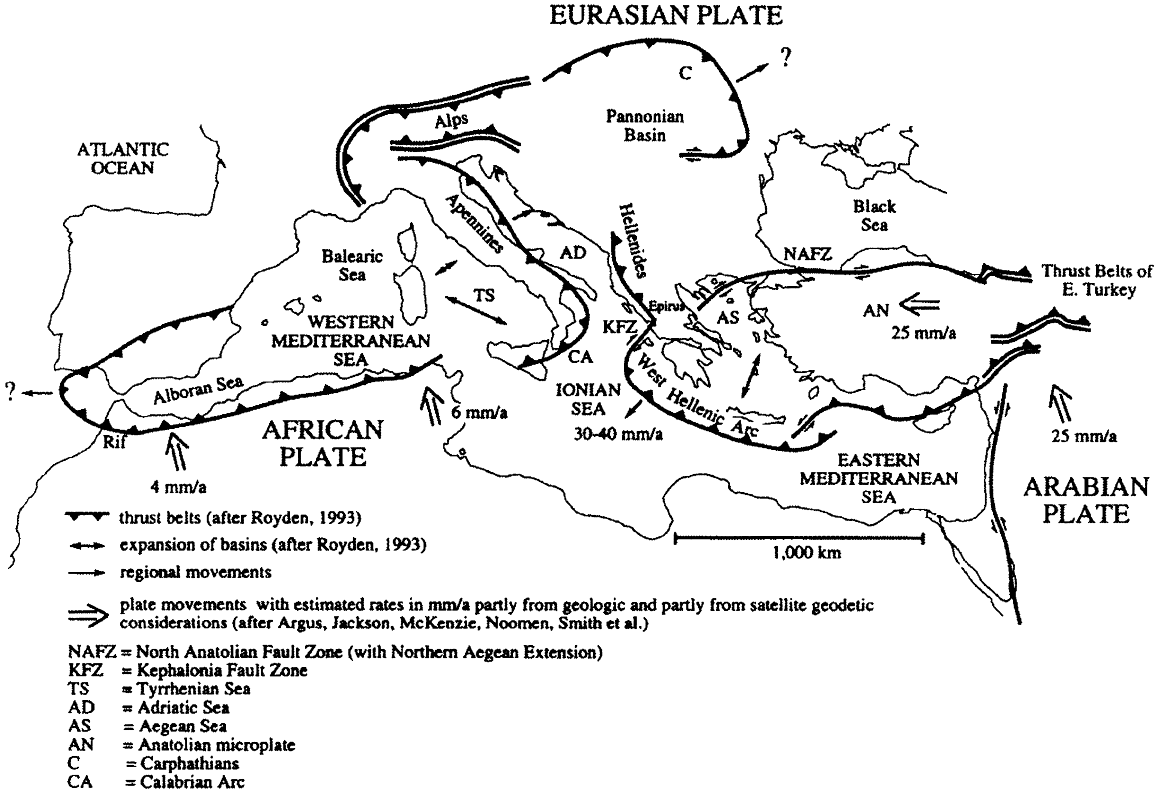

Fig. 7. Simplified sketch-map of main tectonic plates and sub-plates in the Mediterranean area. From Kahle et al. (1995a). Compare also with Fig. 8.

1970). Based on the spreading rates of these young oceanic basins which are derived from magnetic seafloor-spreading anomalies and from slip vectors of earthquakes, it is estimated that the rate of northward motion of the Arabian plate is in the order of 10 mm/a along the Dead Sea Rift (Levant), and 15 mm/a in the southeastern part of the Arabian plate around Oman.

The ridges of the northern Caucasus and the associated forelands in the area between the Black Sea and the Caspian Sea form the northern limit of the deformation zone associated with the active boundary between the Eurasian and the Arabian plates. In this region the plate boundary and the associated deformation zones are characterised by continent–continent collision and the resulting subduction of the Arabian plate beneath Eurasia. These features are evidenced by continued mountain building, accompanied by relatively strong seismicity. No estimates are available for the magnitudes of the horizontal motions, but there is geodetic and geological evidence that in some areas uplift is occurring at a level larger than 10 mm/a.

Since 1985, relative movements in the central and eastern Mediterranean have been measured with SLR using permanent and mobile tracking equipment. SLR measurements from nineteen tracking sites were analyzed with data from the global tracking network (Smith et al., 1994a,b). From this study it could be seen that the kinematic field in the eastern Mediterranean is characterized by the westward motion of Anatolia and the southwest motion of the Aegean. Similar findings by Noomen et al. (1993) led Le Pichon et al. (1995) to describe the velocity field of the Anatolian–Aegean region in terms of an average counterclockwise rigid rotation (2.4°/Ma) about a pole located north of the Nile delta, in northern Egypt.

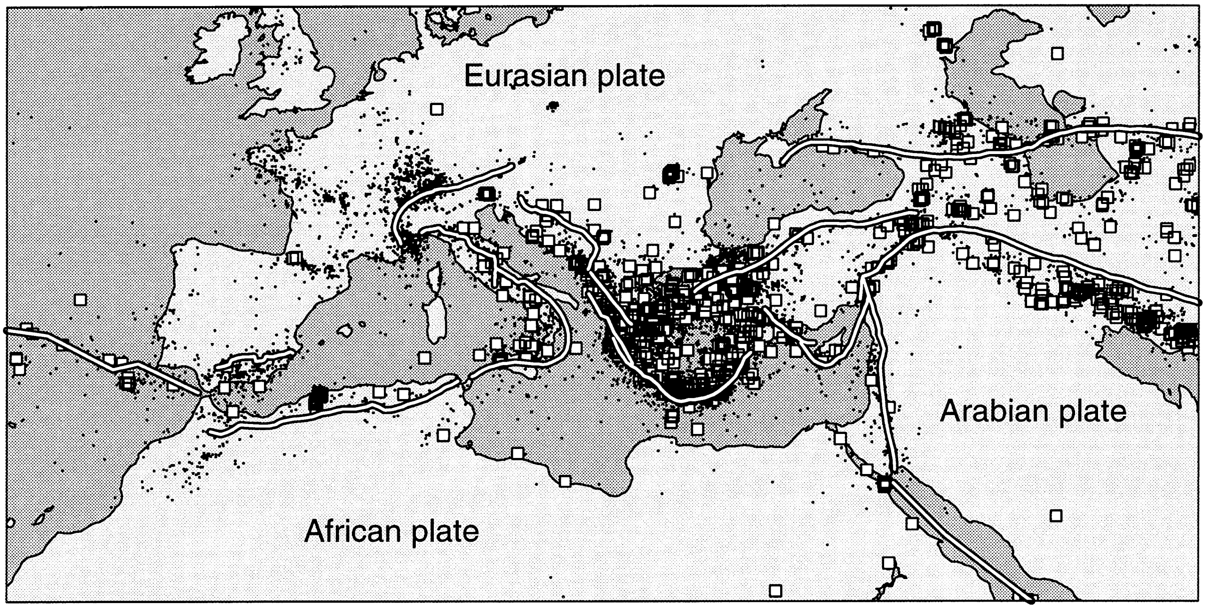

Fig. 8. Seismicity in the Mediterranean and adjacent areas. The lines delineate the main plate boundary structures between the Eurasian, African and Arabian plates. Also included are the large Anatolian fault in Turkey and the Caucasus–Caspian fault. Dots represent earthquakes with ISC magnitudes >1, squares those with magnitudes >5.

From improved focal mechanisms constrained by P and SH body-wave modelling, Taymaz et al. (1991a) showed that distributed right-lateral strike-slip is prevalent in the central and eastern Aegean region, on faults trending NE to ENE, and with slip vectors directed NE. This faulting ends in the western Aegean against NW- and EW-trending normal faults in central and northern Greece. The models have in common that a pronounced motion of the Aegean microplate of ≈40 mm/a is postulated, oriented towards the southwest, relative to a Europe fixed reference. While it is generally agreed that the northern Aegean trough and the northern margin of the Marmara Sea form the boundary in the northeast, uncertainty exists as to where the boundary passes through northern Greece, how it connects with the west Hellenic subduction zone and what the relative displacements rates are. How this zone connects the active dextral Kephalonia fault (Kahle et al., 1995a,b) with the active transtensional dextral North-Aegean fault zone and Sea of Marmara (Straub and Kahle, 1995; Straub, 1996) is as yet unknown.

A summary of the stress distribution in Turkey and Greece is illustrated by well-determined earthquake focal mechanisms (Oral et al., 1993). In eastern and northern Turkey the seismic activity is primarily associated with the east and north Anatolian strike-slip fault zones (Fig. 8). The east Anatolian and Dead Sea transform fault zones exhibit a predominantly left-lateral motion (Taymaz et al., 1991b) while the north Anatolian fault zone motion is governed by right-lateral strike-slip (see e.g. Barka, 1992). The west-southwest movement of the Anatolian microplate from the zone of maximum compression has been confirmed and quantified by GPS measurements (Reilinger et al., 1995; Straub and Kahle, 1995).

Seismic activity in the Alpine–Mediterranean region clearly outlines the plate collision zone between Africa and Eurasia, the dimensions of the Adriatic and Aegean–Anatolian microplates. Also, wide-spread intraplate seismicity occurs which illustrates that the plate collision zone is complex and not sharply defined. Intermediate to deep seismicity is not found below the entire plate collision zone but only below a few regions (southern Spain, the Tyrrhenian and Aegean basins, and the East Carpathians) and has been generally associated with local lithosphere subduction. Maps of geodynamic features (e.g. Rebai et al., 1992) demonstrate how the Mediterranean is made up of an assemblage of tectonic provinces which exhibit a wide range of lithospheric thicknesses and lithosphere rheologies. These tectonic provinces interact through a variety of dynamic processes including large-scale subduction, back-arc spreading, and rifting, with associated thrusting, reverse, and strike-slip faulting processes. In addition, clear lateral motion of tectonic provinces is observed (e.g. Alboran Sea region of the western Mediterranean and the Anatolian plate). The Eurasia/Africa collision is closely related to oceanic and continental subduction and the evolution of foreland fold and thrust belts (e.g. eastern Anatolia, Carpathians, Alps, Apennines, Tell Atlas, Betic Cordillera).

In the past decade seismological investigations, in particular deep seismic reflection surveys and long-range seismic refraction profiles as well as seismic P- and S-wave tomography, have revealed a three-dimensional lithosphere and upper mantle structure (in terms of the propagation velocity of seismic waves) of the Alpine–Mediterranean region with a resolution of the order of 50–100 km (Spakman et al., 1988, 1993; Spakman, 1990, 1991; Valasek et al., 1991; Blanco and Spakman, 1993; Amato et al., 1993; Zielhuis and Nolet, 1994; Kissling and Spakman, 1996). One of the most interesting features that pertains to the collision between Africa and Europe is that lithosphere subduction has occurred to large depths below the entire Alpine–Mediterranean orogenic belt from southern Spain to Turkey. Previously, consensus about deep-reaching subduction only existed for those few regions exhibiting intermediate to deep seismicity, but it seems that some of the subducted slabs behave aseismically (e.g. below the Aegean where seismicity stops at about 200 km depth, whereas the subducted slab is apparently extending to depths of 800 to 1000 km). The interpretation of large-scale subduction from 3-D patterns of seismic velocities has recently been postulated by De Jonge et al., 1994). They specifically addressed the kinematic evolution of the Alpine–Mediterranean during the Cenozoic. Using tectonic reconstructions for that time period they ‘predicted’ a present-day 3-D lithosphere and mantle structure. The comparison of these mantle models with inverse models obtained from tomography demonstrated that large-scale subduction during the Cenozoic up to the present may have strongly influenced the geodynamics of the Alpine–Mediterranean.

The present-day tectonics and the underlying geodynamic process in the Mediterranean–Alpine region have been heavily governed by rifting in its various forms and manifestations. This problem is, of course, strongly related to basin formation and evolution. In the Mediterranean from west to east the following structures can be identified: (1) the Alboran–South Balearic Basin resulting from the large-scale rotation of Africa; (2) the North Balearic Basin with the two asymmetric shapes of Gulf of Valencia (causing rotation of the Balearic Archipelago) and Gulf of Genova (or Ligurian Sea, being responsible for the rotation of Corsica and Sardinia); (3) the Tyrrhenian Sea, which is back-arc of the Calabrian subduction and responsible for the rotation of the Apennine Peninsula; (4) the Pantelleria–Malta–Linosa graben system between Sicily and Tunisia; (5) the Ionian Sea–Gulf of Taranto–Apennine Rift system from the Hongraben to Taranto, with possibly a mantle plume underneath; (6) the Pannonian Basin which is full of intermediate and small rifts; (7) the Gulf of Corinth and the adjacent region to the north, where a transtensional or ‘pull-apart’ structure is evident; (8) the Aegean Basin which is back-arc of Hellenic subduction zone; (9) western Anatolia (and the Gulf of Saros between the Marmara Sea and the Gulf of Antalya) where the coastline shows complex ‘hidden’ rift branches; (10) the Dead Sea and Suez rifts, which are now associated with clear strike-slip motion.

### 5.2. Challenge for the next decade: the geodynamic problem

The Alpine–Mediterranean is geologically and geophysically one of the best studied regions on Earth. The research interest encompasses the past 100 years and, hence, a huge number of publications exist addressing local and regional problems. Due to the WEGENER initiative of the last decade geodetic and geophysical investigations have contributed tremendously to the understanding of large- and regional-scale kinematics, with a focus on the eastern Mediterranean and the Aegean–Anatolian region. Considering this overall research investment one may wonder why as yet no consensus has been reached on a unifying model of the dynamic evolution of the Alpine–Mediterranean up to the present.

The reason may be found in the fact that, as illustrated by the concise overview given in the previous section, most of our knowledge pertains to observation and description of kinematics and structure rather than to a quantitative understanding, explanation and verification of the underlying dynamics. This situation is, however, rapidly changing. Globally, Earth sciences have experienced in the last decade an impressive development in instrumentation, observation techniques, and in theory and application of inverse and forward modelling. This development is specifically pushed by the ever increasing computational power offered by computers. A shift is noticeable from description and qualitative explanations to quantitative interpretation and quantitative assessment of hypotheses. For instance, a long standing debate about whether Aegean extensional tectonics is driven by the westward push of the Anatolian plate or is primarily driven by roll back of the African slab below the Hellenic arc is still open. Meijer and Wortel (1996) have given a quantitative assessment of the relative importance of forces associated with ‘westward push’ and ‘slab-roll back’ and arrive at the conclusion that slab roll-back provides the dominant mechanism, although westward drift of the Anatolian plate is still needed to a small extent to explain part of the geological, geophysical and geodetic observations. In the coming decade, hypotheses and associated dynamic models of the evolution of the Alpine–Mediterranean will be quantified and tested by new measurements and a combination of inverse and forward modelling. WEGENER is in the unique position to initiate and carry out the necessary research programs to accommodate the growing need for kinematic constraints on crustal deformation required for testing and validating dynamic models.

A promising hypothesis for Alpine–Mediterranean dynamics has been proposed by Wortel and Spakman (1992, 1993). They inferred from the results of seismic tomography that, except for the southern Aegean and perhaps Calabria, below the entire Alpine–Mediterranean orogenic belt the subducted slabs are disconnected from the lithosphere at the surface or, stated differently, have broken off (see Fig. 9). The process associated with this observation is called ‘slab detachment’ and has presumably occurred between depths of 50 and 150 km. Currently slab detachment is proposed active below the western Hellenic arc (Epirus and Peleponnesus) (see also Meijer and Wortel, 1996) and perhaps below the Calabrian arc and the East Carpathian arc (Vrancea). Slab detachment would result in strong vertical motions (of the order of 1 km) in a relatively short time interval (0.1–1 Ma), resulting in average uplift rates of 1 to 10 mm/a. Subsidence is expected at the seaward side of the trench, whereas large uplift would occur in the overriding plate.

The core of the hypothesis is concerned with the concept of ‘lateral migration of slab detachment’. A model built from this hypothesis has strong predictive value: it may explain slab-roll back, island arc formation and migration, the increasing curvature of island arcs, lateral and vertical motions, depocenter shifts of sedimentary basins along strike of the subduction zone, evolution of stress and strain patterns, the change of the chemical signature of volcanics along strike of subduction zones. Above all, the model provides a link of lithosphere and mantle dynamics with crustal and surface dynamics and a test of the hypothesis as well as the validation of the associated models therefore is highly desirable.

For WEGENER an opportunity exists to contribute to the testing of this hypothesis. The present-day kinematic deformation of the Mediterranean provides an important constraint on the model proposed by Wortel and Spakman. For instance, the relative motion of the western Hellenic arc is being blocked north of the Kephalonia fault and is SW-directed to the south of it (Smith et al., 1994a; Noomen et al., 1996; Kahle et al., 1996). This sudden change in relative motion can be well explained by the process of slab detachment having reached a position below the Peleponnesus (see Fig. 10; Spakman et al., 1988; Meijer and Wortel, 1996). Mapping the kinematic patterns (horizontal and vertical motions) in specific areas where detachment seems to be active or may have completed recently, yields important kinematic data as boundary conditions on modelling the dynamics of arc evolution and back-arc basin development. Specific areas of interest are the Alboran–Betics region, western Mediterranean and Apennines–Calabrian arc, the Hellenic arc and the

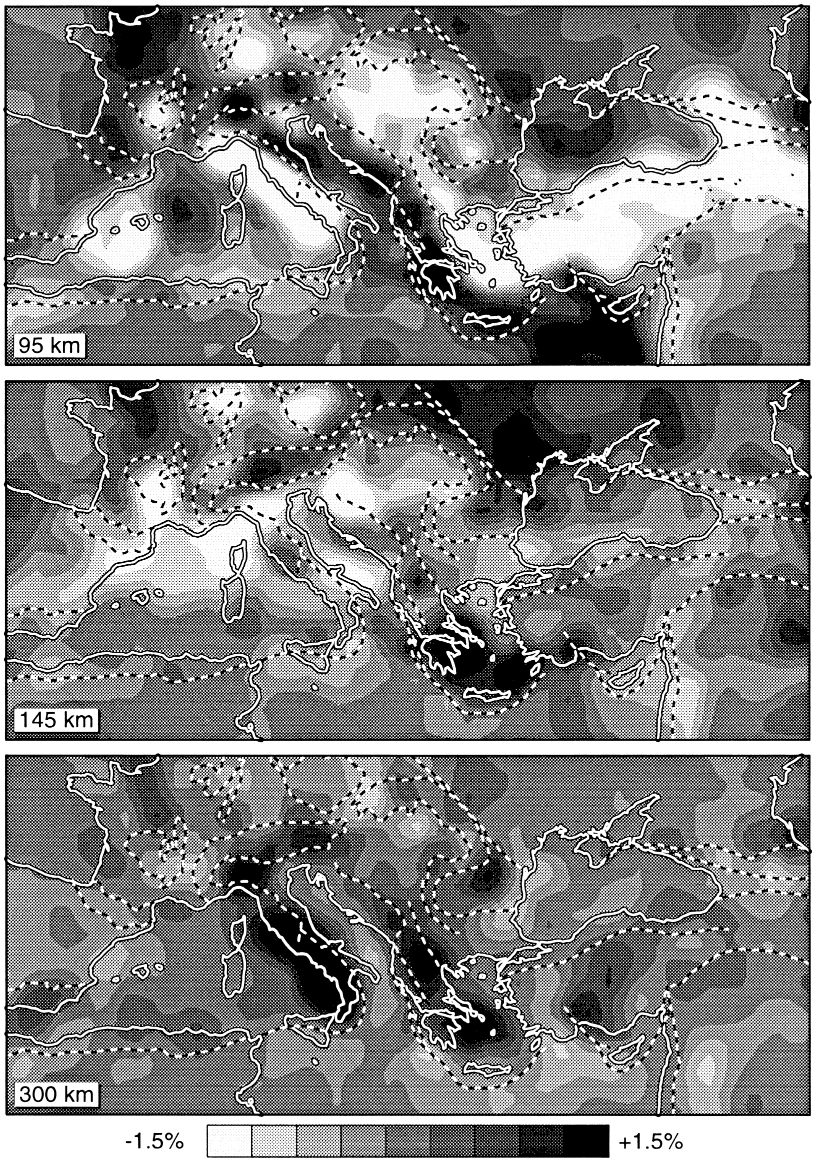

Fig. 9. Seismic P-wave velocities at depths of 95 km, 145 km and 300 km. The velocities are from the model EUR89B of Spakman et al. (1993). High (positive) anomaly regions below the African–European collision zone result from low temperatures in subducted lithosphere. The transition from high- to low-velocity anomalies below the Dinarides and the Hellenides at 95 km depth marks the plate boundary at depth. Below Italy this transition delineates the plate boundary between the Adriatic promontory and the Tyrrhenian region. At 145 km the subducted slab is only imaged below the southern Aegean. At this depth, slab detachment below the Apennines and the Dinarides–Hellenides belt is imaged as a vertical gap between high-velocity structures at 95 km and below 200 km. In the third panel (300 km) high velocities are again imaged below the Dinarides–Hellenides belt and they have also appeared below the Apennines.

Carpathian arc. Since slab detachment may result in considerable vertical motions, space-geodetic measurements and gravity monitoring should provide information on the vertical component. High-resolution reconstructions of the spatial and temporal relationships between vertical motions put clear geological and geodetic constraints on geophysical modelling of the evolution of slab detachment along the

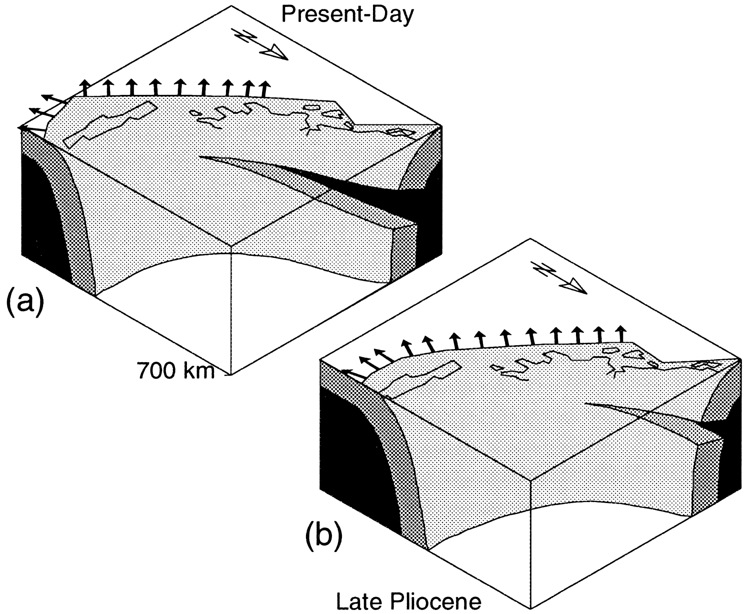

Fig. 10. Schematic sketch of the slap detachment presumably taking place in the Aegean. The figure illustrates plate boundary forces in response to migration of slap detachment. The interpretation is in accord with the modelling results discussed in Meijer and Wortel (1996).

Alpine–Mediterranean plate collision zones. Moreover, a fundamental understanding of crustal deformation in terms of its dynamic causes and relations with lithosphere and mantle processes is indispensable for major advance in the study of earthquake and volcanic hazards, their risks and prediction.

### 5.3. Ongoing projects, current results

The current series of coordinate solutions for the Mediterranean has been obtained with mobile SLR systems and GPS receivers. As an example, Fig. 11 shows a solution for horizontal and vertical motion based on SLR (1986, 87, 89, 92) and GPS (1989, 92, 94). Other examples can be found in, for example, Smith et al. (1994b). Particularly the horizontal motions determined on the basis of roughly ten years of SLR data obtained within WEGENER-MEDLAS have greatly contributed to a better understanding of the regional geodynamics in the Mediterranean.

However, it is expected that in the future a smaller number of mobile SLR systems will be available for observational campaigns. This means that the sites in the Mediterranean will be occupied only incidentally by such instruments. In addition, the SLR campaigns of the upcoming years will be increasingly supplemented by information gathered from permanent GPS networks and repeated GPS campaigns. It is necessary that a number of permanent GPS sites in the Mediterranean are installed (WEGNET) to serve as reference points for regional GPS campaigns (Ambrosius et al., 1998). It is recognized that one essential element in identifying the gross pattern of the collision between Eurasia, Africa and Arabia is missing: geodetic reference stations on the stable part of Africa. The establishment of new sites in the northern part of Africa is mandatory for the completion of our picture of the kinematic pattern at the Eurasian–African–Arabian plate boundary.

Utilizing information from SLR data, it has been logical to aim at resolving in finer detail the kinematics in active earthquake belts by densifying the network with GPS measurements (see for instance Denys et al., 1995; Gilbert et al., 1994; Oral et al., 1993, 1995; Kahle et al., 1993; Gilbert et al., 1994; Altiner et al., 1994; Denys et al., 1995). In hazardous areas either continuous monitoring or repetitive measuring campaigns at shorter time intervals have been initiated. This allows for the determination of the space and time variations of the regional

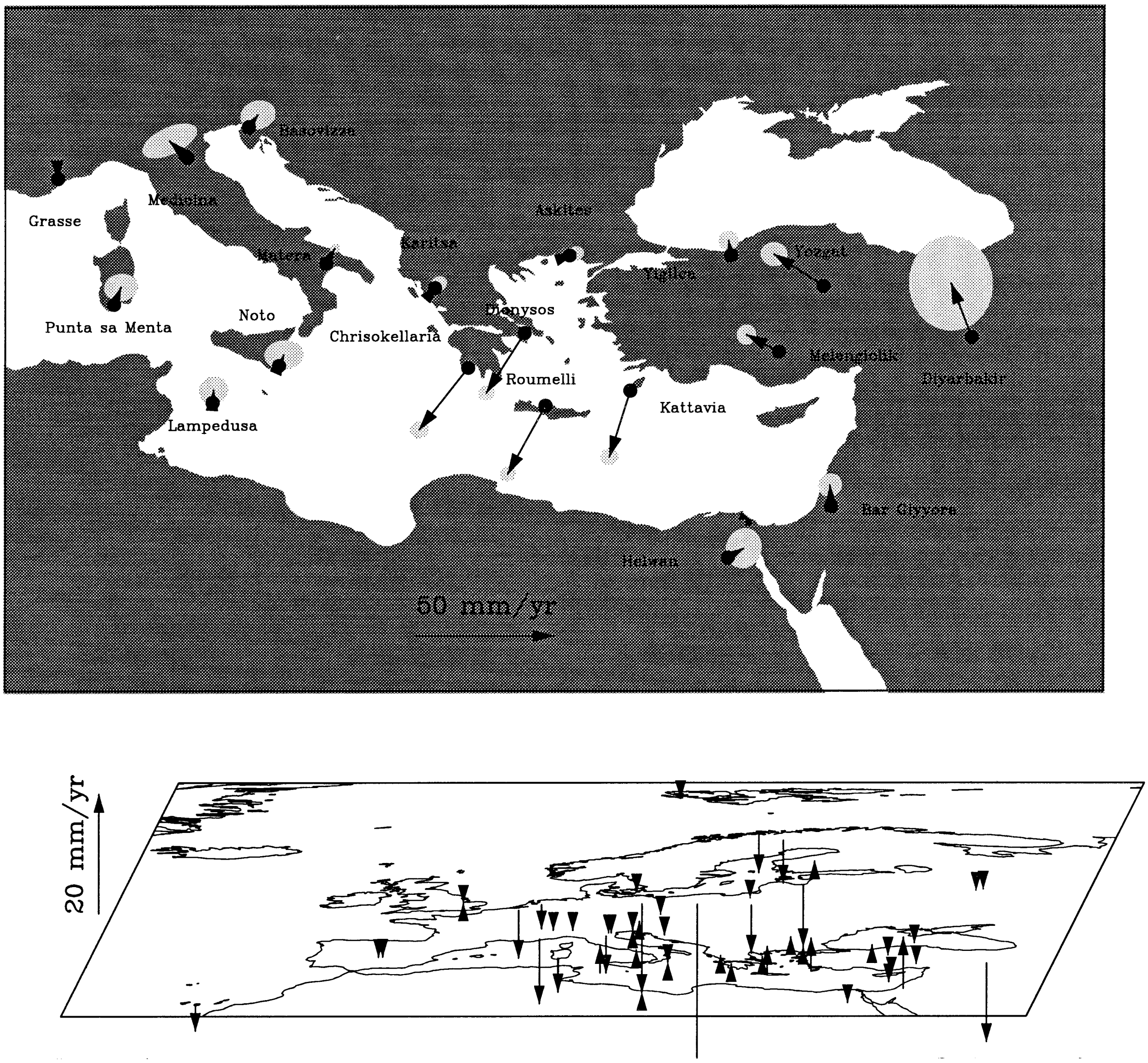

Fig. 11. SLR- and GPS-determined horizontal and vertical rates at European stations. Upper diagram: horizontal motion vectors of Mediterranean stations relative to stable Eurasia. Vectors are given with open uncertainty ellipses. Lower diagram: vertical rates at European stations. Both horizontal and vertical rates were computed at the Delft University of Technology. From Noomen et al. (1996). For a detailed discussion of the computation and the single stations, see Noomen et al. (1996).

strain and stress tensors. For the requested high-precision positioning detailed error budget management is mandatory. Non-permanent measurements demand for atmospheric modelling (see e.g. Geiger et al., 1995) including particularly water vapor radiometry (WVR) (see e.g. Claus et al., 1995).

Over the past years a number of groups have completed GPS campaigns in the central and eastern Mediterranean (see e.g. Kahle et al., 1993, 1995b, 1996; Straub and Kahle, 1995; Reilinger et al., 1995). Significant tectonic results include the following.

(1) The detection of a southwestward motion and counterclockwise rotation of the west Anatolian block.

(2) Quantitative estimates of present-day rates of strain accumulation along the north Anatolian

fault from the Karliova triple junction to the Sea of Marmara, and along the east Anatolian fault.

(3) The detection of a northward motion of the Arabian plate.

(4) The detection of coseismic and postseismic displacements for the Erzinçan earthquake of March 1992.

(5) The identification of the role of the Kephalonia fault system as a major boundary between the Apulian and the west Hellenic blocks.

### *5.4. Proposed activities*

The general aim of this part of the WEGENER activities related to the study of the African–Eurasian plate boundary is the geodetic investigation of regional and local crustal deformation (3-D kinematics and gravity) of the western Alpine–Mediterranean region with a focus on the eastern Atlantic, western and central Mediterranean, and the Alps region. This investigation encompasses the kinematics of the large-scale convergence of Africa and Europe in the region from the Azores to the Iberian Peninsula and further to the western and central Mediterranean. The aim serves to provide fundamental insight in the kinematics of the western and central part of the complex collision zone, whereas previously the emphasis has been on the eastern Mediterranean, the Aegean and the Anatolian region.

This general research aim is too demanding on resources to be realised within WEGENER alone. Nevertheless, as with its previous efforts, WEGENER will attract international research groups, and will initiate and partly carry out the research aimed at resolving the Alpine–Mediterranean geodynamic problem.

With a working hypothesis for the present-day geodynamic setting at hand, the results of the anticipated research program (specified below) provide critical constraints on near-future 3-D models of the geodynamic processes which determine the current crustal stress and strain fields of the Mediterranean. In this interaction between geodetic and geophysical research the emphasis is on quantifying lithosphere–mantle processes and on understanding and prediction of stress and strain in the crust. Knowledge of the stress and strain fields is a crucial piece in the assessment of the risks of natural disasters due to, in particular, earthquakes. Therefore, an integrated approach combining geodetic measurements with geophysical modelling to provide a background for risk assessment responds to the objectives of the present International Decade of Natural Disaster Reduction (IDNDR).

Within WEGENER the following research program was proposed in 1997, and is currently actively promoted.

(a) Establishing the regional kinematic deformation of the large-scale Africa–Europe convergence in the western Alpine–Mediterranean region (eastern Atlantic, Iberian Peninsula, western and central Mediterranean).

(b) Identifying the strategy to combine and use local reference frames for local-scale (100–500 km scale) geodetic programs. Such a clearly defined strategy is indispensable for interconnecting local-scale geodetic programs and provides the means of merging all Mediterranean geodetic data sets (including the outcome of the previous WEGENER program) for regional-scale geodynamic analysis.

(c) Implementing local to regional-scale projects to assess the detailed 3-D kinematics of the Calabrian–Apennines arc and the interaction with adjacent regions, the plate collision between the Adriatic plate and the European plate in the Alps region, and the plate collision between the African plate and the Iberian Peninsula.

(d) Continuing effort in the determination of the crustal deformation of the Hellenic arc and Aegean region and establishing its kinematic connection with the Calabrian–Apenninic arc.

In all projects special attention is given to mastering the problem of extracting the crustal signal from vertical motions. This effort strongly interacts with the research programs on postglacial rebound as well as on height and sea-level changes.

In addition to this research program WEGENER anticipates to stimulate and initiate other local-scale geodetic studies which can be tied in easily with the Mediterranean reference network. For instance, special attention should be given to geodetic constraints on fault movements and fault rheology. This requires continuous geodetic observation using dense instrumentation networks. The Mediterranean with its high seismicity and seismic risk is a natural laboratory for such fundamental studies. Moreover, the results of such studies are mandatory prerequisites for a framework for long-term assessments of seismic risks that allow for a sustainable development of infrastructure in such a hazard-prone region.

This research program provides geodetic observations needed for testing geodynamic hypotheses. Crustal kinematics, stress and strain fields, are expected to be completely different in a given region (e.g. southern Spain, Calabria, Hellenic arc) depending on whether the subducting slab is not detached at all, still partly attached, or whether the slab has completely detached. Geodetic observations of the 3-D kinematics are expected to provide the necessary information to discriminate between the three possibilities and hence would serve as crucial data for testing the hypothesis of slab detachment and lateral migration. 3-D-numerical forward modelling (Yoshioka and Wortel, 1995) results in predictions of the 3-D kinematic field as well as stress and strain patterns as a result of the existence or absence of slab detachment which can be tested against observations. At the end, the goal is to link and explain geodetic observations of crustal deformation as a result of lithosphere and mantle processes. Crucial in these studies is the response of the crust (e.g. structure, rheology and existing fault geometry) to lithosphere processes. This complex problem, however, cannot be solved without geodetic constraints on the 3-D kinematic field of surface deformation. International interdisciplinary research needed to solve depth-to-surface relations has just started. With a clear scientific goal and a dedicated research program complemented with geophysical modelling, WEGENER will be acting in the fore-front of international activities in Earth sciences.

## 6. Postglacial rebound

Deformations of the Earth induced by the ice sheets of the last ice age are important tools for probing the Earth's mantle at long time scales of the order of 1000 years, which are not accessible by other methods. Such deformations, and in particular the postglacial rebound induced by the last ice age, are manifested in a number of different observations. Studies of postglacial rebound contribute to our understanding of the mantle rheology and, in particular, to determining the viscosity of the Earth's mantle on long time scales, which is a crucial input for models of mantle convection. In the past three decades, a number of studies have concentrated on this determination of the viscosity profile in the Earth's mantle on the basis of postglacial rebound observations. However, no consensus has been reached up to now (for summaries see King, 1995b; Mitrovica, 1996; Plag et al., 1998).

Modelling glacially induced or postglacial deformations gains increasing interest, too. Recently, also the modelling of the stress field associated with these deformations has been attempted (as an example, see Klemann and Wolf, 1998). The global scale of the present-day postglacial rebound results in significant contributions to a number of geophysical and geodetic signals, where they either have to be eliminated as a perturbation or where they can be used to study the mantle rheology. Thus, in order to detect a climate-related signal in current sea-level changes, the postglacial sea-level signal has to be modelled and corrected (Peltier and Tushingham, 1989, 1991; Douglas, 1991, 1992). Climate variability induces surface mass movements (e.g. in the cryosphere and oceans), which are associated with deformations of the Earth. Observations and modelling of these deformations may provide useful constraints on these mass movements (James and Ivins, 1995; Wahr et al., 1995). As discussed in the previous section, the footprint of plate-tectonic processes in the present-day 3-D surface deformations may help to distinguish between alternative hypotheses concerning these processes. However, even in regions like the Mediterranean, which are not in the vicinity of the former glaciated areas, the spatial variability of the present-day postglacial signal is large enough to bias significantly the endogenic signal due to internal dynamics. Moreover, inter-model differences in radial velocities for the Mediterranean area are as large as 0.3 mm/a, which is of the same order as the tectonic crustal movement rates in that region (Zerbini et al., 1996).

Most previous studies of postglacial rebound or glacially induced deformations are based on spherically symmetric Earth models with a Maxwell rheology (see for example Mitrovica and Peltier, 1992; Lambeck, 1993). In these models, the mantle is usually represented by a low number of isoviscous incompressible layers, and this approach allows to solve the loading problem with a normal mode method developed by Peltier (1974, 1985). Based on this method, particularly the Pleistocene and Holocene sea-level variations seem to be compatible with a viscosity–depth profile with maximum variations of one order of magnitude between an isoviscous upper and lower mantle, though some recent results seem to suggest higher variations (e.g. King, 1995a; Davis and Mitrovica, 1996). However, the detailed analysis of the radial resolution of inversions of postglacial rebound data (Mitrovica and Peltier, 1991; Mitrovica et al., 1994a,b) revealed that most of the differences in the inferred viscosity models may reflect the lack of resolving power in the data sets (Mitrovica, 1996). Moreover, recent studies by Fang and Hager (1994, 1995) and Hanyk et al. (1995) point out mathematical problems of the traditional normal mode method, which breaks down for viscosity profiles with arbitrarily steep gradients, while Han and Wahr (1995) discussed the complexity of the viscoelastic relaxation of a fine-layered compressible Earth model with a PREM (Dziewonski and Anderson, 1981) structure. Based on analytical methods, several authors have embarked to prove the validity of the normal mode method applied to a low number of isoviscous incompressible layers (e.g. Vermeersen et al., 1996; Sabadini, 1996). For the time being, though, some doubts remain concerning the power of the presently available modelling algorithms for postglacial rebound phenomena to constrain the viscosity profile within the Earth's mantle. Using, on the other hand, laboratory results to set up a rheological model of the mantle and assuming isochemical layers, results in large variations of the viscosity with depth of up to five orders of magnitudes within the lower mantle alone (Plag and Jüttner, 1995). As pointed out by Tackley (1996), over the range of conditions encountered in the Earth's mantle, the extreme dependency of the viscosity of mantle minerals on temperature, pressure and stress most likely results in variations of the mantle viscosity by many orders of magnitude. In the upper mantle, the lateral variations in viscosity may well exceed the radial variations (King, 1995b). Therefore, it may be crucial to consider large viscosity variations in both radial and lateral directions in numerical models of such phenomena as postglacial rebound and mantle convection. In this situation, applying methods that assume more or less constant viscosity with depth and assigning the resulting viscosity values to large mantle regions may easily lead to misinterpretations, as shown by Mitrovica (1996).

Finally, it should be mentioned that most of the studies assume a linear (Newtonian) rheology representing diffusional flow. However, power-law creep is equally likely as creep mechanism in the Earth's mantle, and the possible effects of non-Newtonian rheologies deserve attention in postglacial rebound studies.

### *6.1. Present-day deformations and postglacial rebound*

The rapid improvements in space-geodetic measurements have stimulated new interest in the present-day three-dimensional deformations associated with the on-going postglacial rebound. The current three-dimensional deformations in and around the former glaciated areas have been studied by James and Morgan (1990), Tushingham (1991), James and Lambert (1993), Mitrovica et al. (1994a,b) with main emphasis on estimating their effects on VLBI measurements. James and Lambert estimate the maximum tangential velocities to be of the order of 1 to 2 mm/a. Outside the former ice sheets, they find small velocities of the order of 0.1 mm/a, while Mitrovica et al. (1994b) compute velocities of the order of 0.4 mm/a. The main difference between the two studies lies in the ice model history, where James and Lambert assume isostatic equilibrium at the glacial maximum while Mitrovica et al. take into account a long ice history prior to the glacial maximum. Though the sources of some of these and other inter-model discrepancies in the computed present-day 3-D deformations may be found in the Earth models, the discrepancies between the two nearly identical models seem to emphasize the sensitivity of the present-day horizontal deformations to the ice model history. This conclusion is further supported by the study of Mitrovica and Davis (1995), who investigated the 3-D impulse response of a Maxwell Earth and concluded that the present-day far-field tangential velocities are more sensitive to deviations from the isostatic equilibrium at the last glacial maximum than present-day radial velocities, gravity anomalies or sea-level changes. Therefore, these velocities, if measured, would constitute a new and valuable constraint on the ice history particularly prior to the last glacial maximum.

A more detailed knowledge of the present-day three-dimensional deformations in and around the areas once covered by the ice sheets of the last ice age will help to resolve the viscosity profile of the mantle in better detail. In particular, the mapping of the contemporary location of the peripheral bulge may help to distinguish between different rheological models of the Earth's mantle.

The ice history can be expected to affect the different components of the present postglacial deformations differently. Therefore, a better knowledge of the present-day 3-D deformations will provide new constraints on the ice history and particularly the degree of isostatic disequilibrium during the last glacial maximum.

The interpretation of the present-day deformations has to take into account the geological and geodynamic setting of the postglacial rebound area. A comparison of the Baltic shield and the Russian platform reveals a main difference in their geological structure, i.e. the presence of a thick layer of sediments on the Russian platform at the one hand and Proterozoic complexes outcrops on the Baltic shield on the other hand. This fact indicates a more or less permanent uplift of the Baltic shield from Proterozoic time. Postglacial rebound may be contaminated by such a geological uplift.

### 6.2. Ongoing projects

The present status of postglacial rebound measurements in Fennoscandia has been summarized in Plag et al. (1998). In addition to the more than 40 GPS stations in the Nordic countries listed in this report, a number of new stations have recently been installed in the Baltic states (Vilnius, Lithuania, Feb. 96; Riga, Latvia, Jan. 96; Suurupi, Estonia, summer 96; Svetloe, Russia, Feb. 96) and in Poland.

The Swedish permanent GPS network (SWEPOS) currently includes 21 stations in Sweden, which are all working with dual-frequency receivers. The latest addition to this network is the station 'BORAS' near Goteborg. The Finnish continuous GPS network (FinnNet) will be upgraded from ten stations to twelve stations, with the additional two stations being ready late 1996. Denmark and Norway are setting up their networks in 1996 with three and ten stations, respectively.

Data from SWEPOS have been obtained continuously since August 1993. These data are yielding horizontal velocities with uncertainties of 0.3–0.5 mm/a, and vertical velocities with uncertainties of 1.0–1.5 mm/a (BIFROST, 1996; Scherneck et al., 1998). As discussed above, these uncertainties are small enough to detect the near-field pattern of three-dimensional deformation due to glacial isostatic adjustment, and also to begin to discriminate among various ice-history and Earth models. These uncertainties, however, are not yet at a level where details of the ice-history and Earth models can be determined. Therefore, a great deal of effort will be spent in continuing the acquisition and analysis of the data for the next several years. Data obtained from the one-year-old FinnNet will enhance the geographic coverage and hence the depth resolution (for determinations of viscosity) of the combined array significantly.

So-called discrete (i.e., non-continuous) GPS networks can be used to improve the spatial resolution of continuously operating GPS networks. In the summer of 1996 the establishment of a densely spaced discrete GPS network around the Gulf of Bothnia was started. After completion, fifteen sites, with minimum intersite spacings of less than 100 km, will be used to study the detailed 3-D deformation in this region. This study will serve two purposes. Firstly, it will provide the basis for an investigation of the anomalous deformation in the Furuögrund/Skellefteå area suggested by the analyses of both tide-gauge data and SWEPOS GPS data. Secondly, the data will provide more definitive information concerning the deformation near the center of uplift and, in particular, the exact location of the center, which currently is a highly uncertain (at the level of several hundred kilometers) parameter. A more precise knowledge of this location will help to improve the ice-history model.

### 6.3. Planned or proposed activities

One main geoscientific goal of postglacial rebound research is to investigate mantle viscosity. For such studies, the ice-history model provides the forcing, and geological and glaciological evidence of the ice history remains limited. Therefore, besides improving the observational base of the resulting deformations, considering the ice-history model is of equal importance. To improve the ice model, the group at Onsala plans to proceed in several stages. First, the different regional models for the ice coverage of Fennoscandia will be carefully re-examined in order to determine what the major uncertainties are. Then forward modelling will be used to obtain an understanding of how these uncertainties in the ice model could affect the computed present-day three-dimensional deformation. Parametrized extensions of the ice model will be developed, which then can be adjusted using GPS and tide-gauge data. Finally, a joint inversion for ice and viscosity parameters will be performed.

The present-day position and size of the peripheral bulge is highly sensitive to the viscosity profile of the mantle including lower mantle viscosity (Davis and Mitrovica, 1996). Therefore, an extension of the current networks aiming at postglacial rebound detection to fully include the peripheral bulge can be expected to produce valuable additional constraints for the geophysical models of postglacial rebound. However, to make full use of these new observations, it will be necessary to set up a theory of long-term deformations apt to handle step vertical viscosity gradients.

Postglacial rebound and peripheral bulge subsidence in Britain have been studied using Holocene shoreline data (Shennan, 1989). These data have enabled constraints to be made on the mantle viscosity (Lambeck et al., 1996). GPS and absolute gravity measurements are being made as part of sea-level projects (see next section) and plans are being made to extend these measurements to obtain better coverage of the areas of postglacial rebound and subsidence.

Another area where new observations would be of great scientific value is the region of Russia, which still exhibits some postglacial rebound. Few observations both concerning past rebound and sea-level changes and the magnitude and extent of present-day rebound are available around east and southeast Finland.

## 7. Height variations and sea-level change

### *7.1. Relative sea-level variations*

The anticipated rise in global sea level is certainly one of the more severe consequences of the predicted global warming (see for example, Warrick and Oerlemans, 1990; Warrick et al., 1996). In addition to this impact aspect, sea level may also prove to be an important indicator of global warming, especially if an acceleration of the sea-level rise can be detected (Woodworth, 1990; Douglas, 1992). The ‘climate signal’ in sea level is composed of two parts: (1) melting of land-based ice adds water to the ocean, and (2) warming of the oceans increases the volume of the water. However, extracting this climate signal from sea-level records is a delicate task for several reasons (see for example Pirazzoli, 1989; Emery and Aubrey, 1991; Dobrovolski, 1992; Plag, 1993). In particular, the mass budget of the oceans is not only affected by the mass changes in the cryosphere but also by a number of other, mainly anthropogenic, factors such as groundwater exploitation, deforestation, reservoir construction, irrigation, and melting of perma-frost soils (for a quantitative budget see for example Sahagian et al., 1994; Gronitz et al., 1996). Consequently, a once established change in global sea level cannot directly be equated to the climate signal.

Establishing a global sea-level trend is not trivial, either. The sea level is influenced by a large number of factors operating at different temporal and spatial scales (see for example Emery and Aubrey, 1991) such as tides, atmospheric forcing, and ocean currents. Moreover, for a global sea-level rise resulting from a warming of the ocean waters and from additional water input of the melting ice shields, regional variations can be expected due to regional differences in heating and circulation changes (Mikolajewicz et al., 1990) as well as the elastic response of the Earth to the ocean loading.

Most of the available long sea-level records come from coastal tide gauges. At many coastal sites, tide gauges have been operated for several decades and at some places even for two centuries. Deriving a global sea-level trend from the available local tide-gauge observations introduces two problems: (1) how are the local trends determined from the individual tide-gauge records, and (2) how are the local trends to be averaged to determine a global value?

Tide gauges measure local sea level relative to a benchmark on land. Thus, vertical crustal movement is one of the factors affecting the local relative sea-level signal. In order to extract the global signal from tide-gauge records, local and regional variations including those due to crustal movements need to be removed. However, the spatial distribution of tide gauges is historically biased towards certain coastal segments on the Northern Hemisphere. Therefore, although based on principally the same data base, the considerable number of recent studies aiming at the determination of a global sea-level trend resulted in a scatter of rates roughly between 1 mm/a and 3 mm/a (for a summary see for example Woodworth, 1990; Warrick and Oerlemans, 1990; Gröger and Plag, 1993).

Currently, apparent sea-level trends recovered from satellite altimetry cannot safely be equated to a true sea-level trend (Nerem et al., 1994, 1997; Nerem, 1995; Fu et al., 1996). As expected from tide-gauge studies (see e.g. Gröger and Plag, 1993), the global sea-level time series determined from satellite data appear to exhibit interannual to decadal fluctuations. Thus, determination of a trend requires much longer records than provided by the satellite data available up to now. But even if sufficient satellite data become available, then the historical data will remain of importance for the detection of any acceleration in sea-level rise as well as for the study of local effects and impacts. Moreover, the recently discovered error in the Topex/Poseidon algorithm illustrates the danger inherent in a system relying on a single sensor or algorithm. After correcting the error, Nerem et al. (1997) determine the global (sea-level) trend in the Topex/Poseidon data over the last three years to be $\sim$0 mm/a if based on the internal calibration only, and $\sim$2 mm/a if a tide-gauge calibration is used.

Nevertheless, the Topex/Poseidon satellite altimetry data are now beginning to provide a wealth of information which will hopefully help unravel the various contributions from the ocean, the atmosphere and the solid Earth to the global sea-level fluctuations. Several attempts to determine, at a global scale, mean sea-level trends with Topex/Poseidon data have been realized recently (Nerem et al., 1994; Minster et al., 1995). Despite the still considerable uncertainties, these studies indicate that sea level is rising with a few mm/a. However, interannual and decadal sea-level variations are apparent in the data and therefore several years of altimetry data will be required to obtain a reliable trend in global mean sea level. The complementary nature of the tide gauge and altimetry information should be used in an integrated way to provide a better understanding of the spatial pattern of the temporal variability of the sea level.

Both geological evidence of past sea-level changes and estimates of present changes in the cryosphere as well as thermal expansion of the ocean suggest that non-tectonic secular trends in relative sea level are of the order of 1 mm/a. Such trends have to be detected against a background of interannual to interdecadal coastal sea-level variations, reaching up to 10 cm over a decade (Sturges, 1987; Pirazzoli, 1989; Gröger and Plag, 1993), which can seriously bias trends estimated from short records. The required record length depends both on the local magnitude of the decadal sea-level variability and the tolerable uncertainty in the trend estimates, and several authors have pointed out that records of at least 50 years are required for reliable estimates of the trend (e.g. Pirazzoli, 1986; Trupin and Wahr, 1990; Douglas, 1991). Thus, the number of stations which can be used for the determination of reliable local trends is drastically reduced. However, accounting for the regional coherent parts of the interannual to interdecadal sea-level variability with models derived from a few long records can improve trend estimates considerably (e.g. Thompson, 1979; Zerbini et al., 1996).

### *7.2. Sea level and crustal movement*

From an oceanographic point of view, vertical crustal movement is a perturbation in the sea-level measurements. Tectonic movements, sedimentation, groundwater or oil extractions, all may result in vertical crustal movements of regional and down to local scales. Postglacial rebound contributes to regional-scale vertical movements. Furthermore, changes in the surface mass distribution in both hydrosphere and cryosphere induce a viscoelastic deformation of the Earth affecting the global geoid and consequently the sea level (Farrell and Clark, 1976).

Among vertical movements occurring in coastal areas, subsidence is more frequent than uplift, because of several geologic phenomena occurring along continental margins, such as sedimentary loading and compaction, lithospheric cooling, isostatic adjustments (Pirazzoli, 1989). This may cause the average of all secular trends in relative sea level from tide-gauge stations to be biased towards apparently greater values.

Postglacial rebound, response to surface loads, tectonic and volcanic activity and the deformation occurring in the plate interiors induce both horizontal and vertical surface movements (see for example Berrino, 1998, for the effect of volcanic activity). The horizontal velocities associated with postglacial rebound and, more generally, surface-load-induced deformations are comparable, while the regional vertical motions due to these phenomena are much greater than those attributable to tectonic activities and intraplate deformation. However, in many locations the crustal component is of the same order as, or even in excess of, the long-term sea-level variations. Generally, vertical crustal movements together with associated changes of the geoid are considered as a major factor masking the sea-level changes due to changes in the volume of the ocean water. The capability of determining reliably sea-level trends is thus very much linked to the capability of estimating vertical crustal velocities.

A discussion on the most relevant vertical displacements occurring during the past 1000–2000 years is given by Zerbini et al. (1996). There is a general agreement among different authors that there are regions of the Mediterranean coast which vary very much in terms of stability and lateral coherence. In the most active regions, sites separated by only 10–20 km can show different directions and rates of vertical movements and, because of this pronounced spatial variability, data at one site can only be interpolated or extrapolated laterally for a distance of that order. The knowledge of local geology should be used to see if it is justifiable to extrapolate the predicted rate of crustal movements from the site of a known tide gauge for a distance of 10, 20 or 30 km along the coast (Flemming, 1992).

In order to determine the true sea-level variations, both at a global and regional scale, over limited time intervals (5 to 10 years) it is necessary to measure with high accuracy (1 to 2 mm/a over 5-year intervals) and to control vertical crustal movements at selected tide-gauge stations. Decoupling vertical movements from the observed sea-level variations is nowadays feasible and achievable through the combined use of space techniques and absolute gravity measurements and of sophisticated procedures for the analysis and interpretation of the data sets. The SELF Project (Zerbini et al., 1996) in the Mediterranean Basin has demonstrated the capability to establish tide-gauge station heights in a global well-defined reference system to the 1-cm level of accuracy. It has to be pointed out here that efforts should be concentrated on those tide gauges where sufficient data (of the order of fifty years) are available, so that the sea-level trends can be determined with a similar accuracy to what can be achieved with present-day GPS, SLR and VLBI measurements.

### *7.3. The height definition/determination problem*

As described in Section 3.2, a common reference system is now available, and in the ITRF94, station positions and velocities are known to 2 cm and 3 mm/a, respectively. In northern Europe and in the central-eastern Mediterranean the SLR stations of the WEGENER/MEDLAS network provide a dense spatial coverage. Several of these stations are fixed and operate on a continuous basis while others are observing only during scheduled campaigns (Wilson and Reinhart, 1993). The body of data presently available and spanning about 10 years has made it possible to compute high-accuracy coordinates and station velocities.

The analysis of the GPS observations, using ‘precise orbits’ available through the IGS (Zumberge and Liu, 1995), allows to derive the $X$, $Y$ and $Z$ coordinates which are related to the center of mass and oriented according to the ITRF. The transformation to the WGS84 ellipsoid leads to geographical coordinates and geometrical heights. If the TGBM are tied by short spirit levelling to the GPS benchmarks a geometrical height of the TGBM is available. This step allows the separation of the geocentric globally defined height variations of the TGBM from the variation of mean sea level (Baker, 1993).

Besides the formal error derived from the data analysis, the overall error budget of a geocentric geometrically defined height is systematically affected by, for example, the realization of the ITRF including the variations of the geocenter. It is also affected by the error associated with the determination of the height of the GPS antenna phase center with respect to the ground marker, by the path delays due to atmospheric variations not described by the atmospheric models, and by the loading effects of the ocean and the atmosphere. Significant progresses have been made, particularly regarding a better understanding of the influence of the atmospheric effects on the GPS signal propagation by using WVR (Zerbini et al., 1996). However, there are still systematic effects in the process described above which do not cancel out as it occurs, on the contrary, in the determination of horizontal positions. If presently absolute geocentric heights can be determined with an accuracy of the order of 20 mm, then height differences can be deduced from episodic campaigns, adopting the approach described in Zerbini et al. (1996), to at least 10 mm accuracy. However, because with GPS measurements the height component is the most difficult one to measure accurately and considering also the need for sophisticated data analysis procedures, the IAPSO Working Group (Carter, 1994) recommended the use of CGPS measurements at tide gauges, wherever possible and feasible, rather than episodic campaigns, as recommended previously.

## *7.4. Ongoing projects*

In recent years a number of national and multinational projects in Europe have concentrated on various levels on tying tide-gauge benchmarks into a well-established reference frame.

### *7.4.1. SELF II*

SELF II (SEa Level Fluctuations in the Mediterranean: interactions with climate processes and vertical crustal movements), a follow-up program to SELF (see Zerbini et al., 1996), has been selected and funded by the Commission of the European Union in the framework of its Environment and Climate Programme. The overall aim of the SELF II project is to determine absolute sea level and its variations and to use them in a comprehensive way to study the present interactions as well as those of the recent past among the ocean, the atmosphere and the Earth's crust and to develop appropriate models to predict future aspects. SELF II has the objectives: (a) to improve the long-term monitoring of sea-level variability by applying the most advanced geodetic techniques, including satellite altimetry and airborne laser; (b) to provide additional sea-level related constraints for the validation of climate models; (c) to study past sea levels in the Mediterranean in order to further our understanding of the current processes; (d) to assess the potential hazards in coastal areas in the Mediterranean and to provide a basis for developing strategies to mitigate these hazards. The SELF project stresses the importance of collecting a data set of present and past vertical movements from coastal regions of the Mediterranean. Ideally, this would be based on a data set providing reliable data at closely spaced intervals along the whole coast length of 45,000 km (Flemming, 1992). Tide-gauge, archaeological and geological data all furnish information on the past relative sea level, on the local lateral coherence and vertical movements of coastal regions. Concerning the observational approaches involved in sea-level fluctuations monitoring, the SELF II strategy to determine crustal movements at the tide gauges complies to both scientific and economic requirements, in order to achieve a reliable knowledge of the vertical rates of the TGBMs.

### *7.4.2. Baltic Sea Level Project (BSL)*

The BSL is being carried out in the framework of the activities of the IAG Special Study Group SSG 5.147 (Studies of the Baltic Sea). The project was proposed in 1989 for the study of sea-level changes, land-uplift investigation and connection of levelling networks of the countries surrounding the Baltic Sea.

Altogether two GPS campaigns have been carried out. The first, in 1990, made GPS measurements at 30 tide gauges and an accuracy for ellipsoidal heights of ±4.6 cm was obtained. The second campaign from June 7 to 13, 1993, made measurements at 35 tide gauges and achieved an accuracy of ±2.0 cm (Kakkuri, 1995). Using a new gravimetric geoid for the Baltic Sea area, the mean sea surface topography was computed. This showed that the mean sea level in the Gulf of Bothnia and the Gulf of Finland is 30 to 40 cm higher than in the southern Baltic Sea, which is consistent with oceanographic studies.

### *7.4.3. UK GPS Tide Gauge Project (UKGAUGE)*

The project is funded from 1991 to 1997 by the Flood Defence Division of the UK Ministry of Agriculture, Fisheries and Food. The work is being undertaken by the Institute of Engineering Surveying and Space Geodesy of the University of Nottingham and the Proudman Oceanographic Laboratory. Considerable assistance is also being provided by the Ordnance Survey and the Military Survey.

In 1994, the number of tide gauges included in the project was increased from nine to sixteen. Repeatabilities between different years are at the 10- to 20-mm level for the height component. It has been shown that the best results are achieved when a pure GPS-based global reference frame, such as IGS, is used (Ashkenazi et al., 1993). A parallel programme of absolute gravity measurements has started and it is planned to install permanent GPS receivers at some of the key tide gauges.

### *7.4.4. Atlantic Coast GPS Tide Gauge Project (EUROGAUGE)*

This project has been funded by the Commission of the European Union and involves research groups in the UK, France, Spain and Portugal. The project involved a total of sixteen tide gauges (five in the UK, five in France, three in Spain and three in Portugal). Simultaneous GPS measurements were made at all sixteen tide gauges for 5 days in November 1993 and 5 days in March 1994. Over this 4-month interval, it was assumed that the long-term vertical crustal movement was zero and so the data sets could be used both to test the repeatability of the height component and to provide first epoch height measurements for future work. The data were processed using three independent software packages (University of Nottingham, Bernese and JPL/NASA), and it was shown that the height agreements between the campaigns were better than 15 mm at all of the tide gauges (Ashkenazi et al., 1994).

### *7.4.5. Netherlands GPS Tide Gauge Project (NEREF-MAREO)*

The NEREF-MAREO project started in 1990 to determine the height of the most important tide gauges in the Netherlands. MAREO refers to the sea-level component in the campaign and NEREF refers to the Dutch NEREF GPS network, which is a densification of the EUREF (EURopean REference Frame) network. GPS measurements were made at between seven and ten tide gauges and EUREF sites in campaigns in 1990, 1991 and 1994. The errors for the height component were estimated to be better than 22 mm. It is planned to install a permanent GPS receiver at the Terschelling tide gauge during 1996.

### *7.4.6. Baseline Inference for Fennoscandian Rebound Observations, Sea level and Tectonics (BIFROST)*

The international BIFROST project has permanent GPS sites in Sweden, Finland and a number of Baltic states, with some of these sites close to operating tide gauges. One goal of the BIFROST project is to correct the extensive Fennoscandian tide-gauge record for the influence of vertical motions (BIFROST, 1996). The longest running subnetwork is the Swedish one (SWEPOS), which has collected data continuously since August 1993. It should be mentioned here that outside of California (Bock et al., 1993) and Japan (Tsuji et al., 1995), SWEPOS (BIFROST, 1996) is the largest and longest running CGPS array. After about three years of operation, the determination of vertical motion appears to be precise enough to show the general pattern of postglacial uplift (BIFROST, 1996). It can be expected that the BIFROST results will help to improve the Fennoscandian tide-gauge data set considerably.

### *7.4.7. Black Sea GPS Tide Gauge Project*

Due to its position on the plate boundary and its almost circular form, the Black Sea coastline is subject to considerable tectonic deformation and storm surges that complicate the analysis of sea-level observations at the tide gauges located there. So far, two sets of GPS measurements have been performed at six points to connect the tide gauges to a common height datum and to try to identify the magnitudes of tectonic height deformations. Further measurements are planned. The work to date has been performed in the framework of the SELF project.

## *7.5. Proposed activities*

Considering the multiplicity of sea-level related geodetic activities and projects taking place in Europe and the Mediterranean it is suggested that IAG's Commission 6 takes the responsibility to coordinate the different efforts in an effective and productive way in order to avoid unnecessary duplication of work and in order to disseminate among the different research groups information concerning the development of experiences and achievement of new technical capabilities. This would entail a significant step forward in the attempt of developing a long-term, scientifically meaningful program for monitoring sea-level changes and the related environmental effects in the European, Mediterranean, Black Sea and Caspian coastal zones.

## 8. Summary, conclusions and outlook

WEGENER activities are currently focused on three main scientific objectives, namely the geodynamical processes at the Eurasian/African/Arabian plate boundaries, the postglacial rebound in Fennoscandia and adjacent regions, and the height-determination problem particularly in its relevance for monitoring sea-level variations.

A comprehensive overview of the significant evolutionary, structural and dynamic features which characterize the broad transition zone between the African and Eurasian lithospheric plates has been given by Mueller and Kahle (1993) and Kahle and Mueller (1998). The synthesis is based on recent geologic, geophysical and geodetic data available in the Mediterranean–Alpine region. It is shown that - superimposed on the large-scale counterclockwise rotation of the African plate - complex dynamic non-stationary processes affecting the lithospheric fragments between the two major plates play an important role. De Jonge et al. (1994) quantitatively studied the Cenozoic kinematic evolution of the Alpine–Mediterranean and predicted a present-day 3-D lithosphere and mantle structure. A comparison with the tomographic models of Spakman et al. (1993) demonstrates the importance of large-scale subduction for the dynamic evolution of the region. The results obtained so far can be considered as a first step towards a better understanding of the complex evolution, structure and present-day geodynamics.

The model proposed by Wortel and Spakman (1992, 1993) for the dynamic evolution of the Alpine–Mediterranean region relates lithosphere and mantle dynamics to crustal and surface deformation. Model predictions are highly testable against geological, geophysical and especially geodetic observations. As such, the model provides a strong working hypothesis (best denoted as the slap-detachment hypothesis) for WEGENER initiatives and activities in the Alpine–Mediterranean region, and provides a solid basis for interdisciplinary research.

In particular, geodetic activities should be directed on extending the efforts conducted by the previous WEGENER campaign toward the western part of the Alpine–Mediterranean collision zone. Specific attention should be paid to the vertical component of plate tectonic movements and deformations on a regional and local scale. These are to date not known, but would provide crucial constraints on geodynamic modelling.

High-accuracy observations with high spatial and temporal resolution of present-day three-dimensional deformations due to postglacial rebound are valuable constraints on mantle rheology (Plag et al., 1998). The capability of obtaining such observations with space-geodetic techniques such as VLBI and continuous GPS has been demonstrated, for example, by Ryan et al. (1998) and Scherneck et al. (1998).

Separating variations of the sea level from crustal motion in tide-gauge observations requires a long-term monitoring of crustal vertical motion. Studies such as the one described by Zerbini et al. (1996) have pioneered in demonstrating the capability of space-geodetic techniques combined with gravity observations to achieve this separation, given that the required observation strategy is applied.

The interdisciplinary approach to geophysical problems developed by WEGENER over the past fifteen years on a continent-wide scale has proven to be highly stimulating for the development of both the observational techniques and strategies and the theoretical basis of the models used to predict the observations. Over this time span, space-geodetic techniques have seen an unexpectedly rapid unfolding of capabilities which is still continuing.

Over the past decade, these techniques have contributed to the observation of present-day tectonic motions predicted by global plate-tectonic models (DeMets et al., 1990, 1994), improved kinematic patterns in a number of tectonically active regions (e.g. Mueller and Kahle, 1993; Kahle and Mueller, 1998), and detailed studies of the kinematics in seismotectonic areas (e.g. Reilinger et al., 1995; Kahle et al., 1996). What is still missing is a firm link between the kinematics determined from surface deformations and the dynamics of the Earth's interior. Knowledge of the temporal and spatial variations in the stress and strain fields associated with the surface deformations would provide a key contribution to establish such a link.

While there are well developed and efficient techniques to monitor co-seismic deformations and strain, only a few attempts have been made to observe the postseismic deformation field over periods from months to several years. The nearly total lack of observations of long-term variations of regional strain and stress seriously limits our understanding of the accumulation of strain and stress over time and of the underlying deformation mechanisms. Thus, for example, it is still not clear to what extent inter- and intraplate deformations occur in a continuous or episodic manner. The absence of observational evidence is mainly due to technical boundary conditions, i.e. in the past no technique has been available which was capable of monitoring at low- and ultra-low-frequency three-dimensional deformations of the Earth's surface with sufficient spatial and temporal resolution and the long-term stability required to solve these problems.

Space-geodetic techniques are now on the fringe of providing the technological basis in terms of resolution, precision and stability. Particularly the development of cost-effective strategies for high-precision monitoring of regional Earth's surface deformations opens new and promising possibilities for the application of space-geodetic techniques to the study of geodynamic problems. Such observations can be used to derive strain and stress fields (see e.g. Straub and Kahle, 1995; Straub, 1996) relevant for studies of, for example, earthquake generation processes. In the context of the IDNDR, these applications are expected to contribute to the ultimate goal of a broader scientific basis for hazard estimates and risk assessments.

Out of the repertoire of techniques available, GPS is the most promising one for monitoring three-dimensional deformations in terms of spatial and temporal resolution as well as long-term stability. The latter is guaranteed by the combination of various techniques routinely carried out on an international level by services such as the IGS and the IERS. A continuing development and improvement of, for example, SLR and VLBI networks contributing to the long-term stability of the system is of vital interest to the WEGENER activities.

GPS is likely to be the work-horse in most future studies utilizing space-geodetic techniques for the measurement of three-dimensional deformations. The precision and accuracy of the vertical component is still less favourable than for the horizontal ones. Therefore, considerable emphasis has to be put on the improvement of the vertical component both through better accounting for tropospheric effects on the propagating signal (see e.g. Geiger et al., 1995) and a better understanding of geophysical signals in the deformations due to, for example, surface loads (e.g. Plag et al., 1996).

Within WEGENER, the height problem is central for the achievement of all three scientific objectives. The relations between different space techniques particularly with respect to height observations are important issues today. They are of specific interest for the purposes of WEGENER, because there are many SLR and VLBI observatories in Europe, most of which are also equipped with GPS receivers. Full use should therefore be made of these multi-technique options in future WEGENER projects.

While in recent years GPS was mostly applied in episodic campaigns, in the last three years preference has shifted to more continuously occupied stations and this trend is likely to continue over the coming years. The development of effective strategies and analysis methods for a combination of episodic and CGPS observations as proposed, for example, in Bevis et al. (1997) deserves special attention in the near future. Particularly in seismically active regions, networks of densely spaced, high-precision CGPS sites may provide a fundamental key to ultimately establishing the ability to assess seismic hazards (see the discussion in Prescott, 1996a,b; Savage, 1996). In Europe, WEGENER strongly supports projects based on CGPS stations (e.g. SELF II, see Zerbini, 1995) and aiming at the establishment of CGPS arrays such as the BIFROST one (BIFROST, 1996).

## 9. List of Acronyms

| | |
|---|---|
| BIFROST: | Baseline Interference for Fennoscandian Rebound Observations, Sea Level, and Tectonics |
| BSL: | Baltic Sea Level project |
| CDDIS: | Crustal Dynamics Data Information System |
| CDP: | Crustal Dynamics Project |
| COSPAR: | Committee on Space Research |
| CSTG: | Commission on International Coordination of Space Techniques for Geodesy and Geodynamics |
| DORIS: | Doppler Orbitography and Radiopositioning Integrated by Satellite |
| DOSE: | Dynamics Of the Solid Earth |
| ECMWF: | European Center for Medium Range Weather Forecast |
| EDC: | European SLR Data Center |
| EOP: | Earth Orientation Parameters |
| EOSS: | European sea level observing system |
| ERS: | European Remote Sensing |
| EUREF: | EURopean REference Frame |
| EUROGAUGE: | Atlantic Coast GPS Tide Gauge Project |
| EUROLAS: | European Laser Consortium |
| EUVN: | European Vertical Network |
| FINNET: | Finish GPS Network |
| GLAS: | Geoscience Laser Altimeter System |
| GLONASS: | Global Navigation Satellite System |
| GLOSS: | Global sea level observing system |
| GPS: | Global Positioning System |
| IAG: | International Association of Geodesy |
| IAPSO: | International Association of the Physical Sciences of the Ocean |
| ICRF: | International Celestial Reference Frame |
| ICSU: | The International Council of Scientific Unions |
| IDNDR: | International Decade of Natural Disaster Reduction |
| IERS: | International Earth Rotation Service |
| IGBP: | International Geosphere Biosphere Programme |
| IGS: | International GPS Service for Geodynamics |
| ILP: | International Lithosphere Programme |
| IOC: | Intergovernmental Oceanographic Commission |
| ITRF: | International Terrestrial Reference Frame |
| LAGEOS: | Laser Geodynamics Satellite |
| LLR: | Lunar Laser Ranging |
| LOD: | Length of Day |
| LOICZ: | Land–Ocean Interactions in the Coastal Zone |
| MEDLAS: | Mediterranean Laser |
| NASA: | National Aeronautics and Space Administration |
| NEREF: | Netherlands Reference Frame |
| NMC: | National Meterological Center |
| NOAA: | National Oceanic and Atmospheric Administration |
| PRARE: | Precise Range and Range-rate Experiment |
| RMS: | Root Mean Square |
| SATREF: | Satellittbasert Referansesystem |
| SELF: | SEa Level Fluctuations: geophysical interpretation and environmental impact |
| SELF II: | SEa Level Fluctuations in the Mediterranean: interactions with climate processes and vertical crustal movements |
| SLR: | Satellite Laser Ranging |
| SNREI: | Spherical symmetric, Non-Rotating, Elastic, Isotrop |
| SSG: | Special Study Group |
| SWEPOS: | Swedish permanent GPS network |
| TGBM: | Tide Gauge BenchMark |
| TOPEX/POSEIDON: | The Ocean Topography Experiment |
| UKGAUGE: | UK GPS Tide Gauge Project |
| UT1: | Universal Time 1 |
| UTCSR: | University of Texas Center for Space Research |
| VLBI: | Very Long Baseline Interferometry |
| WEGENER: | Working group of European Geoscientists for the Estab- |

| | |
|---|---|
| | lishment of Networks for Earth-science Research |
| WEGNET: | A permanent WEGENER GPS Network |
| WGS: | World Geodetic System |
| WPLTN: | Western Pacific Laser Tracking Network |
| WVR: | Water Vapour Radiometer |
| WWW: | World Wide Web |

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