Chapter 2
The goals, achievements, and tools of modern geodesy

H.-P. Plag, Z. Altamimi, S. Bettadpur, G. Beutler, G. Beyerle, A. Cazenave, D. Crossley, A. Donnellan, R. Forsberg, R. Gross, J. Hinderer, A. Komjathy, C. Ma, A. J. Mannucci, C. Noll, A. Nothnagel, E. C. Pavlis, M. Pearlman, P. Poli, U. Schreiber, K. Senior, P. L. Woodworth, S. Zerbini, C. Zuffada

2.1 Introduction

Friedrich Robert Helmert (1843-1917) defined geodesy as the science "of measurements and mappings of the Earth's surface". Over time, this definition of geodesy has been extended, mainly as a consequence of technological developments allowing geodesy to observe the Earth on global scales with high accuracy. Today, geodesy is the science of determining the geometry, gravity field, and rotation of the Earth and their evolution in time. This understanding of modern geodesy has led to the definition of the "three pillars of geodesy", namely (1) Geokinematics, (2) Earth Rotation and (3) the Gravity Field (see Figure 1.1 on page 4). These three pillars are intrinsically linked to each other, and they jointly change as a consequence of dynamical processes in the Earth system as a whole. The changes in Earth's shape (including the surface of the water and ice bodies), i.e. the geokinematics, are the result of dynamic processes in the solid Earth and its fluid envelope, affecting mass distribution and angular momentum, and thus changing the gravity field and Earth rotation.

Traditionally, geodesy has been a service science, providing an important utility to other sciences and many applications. This aspect has remained unchanged, and a principal tool and output of geodesy is a reference frame allowing the determination of the position of points relative to each other. But geodesy has developed into a science that can no longer satisfy this service aspect without encompassing and monitoring the whole Earth system, its kinematic and dynamics. As an additional benefit, geodesy is increasingly forced not only to "measure" the geokinematics, gravity field, and rotation, but also to "model" these quantities on the basis of mass transport and dynamics.

The instruments (or measurement tools) are of crucial importance in geodesy. They in essence define the scope of the problems, which may be addressed by geodesy. Before the advent of the space age the geometrical aspects were studied mainly by measuring angles and time (time-tagging of the observations). In the best

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case, angles were measured with sub-arcsecond accuracy, and time with an accuracy of a few microseconds. The angles define a unit vector from the observer to the observed object (a terrestrial target or a celestial object such as stars, the Moon, etc.) at particular epochs. When observing celestial objects, the classical observation technique is called *astrometry*. For time measurement one made the distinction between the *astronomical clocks* (defined, for example, by Earth rotation or, alternatively, by the motion of the Moon and/or planets) and the man-made mechanical clocks. Accuracy and long-term stability of the astronomical clocks could never be reached by mechanical clocks. They were, however, of crucial importance for solving practical problems in navigation (like the problem of determining the longitude at sea or the longitude difference between sites on different continents) and, of course, for interpolating the astronomical time. Gravity was studied by measuring the zenith (actually nadir) direction (i.e., the unit vector along which gravity acts) in a well-defined geometric reference frame and/or by measuring the absolute value of the gravity vector. Both measurement types are heavily affected by the mass distribution in the environment of the measuring instruments, which makes the interpretation of their contribution to global gravity field determination problematic.

The advent of the space age (marked by the launch of the first artificial Earth satellite on October 4, 1957) together with the development of atomic clocks (first realized by crystal oscillators in the 1950s, then by atomic clocks like, for example, the hydrogen masers) to precisely measure epochs and time intervals initiated an extremely rapid development of novel observation techniques and, associated with that, scientific opportunities, which revolutionized the entire field of geodesy. It became in particular possible to

1. connect different continents by simultaneously observing high orbiting, bright satellites from sites located on different continents using astrometry;
2. measure distances through the measurement of the propagation time of short light pulses between an observatory on the Earth's surface and an artificial Earth satellite;
3. exploit the signals emitted by stable oscillators onboard navigation satellites and recorded by receivers on the Earth surface or in the near-Earth space to determine the time development of the distance between the satellite emitting the signal and the receiver(s) recording it;
4. correlate the signals emitted by Quasars (radio galaxies "at rest" in the inertial space) and received by two radio telescopes to establish the distance difference between the telescopes, as seen from the Quasars at the measurement epochs;
5. use the trajectories of artificial Earth satellites to determine the Earth's gravity field;
6. use atomic time to study the rotation of the Earth and the motion and rotation of other objects in our planetary system.

The first of the above items initiated the concept of modern terrestrial reference systems and frames, with the frames being the realization of the systems. Items 2-4 represent "new" observation techniques, which in essence ruled out astrometry and replaced it by the measurement of distances or distance differences. A somewhat simplistic order of magnitude calculation shows that this step resulted in a gain in accuracy of about 2-3 orders of magnitude: A typical error of 0.1”-1.0” in the astrometric position implies a tangential error at a typical distance of 1000 km to a satellite of about 0.5-5 m, whereas the new observation techniques typically measure distances with accuracies of about 1-5 mm. This gain gives access to a whole suite of new problems, which can now be addressed by modern geodesy. Items 1 to 3 are so-called satellite-geodetic techniques. Items 1 to 4 are also referred to as space-geodetic techniques.

Item 5 allows us to study the Earth’s global gravity field in detail. By modeling the satellite orbits as solutions of the equations of motion, which contain the parameters describing the Earth’s gravity field, and by using the satellite geodetic observations in particular of the Laser satellites, and, more recently, of LEOs equipped with GNSS receivers, it became possible to determine the Earth’s global gravity field already before the end of the 20^{th} century in astonishing detail. A quantum jump in accuracy and resolution is being achieved with the suite of dedicated space missions Challenging Minisatellite Payload (CHAMP), GRACE, and, most recently, GOCE, which were deployed in the first decade of the 21^{st} century.

Item 6 marks an important change of paradigm in geodesy and fundamental astronomy: Instead of using the Earth rotation and lunar/planetary motion to define and realize time, in particular Universal Time (UT), it is now possible to study the Earth’s rotation and planetary motion as a function of atomic time (or Coordinated Universal Time (UTC), which is today derived uniquely from atomic time). This aspect is of particular importance for the problems associated with the second pillar of modern geodesy, namely the study and monitoring of Earth rotation.

In accordance with the development of measuring techniques, the concepts of the Earth system, including the solid Earth, changed, influenced by both geodetic observations and a better understanding of the Earth system and its main processes. For a long time, geodetic concepts were based on a static view of the solid Earth, and terrestrial reference frames were based on fixed coordinates of points on the Earth’s surface. Over the last five decades, the development in our understanding of the solid Earth and the total Earth system has made it clear that the solid Earth’s surface undergoes continuous deformations, changing the relative position of all points on a wide range of time scales. The invention and rapid improvement of the space-geodetic technologies have provided a wealth of observations documenting the surface deformations, irregularities in the Earth’s movement in space and the extent of mass movements in the Earth’s system. At the same time, scientific and societal applications pose increasing requirements on the accuracy and reliability of positioning as well as navigation. A detailed review of requirements for geodetic observations and products in Earth observations, scientific studies, and societal applications (see Chapters 3 to 7) demonstrates that in terms of precise point positioning, the requirements in terms of accuracy are on the order of centimeter for real-time or low-latency application, 1 cm or better on daily time scales, a few mm/yr for intraseasonal time scales, and of the order of 0.1 mm/yr on interannual to secular time scales. Thus, relative to the size of the Earth, a general accuracy requirement for geodetic observations and products of the order of 10^{-9} or less can be stated.

Considering the characteristics of the spatio-temporal variations in Earth's shape, rotation and gravity field, the task to establish a reference frame with an accuracy at or below the 1 ppb level is a demanding and scientifically challenging endeavor. The Earth's surface is constantly deformed by internal and external processes including earthquakes, Earth tides, surface loading (present and past) caused by the atmosphere, hydrosphere, and cryosphere, sediment loading, and mantle convection. All these processes have to be accounted for at a level well below the targeted accuracy of 1 ppb. This requires geodesy to interact with other geosciences and to take an Earth system approach, which considers the effects of external forcing, atmosphere, ocean, terrestrial hydrosphere, and cryosphere on the solid Earth. Consequently, the realization and maintenance of reliable reference frames on local, regional and global scales as well as the provision of techniques for high-precision positioning has received growing attention within geodesy and in Earth science in general.

Considering the importance of the geodetic reference frames, in Section 2.2, the concepts for reference systems and their realization through reference frames is introduced and the two main geodetic reference systems are described. This sets the stage for a more detailed discussion of the "three pillars of geodesy" and their interrelations in Section 2.3 and the current state-of-art of the observing system in each of the three pillars in the Sections 2.4 to 2.6, respectively. Subsequently, Section 2.7 addresses a central issue for geodesy, that is access to accurate time. Section 2.8 briefly describes measures taken to ensure consistency between the geodetic observations and identifies key open questions. Finally, Section 2.9 introduces auxiliary applications of geodetic and related observations, which increasingly are developed adding a multi-application aspect to geodesy and opening new fields of research.

2.2 Geodetic reference systems and frames

As pointed out earlier in this book, a principal goal of geodesy is to provide the means to assign coordinates to points as a function of time. Position and movement are not absolute quantities and depend on the reference frame to which they are referred. In particular, observations of any celestial body, be it natural or artificial, or of a point in the Earth system, can be used to describe the motion of this body only if the observations can be referred to a well defined coordinate system. In an ideal world, such a system could be defined through three coordinate axes, the origin, and a scale, with the axis either being fixed in space or having a known movement with respect to something else that is fixed. In the real world, the provision of an accessible coordinate system requires far more definition, which comprises a reference system.

In the context of space geodesy, making use of natural and artificial celestial objects, there is a need for both the Celestial Reference System (CRS) and a Terrestrial Reference System (TRS). The CRS, which is fixed in space, is required to describe the motions of galaxies, stars, the sun, planets including the Earth itself, the Moon and the satellites of other planets, and artificial satellites. Observations of points on the Earth's surface or related to the Earth's surface are often easier to relate to movements of these points if they are referred to a TRS with axes fixed in some way to the solid Earth and moving with the Earth in space.

It is of obvious practical advantage to agree upon one definition for each of the celestial and terrestrial reference systems. This has led to the adoption of conventional celestial and terrestrial reference systems (CCRS and CTRS, respectively). A conventional reference system includes the specification of the origin, the direction of the axes (orientation in space), and the scale of the system in an appropriate way. However, more is needed in order to complete the system such as conventions (see Box 1 for an definition of geodetic conventions) on physical constants.

Box 1: Geodetic conventions and standards.

Convention In the context of this report, convention refers to an agreement between groups, especially an international agreement, that is slightly less formal than a treaty. Conventions are for example the agreed-upon way to transform from inertial frame to terrestrial frame, splitting three unique angles that connect the two frames to a set of conventionally defined sub-group of angles (polar motion, Earth rotation, nutation and precession). In geodesy, conventions often regulate ways to process data in order to ensure comparability of the resulting products. In many cases, standards (see below) adopted by e.g. IAG/IUGG become part of conventions. For example, standards that define the "refractivity" of the atmosphere at various wavelengths adopted by IAG/IUGG are later used in "conventional" approaches of the determination of the propagation delays through the atmosphere.

Standard In geodesy, a standard refers to an authorized model (normally authorized by IAG or IUGG or other international bodies recognized by IAG/IUGG) used to define a unit of measurement. Examples of standards are the definition of the meter, the speed of light, and similar physical constants.

Another issue is to gain access to such a reference system. Modern conventional celestial and terrestrial reference systems in fact are realized through coordinates of a set of points and objects determined from observations analyzed with appropriate mathematical and physical models. Such a realization of a reference system is denoted as reference frame. In practice, the realization of a reference system through such a frame requires continuous monitoring of the points or objects. Given the nature of the problem, any realization also requires the specification of additional boundary conditions that the reference frame should fulfill. Moreover, models used to analyze the observations and to correct for disturbances in the coordinates of the points and objects are an integral part of the realization, and therefore have to be included in the convention specifying the reference system and its realization through a frame.

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

Figure 2.1 gives an overview illustrating the conventional reference systems and their realizations presently adopted by the relevant international scientific unions. The two fundamental systems accepted by the relevant international scientific bodies are the ICRS and the ITRS, which are realized by IERS through the ICRF and the

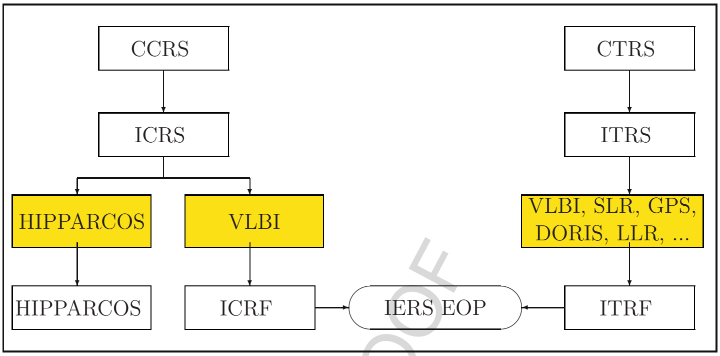


Fig. 2.1. Overview of current conventional reference systems and their realizations. The current Conventional Celestial Reference System (CCRS) adopted by the IAU is the ICRS. In the radio-wavelength, this system is realized as ICRF through VLBI measurements of extragalactical objects and as such maintained by the IERS. At optical wavelengths, the observations made with the HIPPARCOS satellite allowed the materialization of the ICRS through the HIPPARCOS stellar frame.The tie between the HIPPARCOS and the ICRS is determined to a high degree of accuracy (Kovalevsky, 1997). The current Conventional Terrestrial Reference System (CTRS) accepted by IUGG is the ITRS, which is realized through the ITRFmaintained by the IERS. The tie between the ICRF and ITRF is provided by the IERS' EOP. These describe the orientation of the Celestial Ephemeris Pole (CEP) in the terrestrial and celestial systems through the polar coordinates x and y and the nutation offsets $\mathrm{d}\psi$ and $\mathrm{d}\varepsilon$, respectively, and the orientation of the Earth around this axis through UT1-TAI as function of time. From Plag (2006a).

ITRF, respectively. The IERS is a service under the joint auspice of IAG and IAU, and for the ICRF, both organizations take responsibility.

These two frames are linked to each other through the Earth rotation. Today, IERS provides parameters related to Earth's rotation under the name of EOPs.

The ICRS is defined and maintained by the IERS. It was adopted by the IAU and the IUGG as the primary celestial reference system, replacing its optical predecessors based on fundamental star catalogs (see Box 2). The observation and analysis aspects related to the realization of the ICRS through the ICRF are today coordinated by the International VLBI Service for Geodesy and Astrometry (IVS).

The ITRS is also defined and maintained by the IERS. It is adopted by IAG and IUGG as the primary terrestrial reference system, in particular, for Earth science applications. Unlike the ICRS, the realization of the ITRS through the ITRF is based on a combination of results from several space geodetic techniques, and local survey measurements between reference points of geodetic instruments (so-called local ties) co-located at the same sites. The combination is coordinated by the IERS, while the observational aspects for each individual technique involved are coordinated by technique-specific Services. Co-location sites (where two or more instruments are operating in close vicinity), are key elements in the ITRF combinations. While any individual space geodesy technique (VLBI, SLR, DORIS, GNSS) is able to provide necessary information for the ITRF, only the combination of the independent tech-

Box 2: The ICRF

The ensemble of distant extragalactic objects constitutes a quasi-inertial reference frame in which the motion and orientation of the Earth can be measured. In practice, this frame is accessed from the Earth through VLBI observations of compact radio sources, for the most part quasars. The red shifts of these quasars are large enough that their physical transverse movement cannot be detected by current radio or optical techniques, and the objects can be treated conceptually as fixed points in the sky. The International Astronomical Union (IAU) recognized the utility and accuracy of the extragalactic celestial reference frame by adopting the ICRF effective 1 January 1998. ICRF-Extension.2 is a catalog of some 700 radio source positions (Fey et al., 2004, see also Figure 9.5). The positions and errors of the 212 “defining” sources of the ICRF define (realize) the axes and precision of the ICRS on which all celestial positions are now placed. While the right ascension origin and pole of the ICRF are consistent with the previous FK5 stellar frame within the much larger errors of FK5, the concept of the ICRS/ICRF is fundamentally different in several respects. The defining objects of the ICRF have no real proper motions, and the axes of the ICRS are decoupled from the equator, the ecliptic and any particular epoch.

The quasars and other compact radio sources that are included in the ICRF have point-like optical images. Their red shifts indicate great distances so their emissions must be powered by processes different from stars and galaxies, most probably mass inflow onto massive black holes. At the resolution of geodetic/astrometric VLBI using S-band (2 GHz) and X-band (8 GHz), the objects are generally not point-like but have some structure that can also change with time. Such structure changes can be seen as changes in position up to 1 milliarcsecond. The brightest extragalactic radio sources in fact have too much detectable structure to be good astrometric objects. By balancing the competing criteria of source strength, compactness and constancy of structure and position, a set of $\sim$100 geodetic sources has been selected for routine geodetic VLBI observations while the remainder of the ICRF improves the distribution and density over the sky (see Figure 9.5). It should be noted that the small number of VLBI stations in the Southern Hemisphere causes the ICRF to be weaker in all aspects in the southern sky. The quasars in the ICRF emit relatively strongly at microwave frequencies while the great majority of quasars are much weaker or radio-quiet.

The ICRF now constitutes the fundamental celestial frame for all astrometric and geodetic purposes. This includes both planetary ephemerides and satellite orbits. The former have been related to the ICRF by specialized VLBI observations of transmitters on planets and spacecraft as well as from locations of VLBI stations. Satellite orbit determination requires accurate measurements of the actual rotation angle of the Earth UT1-UTC as a priori information since the rotation of the orbit nodes cannot be modeled over a long period. VLBI observations of GNSS satellites should be feasible in the future as the observing bandwidth for geodetic VLBI is extended. Such observations would directly connect the satellite frames to the ICRF. The motion of the Earth’s axis in space, precession and nutation, is also observed using the ICRF. These measurements provide information about the structure of the Earth as it responds to the torques of the Sun, Moon and planets.

The ICRF is essential to geodesy as it is the frame for measuring EOP and the ultimate frame for satellite orbits. The ICRF is also the basis for astrometry. In this regard the ICRF has different realizations at various wavelengths, the microwave VLBI realization being the most accurate at this time. The astrometric satellite GAIA is scheduled for launch in late 2011 and has the potential for generating an optical extragalactic realization with an order of magnitude better precision and two orders of magnitude more objects. Other space missions may refine the positions and proper motions of the brightest stars with corresponding improvement of star tracking for satellite orientation. For most geodetic purposes, however, these improvements will not be applicable since no correspondingly precise ground-based observing system exists. An accurate microwave realization for geodetic VLBI will still be needed.

niques allows for the complete determination of ITRF (origin, scale and orientation). In principle, the particular strengths of one observing method can compensate for weaknesses in others if the combination is properly constructed, suitable weights are found, and accurate local ties in co-location sites are available.

The conventions for both the ITRS and ICRS and their realizations are detailed in the IERS Conventions (e.g., McCarthy & Petit, 2004). As accuracy requirements evolve and technical and modeling capabilities increase, these conventions are modified and developed under the auspice of IERS in a continuous process with support from the broad geodetic science community.

In the conventions, the motion of the reference points in ITRF currently is described by a linear model, thus reducing the information necessary to determine the motion of the reference points relative to their coordinates at a reference epoch and a constant velocity. This representation is no longer appropriate to accommodate possible future user requirements to have access to the actual instantaneous point position over the Earth surface and new representation and models are being discussed (see Chapter 8).

The coordinates and constant velocities of the points that define a particular reference frame depend on the points, techniques, models, and analysis tools used in the determination of these quantities. Therefore, for any given reference system, there can be a multitude of reference frames realizing the system at various degrees of accuracy. For global terrestrial reference frames, the ITRS is increasingly used as the underlying system, thus gaining importance for practical applications. For example, the U.S. Government and the European Commission agreed to align the reference frames of the Global Positioning System (GPS) and GALILEO as close as possible to ITRS (European Commission, 2004). In practice, this goal is achieved by aligning the GNSS reference frames to the ITRF, which is the most accurate realization of ITRS. The reference frame of the positioning services provided by GPS, is the most recent realization of the World Geodetic System 1984 (WGS 84) (e.g., Assistant Secretary of Defence for Command, Control, Communication, and Intelligence, 2001). As a consequence, this realization of WGS84 is today closely aligned to ITRF and in fact supported by ITRF.

ITRF is currently the most accurate realization of ITRS (Altamimi et al., 2002, 2007). The ITRF is updated regularly with the most recent versions being ITRF97, ITRF2000, and ITRF2005. In geodetic analyses of observations of different groups using different techniques and different software packages, coordinates agree to the centimeter level. Secular trends determined from long GPS records using different analysis approaches may disagree on the order of 1 to 2 mm/yr, but most of these discrepancies are due to the approach used to align the solution to ITRF. A significant bias may result from a potential secular translation of the Reference Frame Origin (RFO) with respect to the Center of Mass of the whole Earth system (CM). Recent studies estimate the bias to be of order ± 2 mm/yr (e.g., Ray et al., 2004; Morel & Willis, 2005; Plag, 2006b; Plag et al., 2007a), depending on the geographical location.

The translation of the RFO with respect to the CM introduces particularly large uncertainties in sea level studies. Taking the effect on vertical velocities of the secular translation between ITRF2000 and ITRF2005 (Figure 2.2) as an indication of the uncertainty in the tie of the RFO to the CM, the effect on global sea level trend estimates is of the order 0.2 to 0.3 mm/yr. Consequently, not only maintenance but also improvement of the ITRF as the essential architecture for almost all geodetic measurements is a crucial requirement for sea level studies.

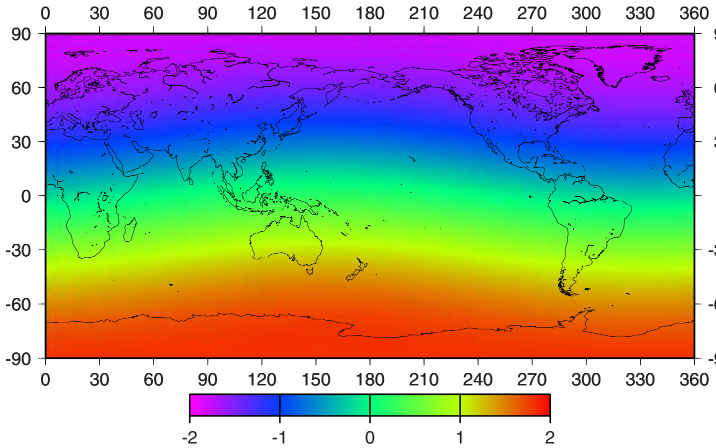


Fig. 2.2. Effect of secular translation between ITRF2000 and ITRF2005 on vertical rates. The vertical rates are for a secular translation velocity of $\mathbf{d} = (-0.2, 0.1, -1.8)$ mm/yr as given on http://itrf.ensg.ign.fr/ITRF_solutions/2005/.

2.3 The tools and products of modern geodesy

Today, the toolbox of geodesy comprises a number of space-geodetic and terrestrial techniques, which together allow for detailed observations of the "three pillars of geodesy" on a wide range of spatial and temporal scales (Figure 2.3). With a mix of terrestrial, airborne, and spaceborne techniques, geodesy today determines and monitors changes in Earth's shape, gravitational field and rotation with unprecedented accuracy, resolution (temporal as well as spatial), and long-term stability (Table 2.1). At the same time, geodetic observation technologies are in constant development with new technologies extending the observation capabilities almost continuously in terms of accuracy, spatial and temporal coverage and resolution, parameters observed, latency and quality. Together, these observations provide the basis to determine and monitor the ITRF and ICRF as the metrological basis for all Earth observations. Equally important, the observations themselves are directly related to mass transport and dynamics in the Earth system. Thus, the geodetic measurements form the basis for Earth system observations in the true meaning of these words. Beutler et al. (1999) suggested a development towards an interdisciplinary service in support of Earth sciences for the IGS. With the establishment of GGOS,

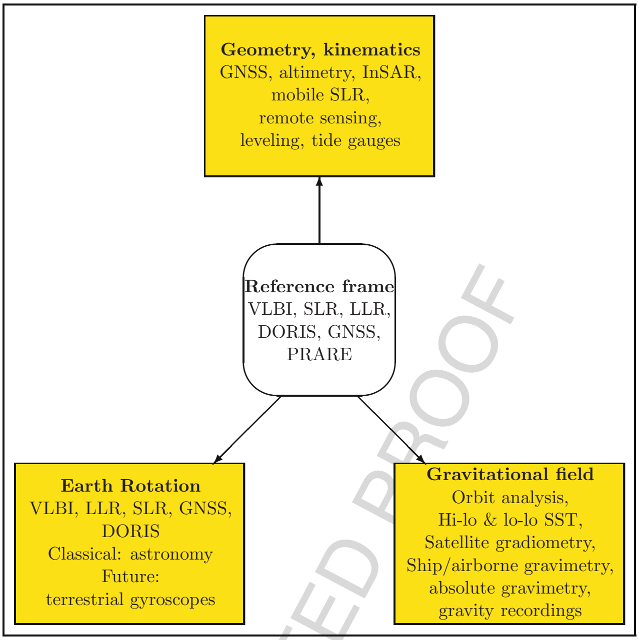


Fig. 2.3. The "three pillars of geodesy" and their techniques. Today, the space-geodetic techniques and dedicated satellite missions are crucial in the determination and monitoring of geokinematics, Earth's rotation and the gravity field. Together, these observations provide the basis to determine the geodetic reference frames with high accuracy, spatial resolution and temporal stability. From Plag (2006a), modified from Rummel (2000). For acronyms, see the list in Appendix 11.

IAG has extended this concept of an observing system and service for Earth system sciences to the whole of geodesy.

From the discussion of the reference systems and frames in the previous section it is obvious that there is an intimate relationship between the three pillars of geodesy and the reference systems and frames (Figure 2.3). For geokinematics and Earth rotation, the relationship works both ways: The reference systems are required for positioning purposes (terrestrial and celestial) and for studying Earth rotation, and monitoring through the space geodetic techniques is necessary to realize the two frames and the (time-dependent) transformation between them.

The ICRF, the ITRF, and the EOPs are needed to derive a gravity field, which is consistent with the ICRF, the ITRF, and the corresponding EOPs. Therefore, one might think at first that the gravity field is not necessary to define and realize the geometric reference systems. However, in order to realize the ITRF, observations made by the satellite geodetic techniques (SLR, GNSS, DORIS) are needed. For these techniques, a gravitational reference system and frame (including a gravity field representation and the parameters associated with it, and the geoid, the mean equipotential surface "near sea level", which may be derived from the gravity field representation) is required as well and cannot be separately determined from the geometrical frames. The problems are obviously inseparable when dealing with the

Table 2.1. The Global Geodetic Observing System (GGOS). For acronyms, see the list in Appendix 11.

Component	Objective	Techniques	Responsible
I. Geokinematics (size, shape, kinematics, deformation)	Shape and temporal variations of land/ice/ocean surface (plates, intra-plates, volcanos, earthquakes, glaciers, ocean variability, sea level)	Altimetry, InSAR, GNSS-cluster, VLBI, SLR, DORIS, imaging techniques, leveling, tide gauges	International and national projects, space missions, IGS, IAS, future InSAR service
II. Earth Rotation (nutation, precession, polar motion, variations in LOD)	Integrated effect of changes in angular momentum and moment of inertia tensor (mass changes in atmosphere, cryosphere, oceans, solid Earth, core/mantle; momentum exchange between Earth system components)	Classical astronomy, VLBI, LLR, SLR, GNSS, DORIS, under development: terrestrial gyroscopes	International geodetic and astronomical community (IERS, IGS, IVS, ILRS, IDS)
III. Gravity field	Geoid, Earth's static gravitational potential, temporal variations induced by solid Earth processes and mass transport in the global water cycle.	Terrestrial gravimetry (absolute and relative), airborne gravimetry, satellite orbits, dedicated satellite missions (CHAMP, GRACE, GOCE)	International geophysical and geodetic community (GGP, IGFS, IGeS, BGI)
IV. Terrestrial Frame	Global cluster of fiducial point, determined at mm to cm level	VLBI, GNSS, SLR, LLR, DORIS, time keeping/transfer, absolute gravimetry, gravity recording	International geodetic community (IERS with support of IVS, ILRS, IGS, and IDS)

definition in the geometry and gravity domains (origin, orientation, scale of the geometric networks, low degree and order terms of the Earth's gravity field).

This consistency between geometric and gravitational products is important today, it will be of greatest relevance in the future for the understanding of the mass transport and the exchange of angular momentum between the Earth's constituents, in particular between solid Earth, atmosphere, and oceans. The aspect of consistency is also of greatest importance for all studies related to global change, sea level variation, and to the monitoring of ocean currents. Only if consistency on the 10^{-9} level or better between all reference frames it achieved, will it be possible to perform meaningful research in the areas mentioned.

In the narrowest possible sense, geodesy has the tasks to define the geometric and gravitational reference systems, and to establish the celestial, terrestrial, and gravitational reference frames. Moreover geodesy has to provide the transformation between the terrestrial and celestial reference frames. These key tasks would be relatively simple to accomplish on a rigid Earth without hydrosphere and atmosphere. However, in the real Earth environment already the definition of the terrestrial and gravitational reference systems is a challenge. The corresponding reference frames can only be established by permanent monitoring based on a polyhedron of terrestrial geodetic observing sites, and of space missions.

This ambitious and expensive geodetic monitoring is necessary and its result, properly time-tagged and mutually consistent, is a stringent requirement in a broad field of scientific and societal applications. There is strong science justification for these geodetic products as a prerequisite (see Chapter 3). Also, some tasks of societal relevance may only be addressed if this permanent geodetic monitoring is available (see Chapter 4), and monitoring of the Earth system, including for example sea level and ice sheet variations, would not be possible without it (see Chapter 5).

The following three sections give an overview of the current status of the global geodetic observing system relevant to the three pillars. Many (but not all) items or activities, which will be mentioned in these section below, are coordinated by entities working under the auspices of IAG. IAG has been in the "monitoring business" since the late 19th century, when the International Latitude Service (ILS) was created to monitor polar motion. More recently the IAG created technique-specific Services to coordinate observation and analysis for the new space geodetic techniques. Also, on the level of IUGG and IAU the IERS was given the charter mentioned above and is coordinating related activities. These Services, which will be mentioned below, are important building blocks of the GGOS.

2.4 Observing Earth geometry and kinematic

2.4.1 Overview

Changes in the Earth's shape are measured with a mix of ground- and space-based techniques. These techniques can be separated into two broad classes:

(1) space-geodetic tracking techniques that monitor the deformation of a polyhedron (points) defined by ground-based networks of tracking stations which either passively utilize signals from satellites (GNSS) or stellar objects (VBLI) or actively send out signals to satellites (SLR and DORIS); and

(2) air- or spaceborne remote sensing techniques that send signals from airplanes or satellites to the Earth's surface and utilize the reflections to map the surface.

The space-geodetic tracking methods provide time series of point movements with high temporal resolution and high accuracy. Tracking stations are normally placed on the land surface. Remote-sensing techniques in general have much lower temporal resolution but provide information with potentially high spatial resolution and much better coverage, including the surface of oceans, lakes, and ice sheets. Beside altimeters, the remote-sensing techniques also include the imaging techniques (such as InSAR and LIDAR), which provide high-resolution images of a surface and its temporal changes.

2.4.2 Space-geodetic tracking techniques

The geometric space-geodetic techniques in general consist of a ground-based component of fixed stations from which the motion of satellites or astronomical objects (moon, quasars) are tracked with electromagnetic waves (including visible light). These stations can be passive in the sense that they do not emit signals but "only" receive signals from remote sources (GNSS, VLBI) or active (SLR, LLR, DORIS).

Common to all these methods is that the data analysis requires a good *a priori* station motion model describing in particular any variation with periods shorter than the analysis interval (for example, 1 day). For the methods based on range measurements, effects on the satellite also need to be accommodated. Coordinate time series resulting from space-geodetic analyses therefore are generally residuals with respect to the station motion model and other modeled effects.

VLBI: Very Long Baseline Interferometry is a space-geodetic technique based on radio astronomy and developed in the 1970s. A radio interferometer consists of a pair of directional antennas (radio telescopes) receiving radio signals from sources in a targeted radio frequency band. The signals from the two receivers are cross-correlated (multiplied and accumulated) to produce a cross-correlation "fringe pattern".

VLBI uses networks of radio antennas typically 20-30 meters in diameter (Figure 2.4) to observe radio signals from extragalactic objects (quasars). Quasars are at such great distances from Earth that they provide fixed points in the sky. Their transverse physical motion cannot be detected with any existing observing system. A radio signal from a quasar passing a VLBI station is received and recorded digitally with very precise time provided by a hydrogen maser. The same signal will travel an additional distance $c\tau$ before arriving at the second VLBI station, where c is the speed of light and τ is the time difference of the signal arriving at the first and second station (Figure 2.5). The distance $c\tau$ depends on the length of the baseline between the stations and its orientation with respect to the direction to the quasar (e.g., Lambeck, 1988; Robertson, 1991; Sovers et al., 1998). The time delay between the arrival times at the two stations can be determined with a precision equivalent to a few millimeters using purpose-built hardware correlators.

The global network of 40 VLBI stations (see Figure 2.6) is today coordinated by the IVS. A typical VLBI session currently includes eight stations observing about 60 quasars several times in a time period of 24 hours. Overlapping networks and network sessions of up to 20 stations connect the 40 global VLBI stations. The time delays from each baseline in the network are used to estimate the station positions with precision of < 1 cm, and the (relative) station velocities can be measured by observations over several years.

Currently, VLBI is the only non-satellite geodetic technique contributing to the IERS. Its unique and fundamental contributions to geodesy and astronomy are (1) the ICRF, the realization of the ICRS, (2) UT1-UTC (apart from leap seconds the difference of universal time as realized by Earth rotation and the atomic time, respectively, see Section 2.7), (3) long-term stability of nutation, and (4) the scale

Fig. 2.4. 32-meter VLBI antenna in Tsukuba, Japan.

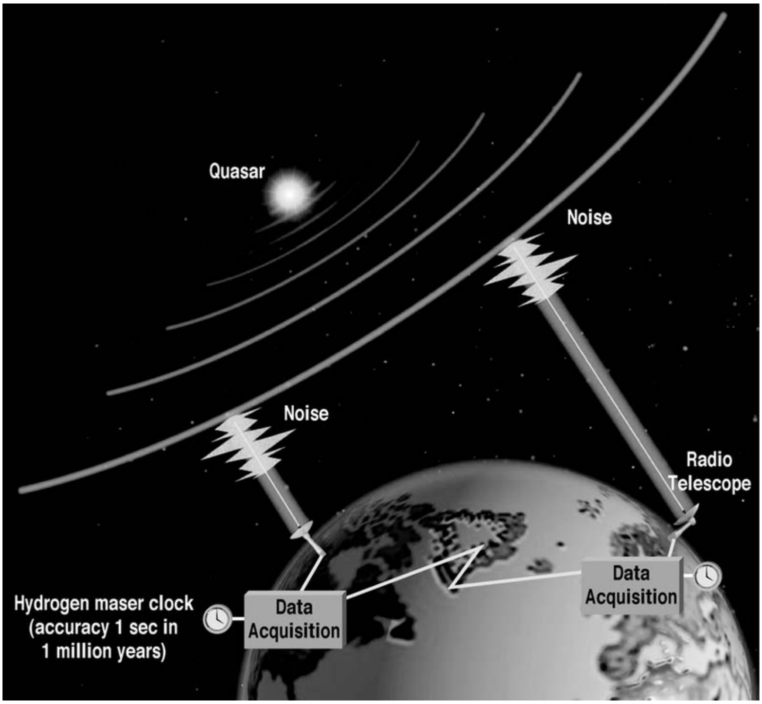


Fig. 2.5. Principle of very long baseline interferometry.

of the ITRF (together with SLR). VLBI also contributes with station positions and velocities to the establishment of the ITRF and is able to provide several further geodynamical, astronomical, or meteorological parameters.

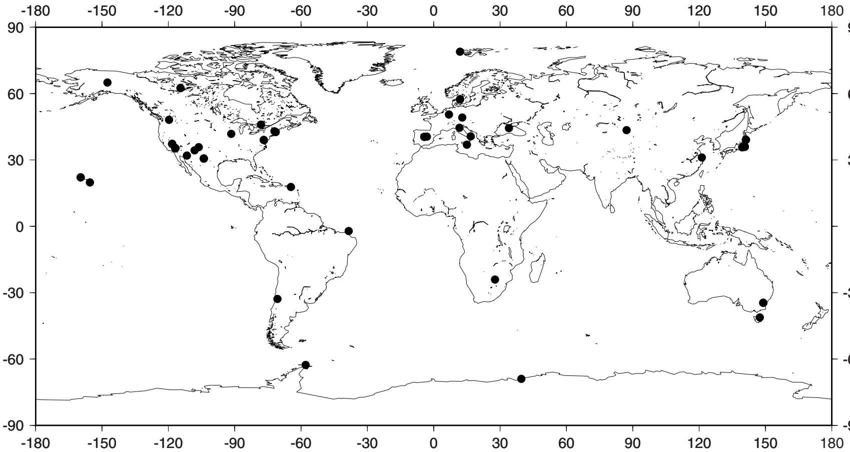


Fig. 2.6. Locations of the 40 VLBI stations in the global network of the IVS.

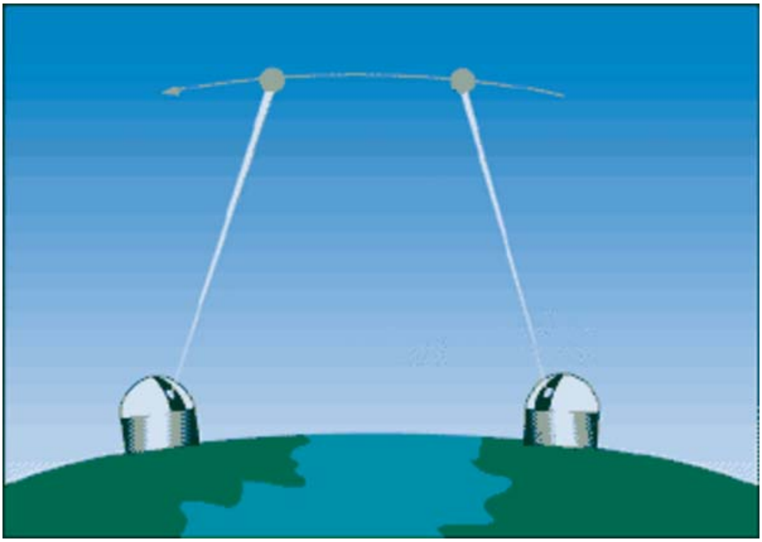


Fig. 2.7. Principle of satellite laser ranging.

SLR and LLR: SLR and LLR use very short laser pulses and fast electronics to measure the instantaneous round trip time of flight of the pulses to satellites equipped with special retroreflectors (Figure 2.7) and to retroreflectors on the Moon (Figure 2.9), respectively. This provides range measurements of a few millimeter precision which are accumulated to help define the terrestrial reference frame and to support Precision Orbit Determination (POD) for active spaceborne Earth sensing missions and studies of lunar science and fundamental physics. The fundamental targets for the reference frame are the LAser GEOdynamics Satellite (LAGEOS)-1 and -2 (Figure 2.8), whose spherical shape and high mass-to-area ratios provide long-term orbital stability for measuring the dynamics of the Earth.

The basic range measurement is sensitive to any geophysical process that changes the distance between the satellite and the observing station, such as displacements of the satellite due to perturbations of the Earth's gravitational field, motions of the observing station due to tidal displacements or plate tectonics, or a change in the orientation of the Earth (which changes the location of the observing station with respect to the satellite). These and other geophysical processes must be modeled when fitting the satellite's orbit to the range measurements as obtained at a number of globally distributed tracking stations. Adjustments to the *a priori* models used for these effects can then be obtained during the orbit determination procedure, thereby enabling, for example, the determination of station positions and Earth orientation parameters (Smith et al., 1985, 1990, 1994; Tapley et al., 1985, 1993).

The technique of LLR is similar to that of SLR except that the laser retro-reflector is located on the Moon instead of on an artificial satellite (Mulholland, 1980; Lambeck, 1988; Williams et al., 1993; Dickey et al., 1994; Shelus, 2001). LLR is technically more challenging than SLR because of the need to detect the much weaker signal that is returned from the Moon. Larger, more powerful laser systems with more sophisticated signal detection systems need to be employed in LLR; consequently, there are far fewer stations that range to the Moon than range to artificial satellites (see Figure 2.10).

The international network of about 40 SLR and two LLR stations (Figure 2.10) currently tracks on a daily basis about 30 satellites ranging in altitude from 400 km to 22,000 km and four retroreflectors on the Moon. As a Service of the IAG and a component of GGOS, laser ranging activities are coordinated by the International Laser Ranging Service (ILRS), which develops standards and specifications necessary for product consistency, sets priorities and tracking strategies, oversees data operations, and provides quality control and a user interface.

These laser ranging activities support programs primarily in geodetic, geophysical, and lunar research activities. The ILRS currently provides the IERS with weekly solutions for station coordinates and EOPs for the monitoring of the ITRF, contributing exclusively the definition and time-varying motion of its origin (with respect to the CM), and in combination with VLBI, its scale. Other contributions include the estimation of static and time-varying components (harmonic coefficients) of Earth's gravity field; accurate satellite ephemerides for POD and validation of altimetry (for satellites such as ICESat, shown in Figure 2.11), relativistic and satellite dynamics tests; and Lunar ephemeris for relativity studies and lunar libration for lunar interior studies. SLR, as a backup system, has also provided POD for missions whose primary tracking systems failed (e.g., GFO-1, ERS-1, Meteor-3M, etc.). Prior to the launch of CHAMP in the 2000, knowledge of the Earth's gravity field was almost uniquely based on SLR and terrestrial gravity measurements. SLR is an essential calibration technique for the GNSS technique and for the new space missions

Fig. 2.8. The LAGEOS-1 satellite (identical to LAGEOS-2). Dedicated laser ranging satellites have a long-term orbital stability because of their spherical shape and high mass-to-area ratio.

Fig. 2.9. Laser reflector on the Moon (image courtesy of NASA).

CHAMP, GRACE, and GOCE. The ILRS is now preparing to support space missions to the planetary system with optical transponders.

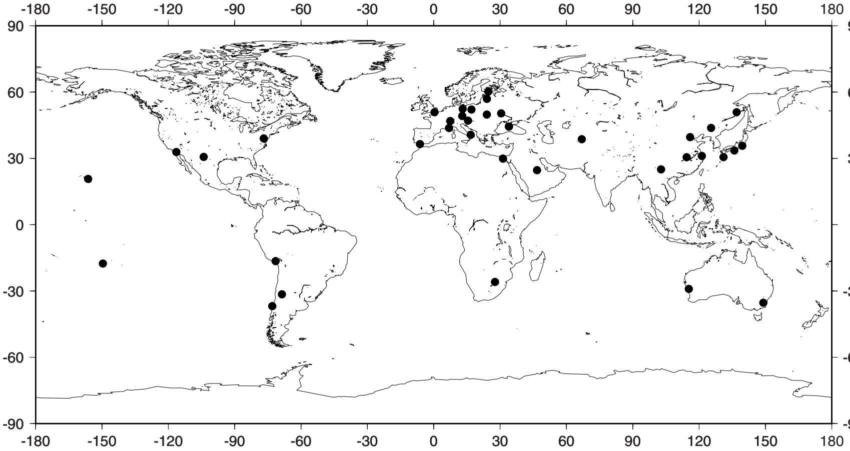


Fig. 2.10. Locations of 38 SLR stations in the tracking network of the ILRS.

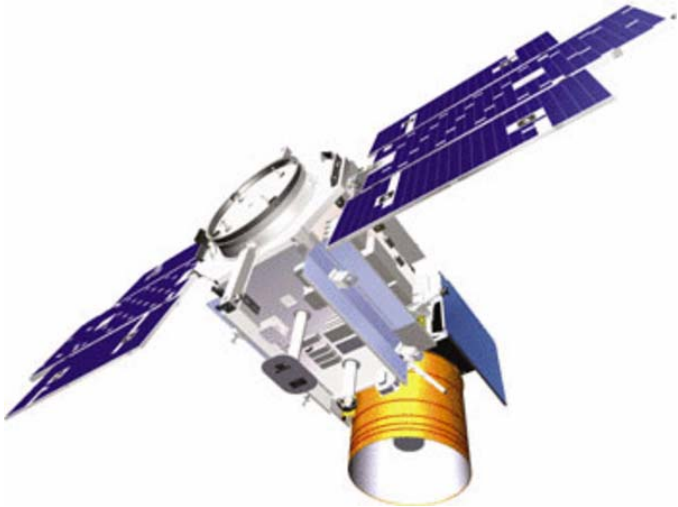


Fig. 2.11. ICESat Satellite (image courtesy of ICESat Science Team).

GNSS: Today's GNSS are the successors of the so-called Doppler systems. They are based (1) on about 30 to 45 satellites emitting microwave signals on at least two carriers, and (2) an unlimited number of receivers capable of tracking the signals of all satellites simultaneously in view (usually between 4 and 12). Today's GNSSs occupy the so-called Medium Earth Orbit (MEO)-belt. The satellites orbit the Earth in heights around 20000 km and complete one revolution within approximately half a day. The U.S. GPS with nominally 24 satellites (see Figure 2.12), uniformly distributed in six orbital planes, which are in turn inclined by 55° with respect to and separated by 60° in the equator, is the best known and most widely used GNSS. The Russian Global Navigation Satellite System (GLONASS) with nominally 24 satel-

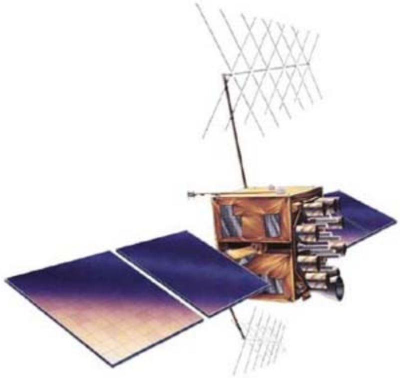


Fig. 2.12. GPS satellite. From http://www.af.mil/shared/media/factsheet/gps.jpg.

lites (Figure 2.13) in three orbital planes inclined by 63 degrees with respect to the equator and separated by 120 degrees in the equator, is currently not fully available (in January 2007 only nine satellites were fully operational). The plan is to achieve Full Operational Capability (FOC) by 2010. The first experimental satellite of the European GALILEO system (GIOVE-A, Figure 2.15) was launched on December 28, 2005 and early in May 2007, this satellite successfully transmitted its first navigation message, containing the information needed by user receivers to calculate their position. GALILEO is planned to reach FOC in 2012. By then, this GNSS is projected to have 30 satellites positioned in three circular MEO planes (Figure 2.15).

Fig. 2.13. Illustration of GLONASS satellite.

The microwave band (the L-band) of the electromagnetic spectrum allows for the weather-independent use of the systems, the two carriers for the elimination of

Fig. 2.14. Artist's impression of the first experimental GALILEO satellite GIOVE-A. From http://esamultimedia.esa.int/images/galileo/GSTB_satellite/.

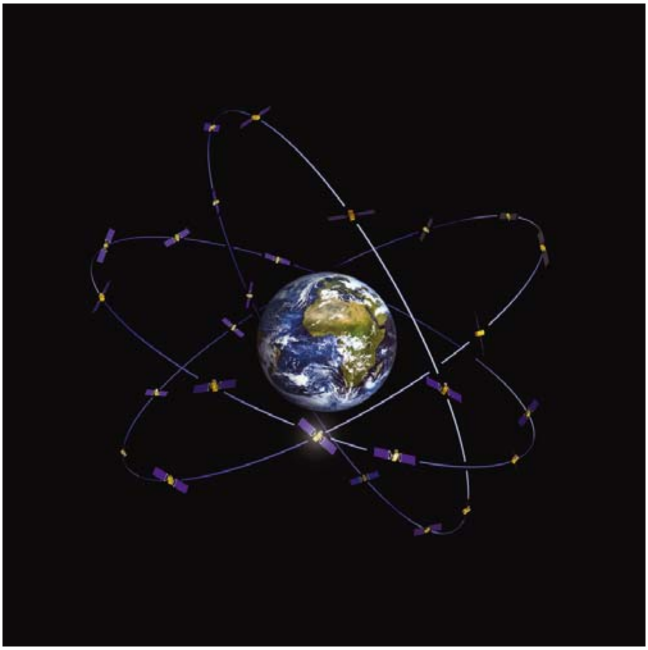


Fig. 2.15. Artist's impression of the complete GALILEO constellation of thirty satellites orbiting in three planes. The three MEO planes are at an inclination of 56° with respect to the equatorial planes, resulting in a good coverage up to a latitude of 75°. From http://esamultimedia.esa.int/images/navigation/.

the ionospheric refraction. The quasi-simultaneity of the observations of different GNSS satellites allows for the elimination (or significant mitigation) of the synchronization errors of the receiver clock with respect to GPS system time (Beutler et al., 2004).

The GNSS were/are deployed primarily for navigation — which is by definition a real time task. They may, however, also be used for science and other positioning applications requiring high accuracy. In this case the observable of choice are not the signals (also called code) modulated on the carrier waves, but the reconstructed carrier itself. The analysis is usually done in the post-processing (but also increasingly in the real-time) mode. This carrier phase observable may be reconstructed with mm-accuracy, which in turns allows for mm-accurate relative positioning, provided not only the receiver clock corrections are estimated from the observations, but the satellite clock corrections, as well. Alternatively to the estimation of the clock errors one may also form the so-called double difference observation (the between-satellite-difference of two between-receiver-difference observations, all observations assumed to be simultaneous).

For science, the following quantities may be determined on a daily basis from a global network of well monumented, permanently operating tracking receivers (the ground tracking network):

- GNSS geocentric satellite positions for the entire day (accurate to few cm)
- GNSS satellite clock corrections (accurate to a few ten picoseconds)
- Mean receiver coordinates per day (accurate to a few mm)
- Position of the Earth's rotation axis on the Earth's surface (polar wobble) (daily estimates, accurate to few mm)
- Length of day (daily estimates, accurate to a few microseconds)
- Tropospheric zenith delays for all stations (which in turn allow it to estimate the total water vapor content over the station - provided station pressure and temperature are recorded as well) with high time resolution.
- Global models/maps of mean electron content (two hours time resolution)
- time and (in particular) frequency transfer between time laboratories (sub-nanosecond accuracy)

It is in essence this catalog of quantities, which is determined every day by the IGS since January 1, 1994 (see `http://igscb.jpl.nasa.gov/`). Since 2003 not only the GPS, but also GLONASS observations are used routinely to derive the official IGS products. The IGS products are based on a weighted combination of the IGS Analysis Centers, generated by the IGS Analysis Coordinator (at least) on a daily basis.

The series of IGS station coordinates is in turn used by the IERS to realize the ITRF together with the corresponding results of the other space-geodetic techniques VLBI, SLR/LLR, and DORIS. The large number of IGS sites (currently more than 400, see Figure 2.16) provides easy access to the ITRF for the user community - going far beyond science.

The IGS series of Earth rotation parameters (see Section 2.5) are also used by the IERS to issue the official transformation parameters between the ICRF and the ITRF. The full set of transformation parameters contains in addition to the above

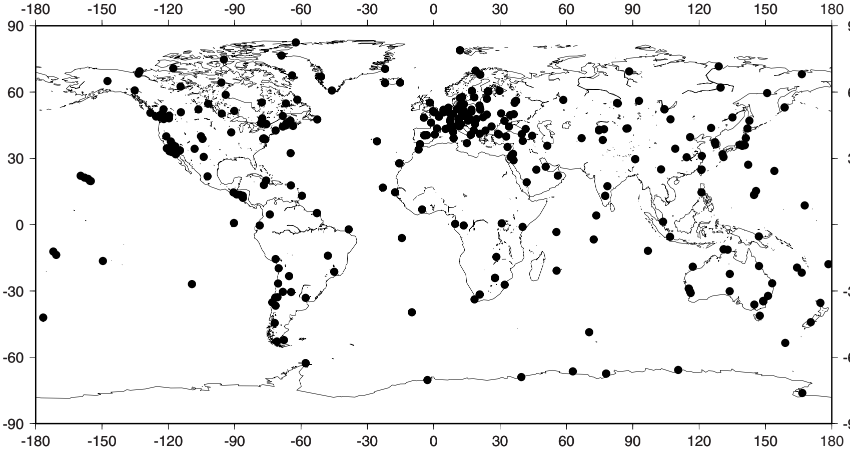


Fig. 2.16. Locations of the more than 400 GNSS stations of the global tracking network of the IGS as of December 2006.

mentioned items UT1-UTC and the nutation angles. These latter quantities can only be provided accurately by VLBI.

In summary one may state that the GNSSs are the workhorses of space geodesy. They provide the basis for numerous applications in geodesy and surveying (virtually all national first order networks refer to the ITRF and are realized using the IGS products) and in the wider area of Earth sciences (in particular atmosphere and ocean sciences, meteorology, and climatology).

DORIS: The DORIS system was designed and developed by the Centre National d'Etudes Spatiales (CNES), in partnership with the Groupe de Recherche de Géodésie Spatiale (GRGS) and the Institut Géographique Nationale (IGN), for precise orbit determination of altimeter missions, and consequently also for geodetic ground-station positioning (Crétaux et al., 1998; Soudarin & Crétaux, 2006). Like GNSS, DORIS is a satellite geodetic technique based on microwave signals, however DORIS is an uplink system from ground stations to spacecraft (Jayles et al., 2006). DORIS beacons transmit on two frequencies, namely 2036.25 Mhz, and 401.25 Mhz. The DORIS system consists of a ground segment, the network of beacons, as well as a space segment, the user satellites, a subset of which actually contribute to the determination of IERS products such as station positioning, and Earth orientation. One characteristic of the DORIS system that is unique with respect to the other space geodetic techniques is the much more homogeneous station distribution. It is the only space geodetic technique with a balanced station distribution in both the Northern and Southern Hemispheres. In addition, another important characteristic is the relative stability of the sites and their longevity with relatively few antenna changes over time (Jayles et al., 2006; Fagard, 2006).

The DORIS network (see Figure 2.17) consists of 50 to 60 stations around the world. The beacons assure an 80% coverage of user satellite orbits near 800 km al-

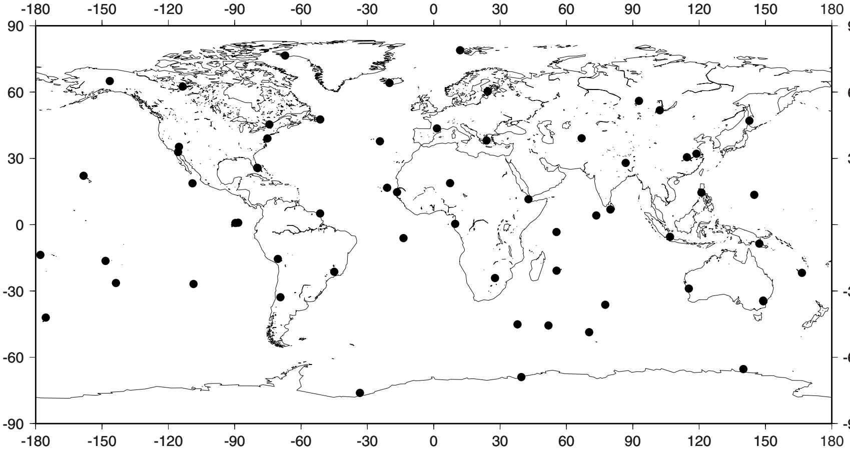


Fig. 2.17. Locations of the 56 DORIS stations of the tracking network of the IDS.

titude, and a 95% coverage of user satellite orbits at 1335 km altitude. Each ground beacon is equipped with a dual frequency transmitter, an Ultra-Stable Oscillator (USO) delivering the reference frequency with a stability of $5.0 \cdot 10^{-13}$ over 10 to 100 seconds, an omni-directional dual-frequency antenna, a a battery pack providing backup power to the beacon during electricity outages, and a meteorological package providing in situ measurements used for the tropospheric correction. Functionally, each beacon may play one of several roles: (1) broadcast upload transmission, (2) time and frequency reference station, (3) time correction beacon, and (4) positioning station. Late in 2005, three stations played the role of master beacons, whose clocks are tied to atomic clocks, and whose delays are estimated with respect to TAI atomic time by time/frequency experts (Jayles et al., 2006). The master beacons serve as time and frequency references for the DORIS system, and handle uploading of data and commands needed by the DORIS spacecraft receivers.

Ground station requirements include the following: (1) The transmitting beacon and its backup power supply must be in a room with moderate temperature with continuous power available; (2) The antenna must be installed outside with a clear sky view above 10° elevation; (3) The local host agency must be willing to carry out minor verifications and adjustments; (4) The frequencies transmitted by DORIS should not interfere with existing receivers in the same area (Fagard, 2006).

An important activity was initiated in 1999 to improve the DORIS system through improvements of the monumentation, installation of new antennae and support structures, and other measures to ensure the stability of the DORIS antenna reference point to within 1 cm over ten years (Fagard, 2006). For example, one goal is that in so far as is possible, ground antennae are now mounted on a concrete pillar deeply anchored into the ground, or on a rigid tower on a deep concrete foundation (see Figure 2.18). As of 2006, 35 of 56 stations are now considered 'excellent' compared to only 10% in 2000 (Tavernier & et al., 2006). The improvements in the network quality are dramatically visible in the residuals (RMS of fit) of DORIS data for the SPOT-2 and TOPEX/Poseidon satellites with the RMS declining from 0.55 mm/s in 1993 to 0.45 mm/s in 2005.

Fig. 2.18. Illustration of two DORIS stations. The stations are Rothera, Antarctica (top), and Thule, Greenland (bottom).

As of 2006, there were co-locations between DORIS antennae and other active IERS techniques at 38 of the 56 permanent DORIS stations. These co-locations are distributed as follows: with GPS at 37 sites, with SLR at 9 sites, and with VLBI at 7 sites. Among these stations, fifteen sites have three co-locations (8 for GPS+SLR+DORIS, and 7 for GPS+VLBI+DORIS). Only two sites worldwide have co-locations with four techniques (GPS+VLBI+SLR+DORIS): Hartebeesthoek and Greenbelt. During the effort of network renovation, some stations were specifically displaced to satisfy both operational constraints and to increase the number of co-locations between DORIS and other geodetic techniques. These include Jiufeng (replacing Purple Mountain), Male (replacing Colombo), Miami (replacing Richmond), Santa Cruz (replacing Galapagos), and Monument Peak (replacing Goldstone) (Fagard, 2006). Since the 1990's, with the growing interest in monitoring changes in global mean sea level, DORIS stations have been increasingly sited near tide gauges. As of 2006, 21 DORIS tide-gauge co-locations were available (Fagard, 2006).

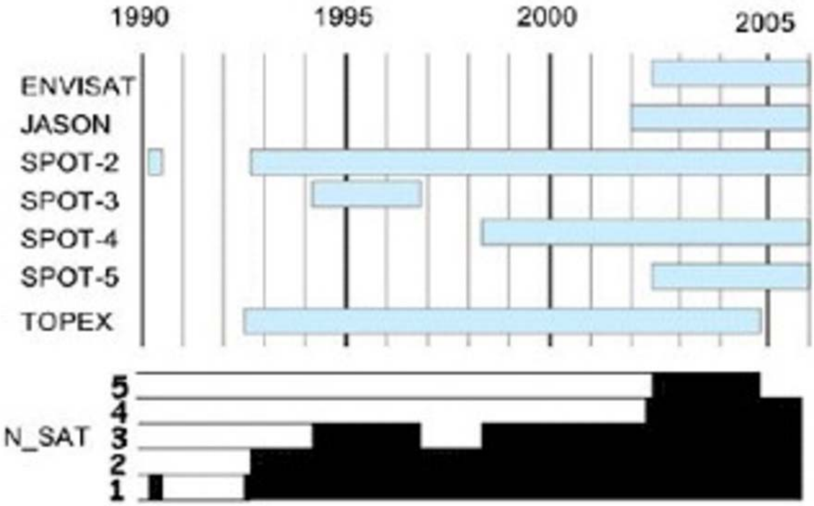


Fig. 2.19. DORIS data available at the IDS Data Centers as of January 2006. With kind permission from Springer Science + Business Media: Tavernier et al. (2006).

The space segment of the DORIS system consists of receivers on user satellites in low Earth orbit. Four satellites have carried first-generation DORIS receivers: TOPEX/Poseidon, SPOT-2, SPOT-3, and SPOT-4. A new second-generation dual channel DORIS receiver was developed in the 1990's. This receiver has been carried on ENVISAT, and a miniaturized version on Jason-1 and SPOT-5 (Tavernier & et al., 2006). Figure 2.19 summarizes the availability of the DORIS data at the data centers of the International DORIS Service (IDS). A DORIS receiver (together with a GPS receiver and a laser retroflector array) is also included on Jason-2 (launched in 2008). Future plans include DORIS receivers on Cryosat-2 (launch in 2009), SARAL/Altika (joint with CNES and the Indian Space Research Organization, launch in 2009-2010). Other possible future DORIS user satellites include Jason-3, HY-2A (a proposed altimeter mission with CNES and the Chinese National Space Agency), and SENTINEL (European Space Agency satellite(s) dedicated to Earth remote sensing).

A major product of the DORIS system are the precise orbits for the user satellites. For satellite altimeter missions such as TOPEX/Poseidon, Jason-1 and ENVISAT, the precise orbits are the key to satisfying the mission objectives of accurately mapping the ocean topography on a routine basis, and determining variations in global mean sea level. The precise orbits have an accuracy of 1-3 cm in the radial direction. DORIS also enables the delivery of routine altimetric science products with latencies of several days. For Jason-1, these rapid delivery orbit products (for use on the IGDR or Interim Geophysical Data Record) have an accuracy of a few cm in the radial component. DORIS near-real-time products will also be available within a few hours on Jason-2. These orbits are expected to have a 10 cm accuracy in the radial component (Jayles et al., 2006). For missions such as Jason-2 and Cryosat-2, a new geodetic bulletin will be available on-board, providing latitude and longitude of the sub-satellite point, and altitude of the satellite over the geoid. The altimeter will use this information in its tracking loops.

The IDS offers routine delivery of ground station positions and Earth orientation based on analysis of the DORIS data in the form of weekly SINEX files. Three analysis centers contributed these SINEX time series to the ITRF2005 solution (Altamimi et al., 2006). The quality of the positioning was evaluated in the construction of the ITRF2005 solution (Altamini et al., 2006). The weighted RMS of the individual weekly time-series combinations can be used as an indication of the positioning quality. The effect of the addition of the large number of satellites in 2002, and the effect of the network improvement project starting in 2000 are clearly visible (see Figure 2.20). Positioning quality with four satellites (post-2002) is 1 to 1.5 cm WRMS. We note that the ITRF2005 DORIS contribution did not include the contribution of Jason, as the USO on the spacecraft experiences a disruption due to periodic passage through the South Atlantic Anomaly (Willis et al., 2004). A correction model has been developed which can partially mitigate the effect (Lemoine & Capdeville, 2006) in the DORIS data. Future DORIS spacecraft USO's will be annealed to prevent this radiation-induced perturbation and resultant data degradation.

Since DORIS is a dual-frequency system, it also measures the ionosphere content along the slant range from the DORIS satellite (800 or 1335 km altitude) to each DORIS ground station. The sampling path is quite different from GPS, whose path from ground station to receiver stretches 20,000 km from Earth. No routine DORIS ionosphere product is delivered as of 2006, however DORIS data were used to validate the ionosphere correction on TOPEX and compute corrections for the Poseidon altimeter (Jayles et al., 2006).

2.4.3 Altimetry

Satellite radar altimetry provides height measurements of the instantaneous surface (sea, ice, or open water on land) with respect to a fixed reference (typically a conventional reference ellipsoid embedded in a global reference frame): the onboard radar altimeter transmits a short pulse of microwave radiation with known power towards the nadir. Part of the incident radiation reflects back to the altimeter. Measurement of the round-trip radar signal travel time provides the height of the satellite (alti-

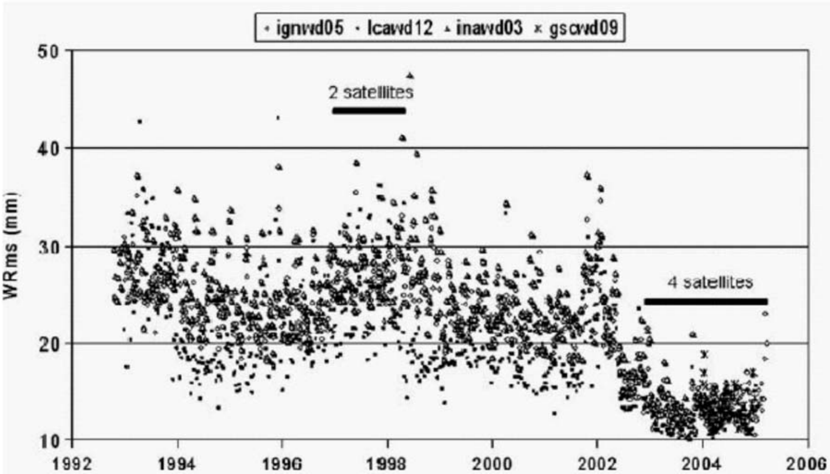


Fig. 2.20. Weighted RMS of the individual weekly time-series combinations from Tavernier & et al. (2006). The results are depicted for four DORIS analysis centers. Note the sensitivity to the number of available satellites, and the effect of the rejuvenation of the network (2000-2005).

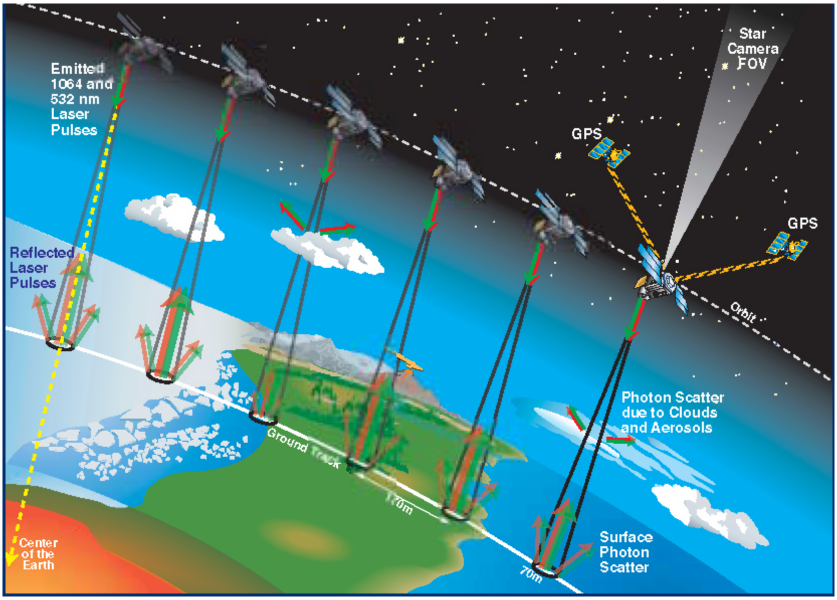


Fig. 2.21. Principle of satellite altimetry. From http://icesat.gsfc.nasa.gov.

metric range) above the instantaneous sea/land water/ice surface. Its difference with the satellite altitude above the reference ellipsoid (computed through precise orbit determination, a long-tested approach in space geodesy) gives sea/land water/ice surface height measurements with respect to the reference (see Figure 2.21).

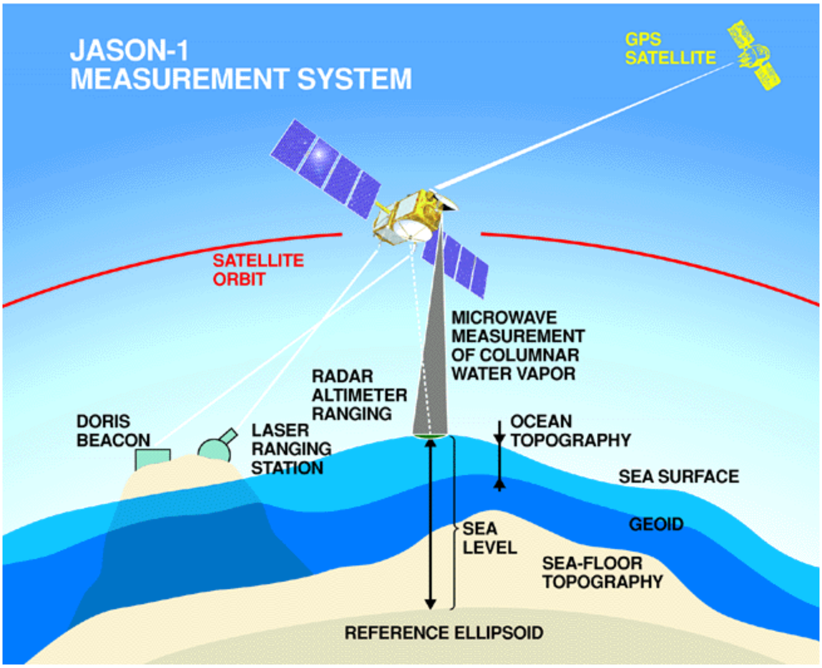


Fig. 2.22. The Jason-1 satellite altimetry mission. Courtesy NASA/JPL.

The range from the satellite to mean sea level must be corrected for various components of the atmospheric refraction and biases between the mean electromagnetic scattering surface and mean sea level at the air-sea interface. A number of corrections due to a number of geophysical effects must also be taken into account.

Table 2.2. Satellite gravity and altimeter mission products to determine mass transport and mass distribution in a multi-disciplinary environment.

Mission	Type	Mission Duration
CHAMP	Gravity, magnetic field, atmosphere	2000–2008
GRACE	Gravity (static and temporal), atmosphere	2002–2010
GOCE	Gravity (stationary, high-resolution)	2009–2011
TOPEX/Poseidon	Ocean altimetry	1992–2005
Jason-1	Ocean altimetry	2001–2008
Jason-2	Ocean altimetry	2008–2015
ICESat	Ice altimetry	2003–2008
CryoSat-2	Ice altimetry	2009–2013
ERS-2	Altimetry, SAR/InSAR, climate, environment	1995–2007
ENVISAT	Altimetry, SAR/InSAR, climate, environment	2002-2008
TerraSAR-X	SAR, InSAR, atmosphere	2006–2011
SWARM	Magentic field	2009–2014

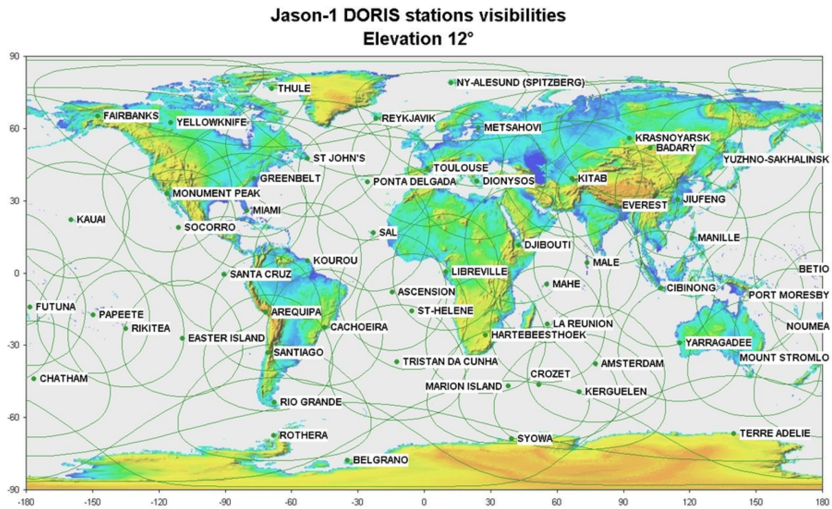


Fig. 2.23. Jason-1 and DORIS. The map shows the visibility of the JASON satellite to each DORIS ground station.

State of the art satellite radar altimetry has more than 2 decades of heritage: GEOS-3 (1975), SEASAT (1978), Geosat (1985- 1989), ERS-1 (1991-1996), TOPEX-/Poseidon (1992-2006), ERS-2 (since 1995), GFO (since 2000), ENVISAT (since 2002) and Jason-1 (since 2001, see Figure 2.22). Over the years, technological improvements (especially for TOPEX/Poseidon, ENVISAT and Jason-1) have decreased considerably the instrumental noise for a point-to-point measurement. Moreover, thanks to a concerted effort in precise modeling of the geophysical and environmental corrections as well as in precise orbit computation, the total rms measurement accuracy of altimetry-based sea surface height is currently about 1-2 cm for a single measurement (e.g., for Jason-1).

Although developed for oceanographic purposes, early altimetry missions have mainly served to map the marine geoid globally with high precision and resolution, leading to considerable achievements in several areas of marine geophysics (e.g., marine tectonics, mechanical and thermal structure of the oceanic lithosphere, seafloor topography, etc.). With the launch of the TOPEX/Poseidon mission in the early 1990s, the precision of sea surface height measurements improved by a factor 10 or more, allowing for the first time precise determination of the temporal variability of the ocean surface, with numerous applications in oceanography. Major results have been obtained on surface currents and the ocean dynamic topography, ocean seasons, El Nino, ocean heat content, sea level rise, ocean tides, waves, etc. Satellite radar altimetry (together with laser altimetry, e.g., the IceSat mission) have also proved very useful for measure the change in elevation of the ice sheets (hence their mass balance in response to global warming) and more recently the water level of lakes, rivers and floodplains on land.

Sea level measured relative to the geoid (the fundamental level surface which will be determined to good accuracy by space geodetic missions such as GOCE in the next few years, see Section 2.6.5), provides the "sea surface topography" which allows estimation of ocean transports, and contributes ultimately to an understanding of climate change (Johannessen et al., 2003).

2.4.4 GNSS scatterometry and reflectometry

In the past few years the potential of GNSS signal reflections for ocean altimetry and remote sensing of sea surface roughness has generated considerable interest. The Passive Reflectometry and Interferometry System (PARIS) was the first concept proposed for ocean altimetry using GNSS L-band signals (Martin-Neira, 1993). Within the PARIS scheme direct and ocean-reflected signals are detected by spaceborne receivers and altimetric height information is extracted from the delay in arrival times of the reflected in relation to the direct signals (Figure 2.24). In the following years altimetric heights with accuracies below 5 cm were determined in a number of airborne and ground-based experiments using special purpose GNSS receiver instrumentation (GNSS reflectometry, e.g., Garrison & Katzberg, 2000; Treuhaft et al., 2001).

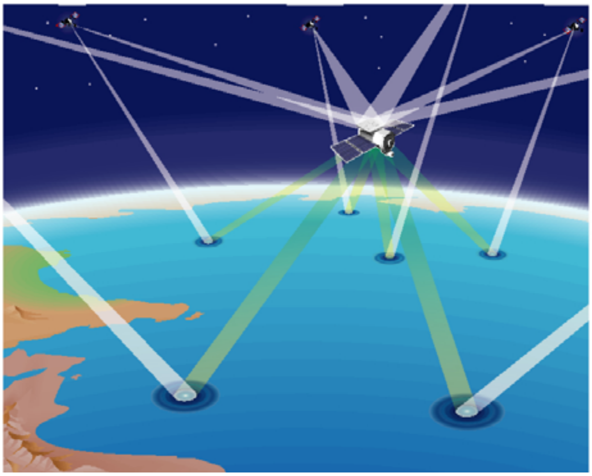


Fig. 2.24. Use of reflected GNSS signals for altimetric measurements. An Earth-orbiting instrument uses direct GNSS signals for precise positioning, but also receives reflected signals to make several simultaneous bistatic altimetric measurements.

In addition, the shape of the code correlation as a function of time delay and Doppler frequency and its dependency on the reflecting surface's slope characteristics can be used to infer the sea surface roughness (GNSS scatterometry, Garrison et al., 1998). Using parameterizations relating the observed roughness to the surface wind vector GNSS scatterometry allows for the remote detection of wind speed and wind direction as well (e.g., Katzberg et al., 2001; Germain et al., 2004).

First spaceborne observations of GNSS signal reflections are reported by Pavelyev et al. (1996) and Lowe et al. (2002). Later, signatures of coherent GPS reflections at grazing incidence angles were found in radio occultation data observed by the GPS/MET, CHAMP and SAC-C satellites (Beyerle & Hocke, 2001; Hajj et al., 2004). More recently, the GNSS scatterometry experiment aboard the United Kindom's Desaster Monitoring Constellation (UK-DMC) satellite successfully demonstrated the feasibility of sea surface state remote sensing from low Earth orbit (Gleason et al., 2005). In the future, satellite constellations furnished with GNSS scatterometry and reflectometry instruments could contribute to the long-term observations of ocean topography as well as constitute essential elements of early warning systems for catastrophic tsunami events.

Science with GPS reflected and scattered signals: This section discusses an emerging technique for Earth remote sensing based on detecting a GNSS signal after it is reflected off the Earth surface, to measure surface topography and roughness at high spatial resolution and rapid temporal coverage. The weak reflected signals require a high-gain multi-beam steerable antenna. Because this technique is promising in terms of spatial and temporal resolution, we devote here some space to the discussion of its potential in a few major areas.

Global Ocean Altimetry: The Oceans, and their interactions with the atmosphere and the lithosphere, play a significant role in Earth's climate. Understanding climate variability implies quantifying all the significant processes that contribute to climate and its changes. One such process, mesoscale ocean eddies, analogous to atmospheric storms, represents one of the dominant global climate errors (see HOT_SWG 2001 for a review); they are essential to understanding ocean circulation on all scales and are an important contribution to the carbon cycle.

On the regional scale, eddies can induce local upwelling and enhance biological production. In the equatorial Pacific, eddies associated with the tropical instability waves can increase the supply of iron and silicate to the euphotic zone resulting in enhancement of the biological productivity (Barber et al., 1996). On the global scale, mesoscale eddies play an important role in the overall transport of heat and momentum. Numerical model simulations with and without the inclusion of mesoscale eddies show a 30% difference in the equator-to-pole heat transport over the Atlantic Ocean (Smith et al., 2000). Ocean eddies have a typical spatial scale on the order of 10 to 100 km and a temporal scale from days to weeks. The sea level signal associated with mesoscale eddies is usually 10 cm or more.

At present, quantifying the role of mesoscale eddies in the ocean circulation and therefore climate variability is limited because their spatio-temporal structures are not resolved by the conventional remote-sensing techniques. Observations of sea surface temperature (e.g., those from Advanced Very High Resolution Radiometers) are frequently contaminated by clouds in the atmosphere. The conventional satellite radar altimeter measures the sea surface height at high spatial resolutions along its ground track (e.g., 7-km for TOPEX/Jason). However, the cross-track distance is usually quite large. For a 10-day repeat orbit with TOPEX/Jason, the cross-track distance is more than 300-km at the equator. Another limiting factor is the long repeat cycle of a given satellite, e.g., 10 days for TOPEX/Jason, 17 days for the Geosat-Follow-On (GFO), and 35 days for Earth Remote Sensings (ERSs). Additionally, some barotropic (i.e., vertically uniform) waves with a periodicity of 20 days or less can be aliased into the 10-day sea level map produced by the TOPEX/Jason data. Hence, there is a need for high spatial and temporal resolution altimetry.

High-resolution ocean altimetric measurements will allow oceanographers to compute high-order quantities like vorticity and eddy fluxes, which will be used to study the interactions between the eddy fields and the time-mean flow. Several important science questions can be addressed by such a high-resolution data. For example, what is the role of mesoscale (ocean) eddies in the large-scale ocean circulation and climate variability? What is the impact of mesoscale eddies on the biological production and therefore the global carbon cycle? If mesoscale eddies are important in modulating the large-scale ocean circulation and climate, there is a need to resolve (or parameterize) ocean eddies in the Earth System Model (coupled atmosphere-ocean-land) for climate prediction purposes.

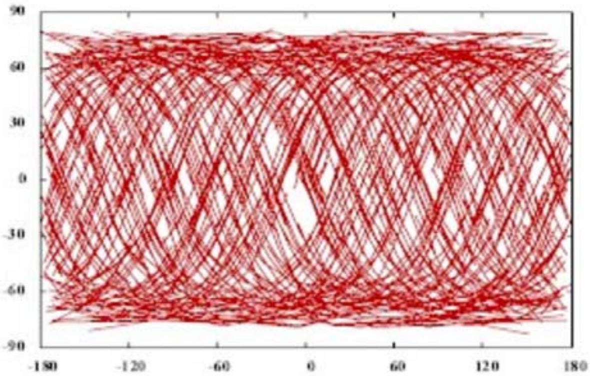


Fig. 2.25. Reflection point loci for one receiver at 400 km, assuming its antenna beam can capture all available reflections, per day. Horizontal axis is longitude, vertical axis is latitude.

Traditional altimetry is limited to looking in the (nominal) nadir direction and obtaining one height observation at a time below the altimeter, following very nearly repeatable tracks passing over the same point every ten days. The concept of wide-swath ocean altimetry improves the coverage and spatial resolution of traditional altimetry by filling the gaps between satellite tracks. However, the wide-swath ocean altimetry uses the same ground tracks of TOPEX/Jason repeating every 10 days. By contrast, a GPS receiver in low-Earth orbit (LEO) with an antenna pointed toward the Earth's surface can, in principle, track about 10 GPS reflections simultaneously, therefore providing a coverage that is an order of magnitude denser than nadir-viewing altimeters. For example, the reflection ground tracks of one single satellite at the altitude of 400 km would cover the Earth nearly uniformly in just 1 day, with at most about 75 km across-track separation, as shown in Figure 2.25. Such dense coverage can be translated into a higher temporal and spatial resolution than that of TOPEX/Jason or the proposed wide swath coverage, thereby providing the ability to recover certain ocean topography features or processes that are precluded with traditional altimeters.

Ocean Surface Statistics and Wind Retrieval: GNSS reflections from the ocean can be used to infer statistical properties of the surface, namely the slope distribution of sea-surface gravity waves, with high spatial and temporal resolution. Such measurements would likely be made concurrent with altimetric measurements (see Ocean Altimetry section above) because the measurement techniques are quite similar. The primary observable is the Mean-Squared Slope (MSS), and recent studies (Germain et al., 2004) have shown a 2D directional-MSS can be obtained. The MSS field provides useful input to ocean-atmosphere coupling phenomena such as surface breaking waves and gas exchange. For example, CO_2 flux measurements may be derived from MSS. With additional assumptions, wind speed or wind vector retrievals can also be obtained from MSS measurements (Garrison et al., 1998; Komjathy et al., 2000; Cardellach et al., 2003; Zuffada et al., 2003). Finally, MSS measurements may clarify the relationship between surface-height dynamics and wind-driven surface velocities (Chelton et al., 2004).

Analysis of the GPS reflection waveform also provides an estimate of the wind speed and direction. While scatterometers such as QuikScat or SeaWinds provide near global coverage in one day, the observations are not necessarily co-located in time and space with the GPS altimetry observations. Instead, GPS reflections provide a unique set of co-located sea surface height and wind observations with near-global daily coverage and with resolution suitable for studying mesoscale features. Accurate sea surface height retrieval requires simultaneous measurements of ocean vector winds. The accuracy of GPS wind measurements is about 2 m/sec for wind speeds ranging from 3 to 15 m/sec, comparable to the traditional radar scatterometer. Thus, the GPS-measured ocean winds will complement the existing radar scatterometer wind observations and, in the context of sea surface height measurement, will provide the needed data set to retrieve the sea surface height with high accuracy. It is anticipated that the GPS altimetry will improve our current capability in two important ways: 1) High-spatial-resolution ocean topography and 2) Improved temporal resolution through rapid coverage. Another possible application of very rapid coverage of the ocean is the monitoring of fast moving barotropic waves that propagate across ocean basins too quickly to be seen by the Jason 10-day repeat cycle.

Ice Science: Detection of GPS reflections at low or grazing angles has the advantage of being coherent and, when combined with the direct signal, provides interferometric fringes from which a very precise estimation of bi-static path delay (down to sub-centimeter) can be detected. In the presence of strong L1 and L2 signals to calibrate the ionosphere, this can be translated into accurate height surface measurements at the specular reflection point.

Recent analysis (Cardellach et al., 2004) used this interferometric signal, detected with the CHAMP radio occultation experiment, to demonstrate a surface height precision of 0.7 m after 0.2 s of integration with a reflection angle of $< 1°$ (i.e., $89°$ incident angle). The GRSPI instrument will allow the detection of the coherently reflected signal at a higher elevation angle reducing the error in inferred ice surface height to less than 10 cm.

Global observations of sea ice, ice sheets, ice caps, glaciers and their surrounding seas, are paramount in order to determine their mass balance, contributions to sea level change, global circulation and climate change. In fact, model simulations and recent observations suggest that the ice-covered regions of the Earth are the most sensitive to climate change. In the polar region the combination of atmospheric, cryospheric, and oceanographic processes have a large influence on the global climate. Unfortunately, these climatic processes are poorly understood, principally because of a dearth of observations for diagnosing the processes and validating numerical models.

Changes in ice thickness are an indicator of climate change in the polar region as a result of heat exchanges between ocean and atmosphere, and are themselves a primary driver of climate change through the effect of these heat fluxes on atmospheric circulation patterns and the strong positive planetary albedo feedback provided by changes in sea ice, snow cover and melt water. Given the multi-beam bi-static reflections of GPS, a GPS cryospheric sensing system can provide a substantially denser and more rapid coverage than traditional ice altimetry instruments and allow the determination of seasonal and annual variations in sea-ice and land-ice thickness.

Soil Moisture: Soil moisture is an important part of the land hydrology cycle, where it represents the immediate store of infiltrating rainfall, before it either evapotranspires or contributes to groundwater recharge. When the soil gets too dry, plant transpiration drops because the water is becoming increasingly bound to the soil particles. Conditions where soil is too dry to maintain reliable plant growth is referred to as agricultural drought, and is a particular focus of land management. Soil moisture may be measured in situ with different instruments, such as Time Domain Reflectometry (TDR), neutron probe, capacitance probe, etc. but no global remote sensing measurements are currently available. The potential for measuring soil moisture with GPS has been explored through some ground-based and airborne experiments over smooth terrain, led by the University of Colorado in Boulder and NASA Langley Research Center. Theoretical models show that moist soils generate strong reflective layers at the GPS frequencies, due to high gradients in dielectric constant. It was experimentally observed that variations in the reflected signal are uniquely related to changes in the dielectric permittivity, and therefore, to soil moisture because roughness of the area with low grass remains constant. More work is needed to assess requirements, including antenna gains, for potential GPS-based systems for global soil moisture measurements.

Traceability Matrix for Ocean Observations: The 2007 NRC Decadal Report (National Research Council, 2007) stresses that future directions for Earth science at NASA/NOAA will focus on achievement of a national strategy for the Earth Sciences that balances international economic competitiveness, protection of life and property, and stewardship of the planet for this and future generations. Based on the need for climate measurements identified in the report, JPL promoted a study (Sherwood et al., 2006) to explore the science benefits of maintaining GPS receivers on all satellites in orbit for climate science. This is a particularly timely topic since there are currently ten GPS-science capable satellites (COSMIC 1-6, MetOp1, CHAMP, SAC-C, GRACE).

The study performed a series of simulations to determine the science return that could be achieved with varying sizes of GPS receiver constellations. This study can be used to consider the advantages of including GPS science receivers on future satellites as dedicated constellations or constellations of opportunity. For ocean science, we assumed each satellite would be equipped with a Toga receiver (now in development under NASA's Instrument Incubator Program, see Table 2.3), and a steerable 20-dB gain antenna with field of view capable of intercepting all available reflections.

Table 2.3. Instrument characteristics of TOGA receiver. The parameters are for multilag processing and 20 dB antenna gain.

Integration time	Height prec. (cm)	Footprint (km)
1 sec	Near nadir, 5	Along track, < 10
	Near grazing, 25	Cross track, < 10

To evaluate the needed size of receiver constellations as a function of the ocean science capabilities, simulations were performed using the following assumptions: a) the current GPS constellation as available as transmitters and b) reflection-capable receivers are available on constellations of 6, 18, and 37 LEO satellites, respectively. In the first case only the orbits of the COSMIC constellation were chosen, whereas the third case simulates the situation where all existing NASA satellites (assuming their orbits are representative of future satellites) are equipped with GPS receivers capable of tracking and processing reflections. The intermediate case assumes that an additional set of twelve LEO satellites, chosen randomly among the existing NASA satellites, have been added to the COSMIC set. The characteristics of a single measurement are summarized in Table 2.3.

Table 2.4. GPS ocean reflections science questions.

No.	Science Question
1	Can we measure sea ice surface topography (freeboard), to determine sea ice thickness and mass balance?
2	Can we measure wind for a) improved vertical mixing at the mesoscale; b) monitoring and prediction of severe weather systems; c) high resolution wind forcing and attendant coastal ocean response (e.g., local upwelling)?
3	Can we measure the sea surface topography with sufficient spatial and more importantly temporal resolutions to monitor the evolution of mesoscale ocean eddies and coastal oceans?

The traceability matrix summarizing the flow down from science questions (Table 2.4) to observations' requirements and constellation size is presented in Table 2.5. Two science areas have been addressed: ice-free sea surface topography and sea ice topography and mass. Correspondingly, the observational requirements are mapped into latitudinal bins, cell sizes and revisit times. For each case, the percentage of cells that records at least one (in some cases more) reflection is reported.

Table 2.5. Traceability matrix from science questions to observation requirements for GPS ocean reflections measurements.

Cellsize (km)	Science Question	Latitude Bin	Time Scale	Precision (cm)	Constellation size 6	18	37
2	1	> 60	15 days	$5 \approx 10$	$< 78\%$	$< 90\%$	$< 95\%$
	1		30 days		$< 95\%$	100%	100%
	2	All lats	6 hours	N/A	-	-	-
5	2	All lats	6 hours	N/A	-	$< 20\%$	$< 25\%$
	3		1 day	$2 \approx 10 < 23\%$	$< 52\%$	$< 75\%$	
	3	$-60 < x < 60$	1 day	$2 \approx 10$	$< 52\%$	$< 78\%$	$< 90\%$
10	3	$-60 < x < 60$	1 day	$2 \approx 10$	$< 63\%$	$< 94\%$	100%
	3		5 days		$< 99\%$	100%	100%
25	3	$-60 < x < 60$	1 day	$2 \approx 10$	$< 95\%$	100%	100%
	3		5 days		100%	100%	100%

The table quantifies coverage, and required precision. It is very difficult to establish how the precision requirement is met. In fact, this depends on the reflection angle, as reported in Table 1, for the individual measurement as well as on the number of reflections in a given cell and time. The required precision is met with the highest confidence for the situation of 25 x 25 km cell size, both 1 and 5 days repeat cycles. By contrast, the simulations clearly show inadequate coverage for the situation of 5 x 5 km cell size (and below), 6 hours repeat cycle. It is noted that if the constellation of transmitters increases while the number and orbit of the receivers is held constant, the number of measurements in any given cell increases commensurately, thus improving the precision. The coverage is not expected to improve dramatically, since it is ultimately determined by the number and position of the receivers.

2.4.5 Geodetic imaging techniques

InSAR: The processing of Synthetic Aperture Radar (SAR) images using the InSAR techniques has demonstrated the potential to revolutionize deformation monitoring from spaceborne platforms. As opposed to conventional point-level positioning techniques, InSAR gives deformation information for extended areas (up to a few hundred km across). In this sense InSAR truly is a remote sensing technique. It can provide spatially smooth three-dimensional maps of surface change, including that from earthquakes, volcanoes, ice sheets, glaciers, fluid extraction, and landslides.

InSAR for geodetic applications is a method by which radar signals are radiated from a moving platform and are reflected back to the antenna from the surface of the Earth. The intensity and phase of the reflected signal are measured. In order to measure topography, two antennas separated in space are used to measure phase differences between the two antennas from a radar signal reflected from one point on the Earth's surface (Figure 2.26, top picture). The Shuttle Radar Topography

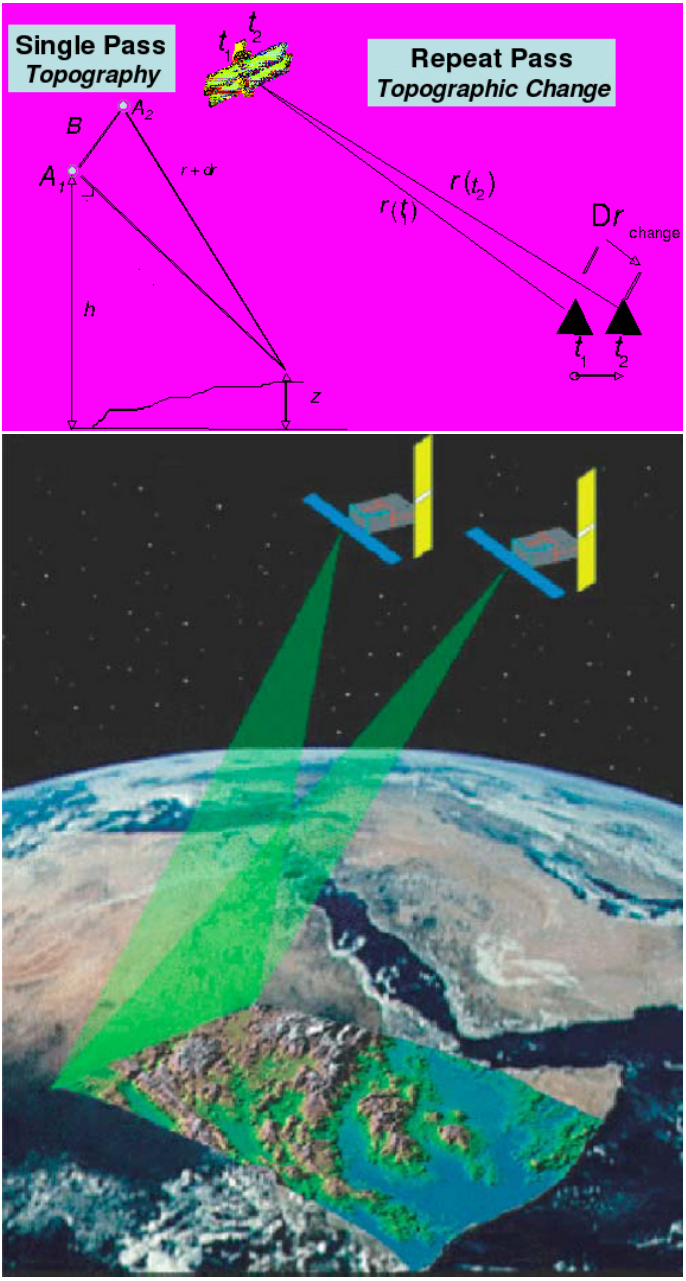


Fig. 2.26. Principle of InSAR. Two antenna separated in space can be used to determine topography (top), while an exact repeat pass of a radar instrument can be used to determine topographic or surface change (bottom).

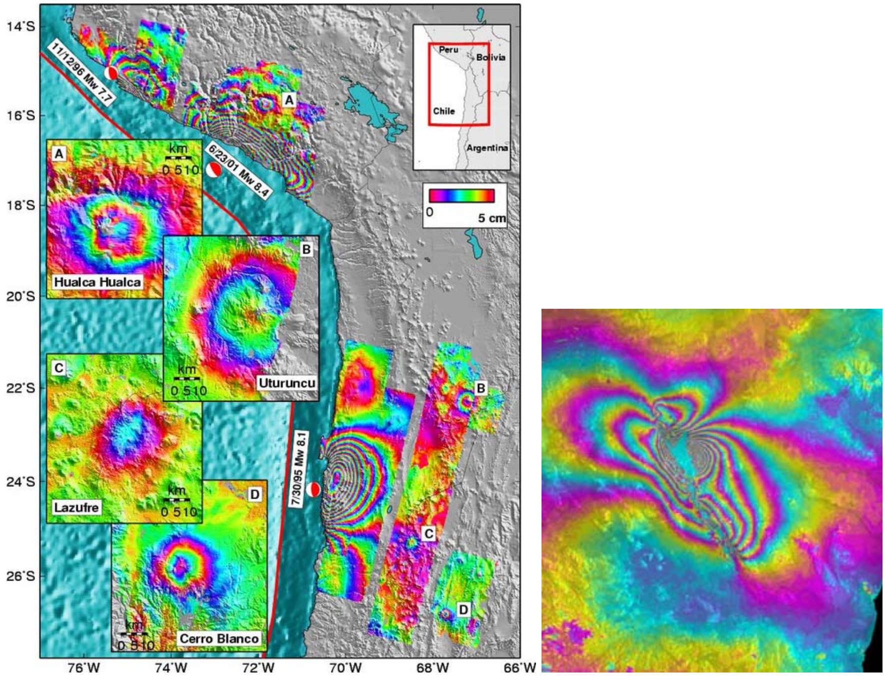


Fig. 2.27. Interferograms from ERS showing deformation. Each color cycle corresponds to 5 cm of deformation. Left image: InSAR has revealed that four Andean volcanoes (named on the small interferograms on the left of the image), thought to be inactive, are now known to be rapidly deforming. The top three volcanoes are inflating and Robledo is deflating (Pritchard & Simons, 2002; reprinted with permission from Macmillan Publishers Ltd). Right image: Hector Mine earthquake observed from ERS (courtesy G. Peltzer, UCLA).

Mission (SRTM) is an example of a radar mission that mapped 80% of the Earth's topography using this technique. In order to measure surface change, a single radar is used, measuring the surface at two times from an exactly repeated pass. A change in the line-of-site distance to the satellite results in a phase change that can be used to infer surface change (Figure 2.26, bottom panel).

Several radar missions have used interferometric techniques for topography and surface change. SRTM mapped 80% of the Earth's topography in a 10-day mission in 2000. The European ERS-1 and ERS-2 missions, the Japanese JERS-1 and ALOS missions, and the Canadian Radarsat missions have provided important data sets for measuring surface change. The European and Canadian missions are C-band instruments, and the short wavelength signal decorrelates over vegetated regions. A recently released report of the U.S. National Research Council (National Research Council, 2007) recommends an L-band InSAR mission with 8-day repeat to provide global coverage of Earth's deforming regions. The report recommends a launch in the 2010-2013 time frame, essentially the earliest possible juncture.

Successes from radar interferometry include the SRTM topographic map, discovery of actively inflating volcanoes that were thought to be dormant (Figure 2.27), measurement of interseismic, coseismic, and postseismic deformation related to earthquakes that have truly influenced physical models of Earth's crust, observation of incipient landslides, and subsidence due to water and oil withdrawal. Long-term systematic measurements will also provide insight into time dependent behavior of earthquake, volcanic, and other solid Earth and cryosphere systems.

The above documents emphasize the increasing importance of image geodesy. However, a major challenge is still the integration of point and image geodesy (Plag et al., 2007b; DESDynI Writing Committee, 2007). Solid Earth science and many applications require observations of Earth's surface displacements at the sub-cm level. Solid Earth processes exhibit temporal scales from seconds (e.g., coseismic displacements) to secular with respect to the lifetime of a mission (e.g., isostatic adjustments), and spatial scales from local (e.g., local subsidence, volcanoes) to global (e.g., great earthquakes, glacial isostatic adjustment). This wide range of temporal and spatial scales poses a major challenge for the extraction of unbiased surface displacements from InSAR observations.

The determination of surface displacements from InSAR requires at a minimum a high-resolution Digital Elevation Model (DEM) and information on tropospheric water vapor content. Additional data of ionospheric Total Electron Content (TEC), for example, from GPS/GNSS is likely to improve the correction of ionospheric path-delay based on InSAR observations alone. If *a priori* deformation models are available, tropospheric water vapor content can be estimated directly. However, the strategies for an optimal combination of *a priori* information on DEM, water vapor, surface deformation, and ionospheric TEC are still the object of research. Particular emphasis should be on consistent treatment of errors in the *a priori* information.

The "Decadal Survey" (National Research Council, 2007) states that a stable global geodetic reference frame is indispensable for all satellite missions, and this is also true for geodetic imaging missions. For most Earth science applications, the surface displacements need to be given relative to such a stable, global geodetic reference frame. For example, for local sea level studies, coastal subsidence or uplift need to be given in a reference frame well tied to the CM. Glacial isostatic adjustment is important for the conversion of ice surface displacements into ice volume and mass changes. The deformation of the solid Earth surface due to ice loads has large spatial scales and need to be referred to the same reference frame as that of the ice surface displacements. Large earthquakes have displacement fields exceeding by far the size of several adjacent images. Likewise, postseismic deformation, which is a key quantity for earthquake process studies, can have spatial scales of the order of 1000 km. For all these phenomena it is crucial to relate the displacements from different interferograms to the same unique reference frame in order to capture the large-scale displacement pattern. However, as discussed in Chapter 8 (see also DESDynI Writing Committee, 2007), the present approach to the realization of the ITRS has limitations that reduce the achievable accuracy and necessitate conceptual improvements.

In particular for early warning and disaster damage assessments, high temporal resolution and low latency are key requirements. Typical InSAR missions have repeat periods of several days of longer. Hazardous volcanoes and unstable slopes can be monitored with such repeat period, but in critical phases, early warning may need much shorter repeat periods. In these cases, supporting measurements with airborne LIDAR (see below) and InSAR can be used to achieve improved temporal resolution. Ground-based GPS/GNSS can also provide a higher temporal resolution, especially if the repeat time increases. In cases of earthquakes, landslides, and volcanic eruptions, emergency response requires rapid information on the extent of damage. Surface displacements are indicative of damage. In order to reduce the latency, again airborne LIDAR and InSAR can support the mapping. In all these cases, the appropriate algorithms for the combination of the spaceborne, airborne, and *in situ* observations need to be developed.

LIDAR: Another imaging technique to be mentioned here is LIDAR. Based on the same principle as RADAR the LIDAR instrument transmits light out to a target (Kavaya, 1999). The transmitted light interacts with and is changed by the target. Some of this light is reflected and/or scattered back to the instrument where it is analyzed. The change in the properties of the light enables some property of the target to be determined. The time for the light to travel out to the target and back to the LIDAR is used to determine the range to the target.

There are three basic generic types of LIDAR:

- Range finders: These are the simplest LIDARs. They are used to measure the distance from the LIDAR instrument to a solid or hard target.
- DIfferential Absorption LIDAR (DIAL): These LIDARs are used to measure chemical concentrations (such as ozone, water vapor, pollutants) in the atmosphere. A DIAL uses two different laser wavelengths which are selected so that one of the wavelengths is absorbed by the molecule of interest whilst the other wavelength is not. The difference in intensity of the two return signals can be used to deduce the concentration of the molecule being investigated.
- Doppler LIDARs: These are used to measure the velocity of a target. When the light transmitted from the LIDAR hits a target moving towards or away from the LIDAR, the wavelength of the light reflected/scattered off the target will be changed slightly. This is known as a Doppler shift - hence Doppler LIDAR. If the target is moving away from the LIDAR, the return light will have a longer wavelength (sometimes referred to as a red shift), if moving towards the LIDAR the return light will be at a shorter wavelength (blue shifted). The target can be either a hard target or an atmospheric target - the atmosphere contains many microscopic dust and aerosol particles which are carried by the wind. These are the targets of interest to us as they are small and light enough to move at the true wind velocity and thus enable a remote measurement of the wind velocity to be made.

2.5 Observing Earth's rotation

Most Earth rotation observations today originate from the geometric space-geodetic techniques described in the previous Section. In the following, focus is therefore only on the specific aspects related to rotation.

2.5.1 Space-geodetic techniques

VLBI: As described in Section 2.4 VLBI observes radio signals emitted by quasars. These fixed points constitute the ICRF (see Section 2.2), and variations in the orientation of the Earth are measured with respect to the ICRF. This technique is sensitive to processes that change the relative position of the radio telescopes with respect to the source, such as a change in the orientation of the Earth in space or a change in the position of the telescopes due to, for example, tidal displacements or tectonic motions. If just two telescopes are observing the same source, then only two components of the Earth's orientation can be determined. A rotation of the Earth about an axis parallel to the baseline connecting the two radio telescopes does not change the relative position of the telescopes with respect to the source, and hence this component of the Earth's orientation is not determinable from VLBI observations taken on that single baseline. Multibaseline VLBI observations with satisfactory geometry can determine all of the components of the Earth's orientation including their time rates-of-change. In fact, the motion of the axis of rotation of the Earth in space (precession and nutation) and the rotation angle around the axis of rotation are uniquely monitored by VLBI through its direct connection to the ICRF.

GNSS: GNSS signals observed by a network of ground stations can be used to determine the orientation of the network of receivers as a whole. In practice, in order to achieve higher accuracy, more sophisticated analysis techniques are employed to determine the EOPs and other quantities such as orbital parameters of the satellites, positions of the stations, and atmospheric parameters such as the zenith path delay (Bock & Leppard, 1990; Blewitt, 1993; Beutler et al., 1996; Hofmann-Wellenhof et al., 1997; Leick, 2003). Only polar motion and its time rate-of-change can be independently determined from GNSS measurements. UT1 cannot be separated from the orbital elements of the satellites and hence cannot be determined from GNSS data. The time rate-of-change of UT1, which is related to the length of the day, can be determined from GNSS measurements. But because of the corrupting influence of orbit error, VLBI measurements are usually used to constrain the GNSS-derived Length of Day (LOD) estimates.

SLR and LLR: Although a number of satellites carry retro-reflectors for tracking and navigation purposes (see Section 2.4.2), the LAGEOS I and II satellites were specifically designed and launched to study geodetic properties of the Earth including its rotation and are the satellites most commonly used to determine EOPs. Including range measurements to the Etalon I and II satellites has been found to strengthen the solution for the EOPs, so these satellites are now often included in the process. The EOPs are recovered from the basic range measurements in the course of determining the satellite's orbit and station coordinates. However, because variations in UT1 cannot be separated from variations in the orbital node of the satellite, which are caused by the effects of unmodeled forces acting on the satellite, it is not possible to independently determine UT1 from SLR measurements. Independent estimates of the time rate-of-change of UT1, or equivalently, of LOD, can be determined from SLR measurements, as can polar motion and its time rate-of-change.

In the case of LLR, the EOPs are typically determined from observations by analyzing the residuals at each station after the lunar orbit and other parameters such as station and reflector locations have been fit to the range measurements (Stolz et al., 1976; Langley et al., 1981; Dickey et al., 1985). From this single station technique, two linear combinations of UT1 and the polar motion parameters can be determined, namely, UT0 and the variation of latitude at that station. A rotation of the Earth about an axis connecting the station with the origin of the terrestrial reference frame does not change the distance between the station and the Moon, and hence this component of the Earth's orientation cannot be determined from single station LLR observations.

DORIS: Processing DORIS observations (see Section 2.4.2) allows the orbit of the satellite to be determined along with other quantities such as station positions and EOPs. As with other satellite techniques, UT1 cannot be determined from DORIS measurements, but its time rate-of-change can be determined, as can polar motion and its rate-of-change (Willis et al., 2006).

2.5.2 Ring laser gyroscopes

Ring laser gyroscopes are a promising emerging technology for determining Earth rotation (Figure 2.28). Ring lasers are active Sagnac interferometers: two monomode laser beams propagate in opposite directions around a polygon (ring) circumscribing an enclosed area. Since the ring laser gyroscope is rotating with the Earth, the effective path length of the beam that is co-rotating with the Earth is slightly longer than the path that is counter-rotating with it. Because the effective path lengths of the two beams differ, their frequencies differ, so they interfere with each other to produce a beat pattern. The beat frequency is strictly proportional to the rate of rotation experienced by the entire apparatus. Therefore, ring lasers are very sensitive to rotational, but entirely insensitive to translational motion. In fact, the beat frequency is proportional to that component of the instantaneous angular velocity $\omega(t)$ of the Earth that is parallel to the normal of the plane of the ring. Ring laser gyroscopes measure the absolute rotation of the Earth in the sense that, in principle, just a single measurement is required to determine the Earth's instantaneous rotation. All of the other techniques discussed above are relative sensors because they infer the Earth's rotation from the change in the orientation of the Earth that takes place between at least two measurements that are separated in time.

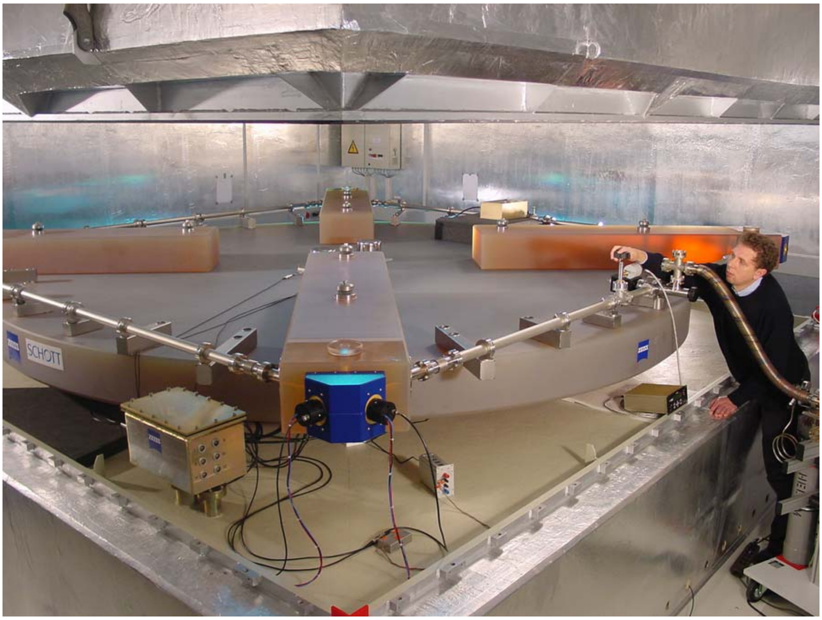


Fig. 2.28. Ring laser gyroscope for Earth rotation monitoring. The picture shows the G ring laser at Wettzell.

The sensitivity of the ring laser depends on the area enclosed. Ring lasers with an enclosed area between 1 and 833 m^2 have been built and they achieved sensor sensitivities reaching from $5 \cdot 10^{-10}$ to $5 \cdot 10^{-12}$ rad/s/$\sqrt{\text{Hz}}$. However, sensitivity is only one of the important parameters. It is also critical to reduce the instrumentally induced drift.

The most stable ring lasers experience a non-negligible drift of $2 \cdot 10^{-6}$ degrees per hour, several orders of magnitude smaller than the best known commercial laser gyros. Therefore, these sensors capture the effect of diurnal polar motion and tilt effects from solid Earth tides. Earth rotation variations are resolved to approximately 1% at integration times of about 1 day. Recent progress in reducing the aging of the laser gain medium substantially reduced the drift by approximately 2 orders of magnitude.

Compared to other space-geodetic techniques such as VLBI and GPS, currently, ring lasers have a resolution about one order of magnitude worse. However, because ring lasers are local sensors, they are already revealing interesting crustal deformation effects from a region several hundred kilometers in diameter around the observatory. Furthermore they are operated continuously. Their main advantage over other techniques is the very high temporal resolution. Within the next decade, a substantial improvement in sensor stability as well as a much higher sensor resolution is expected. Apart from Earth rotation research, ring lasers are the first sensors that have shown their sensitivity for measuring rotations from seismic and tele-seismic events at high resolution. It is expected that this application will expand the global network of ring lasers considerably; a development beneficial for Earth rotation monitoring with ring lasers.

2.6 Observing Earth's gravity field

The gravity field of the Earth is observed with *in situ* airborne and spaceborne sensors. Relative gravimetry surveys gravity mainly in order to improve the geoid locally at short wave-lengths but also for exploration purposes. Superconducting and absolute gravimeters measure temporal variations of gravity locally and stationary at sites at the Earth surface (Sections 2.6.1 and 2.6.2, respectively). Modern gravimetry also supports studies of land motion (Section 2.6.3). Gravimeters on ships and airplane measure profiles along the track of the vessel (Section 2.6.4). Satellite orbits are affected by the gravity field at the satellite, and orbit perturbations can be integrated to determine a static gravity field model with low spatial resolution. Recently, dedicated satellite gravity mission have been designed and placed in orbit. One in particular (GRACE, see Section 2.6.5) not only gives the static field with increasing spatial resolution and accuracy but also the temporal variations of the gravity field with low temporal resolution.

2.6.1 Superconducting gravimetry

With the advent of the cryogenic, or Superconducting Gravimeter (SG), in the mid 1980s, the time resolution of the gravity field routinely increased from sampling intervals of minutes to 1 hour to sampling intervals of 1 to 10 seconds. SGs now overlap with seismometers in the recording of high frequency ground motions caused for example by earthquakes in the 1 to 1000 seconds range. Gravimeters measure acceleration, whereas seismometers are velocity recording devices. This difference determines the transfer function of the instruments and impacts the conversion of the observations to ground displacement. The accuracy of the SG in the time domain is on the level of 1 nms^{-2} (= 10^{-9} ms^{-2} = 0.1 microgal) or better, which translates into a frequency domain accuracy at high frequencies ($< 1\ d^{-1}$) at the level of 0.01 nms^{-2} (= 10^{-11} ms^{-2} = 1 nanogal). SGs are known to have a small instrumental drift (a few microgal per year) that can be established by co-located measurements with an absolute gravimeter, and their calibration is very stable in time and determined to better than 0.1%.

The high temporal resolution of SGs is particularly useful in the high frequency domain for recording the long period normal mode spectrum (Figure 2.29), although a sampling interval of 1 s is insufficient for body wave seismology. In the time domain, the high temporal resolution allows for precise determination of effects

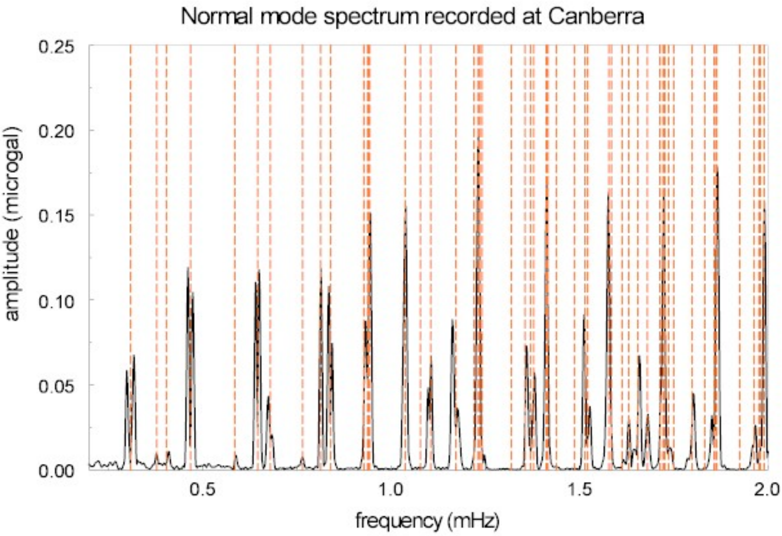


Fig. 2.29. Long period normal modes from the Mw = 9.1 Sumatra-Andamen earthquake (2004/12/26) recorded by the SG at Canberra. The vertical lines are the theoretical multiplet peaks. The high signal-to-noise ratio is generally high.

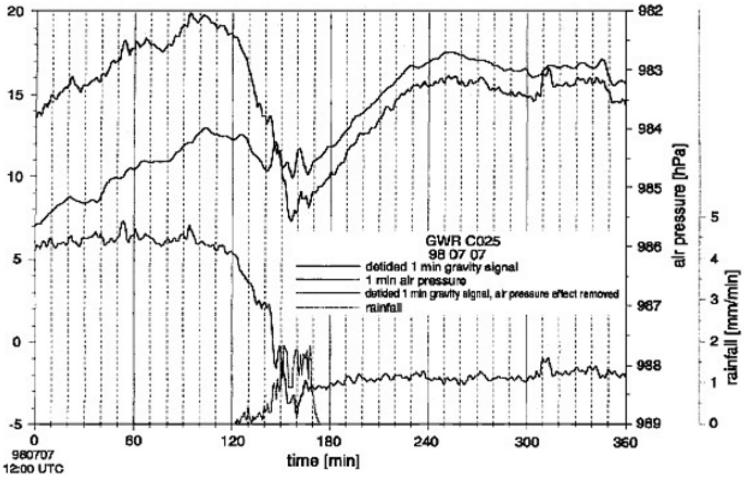


Fig. 2.30. Example of atmospheric mass transport during heavy rain. The signal at the top of the figure (at the start of the record) is gravity with tides removed, and the curve beside it is the pressure. After correcting with a frequency dependent admittance, the residual gravity is the lower curve (left). Note this residual gravity begins to decrease sharply just before the onset of the rain (lowest curve) due to a mass increase above the station that is not seen in the surface pressure.

such as coseismic mass changes associated with of earthquakes, offsets due to rapid atmospheric changes (Figure 2.30), and at periods of minutes the changes in gravity due to hydrological effects such as extreme rainfall. The traditional goal of high accuracy relative gravimetry has been the recording of Earth tides from ter-diurnal to annual periods, mainly for studies of solid Earth an ocean loading tides. Today,

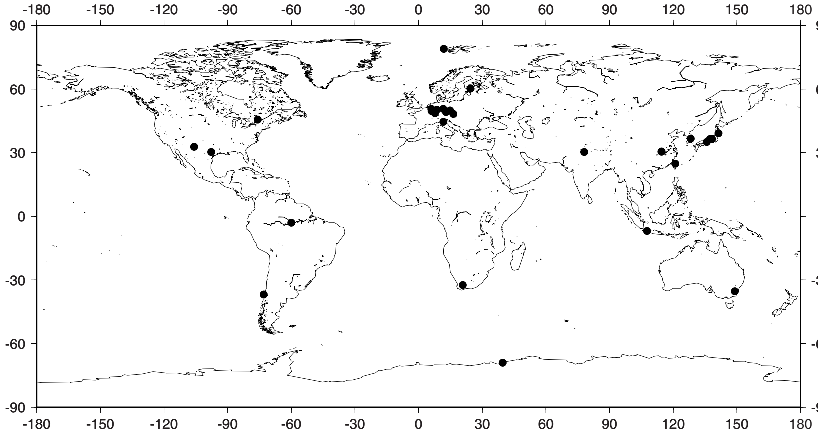


Fig. 2.31. Global network of SG stations contributing to GGP. The stations shown are either operating or planned to start operation in 2007 or 2008.

the solid-Earth tidal component is considered to be a known phenomenon that can be predicted theoretically at the 1 nanogal level. Current interest is in the discrimination between models of ocean tidal loading, which amounts to a few percent of the total tidal signal. With in the frame of the Global Geodynamics Project (GGP), some 30 SG are currently operated or planned in a global network (Figure 2.31, Crossley et al., 1999; Hinderer & Crossley, 2004). .

2.6.2 Absolute gravimetry

The low-frequency variations in gravity at a site are usually determined by episodic observations with an Absolute gravimeter (AG). Today, AG are almost invariably of the free-fall type (FG5) manufactured by "microG" (now LaCoste-Romberg). This instrument is an absolute measurement device that registers the value of gravity over the period of time it takes the mass (a small corner cube) to traverse approximately one meter in free fall. Typical measurement sessions take a few days. Single drops carried out every 20 seconds or so have a high scatter, but an accuracy of 1-3 microgal is achieved from the mean of a large number of drops that are done over typical campaign durations of several hours to days. In order to extract the secular signal from these observations, high-frequency variations caused by solid-Earth and ocean loading tides, polar motion and atmospheric loading have to be modeled and corrected for. Hydrological loading is usually not included in these corrections.

In order to check the instrument stability and calibration, intercomparisons between AGs are done every few years. These intercomparisons have established agreement at the level of a few microgal between the best instruments.

AG measurements have been very successful in measuring long-term gravity changes such as the post-glacial rebound in regions such as Fennoscandia and North

America. For example, Figure 2.32 shows the secular trend cause mainly by post-glacial rebound combined with an interesting long-term saw-tooth signal due to episodic slip on the Cascadia subduction zone. In this example the use of a continuous recording SG would enable interpolation between the AG values and thus give the time history of each slip event. At many sites it has become common to perform intercomparisons between the SG and AG instruments, both from the point of view of calibrating the SGs and to monitor the continuous gravity changes during, and in between, the AG observations.

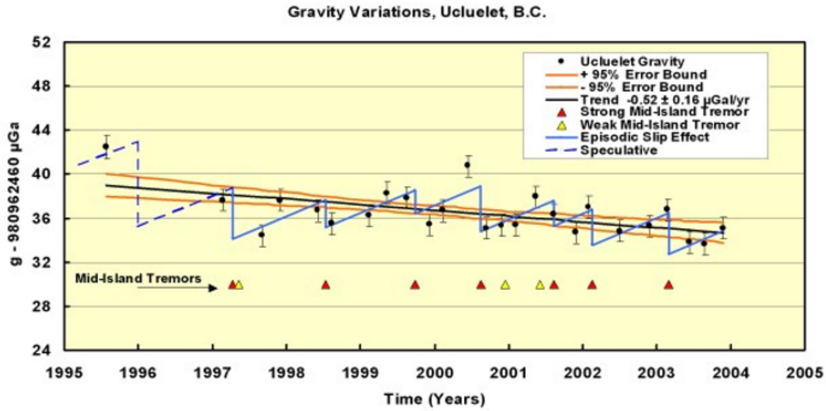


Fig. 2.32. Variations in absolute gravity at Ucluelet (western coast of Vancouver Island) showing some concordance with the episodic slip and seismic tremor activity above the Cascadia subduction zone (figure courtesy of T. Lambert.). The downward trend is due to postglacial rebound.

Gravity changes at a point on the Earth's surface are generally associated with displacements of the Earth surface or some other processes. The gravity anomaly measured by a gravimeter is therefore the sum of the effect due to the vertical motion of the gravimeter through the unperturbed gravity field and the contribution from mass changes in the vicinity of the gravimeter. In order to separate these two effects, gravimeters need to be co-located with geometric instruments such as a GNSS receiver. Wahr et al. (1995) discussed combined gravity and geometric observations, which, in principle, can be used to detect mass changes, for example, in ice sheets, while Plag et al. (2009) showed that spatially distributed observations of secular trends in gravity and vertical displacements constrain the tie between the RFO and the CM, thus supporting SLR in this function.

2.6.3 Land movements and terrestrial gravimetry

Among the terrestrial observation techniques used for estimating vertical land movements, gravimetry is a completely independent method with respect to space geodetic techniques. The task of gravimetry is the measurement of gravity, which is the magnitude of the acceleration due to the force of gravity, and of the gravity gradient at the surface of the Earth, or near to it. Time-dependant gravity variations are important in the study and comprehension of phenomena leading to crustal deformation. The study of crustal deformation plays a key role in the determination of mean sea-level changes. A crustal deformation process implies a variation of the position (coordinates) and a variation of the gravity field. This last because the gravity field is directly affected by the variation of the position of the measuring point (mainly of the vertical component) and because crustal deformation is associated with changes in the density field in the Earth's interior (due to viscoelastic deformation, pre-seismic dilatancy, dislocation or transfer of internal masses). Therefore, the combination of gravity and position changes allows the computation of changes of the potential and can provide important information on the dynamics of the phenomena (Marson, 2000).

Over the last five decades, gravimetry has made impressive progress. The precision of both absolute and relative measurements has improved by almost three orders of magnitude to presently 10^{-9}. The instrumental accuracy of the absolute gravimeter FG5 is about 10-20 nms^{-2} at good stations for a 24 hours observation period (Niebauer et al., 1995). Continuous measurements are not feasible because of the wear and tear of the mechanical system. Van Camp et al. (2005) demonstrated that gravity trends with uncertainties of 1 $\mathrm{nms}^{-2}\mathrm{yr}^{-1}$ can be achieved over a time span of 7 years with annual observations. A technology to measure the temporal variations of the gravity field continuously at a given site by means of superconducting gravimeters (SG) exists. The SGs are relative instruments but very stable in time. Absolute gravimeter observations taken at the location of a SG allows the identification of outliers and the correction for long-period, mostly environmental signals. In this way the accuracy mentioned above can be achieved in a much shorter time span (Zerbini et al., 2002; Richter et al., 2004). Continuous monitoring of height and gravity changes allows the separation of the gravity potential signal due to mass redistribution from the geometric signal due to height changes and the sound interpretation of crustal deformation processes (Zerbini et al., 2006).

2.6.4 Airborne gravimetry

Airborne gravimetry is an effective way to cover the medium-range wavelengths (10-1000 km) of the Earths' gravity field, supplementing the satellite gravity field missions, which at best gives gravity field information for wavelengths longer than some 400 km (corresponding to 200 km resolution on the surface). The high-resolution gravity field information is essential for determining the geoid with sufficient accuracy, especially relevant for unifying height systems and geometric information around core GGOS sites.

The development of airborne gravity has been made possible by the use of the kinematic GPS technique as well as improvement in airborne gravity acceleration sensor systems (Figure 2.33). Current accuracies are routinely in the 1 to $5 \cdot 10^{-5}$

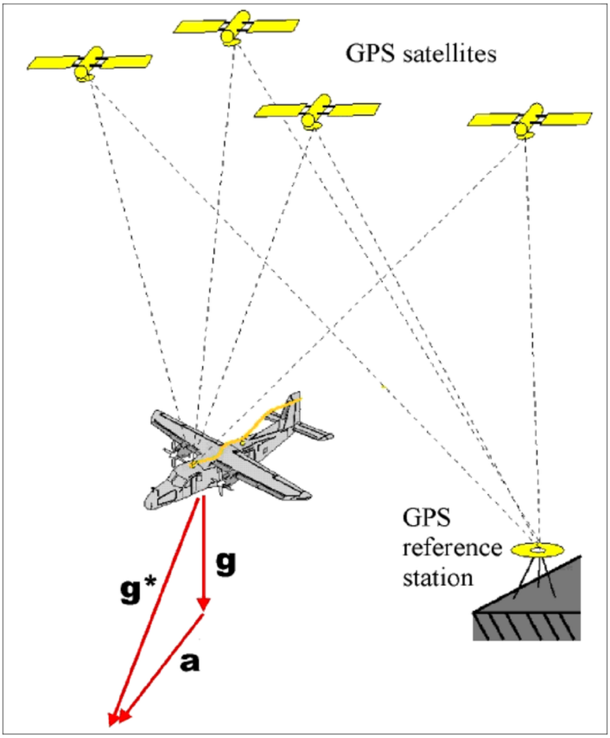


Fig. 2.33. Principle of airborne gravimetry.

ms^{-2} r.m.s. domain, with relatively large differences between different sensor systems and implementations. Major commercial airborne activities are ongoing in connection with geophysical exploration for oil and gas; for mining airborne gradiometry systems at accuracies of 1 E or better have been developed in recent years. Commercial gravity and gradiometry survey projects are generally restricted to relatively small areas, and data are usually not available for more widespread geodetic use. Long-range airborne gravity surveys for geodetic gravity field applications (geoid and spherical harmonic reference models) have been operational since the early 1990s, and many regions of the Earth has been covered, including major parts of the Arctic, and major countries such as Malaysia, Mongolia, Afghanistan and Ethiopia. Currently US, European, Russian and Chinese groups are active in carrying out such surveys.

Albeit many airborne surveys are currently classified or proprietary, experience has shown that many such surveys may fully or in part be included in future high-resolution spherical harmonic reference models. Such reference models, like the new EGM2008, complete to degree and order 2159, would be the major static gravity field product of GGOS. To improve the quality of such models, generally there is a need for continued surveys in many inaccessible areas of the globe, especially the Amazon, mountainous areas, large parts of Africa, coastal regions (high accuracy geoid across the coastal zones) and especially Antarctica, which is the largest continental void of gravity on the globe. Coordinated global surveys should be accompanied by effort to secure release of terrestrial gravity data, still unavailable for large parts of the Earth.

2.6.5 Satellite missions

Artificial satellites have played a dominating role in determining the gravity field of the Earth since the early sixties (e.g., Kaula, 1966). The observations of non-Keplerian variations in orbital motion using either terrestrial (radio or laser) tracking or space-based GPS have long been analyzed to extract the long-wavelength components of the gravity fields. Earth gravity models such as the EGM96 (Lemoine et al., 1998) used decades of tracking data to Earth orbiters to derive the mean long-wavelength gravity models. Determinations of the time-variability were limited to the hemispheric scales, however. The significance of time-variable gravity to climate sciences was well established from the study of three-decade long time series of the Earth's oblateness (J_s), determined from satellite laser ranging to LAGEOS satellites, and showing clear signals from Post-Glacial Rebound (PGR), atmospheric and hydrological mass redistribution, and ice-mass changes (e.g., Cheng & Tapley, 2004).

Data from a large number of space missions have contributed to the determination of the Earth's gravity field in the past. Some recent examples are given in Table 2.2. In addition, terrestrial and space-based tracking to nearly twenty satellites, some dedicated to geodesy and other missions of opportunity, has contributed to the determination of the Earth's gravity field in the past.

A significant step forward in the determination of the gravity field from satellites with respect to resolution and precision has been provided by the satellite missions CHAMP (e.g., Reigber et al., 1999), and GRACE (e.g., Tapley et al., 2004b,a), in orbit since 2000 and 2002, respectively. GRACE (Figure 2.34) has enabled the improvements in our knowledge of the static gravity field to centimeter level accuracy in the geoid determination to spherical harmonic degree 70, with further improvements forthcoming as longer data spans are analyzed. The European GOCE mission (e.g., Le Provost et al., 1999; Drinkwater et al., 2003; Ilk et al., 2005) will complement the results achieved so far with an extremely high precision and resolution of the static part of the gravity field.

Gravity field determination using space missions has also contributed tremendously to advances in geodesy. Improvements in gravity field models obtained over the last three decades have gone hand-in-hand with improvements in the reference frames and Earth orientation from the LAGEOS and other low-orbiting satellite laser-ranging targets. The innovative sensor technologies used in these gravity field missions have already contributed to a substantial improvement of the Earth static gravity field recovery (e.g., Reigber et al., 2003; Tapley et al., 2004b). Figure 2.35 shows the dramatic improvement of the gravity field during the last decade. Gravity field models from GRACE have benefited the space geodetic analysis of the DORIS tracking data (Willis & Heflin, 2004). They have been used to improve the

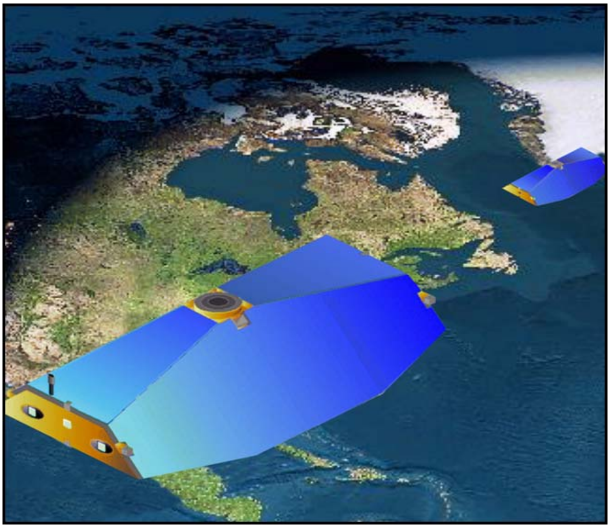


Fig. 2.34. The GRACE satellites.

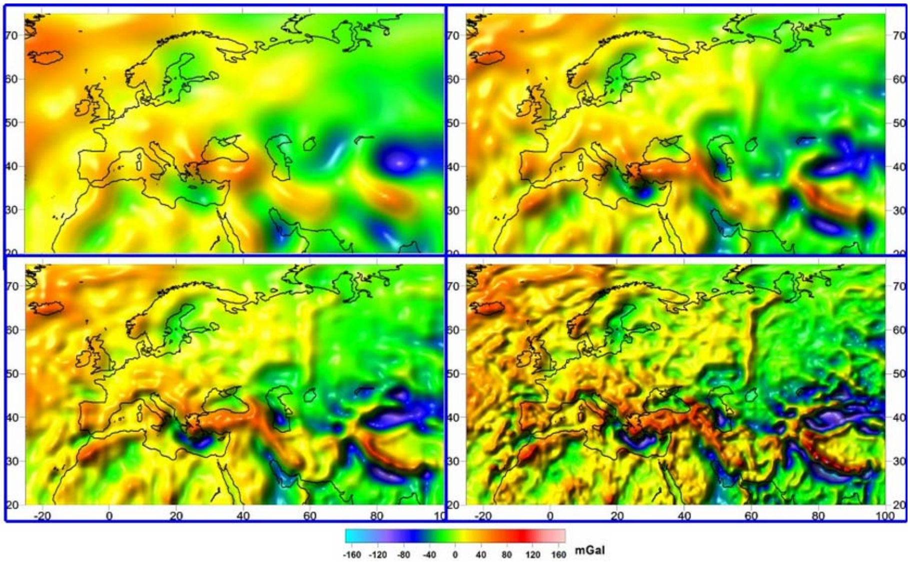


Fig. 2.35. Improvement of the Earth's gravity field models. The models are (from top left to bottom right) GRIM-5S1: Best gravity field model before CHAMP and GRACE computed from SLR data only; EIGEN-CHAMP03S: Gravity field from CHAMP; EIGEN-GRACE03S: Gravity field from GRACE; EIGEN-CG03C: Gravity field from GRACE combined with terrestrial data. Reprinted from Reigber et al. (2005), Copyright 2005, with permission from Elsevier.

knowledge of the orbits of ocean radar altimetry satellites (Haines et al., 2004), and for laser altimeters, thereby enhancing the geodetic contributions from other space missions. Gravity missions are also of central importance for altimetry, because the precise geoids are required to refer the sea surface topography to the geoid. The

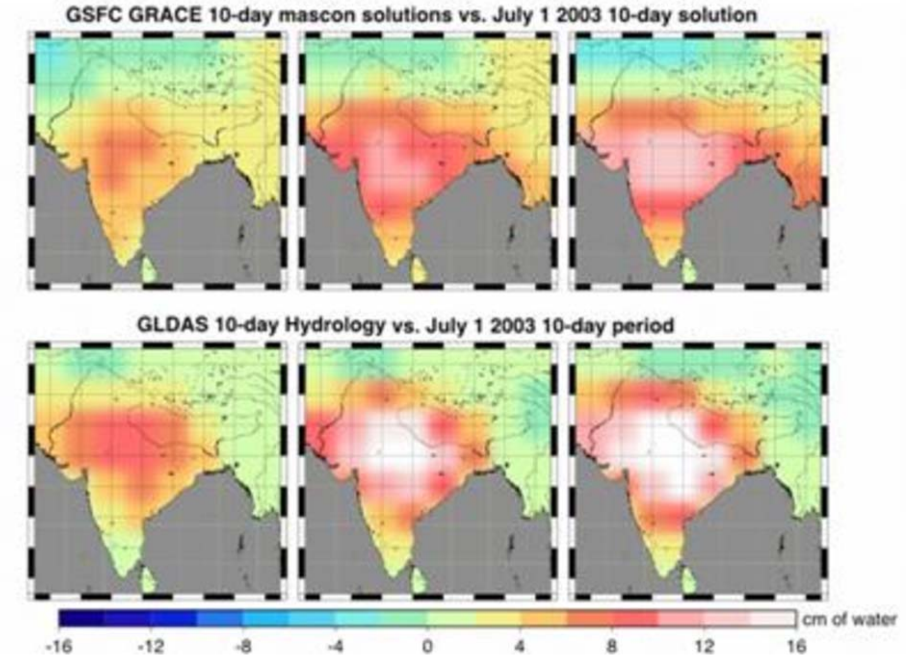


Fig. 2.36. GRACE-determined variations in water storage on land. Upper row: Ten-day estimates of the mass change with respect to a multi-year averaged gravity model in a 4°×4°grid. The values shown are the mass change mapped into an equivalent change in a surface layer of water in units of cm. To estimate these values, the effects of atmospheric pressure changes and solid Earth and ocean tides have been removed based on model predictions. Lower row: Numerically modeled soil moisture and snow mass fields from the Global Land Data Assimilation System (GLDAS) by Rodell et al. (2004). From http://grace.sgt-inc.com/.

integration of all the satellite missions with the existing space-geodetic techniques for the determination of the Earth's shape creates new opportunities to determine and study the mass transport in the Earth system in a globally consistent way (e.g., Kusche & Schrama, 2005; Wu et al., 2006; Gross, 2006) or to derive information on changes in part of the water cycle (e.g., the large ice sheets, see Velicogna & Wahr, 2005, 2006).

The GRACE mission in particular is providing unprecedented insight in the water cycle on regional scales and on intraannual to submonthly time scales. This mission is designed to monitor local, regional, and global changes in the Earth's gravity field. The changes observed in the gravity field are mainly caused by mass transport in the hydrology cycle, in particular the oceans, atmosphere, and on land. Analysis of the data delivered by GRACE using an approach based on Stokes coefficients yields a direct measure of mass flux with high spatial resolution on the Earth's surface with a temporal resolution of one month and a spatial resolution of ∼500 km (e.g., Wahr et al., 2004; Davis et al., 2004; Tapley et al., 2004b,a; Crowley et al., 2006). Recent developments using a mass concentration (mascon) approach have been successful in recovering submonthly mass flux at a high spatial resolution over certain regions of interest. The mascon gravity representation largely mitigates the spatial and temporal aliasing problems encountered with monthly GRACE solutions using Stokes coefficients (Luthcke et al., 2006).

Figure 2.36 shows a time series of discrete ten-day estimates of the mass change with respect to a multi-year averaged gravity model in a $4^\circ \times 4^\circ$grid for the Indian sub-continent and adjacent land areas together with the predictions of the GLDAS. GLDAS ingests satellite- and ground-based observational data products and uses advanced land surface modeling and data assimilation techniques, in order to generate optimal fields of land surface's hydrological state and its fluxes (Rodell et al., 2004). Agreement of the GRACE-derived and model predicted changes in water mass are on the few centimeter level.

2.7 Observing time

2.7.1 Relativity: proper and coordinate time; realized time scales

Relativity distinguishes locally measurable (proper) quantities from coordinate quantities which are, by definition, dependent on conventions. Therefore one should distinguish proper time, which is the output of an ideal clock, from coordinate time, which is one of the coordinates chosen to represent the four-dimensional space time. In its Resolution A4, the IAU in 1991 explicitly introduced general relativity as the theoretical background for space-time reference frames. For the geocentric system, it defined two time coordinates the Geocentric Coordinate Time (TCG) and Terrestrial Time (TT), which differs from TCG by a constant rate so that the scale unit of TT agrees with the International System of Units (SI) second on the geoid. To account for upcoming improvements in accuracy, the IAU refined the relations between these relativistic coordinate times in its Resolution B1 in 2000. International Atomic Time (TAI), established by the Bureau International des Poids et Mesures (BIPM), is a realization of TT. TAI has stability well below $1 \cdot 10^{-15}$ for averaging times between 5 days and 6 months and can be accessed with an uncertainty of about 1 ns with modern time transfer techniques (see Section 2.9.4). UTC differs from TAI by an integer number of seconds. UTC has therefore the same metrological characteristics as TAI and is universally used to date events.

2.7.2 Geodetic measurements and geodetic coordinates

Time enters geodesy in (at least) two ways. First, present-day geodetic measurements (VLBI, GNSS, Doppler, Laser ranging, Radar) are all based on local measurements of proper time or frequency. These raw measurements are subsequently processed to obtain geodetic coordinates. Second, a reference coordinate time scale is required to date all measurements and results. Because the magnitude of relativistic effects in the vicinity of the Earth is close to 10^{-9} in relative value, a complete relativistic treatment is mandatory for all techniques. As a result, (geodetic) coordinates must be understood in a fully relativistic sense and have no direct relationship with a measurable quantity (meter stick). However, coordinate differences, for example, between results from different techniques or the variation of coordinates with time, are small enough to be directly interpreted as physical quantities, provided that the different sets of coordinates have been determined in a consistent manner. Note that the IUGG in 1991 adopted the IAU relativistic framework to define its CTRS. However, as two time coordinates are possible (TCG and TT), geodetic coordinates may differ in scale by $7 \cdot 10^{-10}$ depending on the time coordinate used.

2.7.3 Clocks and geodesy: future trends

The performances of clocks, counters, and other time/frequency devices seem, at least in principle, sufficient to cover the present and foreseeable needs of geodetic measurements. However progress is needed on the one hand in calibration techniques, in order to obtain unbiased measurements. On the other hand, the requirements posed by geodesy to a reference coordinate time scale seem to be fulfilled. For example, a 1-year integration of the motion of a satellite with 1 mm accuracy requires about $1 \cdot 10^{-15}$ accuracy in the reference time scale.

Nevertheless improving clocks and timescales should provide several improvements related to geodesy, in two domains. First, some progress is possible in the geodetic techniques: for example, GNSS will benefit from more stable clocks on board satellites by allowing less frequent updates of clock parameters and yielding a better modeling, i.e. a better determination, of the transmitted clock parameters. VLBI could also benefit from more stable clocks at the stations, however this would necessitate that the entire hardware chain has stability characteristics similar to those of the clock itself. Second, the development of a new domain, that of relativistic geodesy, can be envisaged. Because the relativistic frequency shift experienced by a clock is about 10^{-16} per meter of altitude at the surface of the Earth, clocks accurate to $1 \cdot 10^{-17}$ or $1 \cdot 10^{-18}$ can sense geopotential with 10 cm or 1 cm accuracy, respectively, with respect to some reference. This reference would be free of the limitations inherent to any geophysical realization like the geoid. Ultimately, the fundamental time/frequency reference would be provided by accurate clocks in space, where the relativistic frequency shift can be modeled with $1 \cdot 10^{-18}$ accuracy, while accurate clocks on Earth would be measuring the geopotential. It would also be necessary to reconsider the definition and procedure of realization of TAI in order to benefit from such improvements, in the accuracy range $1 \cdot 10^{-17}$ and below.

Important progress has been accomplished in recent years, bringing new horizons to terrestrial time scales and promising the future development of new ultra-stable and ultra-accurate clocks. Two main directions are being explored for these clocks: laser cooling of atoms and ion traps. In the first direction, several Cs fountains have been in routine operation since the early 2000s, and they realize the SI second with uncertainties that, since 2006, reach a few parts in 10^{16}. It is expected that an accuracy of $1 \cdot 10^{-16}$ may be reached with such a fountain and that a fountain using rubidium atoms may be even more stable. Based on a slow beam of cold atoms, similar devices operating in space in zero gravity may reach an accuracy of $1 \cdot 10^{-17}$. A first step towards operating such clocks in space will be PHARAO/ACES which should fly on board the ISS in 2013. In the second direction, clocks based on optical transitions promise to achieve still better performance in stability and in accuracy, thanks to a transition frequency several orders of magnitude larger. Already in 2006, a clock based on a transition in Hg+ has demonstrated that all systematic effects could be modeled at the level of $7 \cdot 10^{-17}$. The prospects of relativistic geodesy look bright, even though the technical challenge is formidable.

2.8 Ensuring consistency of the observations of geometry, gravity field, and rotation

The "observations" that GGOS will eventually disseminate are really the products of the various supporting IAG Services, i.e., results of the analysis and reduction of the raw observations gathered by various ground and space-based systems. Consistency across these products can only be assured if the raw data are collected using consistent standards and practices, and if their analysis and reduction follows again consistent standards and conventions across all three pillars. Of similar importance is the integration of the various techniques on the observation level, that is through co-location of techniques at the same location and with known local ties between the respective reference points. In the following, we first summarize the situation concerning co-location and then describe the main issues related to common standards and practices across the techniques.

2.8.1 Consistency through co-location

Co-location of techniques at the same location is not only a means to ensure consistency across techniques but it allows full exploitation of the different strength of the individual techniques and mitigation of their weaknesses. Core geodetic sites are those site with three or more space-geodetic techniques co-located and connected through well monitored (on the level of 1 mm) local ties between the techniques. In most cases, a core site will include at least three out of SLR, VLBI, GNSS, and DORIS and also be co-located with absolute and relative (superconducting) gravimeters. However, the number of core sites with three or more of the space-geodetic techniques co-located is only of the order of fifteen sites (see Table 2.6 for

Table 2.6. Co-location sites. Listed are those stations that currently have three or more space-geodetic (geometric) techniques co-located.

Site Name	Latitude	Longitude	GNSS	SLR	VLBI	DORIS	Gravimeter (1)	
							Cryogenic	Absolute
Arequipa	-16.47	-71.49	X	X	-	X	-	-
Concepcion	-36.84	-73.03	X	X	X	-	X	X
Greenbelt	39.02	-76.83	X	X	X	X	-	-
Hartebeesthoek	-25.89	27.69	X	X	X	X	X(2)	X
Kokee Park	22.13	-159.66	X	-	X	X	-	-
Matera	40.65	16.7	X	X	X	-	-	-
McDonald/Fort Davis	30.68	-104.01	X	X	X	-	-	X
Metsahovi	60.22	24.7	X	-	X	X	X	X
Monument Peak	32.89	-116.42	X	X	-	X	-	-
Mount Stromlo	-35.32	149.01	X	X	-	X	X	X
Ny Alesund	78.93	11.87	X	-	X	X	X	X
Shanghai	31.10	121.20	X	X	X	-	-	-
Simeiz	44.41	33.99	X	X	X	-	-	-
Syowa	-69.01	39.58	X	-	X	X	X	X
Tahiti	-17.58	-149.61	X	X	-	X	-	-
Wettzell	49.14	12.88	X	X	X	-	X	X
Yarragadee	-29.05	115.35	X	X	X(3)	X	-	-

NOTES:
(1) Where there is a SCG operating it is assumed that there will also be ABSOLUTE measurements done, since they are part of the SCG's calibration process.
(2) Located in Sutherland
(3) Future VLBI occupation

the current network of core sites) and in fact decreasing over time. In the late 1990s, more than 20 core sites existed, as demonstrated by the larger number of core sites used for the determination of ITRF2000 (Figure 2.37, upper diagram).

The international space geodesy network has recently suffered several debilitating closures and reductions in the last several years due to budgetary cutbacks. NASA support for the SLR stations at GSFC and Texas has been reduced to single shift. The Arequipa and Maui stations have recently reopened after a 2 year hiatus. The budgetary situation has also been a factor in the delayed completion of the Next Generation SLR (NGSLR). Despite clear international recommendations to avoid a "weekend effect" on space-geodetic products, budget cuts in Italy forced weekend operations at the Matera station to be discontinued. There, also lack of funds for necessary maintenance and analysis have hampered the station operation and data processing. In 2005 and 2006, the VLBI network lost both the Algonquin and Yellowknife stations as a result of Canadian government budget cuts and the Gilmore Creek/Fairbanks station in Alaska due to NASA funding reductions. Several stations have been threatened with closure which was averted in part through strong international support.

Table 2.6 also indicates the gravimetric observations carried out at the core sites. Only about half of these sites have co-located superconducting gravimeters. On the other hand, the GGP currently operates or has plans to start operation for about 30

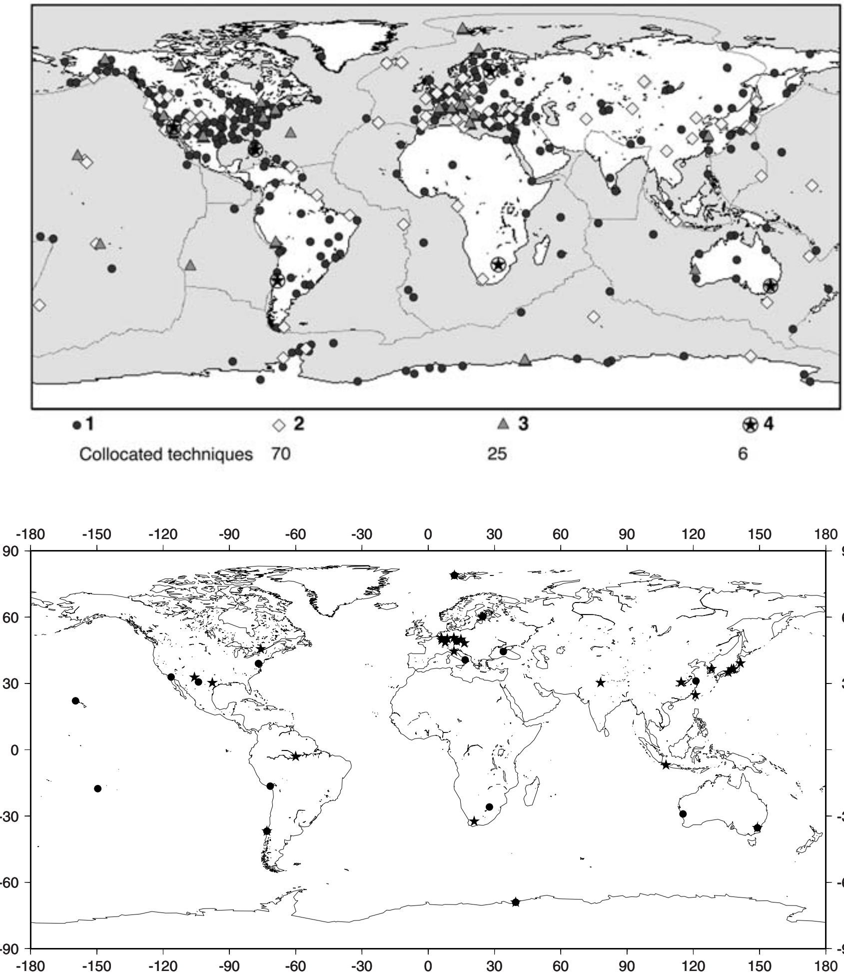


Fig. 2.37. Network of core geodetic sites and the temporal evolution. Upper diagram: Sites used in the determination of ITRF2000, which included 25 sites with three co-located techniques. Lower diagram: Current network of core sites with three or more space-geodetic stations co-located. Circles are core sites, stars indicate the GGP stations (see Section 2.6.1).

superconducting gravimeter sites (see Section 2.6.1). Figure 2.37 illustrates these two networks, and shows that enhanced coordination of the GGP station selection with the choice of core sites has the potential to significantly increase the tie between the geometric and gravimetric techniques.

2.8.2 Consistency of data collection and processing: conventions

Since the very early days, international geodesy has always adhered to some form of standards and conventions, the best known of which being the Geodetic Reference System (GRS), revised appropriately on decadal scales, the last version being GRS80. GRS consistently covered geometry, gravity and rotation, albeit at the very top level of required constants and the most basic formulae, with an eye towards classical techniques and approaches, which at the time were still the main source of geodetic products. At that time however, a new project was conceived and successfully executed with international participation at all levels, including design, execution and evaluation; a project that would eventually lead geodesy from the classical era to that of the space age. The project Monitoring Earth Rotation and Inter-comparison of Techniques (MERIT) (see e.g., Mueller et al., 1982), acted as the pilot for what was later to become the IERS. Along with it came an expanded compilation of constants and standard formulas, mostly associated with the reference frame and Earth rotation, to be used by the project participants. These came to be known as the MERIT standards and with the establishment of the IERS, they became the basis for the development of the IERS Conventions as we know them and use them today (for the last version, see McCarthy & Petit, 2004).

While, at the beginning, the Conventions mainly served as a guideline for the purpose of data analyses and reduction for Earth orientation monitoring only, they gradually developed as "the" reference for geometry and reference frame work as well, including all aspects of the required techniques, from geometric modeling of the observables to all of the required geometric and dynamic corrections in order to achieve the accuracy that IERS expected for these products. To achieve this, the Conventions slowly expanded to encompass models and constants that were well beyond the observations for geometry and rotation, including the gravity field and all of its temporal variations (tides and secular changes as well as loading effects from the oceans and atmosphere), relativistic corrections and environmental corrections (e.g. atmospheric delays). The area where these Conventions are focused is that of the space geodetic observations, leaving out most of the constants and practices for ground-based geodesy. This is perhaps due to the fact that the products that concern IERS are of global nature and none of the ground-based geodetic techniques can contribute significantly or compete with the satellite-borne or space-based techniques. Looking at it from a spectral view, they cover the long-wavelength part of the spectrum of products. Geodesy however can deliver significant information at the high-frequency end of the spectrum, albeit in some areas only. One of these areas, the most important one, is that of the gravitational field of Earth. Ground and airborne surveys provide very high quality and high-resolution local information that is used along with the long-wavelength information obtained from spaceborne instruments (CHAMP, GRACE, GOCE), to develop extremely high resolution global Earth gravity models that will never be derived from space data alone (see, e.g., Reigber et al., 2005, , and the new EGM2008 complete to degree and order 2159). This is the area that the Conventions need to cover in more detail, both, in the description of the required constants and the standard formulas and practices in reducing such data. Once this is accomplished, the foundations of all three pillars will be ably supported by the same, unique set of Conventions and Standards.

While the expansion and enrichment of the existing Conventions and Standards is a rather simple task, the actual enforcement in practice is by far a more challenging task. While most institutions seek to be part of the appropriate IAG Service in order for their products be granted the seal of approval from that Service, it is usually very difficult to force the required changes in the software and the procedures followed by that institution to make it conform with the IERS rules. As most Services discovered, it took years for the various Analysis Centers within a technique to achieve this harmonization. It will take quite an effort to ensure that this harmonization exists also across techniques, since the geodetic products are for the most part a combination of inputs from several if not all of the Services.

An even more difficult and taxing effort will be required in making sure that not only the same constants, theoretical or empirical models, and reduction procedures are consistent, but also all of the background information used in forward-modeling geophysical processes are also consistently derived and applied in the various analyses and reductions of geodetic observations.

When all the above are accomplished, there is still going to be an issue concerning the parameterization of the same effects across techniques. Recognizing that not all techniques are equally sensitive (or sensitive at all) to all of the "geodetic products", we will need to identify what parameters each technique should deliver and at what frequency, in order to ensure that this information can be easily and readily combined with inputs from other techniques. This issue has been given enough attention for the set of parameters that cover the geometric and rotational group, with only minor attention given to some very long-wavelength gravity information.

To some extent this approach has been reasonable since the very short wavelength gravitational information is well below the sensitivity of any space technique at this point, and for many years to come. There are other areas though where part of such information can be applied in a different form, as a constraint to the results obtained from the global space techniques. For example, incorporating some absolute gravity measurements at a few points on Earth in the development of a precise orbit from some type of tracking data is practically meaningless. On the other hand, imposing a constraint on the height change of a tracking station based on repeated absolute gravity measurements at that site is a very useful piece of information independent of the primary source of data determining the position and motion of that site. A global network of combined absolute gravity and space-geodetic stations can constrain the tie between the RFO and CM (Plag et al., 2009).

Such synergistic use of various inputs with a common, single output can only be done if the information from all sources adheres to one set of conventions.

2.9 Essential additional observations and applications

2.9.1 Atmospheric sounding

Besides the variables of direct geodetic interest, the space-geodetic infrastructure enables soundings of the atmosphere and ionosphere by electromagnetic waves of the GNSS. Properly equipped GNSS receivers on the ground can for example observe the integrated precipitable water vapor content in the atmosphere and the total ionospheric electron content in the ionosphere, respectively.

A number of studies conducted in the 1990s have shown that the amount of precipitable water contained in the neutral atmosphere can, in fact, be retrieved using ground-based GPS receivers (Figure 2.38). Assimilation of this information from ground-based GNSS networks into numerical weather forecasting models may improve particularly the prediction of extreme events (e.g., Elgered et al., 2005). Practically, zenith total delay observations collected by European ground-based GPS stations are assimilated operationally in numerical weather prediction since 2006 (Poli et al., 2007).

In addition, it has been demonstrated (Kursinski et al., 1995) that a GPS receiver aboard a microsatellite in a low Earth orbit, supported by a ground-based network of receivers, can be used to collect observations of atmospheric refraction as a function of altitude during the event of satellite occultation by the Earth's atmosphere and ionosphere (Figure 2.39). Thus, the availability of remote sensing observations from GPS radio occultation sensors provides a unique opportunity to improve the quality of ionospheric and meteorological analyses, particularly over the traditionally under-sampled regions, as well as promise higher vertical and temporal resolutions, if a sufficient number of sensors is launched and supported by an adequate ground-based tracking network.

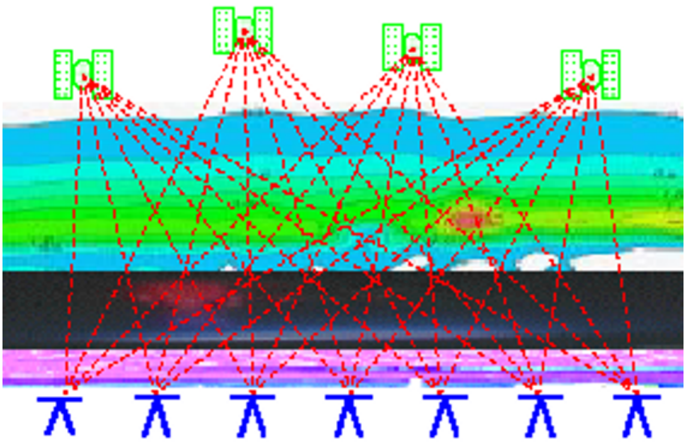


Fig. 2.38. Atmospheric sensing with ground-based GPS receivers.

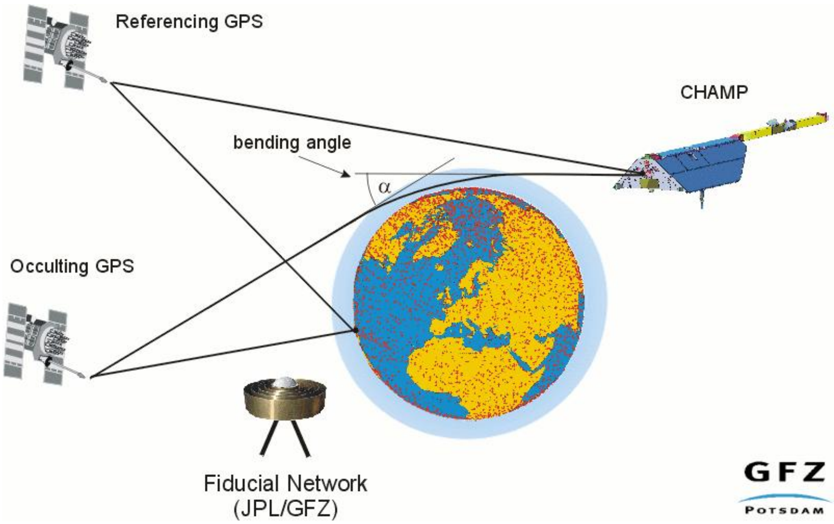


Fig. 2.39. Geometry of GPS occultation illustrated here with the CHAMP satellite.

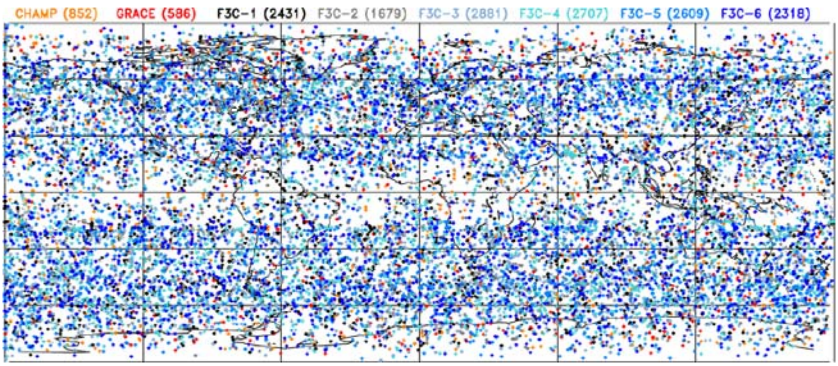


Fig. 2.40. Global coverage of GPS radio occultations. Shown are geographic locations of the soundings collected by CHAMP, GRACE, and FORMOSAT-3/COSMIC (F3C), 1–7 March 2007, and as received in near-real time by national numerical weather prediction centers. The number of GPS radio occultations collected by each GPS receiver is shown in parentheses.

As of 2008, there are twelve satellites in orbit carrying GNSS occultation-capable receivers: FORMOSAT-3/COSMIC (F3C) 1 to 6, METOP, CHAMP, GRACE-A and B, TERRASAR-X, SAC-C. Only the first nine of these produce near-real time observations of GNSS occultations. Such GNSS occultations are particularly promising for meteorological applications and are already today providing routinely information to operational weather services. Figure 2.40 shows the spatial coverage achieved by the radio occultation experiments CHAMP, GRACE, and the six-satellite F3C (Anthes et al., 2008). Each point on the map corresponds to a radio

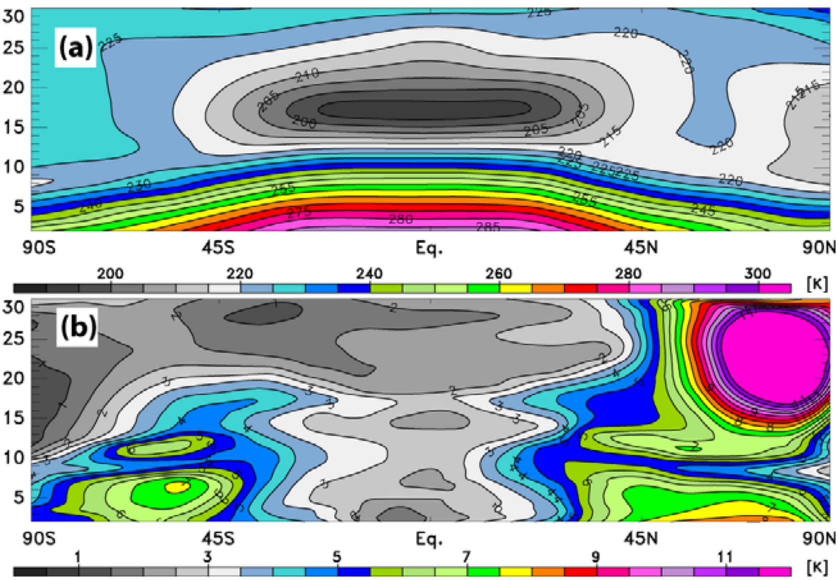


Fig. 2.41. Atmospheric temperature retrievals from GPS radio occultations. (a) Zonal average of one week of FORMOSAT-3/COSMIC retrievals (March 1-7,2007), binned to 1 km vertical and 10 degrees latitude resolutions. (b) Standard deviation of the temperature retrievals within each bin.

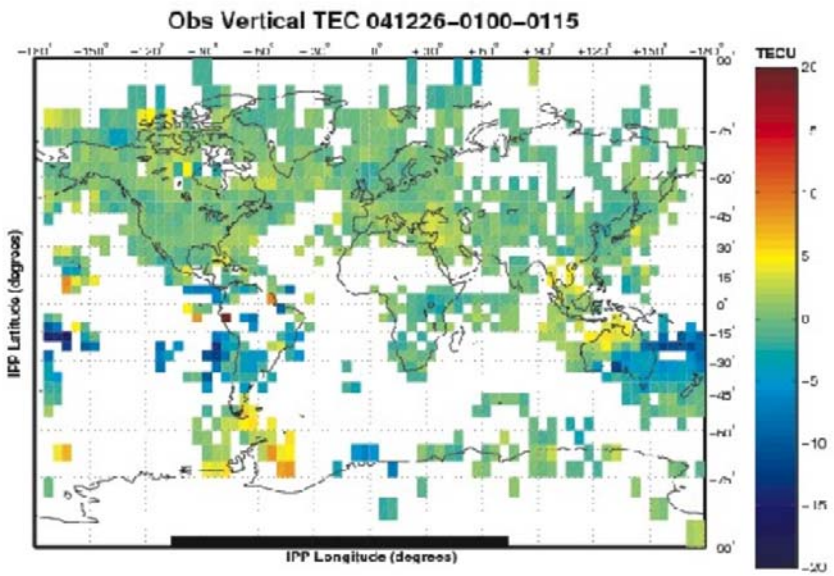


Fig. 2.42. Global coverage of 1000 GPS tracking stations for December 26, 2004. Vertical TEC is plotted and a 5-day average ionosphere has been removed.

occultation event probing the neutral atmosphere from the near-surface up to the upper stratosphere (about 40 km altitude) at 200 meter vertical resolution. The data for the points shown were received by national weather prediction centers between March 1-7, 2007. Figure 2.41a shows the zonal mean temperature retrieved from the F3C GPS refraction measurements. Note that in the lower troposphere (below about 7 km altitude in the tropics, about 2 km altitude in the mid-latitudes), the retrieval of temperature information from GPS radio occultations requires the use of *a priori* information as constraints and hence this information cannot be considered as completely independent measurements. The zonal temperature structure observed by the sole F3C retrievals is consistent with known climatology (for example, tropopause around 15 km altitude in the tropics, double structure around 60°N latitude). As expected, the Tropics present a smaller variability than the mid-latitudes (Figure 2.41b). A region of strong variability can be observed in the stratospheric Northern polar vortex as the Arctic region emerges from the winter polar night. Because of the multitude of receivers, these results can be generated with only one week of GPS radio occultation data with high vertical resolution. In the future, more GNSS receivers in space could decrease the time needed to get such a global picture of the atmosphere. The temperatures retrieved from the GPS radio occultation technique as shown here are invaluable in the sense that they provide atmospheric physicists with a fairly new and now near-complete coverage of the Earth's atmospheric mass field in the upper troposphere and stratosphere, complementing passive measurements from existing infra-red and micro-wave sounders.

Another emerging technique for atmospheric sounding is LIDAR, which, in principle, can be used to measure atmospheric CO_2 (see Section 2.4.5). One currently developed approach is a ground based zenith viewing LIDAR to measure CO_2profiles as function of time (roughly hourly) with an altitude range of a few km, that is essentially to the top of the boundary layer (Burris et al., 2006). The other alternative is a down-looking CO_2 sounder to measure CO_2 content in the column below an aircraft or, eventually, from space (Abshire et al., 2007). The implication of these new developments are further discussed in Section 5.7.1.

2.9.2 Ionospheric remote sensing: one person's signal is another person's noise

The signals from the GNSS satellites must travel through the earth's ionosphere on their way to receivers on or near the earth's surface. To achieve the highest possible positioning accuracies for geodetic and surveying applications, one must correct for the propagation delays imposed on the signals by the ionosphere. Whereas these effects may be considered a nuisance by most GNSS users, they will provide the researchers with an opportunity to use GNSS satellites as a tool to better understand the plasma surrounding the Earth. The dispersive nature of the ionosphere makes it possible to measure its TEC using dual-frequency e.g., GPS observations collected by ground and spaceborne receivers.

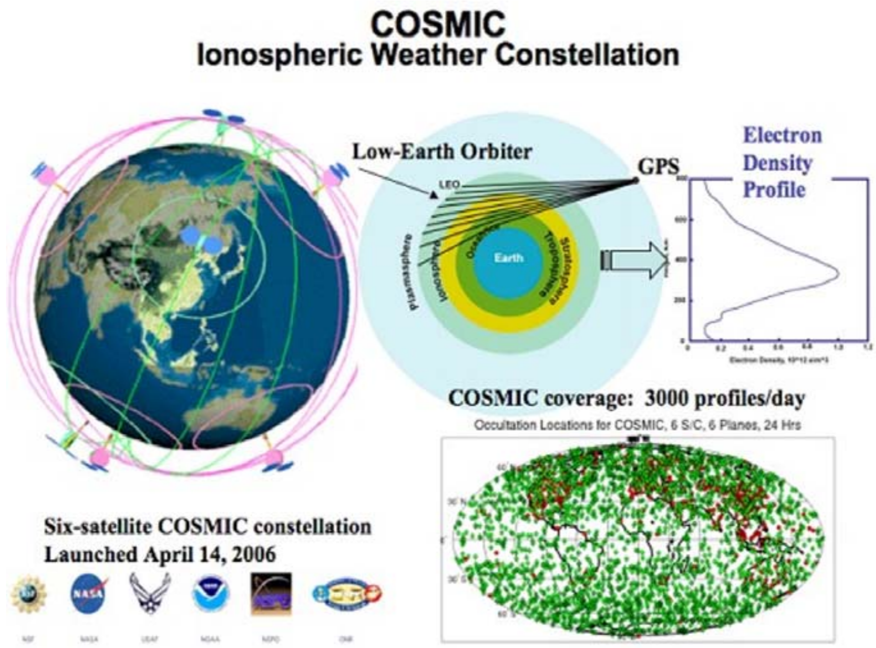


Fig. 2.43. Schematic view of COSMIC ionospheric occultations and the expected 3000 daily profiles.

There are a number of techniques available to mitigate the ionospheric effect including global empirical and physics-based ionospheric models. For geodetic applications, the most effective technique has been to use dual-frequency GPS observations to estimate TEC. Between 1997 and 2007, the number of GPS ground receivers has increased approximately by an order of magnitude. Currently, there are more than 1500 globally-distributed dual-frequency, ground-based GPS receivers available using publicly accessible networks including, for example, the IGS and Continuously Operating GPS Stations (CORS). To take advantage of the vast amount of GPS data worldwide, researchers use a number of techniques to estimate parameters e.g., satellite and receiver inter-frequency biases, directly affecting the GPS TEC measurements of the ionosphere. Most techniques estimate vertical ionospheric structure and, simultaneously, hardware-related biases treated as nuisance parameters (e.g., Mannucci et al., 1998, 1999; Schaer et al., 1998). Other approaches take advantage of all available GPS receivers and calibrate the biases using processing algorithms based on Global Ionospheric Mapping (GIM) techniques developed at various research centers (for illustration using about 1000 GPS stations, see Figure 2.42). These techniques are designed to estimate receiver biases for all stations in the global network and solve for the instrumental biases by modeling the ionospheric delay and removing it from the observation equation (Komjathy et al., 2005).

We seem to be in the midst of a revolution in ionospheric remote sensing driven by not only the abundance of ground but also the space-based GPS receivers, new UV remote sensing satellites, and the advent of data assimilation techniques for space weather. The GLONASS constellation is nearing its completion and GALILEO satellites are expected to contribute significantly to ionospheric data coverage starting in the early next decade. As for spaceborne data coverage in particular, the COSMIC 6-satellite constellation was launched in April 2006 (see Figure 2.43). COSMIC now provides unprecedented global coverage of GPS occultations measurements (1700 per day as of May 2007), each of which yields electron density information with unprecedented $\sim$1 km vertical resolution. Calibrated measurements of ionospheric delay suitable for input into assimilation models is currently made available in near-real time (NRT) from COSMIC with a latency of 30 to 120 minutes. Similarly, NRT TEC data are available from two worldwide NRT networks of ground GPS receivers ($\sim$75 5-minute sites and $\sim$125 additional hourly sites, operated by NASA JPL and others). The combined NRT ground and space-based GPS data sets provide a new opportunity to more accurately specify the 3-dimensional ionospheric density with a time lag of only 15 to 120 minutes. With the addition of the vertically-resolved NRT occultation data, the possibility exists of retrieving the hour-to-hour ionospheric "weather" much more accurately than previously possible.

New Global Assimilative Ionospheric Model (GAIM) techniques are used to monitor space weather, study storm effects, and provide ionospheric calibration for various users including NASA flight projects. GAIM is a physics-based 3D data assimilation model that uses both 4DVAR and Kalman filter techniques to solve for the ion and electron density state and key drivers such as equatorial electrodynamics, neutral winds, and production terms (e.g., Mandrake et al., 2005; Schierless et al., 2004; Spencer et al., 2004). Daily GAIM runs typically accept as input ground GPS TEC data from more than 1200 sites, occultation links from CHAMP, SAC-C, and the COSMIC constellation, UV limb and nadir scans from the TIMED and DMSP satellites, and in situ data from a variety of satellites (DMSP and C/NOFS). Real-Time GAIM (RTGAIM) ingests multiple data sources in real time, updates the 3D electron density grid every 5 minutes, and solves for improved drivers every 1-2 hours.

The abundance of ground and space-based GPS ionospheric observations is expected to help create new and exciting applications including e.g., space weather monitoring during ionospheric and geomagnetic storms (e.g., Fedrizzi et al., 2005) and developing a tsunami early warning system using GPS-derived ionospheric signals. Researchers have shown considerable progress in understanding the geophysics of tsunami-atmosphere coupling and determine the feasibility of using GNSS technology as part of an improved future tsunami warning system complementing more traditional methods of tsunami detection.

2.9.3 Tide gauges

Sea level measured by tide gauges is an important parameter for geodesy for several reasons. For example, geodetic datums in most countries have been defined historically in terms of sea level measured at their coasts. A second example concerns the linkage of GGOS to other components of global observing, notably the Global Climate Observing System (GCOS) and the Global Ocean Observing System (GOOS).

Historical tide gauge records are mainly derived from float and stilling well devices. Tide gauges based on mechanical float devices have lasted for more than 150 years. Still in 1983, a survey conducted by the International Oceanographic Commission (IOC) of United Nations Educational, Scientific and Cultural Organization (UNESCO) showed that 94% of the tide gauges were mechanical. The situation has considerably changed since then. The floating gauges are progressively replaced by new technologies. Modern types of gauges are mainly based either on the measurement of the subsurface pressure, or on the measurement of the time of flight of a pulse, acoustic or radar. It is worth pointing out here that, whatever the technique is employed, the basic quantity provided by tide gauges is an instantaneous height difference between the level of the sea surface and the level of a fixed point on the adjacent land. Hence, tide gauges not only record ocean tides but also a large variety of sea-level signals that can be caused by variations in atmospheric pressure, density, currents, continental ice melt, as well as vertical motions of the land upon which the measurement instrument is located. The recorded processes have characteristic time scales from several minutes to centuries. Many other scientific applications than tidal research and modelling may therefore benefit from tide gauge records (Woppelmann et al., 2006).

Sea-level data from tide staffs or tide gauges have been used for more than a century to establish vertical reference systems on land and on sea in order to define the height and depth datums. The main elements in a height-system definition are an origin, a vertical reference surface of zero level, and a ”type” of height, for example dynamic heights. The geoid, defined as that equipotential surface of the Earth’s gravity field that most closely coincides with the mean sea level, was originally selected as reference surface because it was believed that the average level of the sea was constant over long periods of time, which we now know it is not true. In general, each Country chose one tide gauge station for the computation of the ”mean sea level” over a certain arbitrary period of time. However, whatever the choice of the site, the mean sea level varies from place to place and at one specific place over time. Therefore different height datums may refer to different equipotential surfaces, resulting in constant offsets between them. Space geodesy provides the mean to evaluate these offsets in a well-defined geocentric reference system (Woppelmann et al., 2006).

At present, vertical crustal motions at tide gauges can be measured to high accuracy independently of the sea-level reference surface by means of space techniques, therefore it will be possible to separate the crustal motions from the absolute sea-level variations. Tide gauge measurements are difficult to compare because tide gauges are referred to local reference systems and they have not yet been connected on a common datum. However, it should be pointed out that several international efforts are underway both at global (IOC, 1997; International GPS Service, 2001) and regional scales (Zerbini et al., 1996; Becker et al., 2002) which aim to overcome this problem.

Nowadays, gauges are available based on many technologies (digital float, radar, acoustic, pressure) which can provide low latency, accurate sea level information optimized for the particular installation. For tide gauge details see IOC (2006). Traditionally, tide gauges measure local sea level with respect to a nearby benchmark on land. Modern geodetic techniques provide the means to position the tide gauges in a global geodetic reference frame (see Figure 2.44). Today, permanent GNSS stations (and in some cases DORIS stations) at tide gauges are used to determine the land motion at these sites in a global reference frame, and to position the tide gauge in the same frame as the satellite altimeters (see also Section 3.7 and below). Measurement of vertical land movements at gauge sites allows the determination of sea surface height changes in the same reference frame as the altimeter data. Absolute gravity measurements provide an independent control of the vertical land motion rates determined from the GNSS observations, and help to eliminate a bias of these rates due to a potential secular motion of the reference frame origin with respect to the CM. At some sites, an additional GNSS station is used in a dual-CGPS approach (Plag et al., 2000a) to control the stability of the tide gauge monument with respect to the adjacent land, thus replacing or augmenting episodic leveling.

Internationally, tide gauge sea level measurements are coordinated through the Global Sea Level Observing System (GLOSS) of the IOC (Woodworth et al., 2003). GLOSS defines a worldwide Core Network of approximately 300 stations (see Figure 2.45 on page 83), which is densified by means of inclusion of regional and national networks. The use of GPS at gauge sites is the topic of the current IGS TIde GAuge Pilot Project (TIGA).

GLOSS does not dictate to tide gauge operators which technology is preferable; GLOSS standards simply require measurements to better than 1 cm accuracy in all weather conditions. However, especially since the Sumatra tsunami of December 2004, one would expect that any new GLOSS installation would consist of dual gauges (e.g. a “sea level” gauge based on radar, and a “tsunami” gauge based on pressures) and dual telemetry. Data flow would be both near-real time (especially so for tsunami and storm surge applications) and delayed-mode for scientific applications.

Geodetic techniques have extended the number of ways by which local sea level can be measured. Techniques which have been developed in the last few years include the use of GPS on buoys (in effect extending coastal tide gauge measurements off-shore), and the use of GNSS scatterometry and reflectometry (see Section 2.4.4). The emerging use of GNSS receivers for earthquake magnitude determination (Blewitt et al., 2006b), with tsunamis being the potential sea level consequence, indicates another role for space geodetic techniques in a sea level observing system.

However, even in the established methods, geodesy has resulted in major improvements. Positioning of sensors (such as tide gauges and ocean buoys) in a global reference frame has already been mentioned above. The provision of precise timing

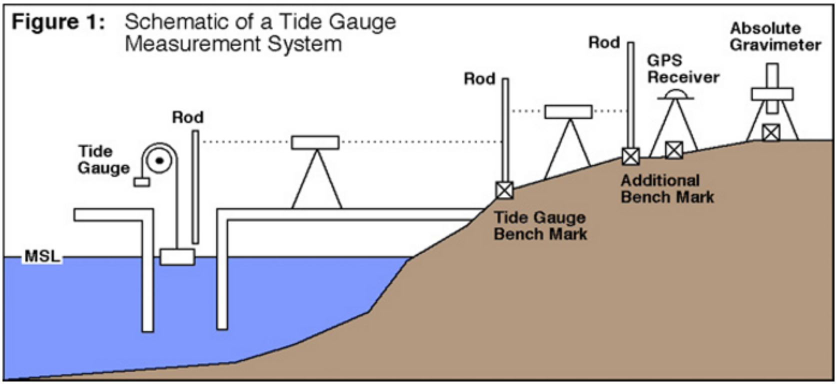


Fig. 2.44. Principle of tide gauge measurements. From http://sealevel.colorado.edu/tidegauges.html. See also IOC (2006).

through GNSS (see Section 2.9.4) to the equipment (for example, the clock of a tide gauge) is another example. Before GNSS, positioning and timing were accomplished by almost as many methods as research groups. The result of the new techniques and a more standardized approach is more precise data and meta-data with consequent improvement in our knowledge about sea level.

Geodesy has in effect terminated some traditional areas of work. An example concerns the replacement of chart datum as the height reference on nautical charts, hitherto based on interpolations of information on lowest astronomical tide at tide gauges, with the use of geo-located tide gauge data and off-shore mean sea surface information from altimetry, together with the availability of GPS positioning to mariners. Another example includes the replacement of long distance leveling by GNSS-minus-geoid, thanks to the availability and accuracy of GPS and regional geoid information, with most recent geoid improvements following GRACE operations and further ones anticipated from GOCE (see Section 2.6.5).

Today, the largest database of monthly mean tide gauge data is provided by the Permanent Service for Mean Sea Level (PSMSL). Since 1933, PSMSL has been responsible for the collection, publication, analysis and interpretation of sea level data from the global network of tide gauges. The PSMSL is a member of the Federation of Astronomical and Geophysical Data Analysis Services (FAGS) established by the International Council for Science (ICSU), and it is based in Liverpool at the Proudman Oceanographic Laboratory (POL).

The database of the PSMSL contains monthly and annual mean values of sea level from almost 2000 tide gauge stations around the world (Figure 2.45, upper diagram) received from almost 200 national authorities. On average, approximately 2000 station-years of data are entered into the database each year, and in December 2006, the database contained over 55000 station-years.

The data are provided in two data sets, namely the METRIC data set containing basically all data, and the Revised Local Reference (RLE) data set containing records for which the history of the local reference is known so that time series anal-

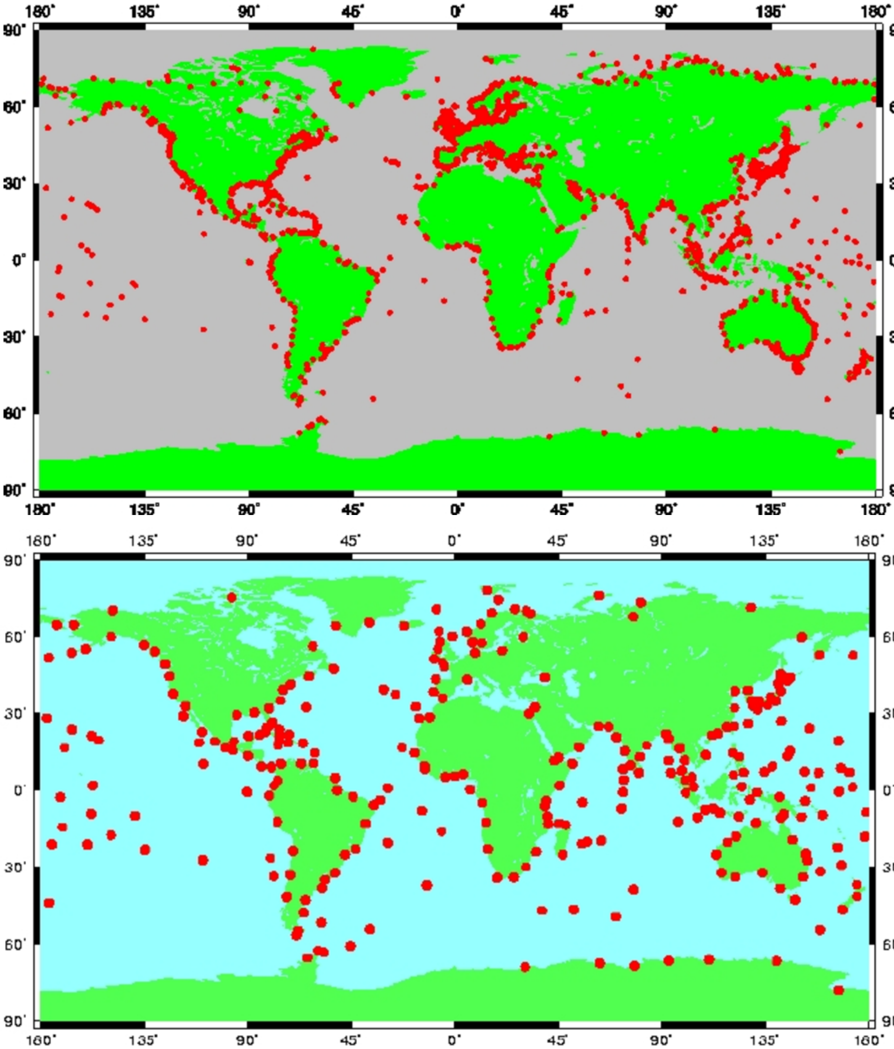
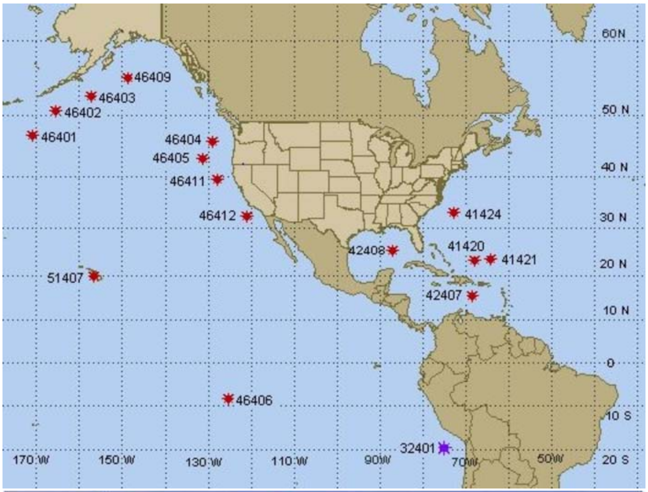


Fig. 2.45. Upper diagram: location of the roughly 2000 tide gauges for which data are stored in the PSMSL data base. Lower diagram: locations of tide gauges in the GLOSS core network.

ysis of secular sea level changes can be performed (Woodworth & Player, 2003). Long records from this data set have been the basis of most analyses of secular changes in global sea level during the last century. The geographical distribution of longer RLR records contains significant geographical bias towards the northern hemisphere, a situation which is being rectified by the establishment of the GLOSS global sea level network (Figure 2.45, lower diagram). A major conclusion from the



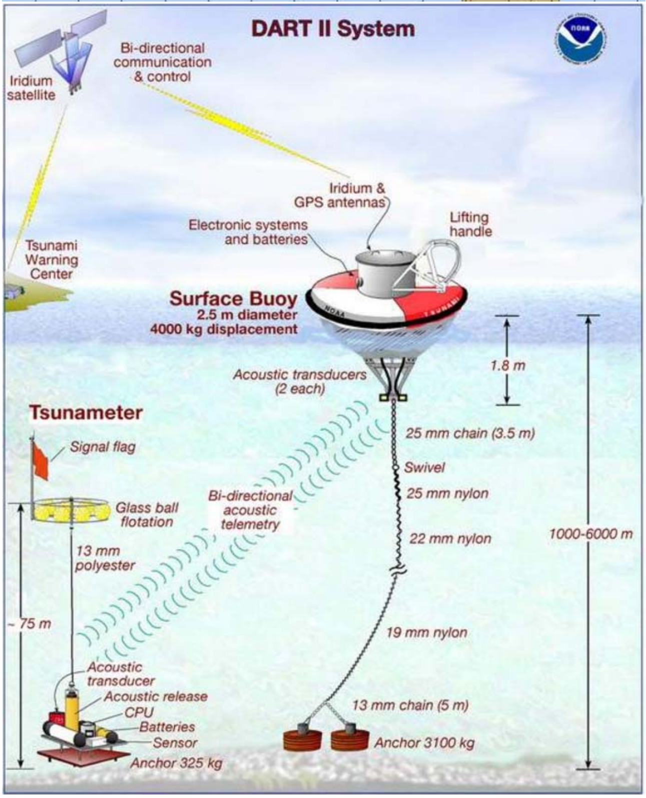


Fig. 2.46. NOAA's DART stations. Top: Location of NOAA's DART stations. Bottom: Schematic illustration of the DART system. For explanation, see text. Figures taken from NOAA's DART system page at http://www.ndbc.noaa.gov/Dart/dart.shtml.

global tide gauge data has been that global sea level has indeed risen by approximately 10 to 20 cm during the past century (Church et al., 2001).

BottomBottom Pressure Recorders (BPRs) use similar pressure sensors to those in coastal pressure tide gauges with two main differences. One is that the sensors obviously have to be capable of operating at greater depths (often down to 5000 m) and as a consequence are more expensive. The other is that they have to be 'absolute' sensors, recording total pressure at the sea bed, which includes the pressure due to the water plus atmospheric pressure. In coastal pressure gauges, it is more normal to use a 'differential' sensor, which is compensated for atmospheric pressure, although absolute sensors employed in combination with conventional barometers are also available and are preferred by some operators.

Data from deep ocean bottom pressure recorders are particularly relevant for comparison to temporal space gravity data from missions such as GRACE. However, only a few BPRs have been deployed so far explicitly for such comparison purposes; the POL BPRs in the South-West Atlantic being one example (Hughes et al., 2007).

BPRs have a long history in oceanography, but were developed most intensively in the 1970-1980s for tidal research (Spencer & Vassie, 1997). Instruments were placed on the sea bed for typically a year and recovered during a second visit by a research ship. This provided a one-year record which was adequate for a tidal analysis. More recently, BPRs have been deployed for longer periods (up to 5 years for the POL Multi Year Return Time Level Equipment (MYRTLE)) for non-tidal studies, such as monitoring the variability of ocean currents. Data retrieval remains a major issue, and recovery by means of acoustic release of the whole BPR by a ship is still the main method. MYRTLE additionally contains a number of 'data podules' which are released by a timing mechanism at regular intervals (e.g., once a year) with data transmitted from the podule to a satellite when on the surface. The podule itself may be recovered if a ship happens to be nearby but can otherwise be considered disposable.

However, this technology can never provide real-time information required for tsunami warning systems. For that, one requires undersea cables or the use of acoustic transmission from a BPR to a surface buoy. The most advanced systems currently in use are the Deep-ocean Assessment and Reporting of Tsunamis (DART) stations deployed by NOAA mainly in the Pacific (Figure 2.46a). DART systems consist of an anchored seafloor bottom pressure recorder (BPR) and a companion moored surface buoy for real-time communications (Gonzalez et al., 1998, see Figure 2.46b). An acoustic link transmits data from the BPR on the seafloor to the surface buoy. The data are then relayed via a GOES satellite link to ground stations (Milburn et al., 1996), which demodulate the signals for immediate dissemination to NOAA's Tsunami Warning Centers.

A major source of uncertainty in understanding sea-level variations from tide gauges is the accurate knowledge of vertical crustal movements which are embodied in the sea-level measurements. In fact, tide gauges measure sea-level changes as the difference between the height of a geodetic benchmark attached to the Earth's crust and the height of the sea surface. Vertical land movements need to be accounted for if tide gauge records are to be compared to satellite altimetry measurements of sea surface height changes. At global scale, post glacial rebound, a vertical crustal motion due to the isostatic readjustment of the Earth's crust to the last deglaciation, is the only coherent geological contribution to the long-term sea-level change for which a thorough understanding of the physical process has been achieved (Mitrovica et al., 1994; Peltier, 2004). Isostatic adjustment is the process by which the Earth attains gravitational balance with respect to superimposed forces. If a gravitational instability occurs, the crust rises or sinks to compensate this instability. Modeling the post-glacial rebound effects, however, still leaves in the vertical crustal rates different regional and local isostatic components as well as tectonic effects which are difficult to model.

At present, vertical crustal motions at tide gauges can be measured to high accuracy by means of space techniques such as, for example, the GNSS DORIS (Soudarin et al., 1999). Continuous GPS, however, has shown to be the technique of use in this particular application due to the ease of use, high precision, and its direct connection to the ITRF through the products of the IGS. On the other hand, by means of simultaneous GPS measurements performed at tide gauges and at fiducial reference stations of the global reference system, tide gauge benchmarks can be tied in a global well-defined reference system (Becker et al., 2002; Zerbini et al., 1996). The possibility to refer the tide gauge data to the same high precision global reference system allows the comparison between the different tide gauge data sets to be made. This was not the case until about 15 years ago when tide gauge benchmark coordinates were mostly available in the different national height systems.

The long-term sea-level trends at tide gauge stations is measured to about 0.3-0.5 mm/yr (Zerbini et al., 1996), provided that the time series are long enough (20-50 years). The accuracy required by GPS shall be in the same range; tide gauge positions must be monitored at the level of 10 mm absolute position error so that a long-term trend with a realistic error of 0.3 mm/yr can be obtained over 20 years or so (Becker et al., 2002). The current accuracy of GNSS products provided by International GNSS Service (IGS) is 3, 3, 6 mm for weekly mean values of the north, east and up coordinates respectively and 2, 2, 3 mm/yr for the associated linear velocities (see for instance Altamimi et al., 2002, 2007), with a significant contribution of the error in the velocities originating from long-term stability of ITRF (Blewitt et al., 2006a). The height determination using GPS data is a delicate task because of several reasons, among them, the atmospheric refraction in the troposphere and the geometric weaknesses in the height component of the GPS in general, and the complicated interactions of the GPS receiver and antenna hardware imperfections (like antenna phase-center variations and multipath). Moreover, with the exception of areas with natural or anthropogenic subsidence, active tectonics and strong seismic events, vertical rates are smaller by an order of magnitude as compared to the horizontal crustal motions, i.e. they are in the mm/yr range (Woppelmann et al., 2006).

2.9.4 Geodetic time and frequency transfer

High-accuracy geodetic methods using dual-frequency GPS observables are now routinely employed to produce positioning repeatabilities globally at the centimeter level for one-day integrations, as demonstrated for example in products of the IGS. Similarly, the same methods have been shown to produce equivalent global time and frequency comparisons with precisions approaching about 100 picoseconds at each analysis epoch, but whose accuracies are limited to roughly the 1-ns level because of instrumental calibration uncertainties, particularly for the GPS antennas. Current techniques yield calibration uncertainties of about 3 ns for standard GPS antennas (Plumb et al., 2005).

The essential ingredients for the geodetic GNSS method involve the availability of dual-frequency carrier phase as well as pseudorange (code) observables, recorded typically at 30 s intervals, together with an analysis modeling of one-way signal propagation accurate to the millimeter level. Standard errors for GPS phase and code data are about 1 cm and 1 m respectively with multipath believed to be the dominant source of error for both. The code data are needed to separate the otherwise indistinguishable clock offset and phase cycle ambiguity. The effect of utilizing both observables in this way is that the noisier code data are effectively smoothed by the more precise carrier data and that the overall accuracy of the time transfer is determined from the code data; the precision within a continuous analysis arc (typically 1 day) is determined from the quieter carrier data. Formal errors for the geodetic clock estimates are typically about 120 ps (3.6 cm), but have been shown to be highly optimistic in many cases. A more realistic measure of the accuracy may be determined by performing a classic repeatability test, comparing the agreement at successive analysis arc boundaries. Such a test is only feasible if the underlying clock stability is sufficient, which effectively restricts its use to GPS receivers equipped with an external H-maser frequency standard. A detailed analysis of day-boundary clock estimate discontinuities was performed for a subset of stations contributing to the IGS Combined Clock Products (Ray & Senior, 2003, 2005). The analysis showed that performance is highly site-specific, varies widely among the stations studied, and is independent of the choice of receiver or antenna model used. In many cases, poor performance or abrupt changes in performance was traced to changes in equipment or installation problems such as loose cable connections or poor external frequency distribution. Some stations showed distinct seasonal variations in the level of discontinuities which can not be fully explained by thermal effects. However, in the best cases sites have day-boundary discontinuities (rms) that are commensurate with the formal errors. The stability floor for the current state of the art geodetic time transfer technique has been inferred to be about $2 \cdot 10^{-13}\tau^{-1/2}$ for τ intervals up to 1 day, consistent with a random walk process. Deducing the limit of the method beyond 1 day will require comparisons using more precise frequency standards such as cold atom clocks.

As evidenced in the above performance measure, the limit of geodetic timing is determined from the quality of the pseudorange data. Therefore, in order to achieve the highest quality time and frequency comparisons, there are some special considerations for monumentation and instrumentation which should be made to minimize multipath and signal reflections. Receivers vary widely with respect to their sensitivity to thermal effects and so thermal control of the receivers is generally necessary. Also, phase stable cabling with low thermal sensitivity should also be employed with cable runs having minimal length and environmental exposure. Thermal control of the antennas is not required (Ray & Senior, 2001, 2003; Rieck et al., 2003), however the antenna siting should strive to minimize code and phase multipath. Some recent work has also indicated the possibility that long-wavelength multipath from below may also be an issue (Ray & Senior, 2005; Elósegui et al., 1995). In the near future, the largest gains in performance will likely come from new GNSS broadcast signal modulations whose multipath characteristics are likely to be greatly improved over those of the current GPS system.

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