Chapter 9
The future Global Geodetic Observing System

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In this Chapter, we focus on the design of the geodetic observing system that will meet the specifications summarized in Section 7.7 and be able to sustain the products listed in Section 7.5. Thus, this Chapter treats GGOS as an observing system (see Section 1.3 for a discussion of the two different meanings of "GGOS"). In Chapter 10, the main focus will be on GGOS as an organization and the integration of GGOS in the global context of Earth observation.

GGOS has been organized by the IAG to work with the established IAG Services in order to provide the geodetic contribution to global Earth monitoring, including the metrological and reference system basis for many other Earth observing systems. GGOS is therefore one of the basic observing systems comprising GEOSS.

GGOS is complex, addressing relevant geodetic, geodynamic and geophysical problems, which have deep impact on vital issues for humankind, such as global change, sea level rise, global water circulation, water supply, natural disasters, risk reduction, etc.(see Chapter 5 for details). It is a visionary concept based on the requirements and specifications given in Chapter 7 and on the assessment of what components are needed to meet the very demanding goals.

In order to address the ambitious GGOS goals, we will integrate a multitude of sensors into one global observing system. In the following sections the focus will be on the technical design and rationale for the proposed GGOS. The individual components of the system will be discussed and the interaction between the components will be outlined, from the geodetic observations and the interfaces to the products for the users.

9.1 The overall system design

The overall GGOS is designed in such a way that it meets the requirements and needs of the scientific and the societal users (see Chapter 7). The tasks listed in Section 7.4 have been identified as the most important high-level tasks for GGOS,

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however, the tasks that will actually be performed individually or collectively by the IAG Services, not GGOS itself. This list implies a very complex system with many different sensors and instruments, on the Earth, in the air and in space, that are integrated to form a global observing system appearing to the outside world as one large, comprehensive “geodetic instrument” for monitoring the Earth system. In order to function as a large Earth observatory for the benefit of science and society, GGOS has to encompass not only global terrestrial networks of observatories and space missions devoted to geodetic Earth observation and planetary exploration, but also the communication infrastructure, analysis centers, coordinating centers, and Internet portals. GGOS will eventually generate the well-defined products that will provide the metrological basis for Earth sciences, geo-information science, and terrestrial and planetary navigation. GGOS, therefore, consists of the following four crucial components:

- **Instrumentation:** global terrestrial networks of observatories, Earth observing satellites and planetary missions;
- **Data infrastructure:** data transfer, communication links, data management and archiving systems, data and product dissemination centers, web portals, etc.;
- **The GGOS Portal:** a unique access point for all GGOS products with a database of relevant metadata compliant with international standards; and
- **Data analysis, combination, modeling:** complete and consistent data processing chains ranging from the acquisition and processing of vast amounts of observational data to the consistent integration and assimilation of these observations into complex numerical models of the Earth system.

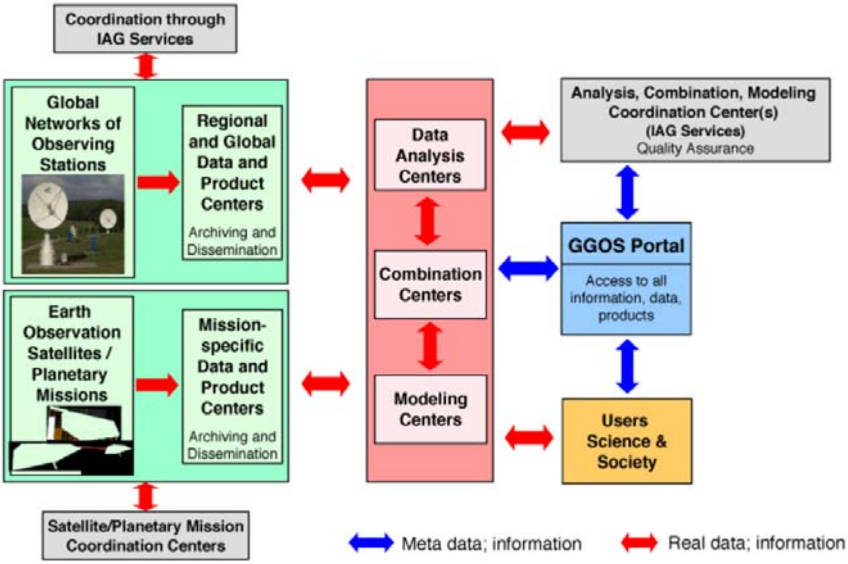

Fig. 9.1. The overall system design of the future GGOS including global observing networks, satellite missions, data centers, analysis centers and coordination centers, etc.

These four components are shown in Figure 9.1 and will be described in more details in the sections below. Figure 3.1 on page 92 shows how GGOS is designed to connect the space and terrestrial geodetic observations (left-hand side) to the Earth system components and their interactions (right-hand side) by way of the "three pillars of geodesy" (the Earth geometry and deformation, the Earth rotation and its variations, and the Earth gravity field with its temporal changes) in the center of Figure 3.1. The principal products of GGOS are summarized in Section 7.5 and the general accuracy requirement is provided in Section 7.6. From the accuracy requirement for GGOS of 1 ppb (including consistency between all GGOS products), it follows that consistent permanent (as opposed to sporadic) ground and space observations are required to meet the needs of science and society. In order to serve the purposes mentioned in Section 7.5, long-term stability and consistency among all GGOS products at a level better than 1 ppb is required, and the products must be available in due time (e.g., in real time for some of the applications) in order to meet user requirements.

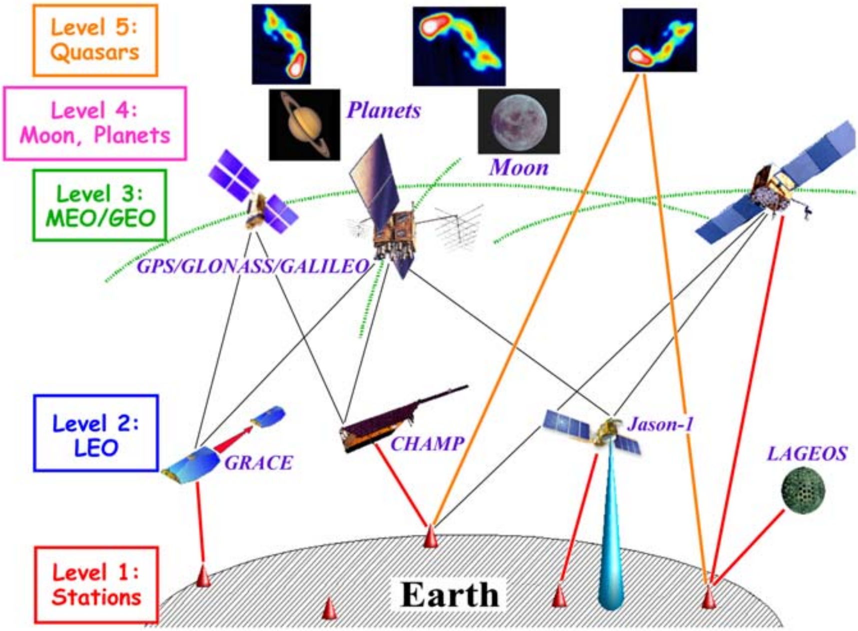

Fig. 9.2. The five levels of GGOS and their interactions with observations of various types. The combined infrastructure allows the determination and maintenance of the global geodetic reference frames, and the determination of Earth's gravity field and rotation. The ground networks and GNSS are crucial foir positioning. In particular, they allow the monitoring of volcanoes, earthquakes, tectonically active regions and landslide-prone areas. The LEO satellites monitor sea level, ice sheets, water storage on land, atmospheric water content, high-resolution surface motion, and variations in the Earth's gravity field. The latter are caused, to a large extent, by regional and global transport in the hydrological cycle.

9.2 The overall observing system design: the five levels

The GGOS will have five major levels of instrumentation and objects, which actively perform observations, or which are passively observed, or both, namely:

- Level 1: the terrestrial geodetic infrastructure;
- Level 2: the LEO (Low Earth Orbiter) satellite missions;
- Level 3: the GNSS and the Lageos-type SLR satellites;
- Level 4: the planetary missions and geodetic infrastructure on planets; and
- Level 5: the extragalactic objects.

These five levels, independent of whether they are active or passive, receivers or emitters or both, are connected (see Figure 9.2) by many types of observations in a complex way to form the integrated geodetic observing system. The major observation types at present are:

- Microwave observations of the GNSS satellites from the ground and from LEO satellites;
- Laser ranging to LEOs, dedicated laser ranging satellites, GNSS satellites, and the Moon;
- Microwave observation of extragalactical objects (quasars) by VLBI;
- Instrumentation onboard the LEO satellites measuring accelerations, gravity gradients, satellite orientation, etc.;
- Radar and optical observations of the Earth's surface (land, ice, glaciers, sea level, etc.) from remote sensing satellites;
- Distance measurements between satellites (K-band, optical, interferometry, etc.);
- absolute and relative gravity measurements; and
- tide gauge measurements.

In the future, new measurement techniques will evolve and will be included into the system. The individual parts (observation types) of the overall system are connected by the co-location of different instruments at the same site on the Earth, or on the same satellite or object. This co-location of instruments and sensors is extremely important for the consistency and accuracy of the system, so that it will act as one large "instrument" (see Section 9.3.8). Each of the techniques has its own strengths and weaknesses, and through co-locations, it is possible to exploit the strengths and mitigate the weaknesses so as to build the strongest possible observing system.

GGOS is not the first global geodetic observing system. Such systems existed for a long time to monitor seasons, to produce maps and to navigate reliably and accurately on the Earth. Prior to the space age, "predecessors" of GGOS consisted of only three levels, namely, globally distributed observatories (Levels 1), the Moon, the Sun and the planets (Level 4) and "fixed" stars and quasars (Level 5). Level 4 (the Sun, Moon and planets) of the historic systems was, so to speak, the predecessor of the GGOS Level 3 (the GNSS). Cross staffs, and then later optical telescopes and watches (first mechanical, then atomic) were the hardware components in Level 1 of the historical systems. Level 5 traditionally was the system of "fixed" stars. The star catalogues were realizations of the celestial reference frame.

9.3 Level 1: Ground-based infrastructure

The first level of GGOS consists of all terrestrial networks of geodetic ground stations contributing to the terrestrial reference frame or to Earth monitoring:

1) The global network of radio telescopes coordinated by the IVS;
2) The global network of SLR and LLR stations of the ILRS;
3) The global network of GNSS stations of the IGS;
4) The global network of DORIS stations coordinated by the IDS;
5) The global network of superconducting gravimeters comprised in the GGP and the global network of sites occupied episodically with absolute gravimeters;
6) The global network of tide gauge stations coordinated by the IOC; and
7) Global networks of geodetic timing stations.

Most of these observing stations are equipped with additional, complementary sensors and instruments (e.g., meteorological sensors, water vapor radiometers, etc.) and at many of the stations more than one instrument are co-located. The design of these networks as fundamental and integral parts of the GGOS is described in the following subsections (see also the respective Sections in Chapter 2).

9.3.1 Core network of co-located stations

The core of the terrestrial global GGOS network, the part realizing the integration of the various instruments on a global scale, will be a set of about 40 globally well-distributed core sites. These stations co-locate the major geodetic observation techniques and a variety of additional sensors. The co-location of the different techniques allows not only the integration of the individual technique-specific networks into a unique terrestrial reference frame (ITRF) but also the assessment of the observation quality and accuracy and the mutual validation of the results. A network of such core sites is mandatory in order to monitor the global reference frame at an accuracy of 1 mm or better over decadal time scales.

These core sites will be equipped with the following instruments, which are based on most recent sensor technologies, connected to real-time communications (data streaming), collecting data at the highest possible observation rates, operated automatically, and are highly reliable:

- at least two geodetic VLBI telescopes to ensure continuous VLBI observation (24 hours per day, 7 days a week), allowing for maintenance periods for individual telescopes;
- an SLR/LLR telescope to track all major satellites equipped with laser retroreflectors and, for some core sites, the Moon;
- at least three GNSS receivers and antennas to guarantee that individual antennas (and receivers) can be upgraded (e.g., for the tracking of new GNSS, such as GALILEO) without losing the precise local ties to the other antennas, thus ensuring long-term millimeter-level stability;

- a DORIS beacon of the most recent generation;
- terrestrial geodetic survey instruments to permanently and automatically monitor the local ties between the reference points of the space-geodetic technologies with 1 mm accuracy;
- ultra-stable oscillators for time and frequency keeping and transfer (with VLBI, GNSS, laser links, etc.);
- a superconducting and an absolute gravimeter to support gravity satellite missions and geocenter determination;
- meteorological sensors for measuring pressure, temperature and humidity;
- seismometer for earthquake detection, epicenter localization and the determination of rupture parameters in combination with deformation from the space-geodetic techniques and GNSS seismology; and
- a variety of additional sensors (water vapor radiometers, tiltmeters, large gyroscopes, groundwater sensors, etc.).

If major new observation technologies are developed in the future, which will supply complementary information, these sensors must be added to the instrument ensemble of a core site.

9.3.2 VLBI station network

The VLBI station network for 2020 is foreseen to have a size of about 40 globally-distributed sites with one or, even better, two telescopes at each site. These telescopes should be of the VLBI2010-type. Most of the currently used VLBI equipment was developed in the 1970s and 1980s, and the equipment is being pushed to the limits of performance and is costly to maintain. The existing antennas at many sites move slowly, which makes it difficult to provide the rapid whole sky coverage needed for the highest accuracy. Therefore, a rejuvenation of the VLBI network is crucial. In view of the requirements of GGOS, IVS Working Group 3 (WG3) on VLBI2010 was charged with examining the current and future requirements for geodetic VLBI systems. The group compiled their findings in the so-called VLBI2010 Vision Paper (Niell et al., 2006) and made recommendations for the next generation of the VLBI system. Recognizing the need for a standing body within IVS that would ensure the realization and implementation of the new system, the VLBI2010 Committee was set up.

The VLBI2010 system is envisioned to meet the following criteria: low cost of construction, low cost of operation, and rapid analysis and delivery of final results. To accomplish this, the center piece of the new system will be a small-antenna observing system (dish diameter of 12 m or larger) in concert with global high-speed network links. The lower sensitivity of a smaller antenna, as opposed to the present $\sim$20 m antennas, will be more than compensated for by high slew rates of at least 5 degree/sec and higher observational data rates (8-16 Gbps and higher), which will allow many more observations to be taken. The observing will be done over a broad, continuous frequency range (broadband delay approach) of 2-18 GHz allowing mitigation of any radio frequency interference.

The rapid advance of both magnetic-disk technology and global high-speed network technology will be utilized in VLBI2010. All data collection and transmission interfaces and formats will adhere to the set of internationally agreed VLBI Standard Interface (VSI) specifications. An array of antennas directly connected to the correlator via high-speed networks provides the possibility for real-time and near real-time processing to produce geodetic results within hours, which is particularly important to the rapid turnaround of Earth orientation parameter results.

The GNSS community has demonstrated the value of increasing the number of receiving sites and improving the geographic distribution. The present geodetic VLBI network has a very irregular distribution of antennas over the surface of the Earth. Africa, South America, and Asia are particularly under-represented compared to the other continents. Thus, important considerations for the planning of a new network are the number and the locations of the sites needed to satisfy the 1 mm goal. Although the detailed choices for deployment of new stations will be driven by a combination of science, economics, and politics, a quantitative estimate can serve to specify the lower limit for the number of sites.

The goal of combining GNSS, VLBI, SLR, and DORIS geodetic networks provides a guideline for the number of VLBI sites. The current uncertainty in GNSS daily horizontal measurements for a global network is approximately 3 to 5 mm and is unlikely to improve significantly. In contrast, the repeatability in regional GNSS networks of $\sim$1000 km is down to approximately 1 to 2 mm. For VLBI the horizontal repeatability of the Very Long Baseline Array (VLBA) antennas has been 1.5 to 3 mm over the past decade, while for the new VLBI system specified by the VLBI2010 Committee the horizontal accuracy is expected to be better than 1 mm. In order to take advantage of the best attributes of both GNSS and VLBI, the spacing of combined VLBI/GNSS sites should be of the order of 2000 km. Such spacing would require approximately forty sites (Eurasia (14), Africa (7), Australia (3), Antarctica (2), Greenland (1), North America (6), South America (6), Southern Pacific (2)) equipped with one (or preferably two or more) telescope(s) to allow continuous operation.

9.3.3 SLR/LLR station network

The estimated size of the GGOS SLR/LLR network is based on meeting 1 mm/decade stability in the origin and scale requirements for the reference frame. This stability is presumed achievable under realistic weather conditions and local network operational strategies. The same network is also expected to address the tracking needs of the large set of satellites anticipated in the GGOS 2020 time frame. In addition to the current distribution of satellite categories being supported by the ILRS, it is anticipated that there will be a significant increase in the number of GNSS satellites (GPS, GLONASS, GALILEO, COMPASS, etc.) that will be tracked in campaign mode. GGOS requires a globally distributed network of 30-40 SLR stations co-located with GNSS and VLBI, where a high percentage of these stations must also be co-located with either gravity instruments or DORIS beacons. These core observatories should be globally distributed, at sites with good weather conditions and stable geology. "Good weather sites" should permit ranging at least 60% of the time, and have weather patterns lacking strong seasonal signatures. Sites with stable geology do not show local motion, which would otherwise corrupt the reference frame stability. They should be several hundred kilometers away from plate boundaries, faults, and ridges. Bedrock would be ideal, but may not be practical at every site. Four stations (on four different continents) should have lunar ranging capability to continue the long time series of LLR since 1969. A number of the current SLR/LLR stations would likely be sites for the GGOS network. All SLR/LLR sites must be co-located with GNSS, and several should, in addition, be co-located with other instruments.

The network should be equipped with fourth generation systems with high repetition rates (10^2-10^3 Hertz), higher quantum efficiency detectors (either avalanche photodiodes or PMT quadrant or pixilated detectors), shorter dead-time between events, increased automated or autonomous operations, real-time communications for data flow and centralized operations monitoring, and improved calibration and diagnostic monitoring. The higher data rate will allow more rapid satellite acquisition and improved pass interleaving for satellite conflict resolution. Real-time data flow will improve upon the current 1 - 2 hour availability cycle.

Many of the fourth generation capabilities are now being demonstrated in current stations. 2 KHz operation is presently operational at the Graz SLR station. Others are actively pursuing it. Semi-autonomous and automated operations are currently routine at the Zimmerwald and Mt. Stromlo stations. The NASA SLR2000 prototype is being developed with many of the fourth generation capabilities. The stations at Zimmerwald, Matera and Concepcion have initiated studies of the two-wavelength concept for a more accurate refraction correction.

Earth ground-based laser experiments in 2005 to the Mercury Laser Altimeter (MLA) onboard the MESSENGER spacecraft enroute to Mercury, and to the MOLA onboard the Mars Global Surveyor (MGS) orbiting Mars, demonstrated that there is sufficient signal strength for interplanetary ranging measurements and that laser transponder experiments are capable of providing accurate spacecraft ranging and timing information. With the deployment of an optical receiver and accurate onboard timing system on the upcoming Lunar Reconnaissance Orbiter (LRO), one-way ranging to the moon should be operational in late 2008. Several groups are now working on two-way transponders for use in lunar and planetary ranging for studies of lunar and planetary dynamics and gravity field. As a result, many lunar range measurements with higher accuracy and much better temporal coverage will become available.

9.3.4 GNSS station network

The future global GNSS network (maintained by the IGS) will be a multi-purpose observation network. It will be of vital importance for:

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

To meet these goals the IGS station network of the proposed GGOS shall consist of a few thousand GNSS stations with the following characteristics:

- State-of-the-art receivers tracking all GNSS satellites, i.e., GPS, GLONASS, GALILEO, COMPASS, and similar navigation satellite systems yet to be developed. To achieve utmost accuracy and reliability all available GNSS satellites have to be tracked. The collection of data from more than one system makes GGOS independent of the individual systems. The receivers will record all major measurements of codes and carrier phases on all frequencies relevant for Earth observation.
- Homogeneous global distribution of sites, densely covering all major tectonic plates. In the case of a large earthquake, the effects on the global reference frame should be known and available in near real-time.
- Core sites (i.e., sites co-located with other space-geodetic instruments) shall be equipped with more than one receiver and antenna to allow for equipment upgrades without loss of accuracy and time-series continuity.
- All VLBI, SLR and the majority of DORIS sites shall be equipped with a co-located GNSS receiver.
- Sites shall be equipped with real-time data communication links and the possibility to collect data at a sampling rate of a few tens of Hz.
- GNSS receivers shall be connected to (and ideally driven by) ultra-stable oscillators, especially from time laboratories.

This network will be fundamental to connect, through co-location of instruments, all the other networks and to ensure that the positions of all sensors of the global geodetic observing system will be known in a unique global reference frame.

9.3.5 DORIS station network

The quality, density and homogeneity of the DORIS network have been continuously improving for 20 years (Fagard, 2006). With 56 well-distributed stations around the globe, it guarantees an excellent orbit coverage for the DORIS-equipped satellites. The density and homogeneous distribution of the DORIS network an important contribution, on the one hand, to the realisation of the ITRF, both by densifying the IERS network and through the co-locations available for a majority of the DORIS stations, and, on the other hand, to sea level monitoring, through co-locations with tide gauges at one third of the stations. Thanks to the general renovation process carried out over the past six years, almost all antenna monuments have now an excellent long-term stability of the antenna reference point. Moreover, the massive deployment of third generation beacons will ensure a higher performance and reliability of the network.

The IDS station network of the proposed GGOS shall consist of 60 to 70 stations with the following characteristics:

- A homogeneous global distribution of sites, covering all major tectonic plates. The IDS network shall permit the determination of the motion of all major plates, and shall provide a global and robust coverage for all DORIS-equipped satellites.
- The current network will be maintained, and a few new stations will be installed to fill gaps or improve robustness.
- The network provides support to current missions (SPOT, JASON-1, ENVISAT), and planned future missions (JASON-2, CryoSat-2, ALTIKA, etc.), at least until 2020.
- Third generation, or new state-of-the-art, beacons will improve the measurement quality and reliability.
- More beacons shall be connected to atomic clocks to provide a better connection to the International Atomic Time.
- All DORIS sites shall be equipped with accurate meteorological sensors to permit precise atmospheric corrections of the measurements.
- Long-term stability of the antenna reference points shall be at the cm-level over time frames of a few decades.
- DORIS equipment will contribute to core sites, i.e., stations co-located with other space-geodetic instruments (SLR, VLBI, GNSS). The DORIS/VLBI interference issue will be investigated and resolved to the extent possible.
- A homogeneous global distribution of sites co-located with tide gauges will help to accurately calibrate sea level change.

The network monitoring will be enhanced to ensure that the DORIS stations consistently provide reliable and precise measurements:

- Periodic site visits for equipment inspection, antenna stability checking, local geodetic survey;
- Daily monitoring of parameters such as status, failures, voltage, transmitted power on both frequencies, time synchronization, meteorological sensors status, USO warming time, etc.;

- Remote management and control of the DORIS beacons; and
- Increase the level of the operating rate to 90%, with daily monitoring of performance indicators.

9.3.6 Networks of gravimeters

For the proposed GGOS it is extremely important to couple the space-geodetic techniques delivering information about the geometry of the Earth (shape, deformation, orientation, and rotation) with gravimetric measurements not only from gravity satellite missions, but also from sensors on the Earth's surface. Most of the processes in the Earth system have an impact on all geodetic observations and the complementarity of gravimetric sensors is crucial for the separation of various processes involving mass transport.

To obtain time series of gravimetric measurements that improve the monitoring of the Earth system on a global level, a network of about 30 gravimetric stations (identical to the extent possible with core sites, see Section 9.4.1) should be established. Each of these stations should consist of a superconducting as well as an absolute gravimeter, both continuously measuring the gravitational acceleration and its time variations.

9.3.7 Network of tide gauge stations and ocean bottom geodesy

As reported in Section 2.9.3, tide gauge sea level measurements are coordinated internationally through GLOSS, which coordinates a network of about 300 tide gauge stations (see Figure 2.45 on page 83). By 2020, it is expected that all of the core tide gauge network sites, the majority of all other sites with long sea-level records, the stations which provide comparison data for altimeter calibration, and indeed many other tide gauge stations, will be equipped with GNSS receivers. These receivers have two functions: to enable the tide gauge measurements to be located in the same reference frame as the altimeter data, and to determine the rates of vertical land movement (see Section 2.9.3).

The historical tide gauge record has been derived primarily from float and stilling well technology. However, nowadays one can deploy acoustic, radar and pressure tide gauges, as well as digital float systems, each of which has its advantages and disadvantages (see Section 2.9.3 and IOC, 2006). Although GLOSS standards simply require tide gauge stations to provide measurements to better than 1 cm accuracy in all weather conditions, one would expect that any new GLOSS installation would learn from the experience of the Sumatra tsunami of December 2004, and therefore include dual gauges (e.g., a "sea level" gauge based on radar, and a "tsunami" gauge based on pressure measurements) and dual telemetry. Data flow should be both near real time (especially for tsunami and storm surge applications) and delayed-mode for scientific applications.

Currently, much experience is available from float, acoustic and pressure systems, while radar devices are relatively new. However, their low cost and ease of installation and maintenance, means that they may be widely used in future. By 2020, one would expect such devices to be both accurate and affordable. However, one would expect there to be an ongoing need for capacity building in their use in developing countries.

BPRs are also of importance for geodetic applications (see Section 2.9.3). 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). By 2020, the installation of a permanent global ocean network of 50-100 BPRs would be technically feasible. However, there are currently no firm plans for such a network, and the challenge of data transmission would need to be addressed seriously, unless the community wished to work only with delayed-mode information.

9.3.8 Co-location of instruments and auxiliary sensors

The co-location of different and complementary instruments is crucial for several reasons:

- Without co-location sites and highly accurate local tie information, it is impossible to establish a unique and common global reference frame for all major space-geodetic techniques.
- Co-location sites allow the comparison, validation and combination of estimated parameters common to more than one technique. The comparison is crucial for the detection of technique-specific biases, and furthermore the combination of common parameters strengthens the solutions.
- Complementary observation techniques may be the only way to separate the signals of different processes taking place in the Earth system.

Co-location should therefore not only be limited to the space geodetic techniques but include additional sensors that aid integration and combination. A list of such instruments is given in Section 9.3.1.

The measurement and monitoring of the local ties between different instruments should have a similar status and accuracy in the future as the observations of the space-geodetic techniques themselves. The local tie measurements should be performed with 0.1 mm accuracy, in a fully automated way and on an almost continuous basis, since local ties may change over time. These measurements have to account for any deflection of the vertical when relating the local ties to the geometric frame. Because of discrepancies in the results from co-located techniques, it is extremely important to be able to fully rely on the measured local ties. This will help to identify (and eventually correct) the considerable remaining systematic effects in the results of the individual observing techniques.

At core sites, local ties do not only have to be established between the reference points of the major space-geodetic observing technologies, but also to other sensors. As an example, the height differences between the reference points of the space-geodetic technologies and atmospheric sensors have to be known with decimeter accuracy for comparison, validation and combination purposes (e.g., the tropospheric delay difference between the GNSS and VLBI antenna reference point has to be taken into account when combining the tropospheric delay estimates from GPS and VLBI). The location of a water vapor radiometer with respect to the other observation techniques has to be known as well, and the same is true for gravimeters, tiltmeters, large gyroscopes, etc.

The core network (see Section 9.3.1) will be fundamental for the co-location of instruments. However, due to environmental conditions at the individual sites (geological and geodynamic stability, weather conditions for SLR/LLR, multipath environment, change in ground water table, etc.), it will not always be possible (or reasonable) to co-locate all instrument types at one location. “Isolated” instruments should then at least be tied to a unique global reference frame by setting up a GNSS receiver at the same location. All instruments must be co-located with GNSS.

9.4 Level 2: Low Earth Orbiter satellite missions and their applications

Satellites observing the Earth from space will be an indispensable component of GGOS in 2020. Satellites have the big advantage that they collect data homogeneously and consistently over large parts of the Earth surface. They also allow the collection of data that cannot be recorded at the Earth’s surface. These satellites are nowadays equipped with a multitude of sensors and instruments, monitoring the land, ocean and ice surfaces as well as the Earth’s gravity field and its temporal variations.

The potential and impact of satellite missions on Earth observation will increase considerably due to the fact that: (1) more and more satellite constellations instead of individual satellites will be launched increasing the temporal and spatial resolution of the data, and (2) satellites will be flown in “formations,” forming large observing instruments composed of sensors on more than one satellite.

Due to the importance of the satellite component for the GGOS design and products, the observation of certain geodetic/geophysical parameters of the Earth (e.g., the gravity field and its temporal variations) by a satellite mission should not end with this dedicated mission, but has to be continued with follow-on missions establishing eventually a chain of missions (as in the case of the altimetry missions TOPEX, JASON-1, JASON-2, and ERS-1, ERS-2, ENVISAT, etc., see Table 2.2). Such “chains” of satellite missions are crucial for monitoring the Earth system over long time periods and for the detection of long-term trends and changes in the Earth system. Therefore, they should be viewed as a strategic element of the GGOS.

9.4.1 Gravity satellite missions

The gravity field missions CHAMP and GRACE (see Section 2.6.5) have made to a huge improvement to our knowledge of the Earth's static and time-variable gravity field. The missions have improved the accuracy of the static gravity field models by a factor of at least 100 compared to pre-CHAMP models, which were mainly determined from satellite laser ranging data. Based on monthly gravity fields determined from CHAMP and, in particular, GRACE data, seasonal variations and trends in the Earth's gravity field can be monitored, providing unique information about relevant mass transport phenomena like the water cycle in large river basins, the melting of ice sheets in Antarctica and Greenland and the associated sea level change, as well as in the ocean current systems. ESA's GOCE mission will lead to another significant improvement in the resolution and accuracy of the Earth's static gravity field and of our knowledge of the ocean current systems. GOCE will also mark an important step toward a more accurate unified global vertical reference frame.

In view of these developments, it is clear that present and future satellite gravity field missions will play a crucial role in GGOS. An uninterrupted monitoring of the temporal variations of the gravity field is of utmost importance for global change studies, i.e., the reliable detection of small trends in the gravity field due to sea level rise, the melting of ice sheets and changes in the ocean current systems.

To avoid any gaps in the time series – GRACE may last till 2013 – a GRACE follow-on mission with only minor design changes is crucial, because the development of new technologies may require several years and might not be ready before the decommissioning of the GRACE pair of satellites. GGOS will have to work with the space agencies to ensure this follow-on mission.

For mission concepts beyond 2013, new scientific challenges, for example, global ocean circulation, hydrological cycle, secular trends of geoid, ice sheet and glacier evolution, crust and lithospheric structure and dynamics, big earthquakes, and vertical datum improvement, require higher temporal resolution, higher spatial resolution and higher accuracy (see Figure 3.5). Accordingly, different sensor designs such as quantum-gradiometers, low-low and high-low Satellite-to-Satellite Tracking (SST) or ranging, optical clocks, etc., might be required.

One obvious concept to improve the accuracy of inter-satellite measurements (low-low SST) is the replacement of the K-band link of the GRACE mission concept by an optical link (i.e., a laser interferometer). A gain of a factor of 100-1000 in the accuracy of the inter-satellite measurements can be expected from such a development. Initial studies of such a concept have been performed by NASA and are presently being conducted by ESA as well. With such accuracies, the de-aliasing of the gravity field determination (removal of effects from high-frequency signals from the atmosphere, ocean tides, etc.) will become a major challenge. The same is true for the separation of the gravity signals resulting from different Earth processes. Different orbit constellations and different types of satellite formations will have to be considered for this purpose. In addition, complementary sensor systems (surface deformation monitoring with GNSS, ocean bottom pressure sensors, airborne gravimetry, superconducting gravimeters, etc.) will be crucial to allow for the separation of different processes. Sensor integration is therefore at the very heart of the GGOS concept.

It is possible that optical clocks will reach stabilities of 10^{-18} in about 10 years (see Section 2.7.3). Using the theory of General Relativity such clocks will allow the direct determination of potential differences between clocks corresponding to height differences on the level of 1 cm (geoid). With frequency comparisons between clocks in space and on ground, a consistent global vertical reference frame can then be established with very high accuracy.

9.4.2 Ocean and ice altimetry satellite missions

Radar altimetry proved to be a reliable and efficient technique for monitoring the global sea level and its changes. With currently four active radar altimetry missions (ERS-2, JASON-1, ENVISAT, GFO-1) and one launched recently (JASON-2), the global ocean can be observed with a reasonable accuracy. However, it must be ensured that the current constellation is maintained also for the future.

In January 2008, a CEOS Ocean Surface Topography Constellation Strategic Workshop held in Assmannshausen (Germany), discussed and outlined implementation plans for the next 15 years (Figure 9.3). Among others it was recommended to:

- maintain continuity of high-accuracy JASON-type altimetry;
- maintain continuity with altimeters on at least two complementary, high-inclination satellites; and
- extend the capability of altimetry to denser observational coverage through the use of the swath altimetry technique.

With JASON-2, high-accuracy missions will continue until at least 2013. Because JASON-2 for the first time is an EUMETSAT-operated mission to provide critical weather forecast data, continuation is likely. JASON-3 is now under approval.

For medium-accuracy high-inclination orbits, also covering much of the polar oceans, HY-2A (China) and Saral/ALTIKA (India/France) missions are to be launch in 2009. The HY-2A mission may be followed by similar missions. In addition, the Sentinel-3A (Europe) mission, to continue on the current ENVISAT orbit, may have follow-on missions.

With the launch of CryoSat-2 in 2009, also a dedicated mission for measuring the polar caps and the ice-covered oceans is planned. However, with no follow-

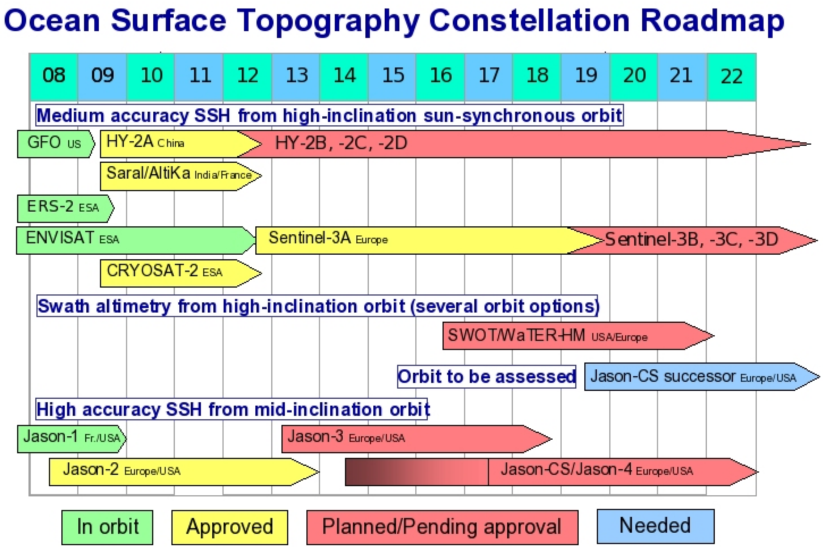

Fig. 9.3. Ocean Surface Topography Constellation, Strategic Workshop on Ocean Surface Topography Constellation, Assmannshausen (Germany, January 2008).

on missions there will be a critical gap in the observations of the climate-sensitive polar regions. GGOS efforts are needed to ensure the continuation of dedicated ice missions.

In the case of swath altimetry, allowing a more dense and flexible coverage, no plans exist so far for a mission before 2016 (SWOT/WaTER-HM mission). Previous attempts to carry a wide-swath altimeter on JASON-2 were cancelled in 2005 by NASA.

In summary it can be noted that, while in the past all missions have been operated by either the USA or ESA and France, future satellite constellations will benefit from contributions by other nations. This change makes it critical that the current open data policy be maintained, including the near real-time data distribution for operational applications as well as to ensure accompanying scientific studies.

9.4.3 InSAR and optical satellite missions

InSAR observations produce spatially continuous images of the deformation of the Earth's surface (see Section 2.4.5 for examples). These images are complementary to other space-based geodetic observations, which produce temporally smooth, but spatially discontinuous point measurements of surface motions. The need for improved coverage of the Earth's surface is obvious, particularly for geohazards and Earth sciences (see Chapter 5).

The recent National Academy of Sciences report "*Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*" (National Research Council, 2007) represents U.S. scientists' consensus on critical Earth observations from space that are required to address issues of climate change, water resources, ecosystem health, human health, solid-earth natural hazards, and weather. The Report recommends that the planned DESDynI mission, an L-band InSAR and laser altimetry mission, be launched in the 2010-2013 time frame. DESDynI would measure surface and ice sheet deformation for understanding natural hazards and climate, and vegetation structure for ecosystem health. DESDynI would help scientists understand the effects of changing climate and land use on species habitats and atmospheric carbon dioxide, the response of ice sheets to climate change and the impact on sea level, and would be used to improve forecasts of the likelihood of earthquakes, volcanic eruptions, and landslides.

Geodetic networks support InSAR by providing geodetic control for the observations. The geodetic networks also provide tropospheric and ionospheric maps for improving the quality of the interferograms. The geodetic data will be used to calibrate and validate the InSAR observations and, as mentioned above, will complement the InSAR observations by providing temporal continuity to the images.

NASA has proposed that a International SAR Information System (ISIS) be established. A group concerned with the ISIS has not yet been formed. This group would set data policies, would establish the ISIS as the vehicle for delivering InSAR data to the general science community, and would coordinate acquisition and processing of data. GGOS could be an important advocate or umbrella organization for this group.

By 2020 it is anticipated that a constellation of InSAR satellites with contributions from the USA, Europe, Brazil, Taiwan, China, and Japan. A coordinated constellation of InSAR satellites would provide multi-baseline observations for detailed topographic mapping and vegetation structure studies. The constellation would also allow for more frequent observations at particular locations, enabling more rapid response to events such as earthquakes, volcanoes, and landslides, as well as a better determination of time-dependent phenomena.

A combined treatment of imaging and point techniques will be crucial in order to calibrate the dynamic Earth reference model proposed in Chapter 8. For that purpose, SAR images need to be available at least for the globally distributed fundamental stations.

9.4.4 Future satellite mission concepts

Over the last few years satellite technology developments have been extremely rapid and have resulted in new concepts for future satellite missions. The most important new concepts are:

- Design of micro- or even nano-satellites;
- Constellations with large numbers of satellites;

- Formation flying; and
- New instrumentation.

Initially, the concept of micro- or nano-satellites has mainly been realized by university projects for students. Nowadays these developments are also pursued by national space agencies as an interesting alternative to small or large satellites to achieve certain mission goals. Due to the miniaturization of satellite components and sensors, micro-satellites can nowadays be used for challenging mission tasks at a fraction of the costs of satellites such as CHAMP or GRACE. Especially in connection with formation flying, or satellite constellations with a large number of satellites, this alternative concept becomes very attractive.

A constellation of a large number of satellites, possibly in different orbital planes and configurations, has the big advantage that the temporal and spatial resolution of Earth observations can be drastically improved. This can be seen from the number of daily radio occultations generated from the constellation of six COSMIC satellites, compared to individual satellites like CHAMP. Near real-time Earth monitoring based on satellite observations (e.g., for early warning systems) will require a constellation approach and inter-satellite communication to allow for a near real-time analysis of the data on the ground. Together with the micro- and nano-satellite concept mentioned above, constellations of 10-100 satellites will become feasible and affordable in the future.

Formation flying is a very interesting new aspect of satellite missions. Compared to conventional missions it adds two new "dimensions": (1) it allows for inter-satellite measurements (e.g., the K-band link between the GRACE satellite pair), and (2) it opens the door to build a virtual, more efficient/accurate instrument by integrating the instruments on several satellites into one large observing system (e.g., the integration of the Terra_SAR-X and TanDEM-X satellites for the generation of high-resolution DEMs). An example of a mixed concept of constellation and formation flying is the ESA SWARM mission, where two of the three different satellites fly in a formation to measure the East-West gradients of the magnetic field, and the third satellite orbits the Earth at a higher altitude to allow separation of different parts of the magnetic field.

In addition to the developments mentioned above, there will also be considerable progress in the instrumentation for satellite missions. Optical clocks may reach a stability of about 10^{-18} in the next decade. This will allow the direct measurement of the gravitational potential based on the effects of General Relativity on clocks (clocks in a strong gravitational field run slower than clocks in a weak gravitational field), and thus enable the unification of physical height reference frames at the centimetre level. Microwave links between satellites will be replaced by optical links (optical interferometers; e.g., for GRACE-type measurements) that will increase the precision of the inter-satellite measurements by at least a factor 100-1000. Reflectometry and scatterometry antennas for GNSS altimetry applications may become important add-ons to Earth observation satellites. In addition, inter-satellite communication technologies will make possible (near) real-time transfer to ground stations, as required for early warning systems.

9.4.5 Co-location onboard satellites

The co-location of different sensors and observation types onboard a satellite is extremely important to establish connections between the different observation techniques. These connections, and their complementarity, may be crucial to correctly modeling certain aspects of the observations (e.g., correction for non-gravitational forces with accelerometers in gravity field determination) and to separate effects stemming from different processes or components of the Earth system. In addition, the availability of complementary instruments on a satellite (e.g., different tracking systems like GNSS, SLR, and DORIS for precise orbit determination) allows for the connection of techniques at the satellite, which is complementary to those at co-location sites on the Earth's surface, and in addition allows for the detection of technique-specific biases.

A good example for this development is the rapid progress achieved in orbit determination with the tracking data of the TOPEX/Poseidon satellite using DORIS, GPS, SLR and altimetry (crossovers). For future satellite missions, emphasis should therefore be placed on satellites that establish links between different observation and tracking techniques. It is of particular importance that all GNSS satellites be equipped with laser retro-reflector arrays (Figure 9.4). Future VLBI observations of GNSS satellites should also be performed, establishing another link between techniques, which would directly connect the satellite frames to the ICRF.

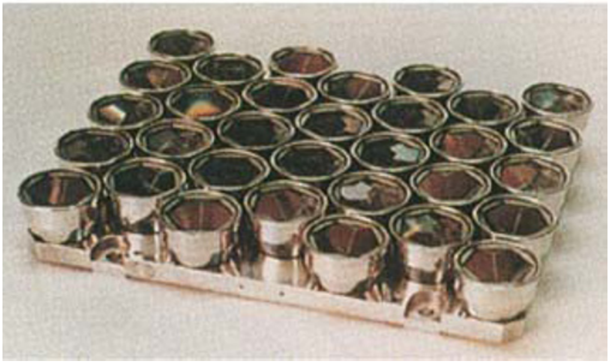

Fig. 9.4. Retro-reflector arrays on GPS-35 and GPS-36 satellites.

9.4.6 Airborne and shipborne sensors

Data from terrestrial and spaceborne instruments should be supplemented with data obtained from airborne platforms and ships. Typically, the data stemming from aircrafts and ships are rather local or regional in nature compared to the data collected by satellite missions. However, airborne and sea surface data with high spatial resolution are very important for assessing the quality and accuracy of satellite or ground-based data. They provide more detailed information about the processes being studied. Although the main focus of GGOS is on global aspects of Earth monitoring, most of the natural hazards are rather regional or local in extent. To understand them in detail, GGOS will strive, starting with the global perspective, for higher and higher resolution of the Earth monitoring in space and time.

Airborne and shipborne gravimetry illustrate how our knowledge of the global Earth gravity field from satellite missions can be densified and improved. The regional gravity data is combined with the global gravity field models from satellites to obtain the high-frequency part of the field.

9.5 Level 3: GNSS and laser ranging satellites

9.5.1 Global Navigation Satellite Systems

The GNSSs are evolving rapidly and a Global Navigation Satellite System of Systems (GNSSS) becomes realistic (Hein et al., 2007). The GLONASS is being replenished with a new generation of satellites to be completed by 2010. The first two GALILEO engineering satellites have been launched, with the full constellation to be completed by 2013. China is also working on a civil satellite navigation system (COMPASS). GPS will be upgraded as well: the first new generation satellites with a second civil signal (L2C) have already been launched. New GPS IIF satellites with three civil frequencies will be launched from 2009. A new GPS III constallation is planned for the end of the 2020 time frame.

Both Japan and India plan to launch smaller regional systems. The Japanese Quasi-Zenith Satellite System (QZSS) is planned to have three satellites in highly inclined geostationary orbits. The Indian Regional Navigation Satellite System (IRNSS) will consist of a seven-satellite constellation.

In addition, Satellite-Based Augmentation System (SBAS) for the GNSSs are developing and adding relevant infrastructure. The European Geostationary Navigation Overlay Service (EGNOS), the U.S. Wide Area Augmentation System (WAAS), the Japanese Multifunctional Transport Satellite Space-based Augmentation System (MSAS), the Indian GPS Aided GEO Augmented Navigation (GAGAN), and the Nigerian Communication Satellite (NIGCOMSAT). The SBAS are transmitting or will transmit additional signals to those of the GNSS signals, and all SBAS are planned to be interoperable with the GNSS on two frequencies.

GNSS are also crucial for the reference frame realization and for many applications in Earth science and Earth observation (see Chapters 2 to 5). After $\sim$2013 approximately 100 GNSS satellites will be available, promising a new level of positioning quality and accuracy. This will have a fundamental impact on most GGOS products, from the reference frame to GNSS atmospheric sounding, to reflectometry and scatterometry.

It is therefore essential for GGOS to make the best possible use of a combination of the GNSS systems available for civil applications. GGOS, through the IGS, will have the goal to generate consistent products of the highest accuracy for all GNSS systems. The ground network of GNSS stations should support this by the installation of receiver technology able to track all relevant GNSS signals at the same time.

In order to link the GNSS to SLR, laser retro-reflectors should be installed on all new GNSS satellites (see Section 9.4.5). All GLONASS and GALILEO satellites are (or will be) equipped with laser retro-reflectors.

9.5.2 Laser ranging satellites

Stations in the ILRS network range to a constellation of both, passive and active satellites including the Moon (see Section 2.4.2). The SLR network will track the set of passive, spherical geodetic satellites such as LAGEOS-1 and -2 (see Figure 2.8), Etalon-1 and -2, Starlette and Stella for reference frame maintenance and measurements of time-varying components of the gravity field. SLR measurements will continue on the GPS-35 and GPS-36 satellites, the GALILEO satellites and selected satellites in the GLONASS series. Efforts are underway to include retroreflectors on the upcoming GPS-III constellation. Tracking these GNSS satellites is crucial for the assurance of positioning quality, long-term stability, verifying orbit and timing accuracy, and aligning other reference frames (e.g., WGS 84) with the ITRF. This tracking will also guarantee the interoperability of the different GNSSs.

The retro-reflector arrays flown in space to date have been made from solid quartz cubes, (either back-coated or uncoated). Engineering studies indicate that hollow cubes made from either aluminum or glass may provide considerably higher return signal strength for similar weight and area conditions on arrays at GNSS altitudes.

9.6 Level 4: planetary missions

In the coming years, there will be significant advances in studies of reference frames, gravity fields and rotation of Solar System planets and their satellites. With the current interest of space agencies worldwide in lunar exploration, much progress is expected in the geodesy and cartography of the Moon. The Japanese spacecraft Kaguya (former name: SELENE), the Chinese Chang'e 1 spacecraft, and the Indian spacecraft Chandrayaan-1 are currently in lunar orbit. Kaguya is in a circular polar orbit, and its powerful laser altimeter has completed the first global topographic map. Coverage includes the polar areas for the first time, which were beyond the reach of the altimeter on the previous Clementine spacecraft. Using an elaborate radio tracking scheme, Kaguya and its two sub-satellites will also improve the lunar gravity field, in particular on the far side, where reliable data are hitherto lacking.

The LRO, scheduled for launch in May 2009, will provide further significant contributions to lunar geodesy. The orbiter will carry the Lunar Orbiter Laser Altimeter (LOLA) to further densify the topographic grid (25 m along-track shot spacing, 1.2 km across-track spacing at the equator, after one year). LRO will also carry a laser receiver, which can be targeted from ILRS stations for precise range measurements to the orbiter at the 10-cm level. Images obtained by LRO will also form the basis for a new generation of accurate lunar standard maps which will essentially realize the Moon-fixed reference frame. The GRAIL mission in the NASA discovery program scheduled for launch in 2011 will focus on lunar gravity. Using techniques pioneered by the joint U.S.-German Earth GRACE mission, the GRAIL twin spacecraft will aim at improving the current knowledge of the lunar gravity field to higher-resolution (30 x 30 km) and higher accuracy (< 10 mGal).

A robust international program of lunar robotic lander missions is expected in the coming decade. The strawman payloads that are currently being discussed will include geodesy packages, involving active lasers for range measurements at mm-level and radio transmitters suited for observations by terrestrial VLBI stations. These new techniques will firmly tie the Moon into the ICRF and should improve the knowledge of the tracking of lunar orbital and rotational dynamics as well as tidal deformation.

Likewise, future missions are expected to further our knowledge of the dynamics of the terrestrial planets. The Exomars spacecraft, scheduled for launch in 2013, would deploy a geophysics package on the surface of Mars. The package would include a radio experiment for monitoring of variations in the Mars rotation, caused by atmospheric dynamics and the condensation/sublimation cycles of ice in the polar caps (see Section 6.1.2). Accuracies are expected to approach the milli-arcsecond level. The MESSENGER spacecraft, the first ever to enter Mercury orbit (orbit entry scheduled for 2011) is expected to produce the data base for the definition of a new coordinate system and for the production of a standard global map. MESSENGER will also determine the Mercury gravity field (parameters of expected degree and order 16) and study the planet's rotation including the complex librational motion (see Section 6.1.1).

The MESSENGER spacecraft on its way to Mercury recently demonstrated a 2-way laser link experiment over a distance record of 24 Mio km. By operating the onboard laser altimeter transmitter and receiver in combination with the terrestrial SLR station at the Goddard Space Flight Center, the spacecraft position was determined to 20 cm formal standard deviation, along with parameters of onboard clock offsets and drift (Smith et al., 2006). Laser link techniques (highly collimated laser beams not affected by the Earth's troposphere and ionosphere) are expected to become the tracking method of choice, which will establish firm ties of distant planets into the Solar System reference frame.

9.7 Level 5: extragalactic objects

The quasars and other compact radio sources included in the ICRF have point-like optical images. Their red shifts indicate great distances, hence their emissions must be powered by processes different from stars and galaxies, probably mass flows into 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 a structure that may change with time. Such structure changes can be seen as angular position changes of up to 1 milliarcsecond. The brightest extragalactic radio sources have in fact 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 about 100 geodetic sources has been selected for routine geodetic VLBI observations, while the rest of the ICRF sources improve the distribution and density over the sky (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.

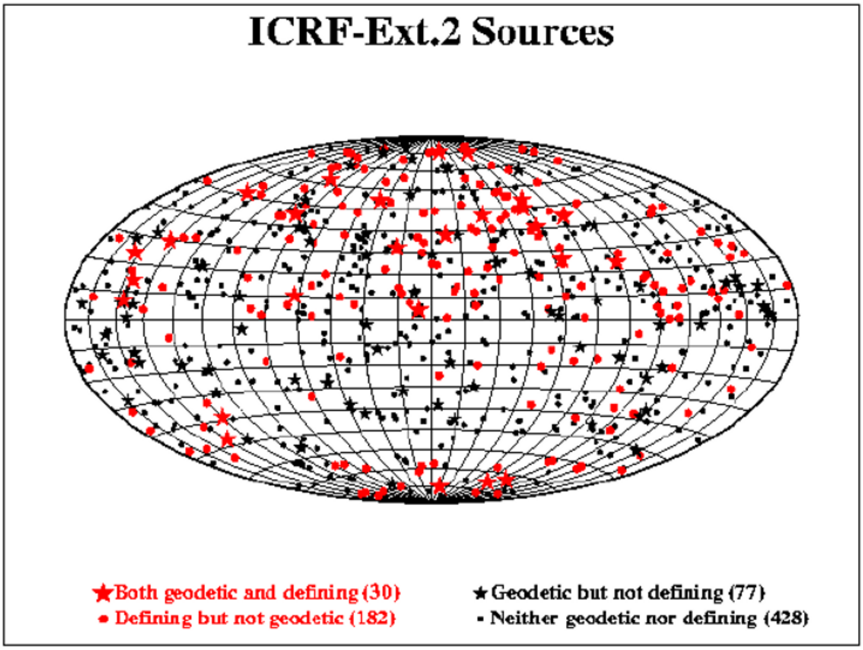

Fig. 9.5. Source locations of ICRF-Ext.2. The second extension of ICRF was computed based on VLBI data obtained between mid-1995 and the end of 2002 May and included an additional 109 new sources. From Fey et al. (2004). See also Box 1 in Section 2.2.

It is therefore essential that the proposed GGOS realizes a much more homogeneous coverage of the southern and northern hemispheres. This implies that about half of the 40 core sites of the future GGOS (equipped with VLBI telescopes) have to be located in the southern hemisphere. Because of rapid developments in communication technologies it should be possible to install such a network in the coming decade.

The ICRF is essential to geodesy as it is the frame for observations of Earth rotation and the celestial frame for the satellite orbits. The ICRF is also the basis for astrometry. The ICRF thus 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 of 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 a corresponding improvement of star tracking for satellite orientation. For most geodetic purposes, however, these improvements will not be usable because no correspondingly precise ground-based optical observing system exists. An accurate microwave realization for geodetic VLBI will still be needed.

9.8 GGOS data flow: from measurements to users

The official products generated by the technique-specific Services will be the basis for the products made available through the GGOS Portal (see Section 9.9). GGOS will thus rely on the data system infrastructure of the IAG Services.

The success of the IAG Services is partly due to the underlying support of their information and archive services. Each Service has a coordinating entity (coordinating center or central bureau) managing the daily operations of the Service. This function also facilitates communications and coordinates activities both within the Service and with a broad user community. A central coordinating function will be established for GGOS (see Chapter 10), providing coordination within GGOS and to the IAG Services.

The IAG Services' data centers are the central source for data for the analysis community and for products generated by the Services for the user community. GGOS will rely heavily on these data centers for service products and for input to the GGOS Portal.

9.8.1 Data centers and data flow

Each of the geometric IAG Services utilizes a similar structure (shown in Figure 9.6) for the flow of information, data, and products from the observing stations to the user community: Network Stations (track continuously, transmit data using predetermined schedules), Data Centers (interface to stations and users, perform data quality checks/conversion, archive data and products for analysis center and user access) and Analysis Centers (generate products). Participants in service activities

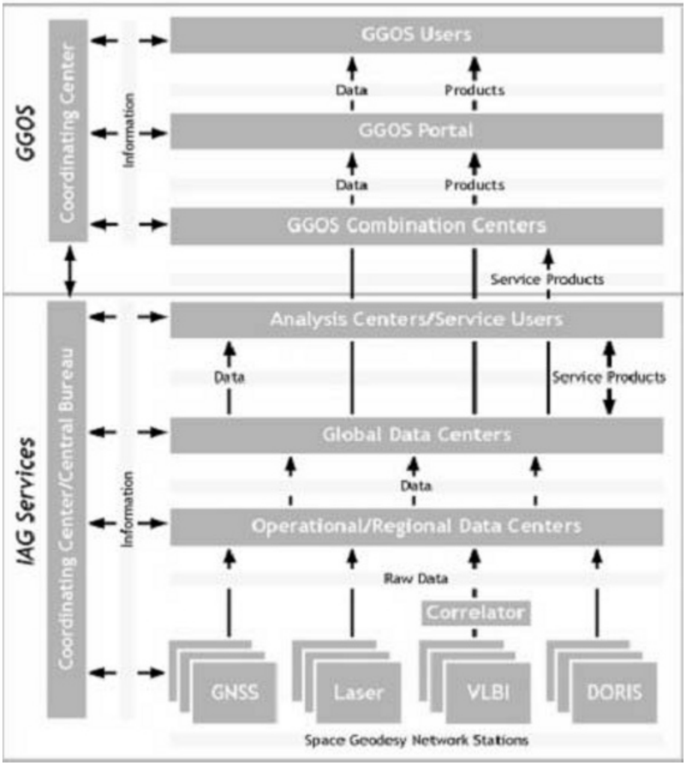

Fig. 9.6. Each of the geometric IAG Services operates with a similar component structure for data flow and archive. The service-specific global data centers will provide data and products to the GGOS combination centers; GGOS users will obtain data and products through the GGOS Portal or through direct access to the service data centers.

collaborate at all levels to ensure consistency and timely delivery of data and products.

Networks of tracking stations transmit data through various levels of data centers to ultimately reach the service analysis centers and user community. During the design phases of the IAG Services, it became clear that a distributed data flow and archive scheme would be vital for mission success. Thus, each Service established a hierarchy of data centers to distribute data from the network of tracking stations: operational, regional, and global data centers. This scheme provides efficient access to and storage of data, thus reducing traffic on the Internet, as well as a level of redundancy allowing for security of the data holdings. Operational data centers serve as the direct interface to the network stations (or correlators in the case of VLBI), connecting to the remote sites daily/hourly/sub-hourly, downloading the data, and archiving the raw station data. Regional data centers gather data from various operational data centers and maintain an archive for users interested in stations of a particular region. Furthermore, to reduce communication traffic, the regional data centers are used to collect data from several operational data centers before transmitting them to the global data centers. The global data centers are ideally the principal data source for the analysis centers and the general user community. Operational and regional data centers transmit data to these global data centers where they are then available on-line for ftp/web access. These data are utilized by the service analysis centers to create a range of products, which are then transmitted to the global data centers for public distribution. Multiple global data centers provide each Service with a level of redundancy, thus preventing a single point of failure should one data center become unavailable. Users can continue to reliably access data from one of the other available data centers. Furthermore, multiple, geographically-distributed global data centers reduce the network traffic that could occur to a single geographical location.

9.8.2 Synergies between observing techniques

Each of the four geometric IAG Services utilizes a similar flow of data, pioneered by the IGS and shown in Figure 9.6, from the measurement networks to the analysis centers. Standards, both technique-specific and cross-disciplinary, in data and product generation are adhered to throughout all levels in each of the Services. Each Service has developed its products using standard models and algorithms to ensure consistency over time. Data are currently archived in technique-specific formats (e.g., Receiver Independent Exchange Format (RINEX) for GNSS); however, products derived from the different techniques are moving towards common formats across data types (e.g., Software Independent Exchange Format (SINEX) for station positions, Standard Product 3 Orbit Format (SP3) for satellite orbits). All data are in American Standard Code for Information Interchange (ASCII), thus machine independent, and compressed for transmission and archiving. The Services are also evolving, as requirements change, by developing new formats and standards for the exchange of data and products.

9.8.3 Operating centers and communications

Operating (or operational data) centers are responsible for providing the communication infrastructure for network stations, downloading data on a routine basis, re-formatting and checking the downloaded data, maintaining these network stations, and archiving the raw data. Connections to the stations are typically provided through the Internet or dial-up methods with satellite communications used in more remote areas. Direct connections allow for rapid download, at least daily but often sub-daily (or even sub-hourly). Currently, GNSS and laser ranging stations are required to transmit data on a daily basis (although most stations send their data on an hourly basis), at a minimum, to these operating centers. VLBI data are sent from the network stations to a correlator on disk packs, and in some cases the data are electronically transferred via high-speed networks (e-transfer). As VLBI observations are organized in sessions, the data transmission follows a session schedule. DORIS stations uplink data to the DORIS receiver onboard the observed satellite, thus enabling installations in more remote areas. DORIS-equipped satellites then download these data to the DORIS control center for transmission to IDS data centers.

The future GGOS, striving for a much more homogeneous distribution of core sites and technique-specific observation networks, will have to rely heavily on satellite communication technologies, i.e., technologies that are accessible from remote areas of the globe. Communication links via satellites become cheaper every year, making this technology more and more attractive for GGOS.

In the case of satellite constellations observing the Earth in near real-time (e.g., for tsunami early warning systems using GNSS reflectometry), only inter-satellite communications or communications via geostationary satellites will ensure the data arrives at the data centers and analysis centers with minimum delay so that analysis can take place.

9.8.4 Future technologies and capabilities for data infrastructure

Several of the geometric IAG Services are moving into the era of real-time data streaming. Real-time and near real-time applications (e.g., weather forecasting, tsunami early warning systems) require low-latency data and product delivery. Real-time data transfer also allows operating centers and analysis centers to monitor station health and to provide rapid notification and correction of station problems. Standards, and protocols for real-time operations, liaisons with regional real-time networks, and technologies to broadcast products for real-time users are currently under development. Near real-time products derived from these data streams will be investigated. The development of the future VLBI system (VLBI2010) aim at real-time e-VLBI, where the transmission of station data is accomplished through high-speed network transfer to the correlator during an observing session and the data are correlated in real-time. Before full real-time capability, intermediate steps with e-transfer and correlation after the observing session will likely be necessary. GGOS will play a critical role in promoting standards by which real-time networks can operate and exchange data products on a global basis.

The data rates of observation of the space-geodetic techniques will dramatically increase in the decade to come. GNSS stations will observe more than 100, instead of 30 satellites, and the data rate may be as high as 50-100 Hz. Such data rates will enable not only, for example, the observation of seismic events with GNSS observations (site motion during the earthquake) and subsequent determination of rupture parameters, but also the monitoring of rapid scintillations in the ionosphere. The new generation of VLBI telescopes will record about ten times as much data as at present. The upcoming InSAR missions (TerraSAR-X and TanDEM-X) will collect data volumes of gthe order of petabytes (10^{15} bytes). The data infrastructure capable of handling such huge amounts of data has not yet been designed or developed, but should be part of the responsibility of GGOS in 2020.

9.9 GGOS User Interface: Database, Portal, and Clearinghouse

It is difficult to predict the development of web technologies, methodologies and approaches that will prevail in 2020. Considering developments over the last ten to fifteen years and extrapolating this into the future, suggests considerable changes in the nature of the interaction of human and web interfaces and the methodology for presenting information. Therefore, this section may be out-dated rather rapidly.

The GGOS User Interface will likely have three main elements:

(1) a GGOS database, which mainly contains general information, meta information and catalogues, and facilitates access to observations and products provided by the various IAG Services;
(2) the GGOS Portal, which will be the unique access point for all products and information made available through GGOS; and
(3) the GGOS Clearinghouse for geodesy, which will enable the search for information related to all aspects of geodesy.

The GGOS Portal will be the access point for all GGOS products. The Portal will also provide a route to the heterogeneous information systems of the IAG Services. The Portal will be linked with a GGOS database of relevant metadata and web services to enable searches for relevant data and products in the most effective way.

The IAG Services will provide very important and valuable data, information, and products, which are indispensable for Earth sciences and their applications. The GGOS Portal will give access to these data and products as well as general information about geodesy. The Portal will contribute to the GGOS objectives to promote and improve the visibility of geodetic research and to achieve maximum benefit for the scientific community and in society in general. Behind the GGOS Portal, each contributing Service will have its own visibility, and responsibility to maintain and manage its supporting data and information system.

The IAG Services produce products that are critical to the generation of GGOS products. These products and data are only available at the data centers of the individual components of GGOS. It is clear that for a future GGOS, all the relevant products for Earth sciences and applications will have to be made accessible through the GGOS Portal that leads the user – including the non-specialists working in different fields – to the individual products. The products and data themselves will be physically located at many different data and product centers and will be promoted by the individual IAG Services as well. For the benefit of new users who are not familiar with space geodesy, the initial web pages of the GGOS Portal will highlight the “burning questions” of geodesy and point the way to the relevant products, as well as their characteristics, location, availability, latency, accuracy, etc. General information about GGOS will also be available through the Portal, providing a valuable resource for both the external and internal GGOS communities.

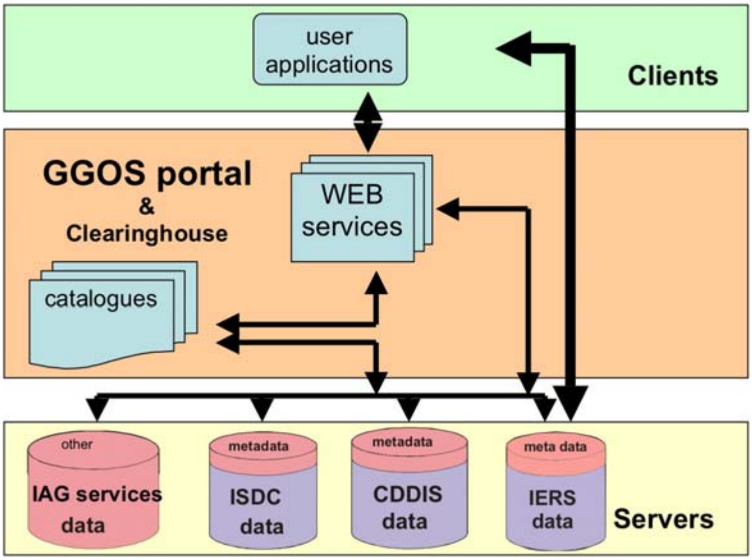

Fig. 9.7. GGOS portal architecture.

9.9.1 GGOS Portal architecture

The utility of the GGOS Portal will depend on data and information providers accepting and implementing a set of interoperability arrangements, including technical specifications for collecting, processing, storing, and disseminating shared data, metadata and products. GGOS interoperability will be based on non-proprietary standards, with preference given to formal international standards. The eXtensible Markup Language (XML) has become a quasi standard to facilitate the sharing of data across different information systems, particularly via the Internet. Moreover, web services for the support of interoperable machine-to-machine communication over a network are built on XML-based standards (e.g., Simple Object Access Protocol (SOAP), Web Services Description Language (WSDL)).

Data, products, and information from contributing IAG Services will becatalogued in a registry publicly accessible through the Clearinghouse. It is envisioned that this Clearinghouse is maintained collectively under the GGOS Portal. The catalogue will itself be subject to GGOS interoperability specifications, including the standard search and portrayal services.

The functions of the GGOS Portal (e.g., search capabilities for stations, satellites, data, products, institutions, data mining tools, visualization, web services, connec-

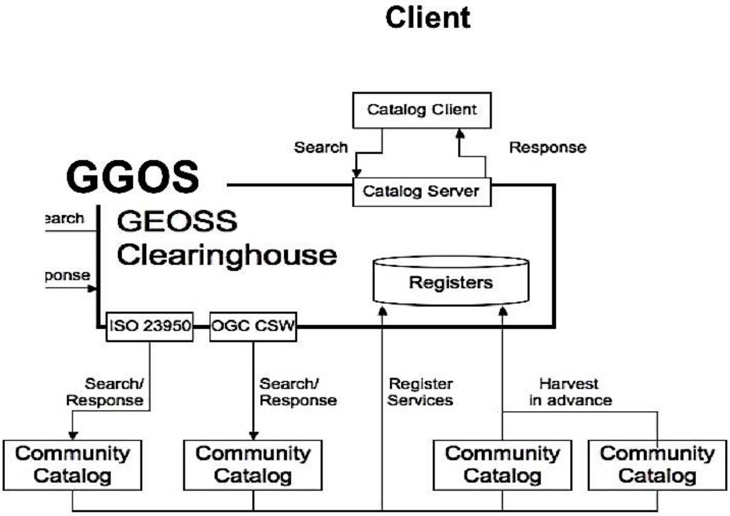

Fig. 9.8. GGOS Clearinghouse architecture – engineering viewpoint (according to D. Nebert). Here, the term clearinghouse is used in its modern meaning of a search-able registry, i.e., a set of catalogs.

tions to other catalogues, etc.) are supported by the GGOS Clearinghouse (Figure 9.7). The GGOS Clearinghouse will be a facility that collects and distributes information concerning the data catalogues and services. In a broader sense, the GGOS Clearinghouse will allow for a dialog between stakeholders on relevant issues in geodesy. The GGOS Portal will also provide access to a distributed network of catalogue services supporting the interoperability agreements of GGOS. Contributing IAG Services may nominate catalogues containing structured, standards-based metadata and other web services for access by the GGOS Clearinghouse. The Clearinghouse provides search capability across the catalogues and their registered resources by mapping these catalogues. The GGOS Portal will search the GGOS Clearinghouse but will also provide access to other GGOS resources e.g., calendar functions, forums, etc. Through the use of interoperability standards, additional portals may be established for national or professional communities to allow access to the GGOS Clearinghouse.

The metadata to be held by the Clearinghouse depends upon the search method. Two anticipated approaches to accessing remote catalogues (see Figure 9.8) include:

- Distributed search approach: search requests are sent in parallel to registered distributed catalogues of the IAG Services.
- Harvested approach: The Clearinghouse periodically harvests all metadata from registered distributed catalogues. A user search request is executed against the metadata harvested from the remote catalogues and the results are managed and visualized in the GGOS Clearinghouse.

9.9.2 GGOS Portal goals and objectives

The GGOS Portal will provide a web site which:

- represents a single web access point for all geodetic products relevant in the framework of GGOS;
- offers a set of tools for organized knowledge discovery including visualization to assist identification and selection of appropriate resources (information, data, products);
- accesses the GGOS Clearinghouse to search data catalogues, products and data sets generated by GGOS components;
- helps to answer the "burning questions of society" and points the way to the products, their characteristics, location, availability, latency, and accuracy;
- allows the searching of information and the retrieval of descriptive metadata from multiple, diverse target resources, databases, web pages, and library catalogues; and
- provides access to general information about GGOS.

Functions of the GGOS Portal include (but are not limited to):

- Basic functions of the GGOS web site such as hot spot information, news, tutorials, quick links, announcements, etc.
- A registry to host catalogues for metadata for all products of the IAG Services based on GGOS standards to ensure interoperability within the GGOS community and to other systems, in particular GEOSS.
- Search (temporal, spatial, multi-technique, keywords, etc.) of metadata, data, and product databases.
- Visualization of products (time series, maps, etc.).
- Information on and explanations of data, products, and geodetic techniques, with links to service-specific resources.

The GGOS Portal will likely be based on an open-source platform and web portal application allowing users to download, install and customize the portal services in their own environment. Based on modern architecture, standards and web services the GGOS Portal can be realized not only by single institutions but also by consortia with distributed server architecture. The Portal should be designed and implemented in such a way as to permit mirroring installation at alternate physical locations.

9.9.3 A GGOS clearinghouse mechanism for geodesy

A major function of the GGOS Clearinghouse will be to provide access to information on observations, products, and information relevant to GGOS, IAG, and geodesy in general. In a broader sense, the GGOS Portal, registry, and search engines should be complemented by a general clearinghouse mechanism (comparable to the clearinghouse mechanism for the Convention on Biodiversity, which links all stakeholders of the Convention; see http://www.cbd.int/chm/default.shtml). The mission of such a future GGOS clearinghouse mechanism would be to contribute to the implementation of GGOS, its standards, and its conventions, for the maximum benefit of its users. In particular, the GGOS clearinghouse mechanism should have three major goals:

- Promote and facilitate technical and scientific cooperation, among the IAG Services and Commissions, among GGOS components and other organizations, and within and between countries.
- Develop a global mechanism for exchanging and integrating information on geodesy.
- Develop the necessary human and technological networks.

Such an extended clearinghouse mechanism would have to be compatible with different levels of national/component capacity, driven by users' needs, and structurally decentralized. It would provide access to information, support decision-making, and have no vested interest in controlling the expertise or information. It would thus be created for the mutual benefit of all IAG Services and Commissions and other stakeholders.

Table 9.1. Parameter Space for a rigorous combination and integration of the geodetic observation techniques. Entry 1 defines the ICRF. Entries 2 to 5 related to the EOPs. Entries 6 and 7 together define the ITRF, while entries 7 to 10 are related to the gravity field. The atmosphere is covered by entries 11 and 12.

No.	Parameter	VLBI	GNSS	DORIS PRARE	SLR	LLR	Altimetry
1	Quasar Coordinates	X					
2	Nutation	X	(X)		(X)	X	
3	Polar Motion	X	X	X	X	X	
4	UT	X					
5	Length of Day		X	X	X	X	
6	Coordinates and Velocities	X	X	X	X	X	(X)
7	Geocenter		X	X	X		X
8	Gravity Field		X	X	X	(X)	X
9	Orbit		X	X	X	X	X
10	LEO		X	X	X		X
11	Ionosphere	X	X	X			X
12	Troposphere	X	X	X			X
13	Time/Frequency	(X)	X		(X)		

The activities of this clearinghouse mechanism would support GGOS' thematic and cross-cutting work programs by promoting cooperation, exchanging information and developing a network of partners. A first priority would be to ensure universal access to the GGOS Implementation Plan, including the underlying documents of the GGOS 2020 process, the GGOS standards, and conventions. The information provided would include case studies, national reports, and other relevant documentation. The mechanism would increase public awareness of the geodetic programs, issues, and products. It would be established as an Internet-based system to facilitate

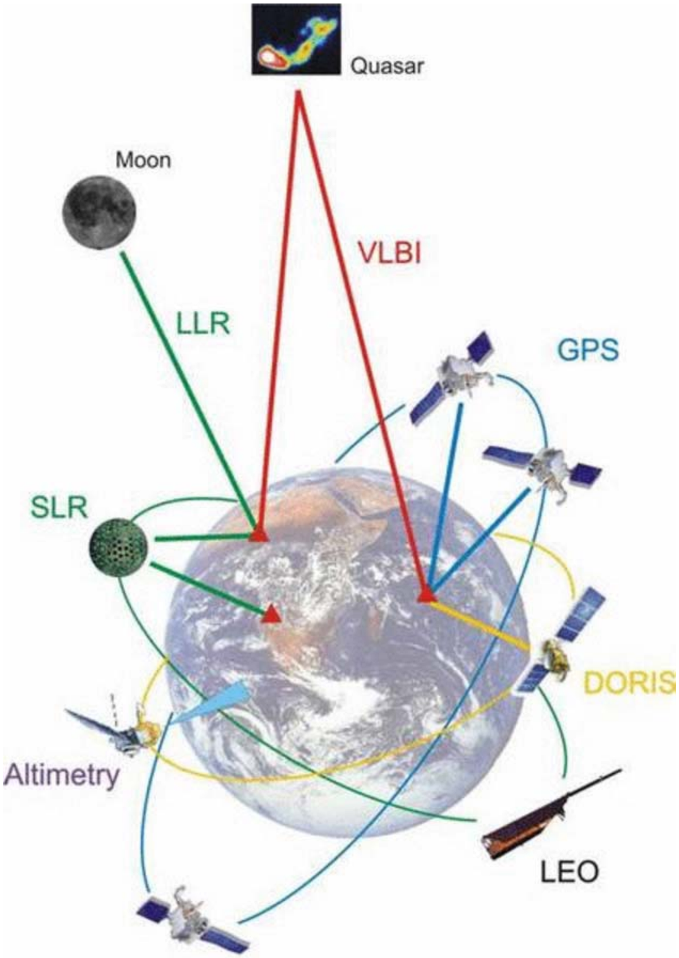

Fig. 9.9. Combination and integration of the geodetic observation techniques. The combined infrastructure allows the determination and maintenance of the global geodetic reference frames, and the determination of Earth's gravity field and rotation. The ground networks and navigation satellites (currently in particular GPS) are crucial in positioning, with applications to all SBAs. In particular, they allow the monitoring of volcanoes, earthquakes, tectonically active regions and landslide-prone areas. The Low Earth Orbit (LEO) satellites monitor sea level, ice sheets, water storage on land, atmospheric water content, high-resolution surface motion, and variations in the Earth' gravity field. The latter are cause, to a large extent, by regional and global mass transport in the hydrological cycle.

greater collaboration among the IAG Services and Commissions, the GGOS stakeholders, across national borders, through education and training projects, research cooperation, funding opportunities, and access to and transfer of technology.

This clearinghouse mechanism would be based on the philosophy that broad participation and easy information access must be a top priority. The underlying database can therefore be tapped through both traditional and electronic means of communication. Special efforts will have to be made to ensure the participation of organizations and institutions in developing countries.

9.10 Data analysis, combination, modeling, and products

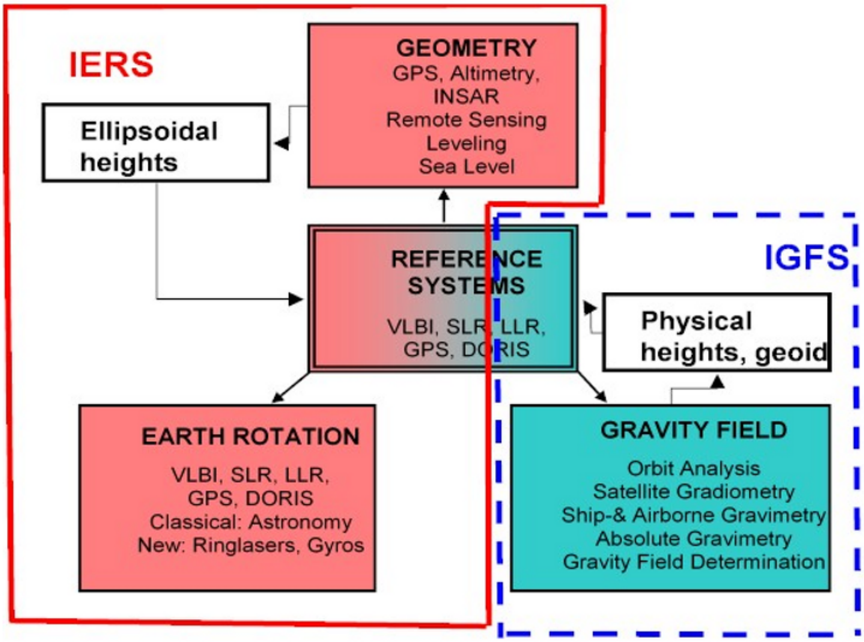

Fig. 9.10. Interactions in the Earth system centered around the three pillars of geodesy.

A major function of GGOS will be to facilitate the integration of the various levels of GGOS into a consistent observing system (Figure 9.9), delivering products and services as far as possible independent of the observing techniques and the processing. Considering the multi-technique, multi-component, and multi-parameter nature of GGOS, this will require consistency of processing strategies, models and standards across all components of GGOS. GGOS will facilitate communication and standardization between the analysis centers for the individual techniques and sensors, initiate intercomparison of products generated by the various components, and promote the study and modeling of technique-specific effects and other geodetic/geophysical signals. Redundancy and reliability will be achieved by having more than one analysis center for the major tasks and by developing full reprocessing capabilities for all data types.

Combination of the geometric products is currently achieved by the IERS. The International Gravity Field Service (IGFS) is developing the combination capabilities for the gravimetric products. The borderline between, and potential overlap of, IERS and IGFS (Figure 9.10) will require careful attention. GGOS will have to facilitate combination across the full parameter space (Table 9.1), and fully utilize synergies and advantages of the combination approach in partnership with the IERS and the IGFS.

The GGOS conventions will be a central issue for achieving consistency and highly accurate products. Currently, the conventions in the fields of geometry and rotation are taken care of by the IERS. In future, these conventions will have to be extended to cover the gravity field as well. They will have to address the geodetic, geophysical, geodynamic, etc., models to be used or, if not sufficient, to be developed. Coupling of models from oceanography, meteorology, geodesy, geophysics, glaciology, mass transport, energy budget, will have to be undertaken in order to achieve the GGOS accuracy goals. As pointed out in Chapter 8, 4-D Earth system modeling and the assimilation of diverse data into these 4-D Earth system models will have to be studied and eventually be covered by the conventions. The need for modeling and/or assimilation centers may thus arise. The importance of global geophysical fluids for validation will give a high weight to the Global Geophysical Fluid Center (GGFC) or an equivalent component of GGOS. However, the tools and methods for validation need more research and development.

GGOS as an observing system has to be more than just an Earth observing system collecting a tremendous volume of data. The observations have to be analyzed with state-of-the-art processing software and processing standards to generate time series of relevant geodetic, geodynamic, geophysical, hydrological and atmospheric parameters. To reach consistency between the different observation techniques the results of the individual techniques have to be rigorously combined and integrated using information on the local ties between the different instruments at co-location sites and satellites. Finally, the resulting products have to be validated and interpreted by making use of physical and geophysical models and modeling software packages, and by using additional observation data from other disciplines such as, for example, the meteorological, oceanographic, hydrological, etc. communities. This will require data analysis centers and centers combining the solutions from different analysis centers and different observation techniques and generating a series of GGOS products. Finally, the products have to be carefully validated.

With respect to the data analysis itself, software and modeling improvements are expected in form of, e.g., the development of new tropospheric mapping functions, gradient models, and atmospheric turbulence models, etc. Further areas of improvement are loading effects including mass loading models for hydrological variables, thermal and gravitational antenna deformations, and source structure effects. In addition, new analysis strategies will be investigated, in particular, the generation of consistent VLBI multi-purpose solutions for TRF, EOP, and CRF. Also, the “software noise” of solutions obtained from different software packages will need to be studied.

The processing and analysis procedures will have to progress towards fully automated processing in near real-time or even in real-time (particularly for early warning systems, GNSS seismology, atmosphere and ionosphere sounding). Full reprocessing capabilities for all data available will be crucial in order to provide long and consistent time series. A key development will be the combination of all data types at the observation level. This includes the combination of terrestrial data with LEO data (co-location, gravity, geocenter, atmosphere), as well as the combination with satellite altimetry data, and with InSAR and/or LIDAR. Finally, the combination of products from different analysis centers will increase redundancy, reliability, and accuracy.

The major outcome of GGOS in 2020 is expected to be a set of highly accurate, consistent and long-term stable products which will be the geodetic contribution to the observation and monitoring of the Earth system (i.e., to GEOSS and other international and regional initiatives). The high-level list of products is given in Section 7.5. It is anticipated that all GGOS product accuracies in 2020 will be of the order of about 10^{-9} relative to the absolute values of the measured quantities. However, in order to satisfy the goals mentioned above and in previous chapters, consistency between all GGOS products at the 10^{-9} level is also required.