

GGOS Working Group on Ground Networks and Communications

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Abstract. Properly designed and structured ground-based geodetic networks materialize the reference systems to support sub-mm global change measurements over space, time and evolving technologies. Over this past year, the Ground

Networks and Communications Working Group (GN&C WG) has been organized under the Global Geodetic Observing System (GGOS) to work with the IAG measurement services (the IGS, ILRS, IVS, IDS and IGFS) to develop a

strategy for building, integrating, and maintaining the fundamental network of instruments and supporting infrastructure in a sustainable way to satisfy the long-term (10-20 year) requirements identified by the GGOS Science Council.

Activities of this Working Group include the investigation of the status quo and the development of a plan for full network integration to support improvements in terrestrial reference frame establishment and maintenance, Earth orientation and gravity field monitoring, precision orbit determination, and other geodetic and gravimetric applications required for the long-term observation of global change. This integration process includes the development of a network of fundamental stations with as many co-located techniques as possible, with precisely determined intersystem vectors. This network would exploit the strengths of each technique and minimize the weaknesses where possible.

Keywords. GGOS, GEOSS, IAG, GPS, SLR, VLBI, DORIS, Gravity, Tides, Geoid

1 Introduction

The Ground Networks and Communications Working Group (GN&C WG) of the Global Geodetic Observing System (GGOS) is charged with developing a strategy to design, integrate, and maintain the fundamental space geodetic network. In this report, we review the significance of geodetic networks and the GGOS project. We also summarize the present state of, as well as future improvements to, and requirements on space geodetic networks, services, and products. The approach of the GN&C WG and preliminary conclusions follow.

1.1 Significance of the Terrestrial Reference Frame

Space geodesy provides precise position, velocity and gravity on Earth, with resolution from local to global scales. The terrestrial reference system defines the terrestrial reference frame (TRF) in which positions, velocities, and gravity are reported. The reference surface for height reckoning, the geoid, is defined through the adopted gravity model, which is referenced to the TRF. The TRF is therefore a space geodesy product that links each of these observable quantities to other geophysical parameters on Earth. Its position, orientation and evolution in space and time are the basis through which we connect and compare such measurements over space, time, and evolving technologies. It is the means by which

we verify that observed temporal changes are geophysical signals rather than artifacts of the measurement system. It provides the foundation for much of the space-based and ground-based observations in Earth science and global change, including remote monitoring of sea level, sea surface and ice surface topography, crustal deformation, temporal gravity variations, atmospheric circulation, and direct measurement of solid Earth dynamics. A precise TRF is also essential for interplanetary navigation, astronomy and astrodynamics. The realization of the TRF for its most demanding applications requires a mix of technologies, strategies and models.

1.2 The Role of GGOS

In early 2004 under its new organization, the International Association of Geodesy (IAG) established the GGOS project (www.ggos.org) to coordinate geodetic research in support of scientific applications and disciplines (Rummel, 2002). GGOS is intended to integrate different geodetic techniques, models and approaches to provide better consistency, long-term reliability, and understanding of geodetic, geodynamic, and global change processes. Through the IAG's measurement services (IGS¹, ILRS², IVS³, IDS⁴, IGFS⁵, and future IAS⁶), GGOS will ensure the robustness of the three aspects of geodesy: geometry and kinematics, Earth orientation, and static and time-varying gravity field. It will identify geodetic products and establish requirements on accuracy, time resolution, and consistency. The project will work to coordinate an integrated global geodetic network and implement compatible standards, models, and parameters.

A fundamental aspect of GGOS is the establishment of a global network of stations with co-located techniques, to provide the strongest reference frames. GGOS will provide the scientific and infrastructural basis for all global change research and provide an interface to geodesy for the scientific community and to society in general. GGOS will strive to ensure the stability and ready access to the geometric and gravimetric reference frames by establishing uninterrupted time series of state-of-the-art global observations.

¹ International GNSS Service, formerly the International GPS Service

² International Laser Ranging Service

³ International VLBI Service for Geodesy and Astrometry

⁴ International DORIS Service

⁵ International Gravity Field Service

⁶ International Altimeter Service

1.3 Role of the Ground Networks and Communications Working Group

The ground network of GGOS is fundamental since all GGOS data and products emanate from this infrastructure.

The Charter of the Ground Networks and Communications Working Group (GN&C) within GGOS is to develop a strategy to design, integrate and maintain the fundamental geodetic network of instruments and supporting infrastructure in a sustainable way to satisfy the long-term (10-20 years) requirements identified by the GGOS Science Council. At the base of GGOS are the sensors and observatories situated around the world providing the timely, precise and fundamental data essential for creating the GGOS products. Primary emphasis must be on sustaining the infrastructure needed to maintain evolving global reference frames while at the same time ensuring support to the scientific applications' requirements. Opportunities to better integrate or co-locate with the infrastructure and communications networks of the many other Earth Observation disciplines now organizing under the Global Earth Observation System of Systems (GEOSS) should be sought and taken into account (Group on Earth Observations, 2005).

Recognizing that the infrastructure and operations collectively contributing to the Services of the IAG are possible solely due to the voluntary contributions of the globally distributed collaborating agencies and their interest in maximized system performance and sustainable long term efficient operations, the Working Group is made up of representatives of the measurement services plus other entities (e.g., IERS, ITRF and data center and analysis communities) that are critical to guiding the activities of the Working Group.

2 Global Geodetic Network Infrastructure

All infrastructure, and resulting analysis and products of GGOS and its constituent services are made possible through the goodwill voluntary contributions of national agencies and institutions and are coordinated by the IAG governance mechanisms.

The ground network of GGOS includes all the sites that have instruments of the IAG measurement services either permanently in place or regularly occupied by portable instruments. Some sites have more than one space geodesy technique co-located, and knowledge of the precise vectors between such co-located instruments (known as "local ties") is essential to full and accurate use of these co-locations.

Analysis centers use the ground networks' data for various purposes including positioning, Earth orientation parameters (EOP), the TRF, and the gravity field. The ground stations of the satellite techniques provide data for precise orbit determination (POD). The individual sites' reference points of the contributing space geodesy networks are the fiducial points of the TRF.

2.1 IAG Measurement Services

Each service coordinates its own network, including field stations and supporting infrastructure. Here we will review the current status of each measurement service.

2.1.1 IGS

The foundation of the International GNSS Service (IGS, formerly the International GPS Service) is a global network of more than 350 permanent, continuously operating, geodetic-quality GPS and GPS/GLONASS sites. The station data are archived at three global data centers and six regional data centers. Ten analysis centers regularly process the data and contribute products to the analysis center coordinator, who produces the official IGS combined orbit and clock products. Timescale, ionospheric, tropospheric, and reference frame products are analogously formed by specialized coordinators for each. More than 200 institutes and organizations in more than 80 countries contribute voluntarily to the IGS, a service begun in 1990. The IGS intends to integrate future GNSS signals (such as Galileo) into its activities, as demonstrated by the successful integration of GLONASS. (Beutler et al., 1999).

2.1.2 ILRS

The International Laser Ranging Service (ILRS), created in 1998, currently tracks 28 retroreflector-equipped satellites for geodynamics, remote sensing (altimeter, SAR, etc.), gravity field determination, general relativity, verification of GNSS orbits, and engineering tests (Pearlman et al., 2002). Satellite altitudes range from a few hundreds of kilometers to GPS altitude (20K kilometers) and the Moon. The network includes forty laser ranging stations, two of which routinely range to four targets on the Moon. Satellites are added and deleted from the ILRS tracking roster as new programs are initiated and old programs are completed. The collected data are archived and disseminated via two centers, and several analysis centers voluntarily and routinely deliver products for TRF, EOP, POD, and gravity modeling and development.

2.1.3 *IVS*

The International VLBI Service for Geodesy and Astrometry (IVS) was established in 1999 and currently consists of 74 permanent components: coordinating center, operation centers, network stations, correlators, analysis centers, and technology development centers. The IVS observing network includes about 30 regularly-observing IVS stations and 20-30 collaborating stations participating in selected IVS programs on an irregular basis (Behrend and Baver, 2005). 24-hour sessions twice per week as well as other less frequent sessions are used to determine the complete set of EOP (polar motion, celestial pole coordinates, UT1-UTC), station coordinates and velocities, and the positions of the radio sources. Daily 1-hour single baseline sessions are used to monitor Universal Time (UT1) with low latency (Schlueter et al., 2002).

2.1.4 *IDS*

The International DORIS Service (IDS) was created in 2003 (Tavernier et al., 2005). The current ground tracking network is composed of 55 stations allowing an almost continuous tracking of the current five satellites (SPOT-2, -3 and -4 used for remote sensing applications, Jason-1 and Envisat used for satellite altimetry). The main applications of the DORIS system are precise orbit determination, geodesy and geophysics (Willis et al., 2005). Using improved gravity Earth models derived from the GRACE mission (Tapley et al., 2004), DORIS weekly station positions can now be regularly obtained at the 10 mm level (Willis et al., 2005). DORIS data are available at the two IDS Data Center since 1990 (SPOT-2). The French space agency (CNES) has the leading role in the IDS.

2.1.5 *IGFS*

The International Gravity Field Service (IGFS) was created in 2003 to provide coordination and standardization for gravity field modeling. It supports the IAG scientific and outreach goals and therefore GGOS, through activities such as collecting data for fundamental gravity field observation networks (e.g., a global absolute reference network, co-located with satellite stations and other geodetic observation techniques), data collection and release of marine, surface and airborne gravity data for improved global model development (e.g., EGM96 (Lemoine et al., 1998)), and advocating consistent standards for gravity field models across the IAG services. Establishing new methodology and science applica-

tions, particularly in the integration and validation of data from a variety of sources, is another focus of the service. The IGFS is composed of a variety of primary service entities: Bureau Gravimétrique International (BGI), International Geoid Service (IGeS), International Center for Earth Tides (ICET), and International Center for Global Earth Models (ICGEM), with the National Geospatial-Intelligence Agency (NGA) participating as an IGFS Technical Center.

2.2 Communications

Most of the data collected from network instruments are transmitted to data centers and processing or analysis centers primarily via Internet or satellite communications. Due to the terabyte-volume of data, VLBI data are currently shipped on recorded media, but transmission of data via high-speed fiber is a future goal. Gravity data are currently exchanged via Internet or massive storage media on an “as needed” basis. Control and coordination information is also routinely and primarily sent via Internet. Communications costs are borne by the operating agencies, which in remote areas is often at considerable expense, although most sites are ideally situated in areas with easy access to Internet. The GN&C WG will improve the efficiency through coordinated implementation of modern methods and additional sharing of communications facilities and infrastructure.

3 Synergy of the Observing Techniques

At the dawn of space age, the individual national classical systems started slowly to be replaced by initially crude global equivalents (e.g., the SAO Standard Earth models), and later on, by more sophisticated “World Geodetic Systems” (e.g., the US DoD-developed WGS60, 66, 72, and WGS84). As space techniques proliferated, it soon became apparent that the optimal approach would be to make use of all available systems, and to share the burden of the development through international coordination and cooperation.

3.1 The Terrestrial Reference Frame

The dramatic improvement of space geodesy techniques in the eighties, thanks to NASA’s Crustal Dynamics Project and Europe’s WEGENER Project, has dramatically increased the accuracy of TRF determination (Smith and Turcotte, 1993). However, none of the space geodesy techniques alone is able to provide all the

necessary parameters for the TRF datum definition (origin, scale, and orientation). While satellite techniques are sensitive to Earth's center of mass, VLBI is not. The scale is dependent on the modeling of some physical parameters, and the absolute TRF orientation (unobservable by any technique) is arbitrary or conventionally defined through specific constraints. The utility of multi-technique combinations is therefore recognized for the TRF implementation, and in particular for accurate datum definition.

Since the creation of the International Earth Rotation and Reference Systems Service (IERS), the current implementation of the International Terrestrial Reference Frame (ITRF) has been based on suitably weighted multi-technique combination, incorporating individual TRF solutions derived from space geodesy techniques as well as local ties of co-location sites. The IERS has recently initiated a new effort to improve the quality of ties at existing co-location sites, crucial for ITRF development (Richter et al., 2005).

The particular strengths of each observing method can compensate for weaknesses in others. SLR defines the ITRF2000 geocentric origin, which is stable to a few mm/decade, and SLR and VLBI define the absolute scale to around 0.5 ppb/decade (equivalent to a shift of approximately 3 mm in station heights) (Altamimi et al., 2002). Measurement of geocenter motion is under refinement by the analysis centers of all satellite techniques. The density of the IGS network provides easy and rigorous TRF access world-wide, using precise IGS products and facilitates the implementation of the rotational time evolution of the TRF in order to satisfy the No-Net-Rotation condition over tectonic motions of Earth's crust. DORIS contributes a geographically well-distributed network, the long-term permanency of its stations, and its early decision to co-locate with other tracking systems. We recognize that we will need to consider non-linear motions in future reference frame solutions. A first step towards this goal is the use of time series analysis rather than just position and velocity products.

3.2 Earth Orientation Parameters

Earth orientation parameters measure the orientation of Earth with respect to inertial space (which is required for satellite orbit determination and spacecraft navigation) and to the TRF, which is a precondition for long-term monitoring. Polar motion and UT1 track changes in angular momentum in the fluid and solid components of the Earth system driven by phenomena like weather patterns, ocean tides and circulation, post-glacial rebound and great earthquakes. The celestial pole

position, on the other hand, is dependent on the deep structure of Earth. Only VLBI measures celestial pole position and UT1, and VLBI also defines the ICRF (International Celestial Reference Frame) (Ma et al., 1998), whose fiducial objects (mostly quasars) have no detectable physical motion across the sky because of their great distance. The two-decade VLBI data set contributes a long time series of polar motion, UT1 and celestial pole position. Satellite techniques (GPS, SLR and DORIS) measure polar motion and length of day relative to the orbital planes of the satellites tracked. In practice, recent polar motion time series are derived from GPS with a high degree of automation, and predictions of UT1 rely on GPS length of day and atmospheric excitation functions.

3.3 Gravity, Geoid, and Vertical Datum

Gravity is important to many scientific and engineering disciplines, as well as to society in general. It describes how the "vertical" direction changes from one location to another, and similarly, it defines at each point the equipotential surface; therefore, it describes the direction that "water flows". Global scale models of terrestrial gravity and geoid (Lemoine et al., 1998) are now routinely delivered on a monthly basis by missions like GRACE, with a resolution of 200 km or so, and high accuracy (Tapley et al., 2004). The addition of surface gravity observations can extend the resolution of these models down to tens of kilometers in areas of dense networks. Worldwide databases of absolute and relative gravity, airborne and marine gravity are collected and maintained by IGFS. Astronomically-driven temporal variations of gravity (Earth, ocean and atmospheric tides) are also a product of this and other IAG services. The combination of all this information is crucial in precisely determining instantaneous position on Earth or in orbit, the direction of the vertical and the height of any point on or around Earth, and the computation of precise orbits for near-Earth as well as interplanetary spacecraft. Similarly, the vertical datum is the common reference for science, engineering, mapping and navigation problems. Achieving a globally consistent vertical datum of very high accuracy has been a prime geodetic problem for decades, and only recently (thanks to missions like CHAMP and GRACE) is a successful result in reach. Strengthening and maintaining a close link between the "geometric" and "gravimetric" reference frames is of paramount importance to the goals of GGOS.

3.4 Precise Orbit Determination

Precise orbit determination is one of the principal applications of the satellite techniques (GPS, SLR, DORIS), and has direct application to many different scientific disciplines such as ocean topography mapping, measurement of sea level change, determination of ice sheet height change, precise geo-referencing of imaging and remote sensing data, and measurement of site deformation using synthetic aperture radar (SAR) or GPS. The techniques have evolved from meter-level orbit determination of satellites such as LAGEOS in the early 1980's to cm-level today. The computation of precise orbits allows these satellite tracking data to be used for gravity field determination (both static and time-variable) and the estimation of other geophysical parameters such as post glacial rebound, ocean tidal parameters, precise coordinates of tracking sites, or the measurement of geocenter motion.

Precise orbit determination, which requires precise UT1 and gravity models, underpins the analysis that in parallel has resulted in improved station coordinate estimation, and thereby improved realizations of the TRF (e.g., ITRF2000); There is close synergy between POD and TRF realization. The density of data available from GPS (and in the future from other GNSS including Galileo) allows the estimation of reduced-dynamic or kinematic orbits with radial accuracy of a few cm even on low-altitude satellites such as CHAMP and GRACE. Only a few satellites carry multiple tracking systems, but space-based co-location is invaluable. The detailed intercomparison of orbits computed independently from SLR, DORIS, and GPS data confirms that Jason-1 orbits have a one-cm radial accuracy (Luthcke et al., 2003). These techniques are complementary; the precise but intermittent SLR tracking of altimeter satellites, such as Envisat or TOPEX/Poseidon, is complemented by the dense tracking available from the DORIS network. SLR tracking of the GPS, GLONASS or future Galileo satellites is and will be vital to calibrating GNSS satellite biases and assuring the realization of a high quality TRF.

4 Future Requirements

The measurement requirements for GGOS will be set by the GGOS Project Board with guidance from the Science Council (Rummel, 2002). Until these requirements are formally specified, we judge the practical useful target for the TRF and space geodetic measurement accuracy to be roughly a factor of 5 to 15 below today's levels. Given that the TRF and global geodesy are now

accurate to the order of 1 cm (or 5-15 mm for different quantities) and 2 mm/yr, we foresee near-term utility in global measurements with absolute accuracies at or below 1 mm and 0.2 mm/yr. Corresponding levels of improvement are required for Earth orientation and gravity.

5 Evolution of the Techniques

Each of the GGOS Services techniques envisions technological and operational advances that will enhance measurement capability. Some advances are currently being implemented while others are in the process of design or development. In addition, each technique-related service is seeking to improve not only data quality and precision, but also reliability of data and product delivery, performance, continuity, station stability, data latency (which in the case of GNSS includes real-time), and data handling techniques and modeling. While making these improvements, contributors seek operational efficiencies in order to minimize costs.

5.1 GNSS

Geodetic GNSS has already evolved from GPS-only operations to inclusion of GLONASS, and upgrades to next-generation receivers will allow full benefit from modernized GPS signal structures, Galileo signals, and GLONASS signals. Studies leading to improved handling of calibration issues such as local signal effects (e.g., multipath) and antenna phase patterns are underway, as are initiatives to fill remaining network gaps, particularly in the southern hemisphere. Elsewhere, station density is less problematic and the focus has shifted to consolidation of supplementary instrumentation such as strain meters and meteorological sensors.

5.2 Laser Ranging

Newly designed and implemented laser ranging systems operate semi-autonomously and autonomously at kilohertz frequencies, providing faster satellites acquisition, improved data yield, and extended range capability, at substantially reduced cost. Improved control systems permit much more efficient pass interleaving and new higher resolution event-timers deliver picosecond timing. The higher resolution will make two-wavelength operation for atmospheric refraction delay recovery more practical and applicable for model validation. The current laser ranging network suffers from weak geographic distribution, particularly in Africa and the southern hemisphere. The comprehensive fundamental network

should include additional co-located sites to fill in this gap.

Improved satellite retroreflector array designs will reduce uncertainties in center-of-mass corrections, and optical transponders currently under development offer opportunities for extraterrestrial measurements.

5.3 VLBI

The VLBI component of the future fundamental network will be the next-generation system now undergoing conceptual development. Critical elements include fast slewing; high efficiency 10-12 m diameter antennas; ultra wide bandwidth front ends with continuous radio frequency (RF) coverage; digitized back ends with selectable frequency segments covering a substantial portion of the RF bandwidth; data rate improvements by a factor of 2–16; a mixture of disk-based recording and high speed network data transfer, near real time correlation among networks of processors, and rapid automated generation of products. Better geographic distribution, especially in the southern hemisphere, is required.

5.4 DORIS

The DORIS tracking network is being modernized using third-generation antennae and improvements to beacon monumentation (Tavernier et al., 2005). Efforts are underway to expand the network to fill in gaps in existing coverage. DORIS beacons are also being deployed to support altimeter calibration, co-location with other geodetic techniques, or specific short-term experiments. A specific IDS working group is selecting sites and occupations for such campaigns, using additional DORIS beacons provided by CNES to the IDS.

5.5 Gravity

Gravity observations are most sensitive to height changes; they therefore provide an obvious way to define and control the vertical datum. A uniformly-distributed network of regularly cross-calibrated absolute gravimeters supported by a well-designed relative measurement network that will be repeatedly observed at regular intervals, and a sub-network of continuously operating superconducting tidal gravimeters are expected in a fundamental network of co-located techniques. These permanent networks should be augmented with targeted airborne and ship campaigns to collect data over large areas that are devoid of gravimetric observations. A well-distributed global data set of surface data is necessary to calibrate

and validate products of the recent (CHAMP and GRACE) and upcoming (GOCE) high-accuracy and -resolution missions. The organization of a gravity field service is underway and the integration of its activities should emerge shortly.

6 Approaches to Network Design

The final design of the GGOS network must take into consideration all of the applications including the geometric and gravimetric reference frames, EOP, POD, geophysics, oceanography, etc. We will first consider the TRF, since its accuracy influences all other GGOS products. Early steps in the process are:

1. Define the critical contributions that each technique provides to the TRF, POD, EOP, etc.
2. Characterize the improvements that could be anticipated over the next ten years with each technique.
3. Examine the effect in the TRF and Earth orientation resulting from the loss of a significant part of the current network or observation program.
4. Using simulation techniques, quantify the improvement in the TRF, Earth orientation and other key products as stations are added and station capability (co-location, data quantity and quality) is improved. We will also explore the benefit of adding new SLR targets.

7 Sustaining the Ground Network Over the Long Term

The measurement techniques services have each maintained their own networks and supporting infrastructure, routinely producing data, but suffer from severe budget constraints of the voluntarily contributing agencies that prevent appropriate maintenance and development of physical and computational assets. This degradation of the observing network capability coincides with the deployment of high-value science investigations and missions, such as sea level studies from ocean and ice-sheet altimetry missions, eroding their scientific return and limiting their ability to meet the mission goals.

Many of the elements of the current networks are funded from year to year and depend upon specific activities. Stations are often financed for capital and maintenance and operations costs through research budgets, which may not constitute a long-term commitment. Sudden changes in funding as priorities and organizations change have resulted in devastating impacts on station and network performance. On the other hand,

missions and long-term projects have assumed that the networks will be in place at no cost to them, fully functioning when their requirements need fulfillment. GGOS will be proactive in helping to persuade funding sources that the networks are interdependent infrastructure that needs long term, stable support. The GGOS community must secure long-term commitments from sponsoring and contributing agencies for its evolution and operations in order to support its users with high-quality products. Since the present networks must support current as well as future requirements, the GGOS network must evolve without interruption of data and data products. In view of the difficulties in securing long-lasting and stable financial support by the interested parties, new financial models for the networks must be developed. This Working Group will work with the Strategy and Funding Working Group to develop an approach.

8 Summary

A permanent geodetic network of complementary yet interdependent space geodetic techniques is critical for geodetic and geophysical applications and underpins the Global Earth Observation System of Systems. Thanks to the generous and voluntary contributions of many national agencies and institutions around the world, the IAG has been able to coordinate global collaborations for geodetic technique based services from which all benefit. There is a strong need for coordination of the planning, funding and operation of future integrated geodetic networks to maximize performance in meeting evolving requirements while taking into account the need for sustainable infrastructure and efficient operations. The GGOS Ground Networks & Communications Working Group has initiated studies, which will guide the services in infrastructure planning for optimal benefit to Earth science and associated engineering and societal concerns.

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