Hartebeesthoek Radio Astronomy Observatory: Space Geodesy status and progress

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Abstract

A brief overview of the current status of the global space geodetic networks is given and a sketch of the future of space geodesy from South Africa's perspective is made relative to a global perspective. The development of the Global Geodetic Observing System is brought into context with what is required in South Africa to allow participation in this new modernized space geodetic network. Additional space geodesy observatory sites should be developed at Matjiesfontein, Sutherland and Klerefontein to facilitate an improved and expanded South African network which is compatible with the stringent and high accuracy requirements of the new global network. Simulations indicate that HartRAO is an extremely valuable component in the global network of geodetic stations and that total network efficiency suffers if it were not to participate in the new network. HartRAO will be upgraded and equipped with modern geodetic instrumentation, including a state of the art, wide-band, fast slewing radio antenna, which will enable participation in new global developments in space geodesy.

1. Introduction

Space geodesy is a multidisciplinary branch of science which supports many scientific endeavours such as the development and maintenance of global gravity field models, celestial and terrestrial reference frames, Earth sciences, long-term climate and climate-change induced events (e.g. ocean level changes) to mention but a few. More knowledge of natural hazards, climate change and space engineering requirements demand an increase in performance from the global geodetic networks. In terms of fundamental physics, it continues to play an increasing role in the evaluation of the General Theory of Relativity (GTR), by testing limitations of currently accepted and alternative theories of spacetime geometry. The different space geodesy techniques need to meet requirements of the Global Geodetic Observing System (GGOS) (http://www.ggos.org/), a project of the International Association of Geodesy (IAG).

2. Space Geodesy Techniques

2.1. Introduction

Space Geodesy evolved rapidly after the first Earth orbiting satellites were launched. The 1960s saw the development of SLR, a technique that allowed accurate determination of satellite orbits by emitting short, time-of-flight determined laser pulses from a network of Earth-based stations to satellites equipped with corner cube reflectors (Combrinck, 2010). From these observations the first global gravity field models were determined; a new era had begun concerning the measurement of Earth in space. After the placement of a corner cube retroreflector array on the Moon in 1969 by the astronauts of Apollo 11, Lunar Laser Ranging became possible. More developments followed, which included the development in the 1970s of VLBI, utilising radio astronomy techniques and instrumentation. The 1980s saw the development of the Global Positioning System (GPS), which is now one of the GNSS constellations, as well as the development of the French DORIS network

2.2. Global Geodetic Observing System (GGOS)

Current global accuracies in positioning for space geodesy techniques are at the 1-2 cm level, with formal uncertainty levels at the 1 mm level or less for stations with a long time series. The global networks of these techniques are set to change with the introduction of GGOS, a modernised and much improved space geodesy network. This network is in various stages of development and implementation, with certain countries at the forefront, notably Germany, Sweden, Norway, Australia and the USA. HartRAO needs to upgrade as well and should extend its operations to additional sites that would be more suitable for scientific purposes on the long term. At these new sites, the atmosphere is more benign for observations which rely on the transparency and stability of the atmosphere (such as SLR and LLR). In addition they are remote enough from cities to be relatively protected against Radio Frequency Interference (RFI). The adverse RFI effect of terrestrial radio transmitters can be avoided largely through careful site selection. Unfortunately the antipode of this is satellite based transmitters, the effect of which can be disastrous for sensitive radio astronomy telescopes (Combrinck et al., 1994).

2.3. Synergy between space geodetic techniques

All the space geodetic techniques deliver products which are mutually supportive and linked in one way or another; the different techniques, the science and product rationale for each technique, are inseparable and combine to create unique products such as the International Terrestrial Reference Frame (ITRF) and the International Celestial Reference Frame (ICRF). Maintenance of the ICRF and EOPs are extremely important for optical and radio astronomy purposes. The science plans and rationale of astronomy (as *a priori* fundamental reason for the funding and existence of the scientific field of astronomy, including projects such as the Square Kilometre Array) can therefore directly be used as the rationale for the existence of space geodesy networks. In addition, a multitude of additional applications are derived from the space geodetic data which have applications in satellite orbital management, Earth gravity field determination and evaluation (Botai and Combrinck, 2012), ocean and land mass level monitoring, hazard mitigation and crustal dynamics. The equipment form networks in the space geodesy arena and each network has analysis groups and specialised working groups within the services of the IAG. These services are the International VLBI Service for Geodesy and Astrometry (IVS), International GNSS Service (IGS), International Laser Ranging Service (ILRS) and International DORIS Service, (IDS).

2.4. Commitment to GGOS

In response to the Call for Participation issued by the GGOS Bureau for Networks and Communication, HartRAO has committed itself to support the GGOS project. As one of the few sites globally, and the only site on the African continent, hosting four space geodesy techniques, HartRAO supports the GGOS concept and its objectives towards addressing requirements that the nine Societal Benefit Areas of Earth Observations (defined by the Group on Earth Observations) have in terms of geodetic observations and products. The acronym VLBI2010 has now been surpassed by VLBI2010 Global Observing System (VGOS), and the IVS community has been asked to use the new term (Nothnagel, personal communication, March 2014).

3. Very Long Baseline Interferometry (Geodetic and Astrometric)

Geodetic and astrometric VLBI utilises radio telescopes in a global network to measure the differential delay in the arrival times of micro-waves emitted by extragalactic radio sources. Utilising this delay, accurate baseline lengths and the orientation of Earth in space can be determined. Typically these radio antennas are large and expensive in comparison to the other space geodetic techniques. The VLBI technique is particularly suitable for determining EOPs due to the high angular resolution achieved. The EOPs can be summarised as precession-nutation (Earth rotation axis variations in space), polar motion (Earth rotation axis variations in the Earth) and variations of the rotation speed of Earth (excess in the Length of Day or LOD). Currently VLBI is the only space geodesy technique that produces the complete set of EOPs as well as maintains and realizes the International Celestial Reference Frame (ICRF). These parameters are required for optical and radio astronomy as well as for precise satellite orbit determination. Furthermore, the technique contributes to the realization of the International Terrestrial Reference Frame (ITRF) by providing accurate antenna positions and the scale component of the ITRF. A recent review by Schuh and Böhm (2012) contains more technical details. A simulation study using data from the CONT08 geodetic VLBI campaign (personal communication Mayer, March 2013) revealed that the exclusion of HartRAO from the network nearly *triples* the standard deviation of the y-coordinate of polar motion as well as the x-coordinate of nutation. The impact of including or excluding HartRAO in a simulated GGOS VLBI network on the network volume is (19.58%). This is a severe impact, as the next most influential station is Fortaleza (Brazil) with a volume impact of 7.61%. HartRAO is therefore of highest importance for precision and accuracy of the EOPs. It is thus essential to include HartRAO in the future GGOS network. The IVS (see http://ivscc.gsfc.nasa.gov) is a service of not only the International Association of Geodesy (IAG), but also of the International Astronomical Union (IAU) and the Federation of Astronomical and Geophysical Data Analysis Services (FAGS). This clearly illustrates the organisational and high level global synergistical link between space geodesy, astronomy and geophysics and extends to many of the Earth sciences and also into fundamental physics where the geodetic VLBI technique is used to evaluate GTR (Combrinck 2012). According to Schlüter and Behrend (2007) the IVS objectives include the facilitation of geodetic, geophysical, and astrometric research as well as operational activities. In addition, the IVS promotes research, technical development and inter-community activities

(Schleuter at al., 2002; Schlüter and Vandenberg, 2002) (working groups, workshops, training sessions, product user interaction). Currently a major drive within the IVS (and other services for their own products) is to integrate VLBI into GGOS, which will feed high quality and extremely accurate products to the Earth science and other communities. The distribution of IVS stations (Figure 1) is not homogeneous as most stations are located in the Northern Hemisphere with clusters in Europe, North America and Japan.

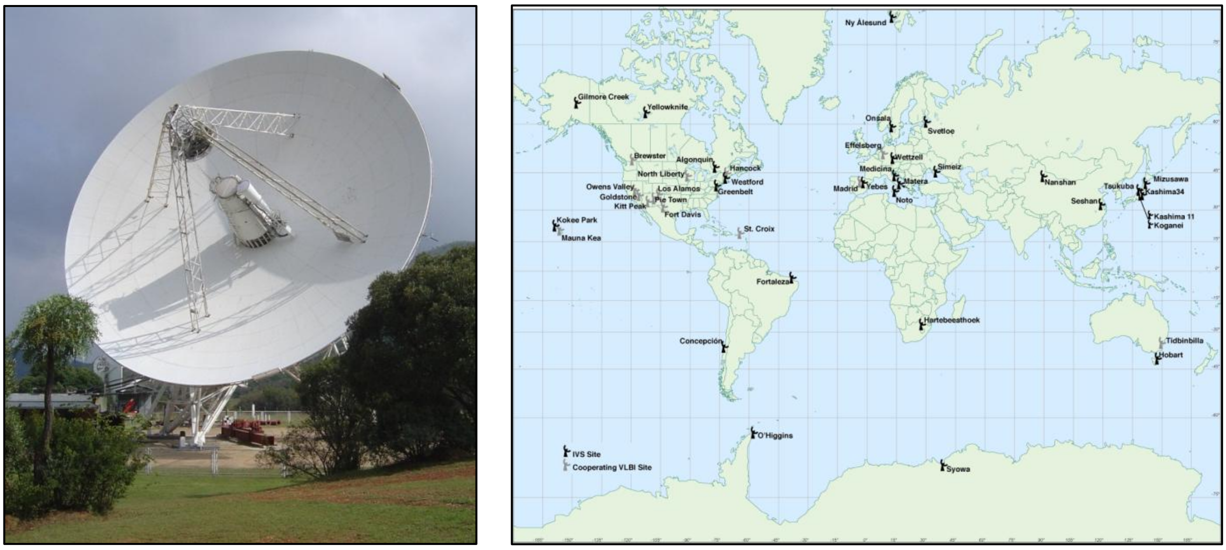

Figure 1. (Left) the 26m diameter astronomy and geodetic VLBI antenna located at HartRAO. (Right) the IVS network indicating the sparse population of geodetic VLBI antennas. Source: http://ivscc.gsfc.nasa.gov/stations/ns-map.html.

3.1 Future of geodetic and astrometric VLBI

The 2nd IVS General Meeting held in Tsukuba/Japan in February 2002 led to the following resolutions (Schlüter and Vandenberg, 2002):

1) geodetic and astrometric VLBI is fundamental for the establishment and maintenance of the ICRF and contributes extensively to the generation of the ITRF, and

2) geodetic VLBI plays an essential role in geodesy and astrometry due to its uniqueness in observing all of the EOPs which describes the transformation between the ICRF and ITRF stable over a time span longer than a few days, and

3) that providing the reference frames and EOPs consistent over decades on the highest accuracy level will be a challenging role for IVS.

During 2001, IVS Working Group 2 reviewed the IVS products and the corresponding observing programs and in an interpretation by Schlüter et al. (2001) the required steps to improve the current IVS products would include: improving the currently unbalanced network configuration, increasing observing capabilities, reducing technical failures of old components (legacy antennas such as at HartRAO), avoiding RFI, obtaining compatibility in technology, in particular in data recording, developing dynamical scheduling to make best use of observation resources, increasing data transmission bandwidths, reducing latency between observations and product provision, reducing systematic errors of the instrumentation, and systematic errors caused by analytical and numerical models, increasing automation in the data handling process from the correlator to final analysis and supporting combination with other space geodetic techniques. In a report (Niell et al., 2005) prepared by IVS Working Group 3 during 2005, consideration is given to certain performance enhancing strategies, which required a complete examination of all aspects of geodetic VLBI, including equipment, processes, and observational strategies; recommendations includes small antennas (10-12m diameter) that are fast-moving and mechanically reliable. The new network will include some components of the existing network therefore the best of the existing large antennas must be equipped with the new small-antenna radio receiver systems for compatibility, allowing co-observations to preserve continuity with the historical record and improvement of the ICRF measurements made primarily by the large antennas. This of course will not make the old large antennas fully VGOS compatible as they will not be able to slew (move) as fast. The larger antennas (such as the 26m at HartRAO) are required where high sensitivity is essential. Realization of VGOS is rapidly occurring as several role players are already involved in the conceptualisation, detail design and construction of the various components which will be required for the new system. As an example, the fundamental station at Wettzell has already installed two high quality VGOS antennas and several other countries have allocated funding for VGOS antennas. HartRAO has been funded (2014-2016) for such a VGOS antenna as the existing 26m antenna, or the XDM (15m) Experimental Development Model (built as an SKA prototype) azimuth-altitude antenna, do not meet the stringent requirements of VGOS.

4. IGS GNSS Network

The IGS network (Figure 3), Data Centres, and Analysis Centres provide high-quality GPS data and data products (some of it in near real time) to meet the objectives of a wide range of scientific and engineering applications. HartRAO is an IGS Regional Data Centre, and provides GPS data to local and regional users. These products include improvement and densification of the ITRF, crustal dynamics (plate tectonics, earth crust movement due to earthquakes), the monitoring of Earth rotation and variations in the liquid Earth (sea level, ice-sheets, etc.), scientific satellite orbit determinations, ionosphere monitoring (total electron content maps), and determination of precipitable water vapour. Special projects such as TIGA (Tide Gauge at GPS) allow calibration of ocean level studies, which is important for global warming and long-term climatological studies. HartRAO has installed 4 TIGA stations (at Richards Bay, Simons Town, Marion Island and Gough Island). A GNSS receiver was installed on Gough Island during September 2012 and a tide gauge during September 2013. The fact that GNSS receivers are (relatively) more affordable than the other space geodetic techniques allows a denser network and this facilitates projects such as the African Reference Frame (AFREF), which strives towards the unification and standardisation of a geodetic reference frame throughout Africa (Combrinck, 2009a). Through support from the NRF and the Inkaba yeAfrica (De Wit et al., 2007) project (a multi-disciplinary Earth-science project with Germany), several GNSS stations will be installed in the SADC region in the near future.

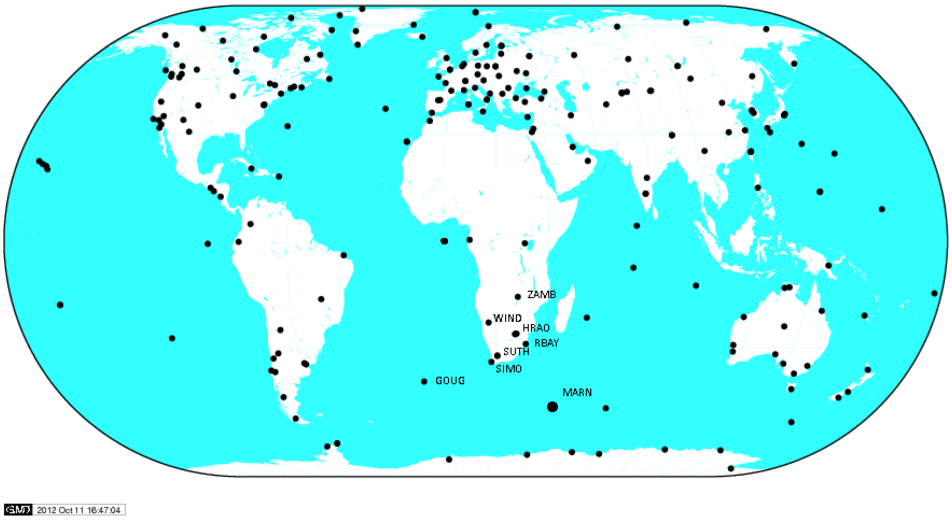

Figure 3. The IGS GNSS network of ITRF2008 reference sites with the names of HartRAO installed stations shown. Most of our installations are in collaboration with other institutions, in particular GFZ Potsdam and JPL (NASA). Adapted from http://igscb.jpl.nasa.gov/images/maps/.

5. **DORIS network**

The French DORIS network (Tavernier et al., 2006) is a satellite tracking system developed for precise orbit determination and precise ground location. It is on board several satellites (Cryosat-2, Jason-1, Jason-2 and HY-2A altimetric satellites and the remote sensing satellites SPOT-4 and SPOT-5). The DORIS system is based on the principle of the Doppler effect that causes the frequency of an electromagnetic wave to shift when a transmitter and receiver are in motion relative to one another. Figure 4 illustrates the good geometry of the DORIS network.

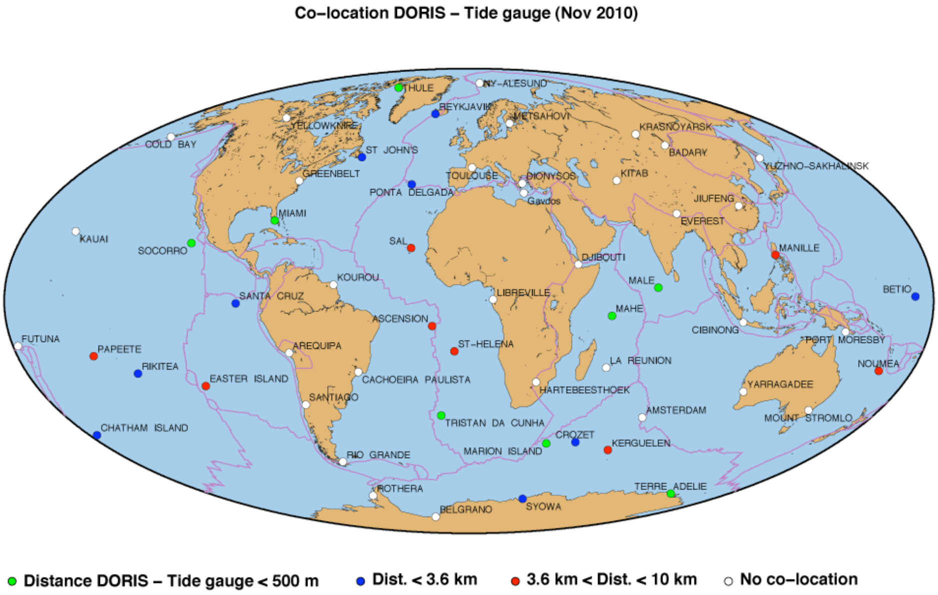
Co–location DORIS – Tide gauge (Nov 2010)

Figure 4. The DORIS network and its collocation with tide gauges. This network is well distributed globally in comparison to the VLBI and SLR networks. Source: http://ids-doris.org/images/doris/.

The receiver is satellite-bound and the transmitters act as Earth-located beacons. This system (see http://ids.cls.fr/) is an active, autonomous system and can practically be located anywhere where power is available. The equipment on the ground does not have to be located where access to Internet is available (there is no need for a satellite data link) as is required with the other techniques.

6. ILRS network

The primary mission of the ILRS (Pearlman et al., 2002) as stated in the organisation's Terms of Reference is "*to support, through satellite and lunar laser tracking data and related products, geodetic and geophysical research activities.*" The global network (Figure 5) is very well presented in Europe, but in Africa only two stations are listed; HartRAO (operational) and Helwan in Egypt (not fully operational). Furthermore only about twenty stations contribute high quality and sufficient quantity of data to form a sub-network of Operational Stations, the others are termed Associate Stations. HartRAO (MOBLAS-6) is an operational station (Combrinck, 2009b), and serves an important geographical role by providing data in an underserviced area.

The ILRS (http://ilrs.gsfc.nasa.gov) collects, merges, archives and distributes SLR and LLR observation data sets. These data are of sufficient accuracy to be used in a wide range of scientific, engineering, and operational applications as well as tests of fundamental physics (Combrinck, 2011a). The accuracy of SLR/LLR data products is sufficient to support a variety of scientific and operational applications including, realization and improvement of the ITRF, monitoring three dimensional deformations of the solid Earth, EOPs, and to support the monitoring of variations in the topography and volume of the liquid Earth (ocean circulation, mean sea level, ice sheet thickness, wave heights, etc.).

Currently we are developing (Combrinck, 2011b) a Lunar Laser Ranger in collaboration with the Observatoire de la Côte d’Azur (OCA) of France and Goddard Space Flight Center (NASA). A 1m aperture Cassegrain telescope (azimuth-elevation mount) has been donated to HartRAO by OCA for this development. This telescope is being refurbished and a Satellite/Lunar Laser Ranger system is being developed using the 1m telescope as the optical component. Development at HartRAO of SLR analysis software has allowed investigations into the feasibility of estimating parameterised post-Newtonian parameters γ and β using a locally developed strategy (Combrinck, 2011c) and additional software is being developed which will allow spacetime geometry tests using LLR data.

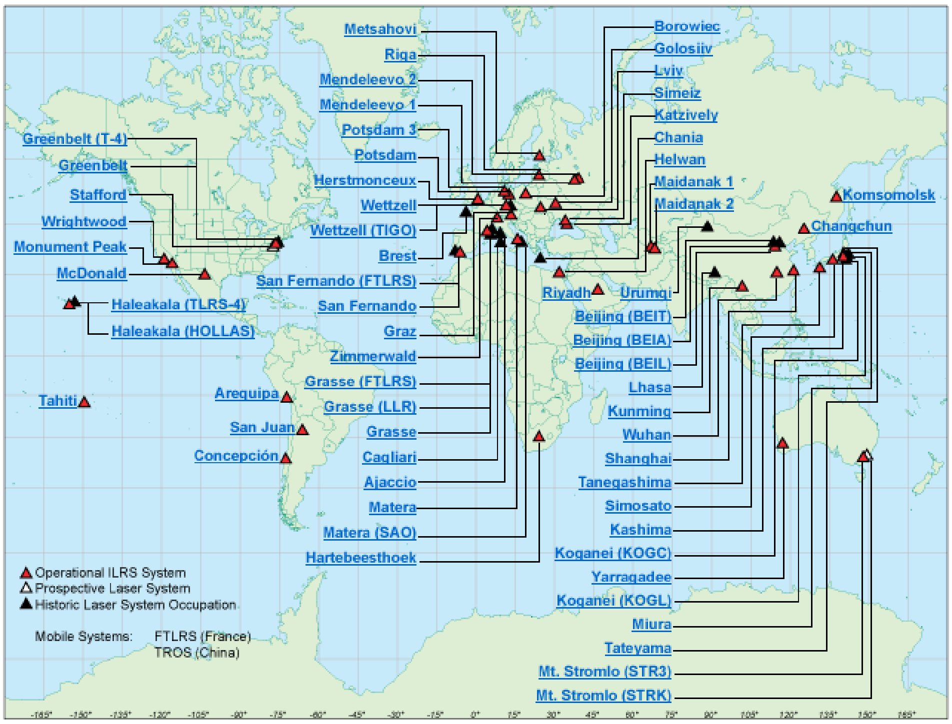

Figure 5. The ILRS network, only two stations are located in Africa, of which only HartRAO (MOBLAS6) is fully operational. Source: http://ilrs.gsfc.nasa.gov/network/

7. South Africa's role in Space Geodesy

South Africa plays a unique role in space geodesy by providing a fundamental station (station where 4 space geodesy techniques are collocated) in Africa and the Southern Hemisphere. Not only is there the huge geographical advantage, but also the skilled manpower and political will to support such a station; this has provided South Africa with a positive image in the science arena. The country's contribution has extended beyond its borders into the SADC region and GPS stations have been installed in Namibia, Botswana, Zambia, Malawi, Antarctica, Marion Island and Gough Island through collaboration with other agencies. This works supports the African Geodetic Reference Frame (AFREF) project and densifies the ITRF in Africa. We have collocated GNSS stations with tide gauges in South Africa and Marion Island to assist global sea level monitoring.

7.1 International support

Most of the GPS equipment installed since 1996 were provided by foreign collaborators, especially the Jet Propulsion Laboratory (JPL) of NASA. The SLR (MOBLAS-6) operated by HartRAO is a NASA/HartRAO collaboration. For South Africa to continue playing a growing, academically and technologically competent role, the ageing equipment and the too small scientific and technical component in terms of manpower, must be radically enhanced to secure our continued (and improved) global participation.

7.2 Capacity building

Development of local human capacity and technical competence, training of keen young scientists within a system that will provide careers and job satisfaction, as well as the development of additional space geodesy observatories equipped with state of the art equipment are exigencies that require immediate support. Several students are undergoing their postgraduate training at HartRAO and it is planned that a selection of these students will become the core of the future of space geodesy in South Africa. Links with several universities have been established and we currently have space geodesy postgraduate students registered at the University of Kwa-Zulu Natal, University of Cape Town, University of Pretoria and the University of Stellenbosch.

8 Science requirements, trends and projections

The interdisciplinary nature of space geodesy provides additional input and a means to understand the processes leading to global climate change, the mitigation of natural hazards such as tsunamis, sea level rise and tectonic events. The inclusion of space geodesy as a project within the Global Earth Observation Systems of Systems (GEOSS) reflects the value that is placed by the international community on the contribution of reference frames and space geodesy data in supporting spatially distributed data dependent on position. The importance of space geodesy is furthermore recognised by cadastral surveyors and government departments dependent on accurate ITRF coordinates to enable modern maps and land management techniques to be utilised through the establishment of ITRF based mapping systems for countries (e.g. ITRF94 Hartebeesthoek Datum for South Africa adopted by the Chief Directorate: National Geo-spatial Information).

Changes in the Earth’s gravity field caused by the moving ocean mass, earth-tide, ocean-loading, atmospheric-loading and pole-tide, the change in the Earth’s shape and changes in rotation and orientation in space can be measured by space geodetic systems. The rotation vector of the solid Earth undergoes small changes (which cannot be modelled but must be measured), which results in a variation of several milliseconds in the length of the day. The rotation vector’s orientation relative to the solid Earth’s axis of figure varies several hundred milli-arcseconds in polar motion (Gross et al., 2003). Changing ocean levels and ice sheet mass variations contribute to these changes. As geodetic observations (in particular SLR) are used to calibrate and determine the orbits of satellites equipped with sea surface height measuring equipment (radar altimeters), space geodesy contributes to the measurement of ocean level change. It also defines and maintains the ITRF within which these measurements are made. According to Douglas et al., (2001) the global rate of ocean level rise has been about 1 mm/yr during the last century. Validation and maintenance of these measurements rely on reference frame stability, and accuracy should be at least ten times better, i.e. to within 0.1 mm/yr. This leads to the rather stringent requirement that geodetic site positions must be determined with sub-millimetre accuracy. Accelerated or long term ocean level rise (of the order of 50 cm) would have major impacts (Woodworth and Aarup, 2003) on all coastlines in all countries, rich or poor.

9 Additional space geodesy sites

We have been acutely aware during the last decade that the space geodesy activities at HartRAO needs to be expanded and augmented with additional sites within the framework of GGOS and its new requirements. These locations will have to meet the criteria of clear skies, low cloud cover, relatively low radio frequency interference and existing infrastructure. These sites should eventually contain a selected combination of LLR, SLR, GNSS, DORIS, VLBI, and supportive science instrumentation (gravimeter, seismometer, meteorological sensors).

9.1 Matjiesfontein

Several attempts were made to garner support for a new facility, dubbed “The International Institute for Space Geodesy and Earth Observation (IISGEO)”, which would have been a GGOS node and focus point for African participation (Combrinck, 2004). Efforts at Matjiesfontein are continuing, with support by Stoffel Fourie of Tshwane University of Technology and Leon Croukamp of the University of Stellenbosch. An environmental impact assessment is currently (March 2014) being done and a seismic vault was built during 2013. The name of the Matjiesfontein observatory has been changed from IISGEO to Matjiesfontein Space Geodesy and Earth Science Observatory (MSGESO). Several workshops were held at Matjiesfontein from 2005 to 2014 to inform and attract potential participants. A GNSS station was installed during December 2008. Details of a geotechnical survey have been published (Combrinck et al., 2007). Matjiesfontein has many benefits in terms of existing infrastructure, and meets requirements in terms of cloud cover, seeing conditions and site stability. A tract of land towards the south of the town has been allocated to the project based on discussions during 2005 between Combrinck and the late Mr David Rawdon. This agreement is now formalised in contractual form between Tshwane University of Technology, the Matjiesfontein Educational Trust and HartRAO.

9.2 Klerefontein and Sutherland

Klerefontein (located 10 km west from Carnarvon) in the Northern Cape (SKA/Meerkat Project support base and site of the C-BASS radio telescope) and the South African Astronomical Observatory Sutherland site will be a good location for a seismic vault, gravimeter and GNSS as it exploits synergies, logistical efficiencies and cost effectiveness. The Klerefontein data can also be used to develop a long-term time series for a proposed gravity wave observatory in the vicinity.

10 Conclusion

Participation in GGOS and consequent upgrades, new developments and expansion in the observational and research capacity of radio astronomy and space geodesy in South Africa is essential to ensure continued high-level participation in the space geodesy networks These developments are partially dependent on postgraduate student projects, providing opportunities for young scientists as well as science career opportunities. High level participation in GGOS will ensure access to opportunities in many different fields of science linked to space geodesy and its products.

References

Botai, CM and Combrinck, L 2012, Global geopotential models from Satellite Laser Ranging data with geophysical applications: A review. *S Afr J Sci.* 2012; vol. 108, no. (3/4), pp.1-10.

Combrinck, WL, West, and Gaylard, MJ 1994, 'Coexisting with GLONASS: Observing the 1612 MHz Hydroxyl Line', *PASP*, vol.106, pp. 807-812.

Combrinck, L 2004, 'International Institute for Space Geodesy and Earth Observation', in *Proceedings of the 14th International Workshop on Laser Ranging*, San Fernando, Spain, available: http://cddis.nasa.gov/lw14/, [March 2014]

Combrinck, L, Fourie, CJS, Croukamp, L, and Saunders, I 2007, 'Geotechnical and tropospheric site investigation for a proposed space geodesy observatory near Matjiesfontein in the Great Karoo'**.** *South African Journal of Geology*, vol. 110, no. 2-3, pp. 225-234.

Combrinck, L 2009a, 'Status of the African Geodetic Reference Frame (AFREF) project as at September 2008', in *Proceedings of the International Symposium on Global Navigation Satellite Systems, Space-Base and Ground-Based Augmentation Systems and Applications*, Berlin, pp. 11-14.

Combrinck, L 2009b, 'MOBLAS6 Satellite Laser Ranger: Technology and Applications of Data', in Proceedings of the IEEE International Geoscience & Remote Sensing Symposium: *Earth observation, origins to applications*, Cape Town, July 2009, pp. 161-164.

Combrinck, L 2010, 'Satellite Laser Ranging', in G Xu (ed.), *Sciences of Geodesy I*, Springer Publishers, Berlin.

Combrinck, L 2011a, 'Evaluation of satellites LAGEOS I and II; general relativistic accelerations in the Schwarzschild field of Earth', in I Basson and AE Botha (eds.), *Proceedings of SAIP2011, the 56th Annual Conference of the South African Institute of Physics*, available: http:\\www.saip.org.za, [March 2014].

Combrinck, L 2011b, 'Development of a satellite and lunar laser ranger and its future applications in South Africa', in International Astronautical Congress 2011, Cape Town, IAC-11-A2.1, available: http://www.iafastro.net/iac/archive/browse/IAC-11/A2/1/11785/, [March 2014].

Combrinck, L 2011c, 'Testing the General Relativity Theory through the estimation of PPN parameters γ and β using Satellite Laser Ranging data', *South African Journal of Geology*, vol. 114, no. 3-4, pp.

Combrinck, L 2012, General Relativity and Space Geodesy, in G Xu, *Sciences of Geodesy II*, pp 53-95, Springer Berlin Heidelberg.

De Wit, M, Horsfield, B, Combrinck, L, Compton, J, Kounov, A, Tinker, J, Tredoux, M, Partridge, T, Uenzelmann-Neben, G, Gohl, K, Jokat, W, Neben, S, Mandea, M, Di. Primio, R, Ritter, O, Weckmann, U and Oberhänsli, H 2007, 'Inkaba yeAfrica project surveys sector of earth from core to space', *EOS*, vol. 87, no. 11, pp. 113-117.

Douglas, BC, Kearney, MS and Leatherman SP (eds.), 2001, *Sea level rise: History and Consequences*, 242 pp., Academic Press, San Diego, California.

Gross, RS, Fukumori, I and Menemenlis, D 2003, 'Atmospheric and oceanic excitation of the Earth's wobbles during 1980–2000', *J. Geophys. Res.*, vol. 108, no. (B8), 2370, pp.6-1 – 6-16.

Niell, A, Whitney, A. Petrachenko, B, Schluter, W, Vandenberg, N, Hase, H, Koyama, Y, Ma, C, Schuh, H and Tuccari, G 2005, *VLBI2010: Current and future requirements for geodetic VLBI systems*, Report of Working Group 3 to the IVS Directing Board, Sept 16, 2005. Greenbelt, MD: IVS Coordinating Center, NASA Goddard Space Flight Center.

Pearlman, MR, Degnan, JJ, and Bosworth, JM 2002, 'The International Laser Ranging Service', *Advances in Space Research*, vol. 30, no. 2, pp. 135-143.

Schlüter, W, Behrend, D, Himwich, E, Nothnagel, A, Niell, A and Whitney, A 2001, *IVS High Accuracy Products for the Maintenance of the Global Reference Frames as a contribution to GGOS*, [online], Available: http://ivscc.gsfc.nasa.gov, [March 2014].

Schlueter, W, Himwich, E, Nothnagel, A, Vandenberg, N and Whitney, A 2002 "IVS and Its Important Role in the Maintenance of the Global Reference Systems", *Advances in Space Research*, vol. 30, no. 2, pp. 145-150.

Schlüter, W and Vandenberg, N 2002, *Prospective Development of the International VLBI Service for Geodesy and Astrometry over the next few years (Status: July, 2002)*. Report for the IVS Directing Board.

Schlüter, W and Behrend, D 2007, The International VLBI Service for Geodesy and Astrometry (IVS): current capabilities and future prospects. *Journal of Geodesy*, vol. 81, no. (6-8), pp. 379-387.

Schuh, H and Böhm, J 2012, 'Very Long Baseline Interferometry for Geodesy and Astrometry', in G Xu, *Sciences of Geodesy II*, pp. 339-376, Springer Berlin Heidelberg.

Tavernier, G, Fagard, H, Feissel-Vernier, M, Le Bail, K, Lemoine, F, Noll, C, Noomen, R, Ries, JC. Soudarin, L, Valette, JJ, Willis, P 2006, 'The International DORIS Service: genesis and early achievements', P Willis (ed.), *Journal of Geodesy*, vol. 80, no. 8-11, pp.403-417.

Woodworth, PL and Aarup, TA 2003, 'A report on the status of the GLOSS programme and a proposal for taking the programme forward', IOC/INF-1190, Paris.