Space Geodesy at HartRAO

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Abstract HartRAO participates in international space geodesy projects using the techniques of VLBI, GPS and SLR. We present the status of our present involvement and discuss exciting future developments of the Space Geodesy Programme. Some preliminary GPS results are presented and compared with NASA VLBI results.

VLBI

Introduction

Very Long Baseline Interferometry (VLBI) is a technique developed by astronomers to measure accurately the positions and spatial structure of astronomical radio sources utilising radio telescopes. Radio astronomers use radio interferometers for aperture synthesis imaging, which allows radio telescopes with resolution equivalent to very large effective apertures to be built by using an array of radio telescopes. These telescopes can be separated by hundreds of meters or one can have networks of inter-continental spaced antennas.

Geodesy has benefitted from radio astronomy by using the radio interferometry technique in an inverse sense. VLBI has been used since the early 70's in high precision geodynamical studies for determining the position of and baseline between stations. The Hartebeesthoek Radio Astronomy Observatory (HartRAO) currently supports several long term international geodetic VLBI projects, using a 26 m diameter radio telescope (figure 1). The geodetic VLBI technique utilises very distant, extra-galactic, radio sources (quasars), as apparently motionless objects of reference and for this purpose are taken to be point sources. This apparently motionless character of quasars allows the implementation and maintenance of a very stable reference frame which is required for the measurement of slow geodynamical processes which is normally of the order of millimetres per year.

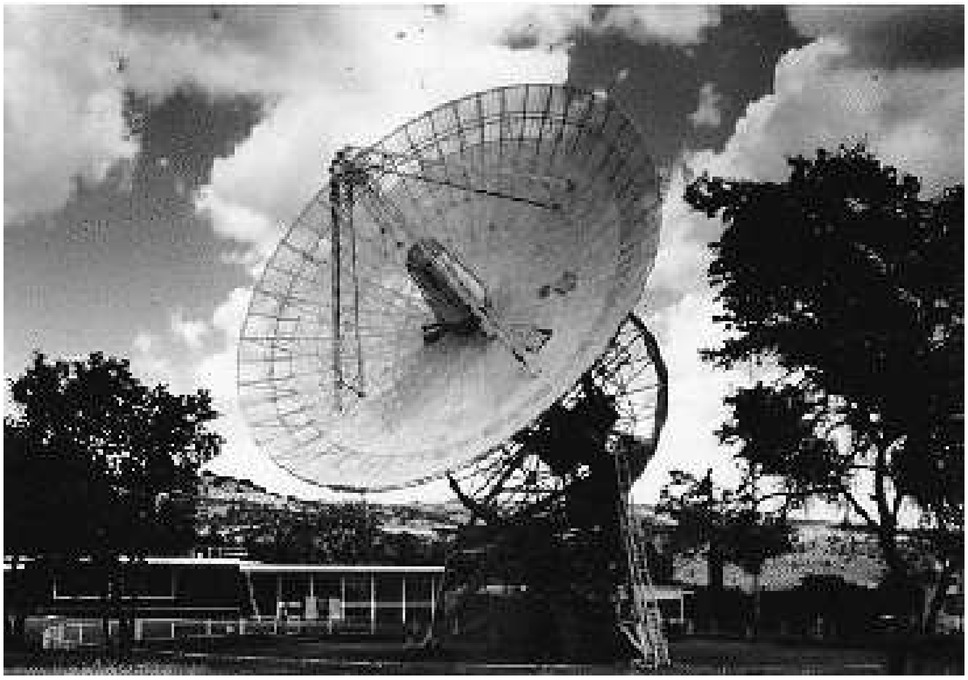

Figure 1: The HartRAO 26 m antenna.

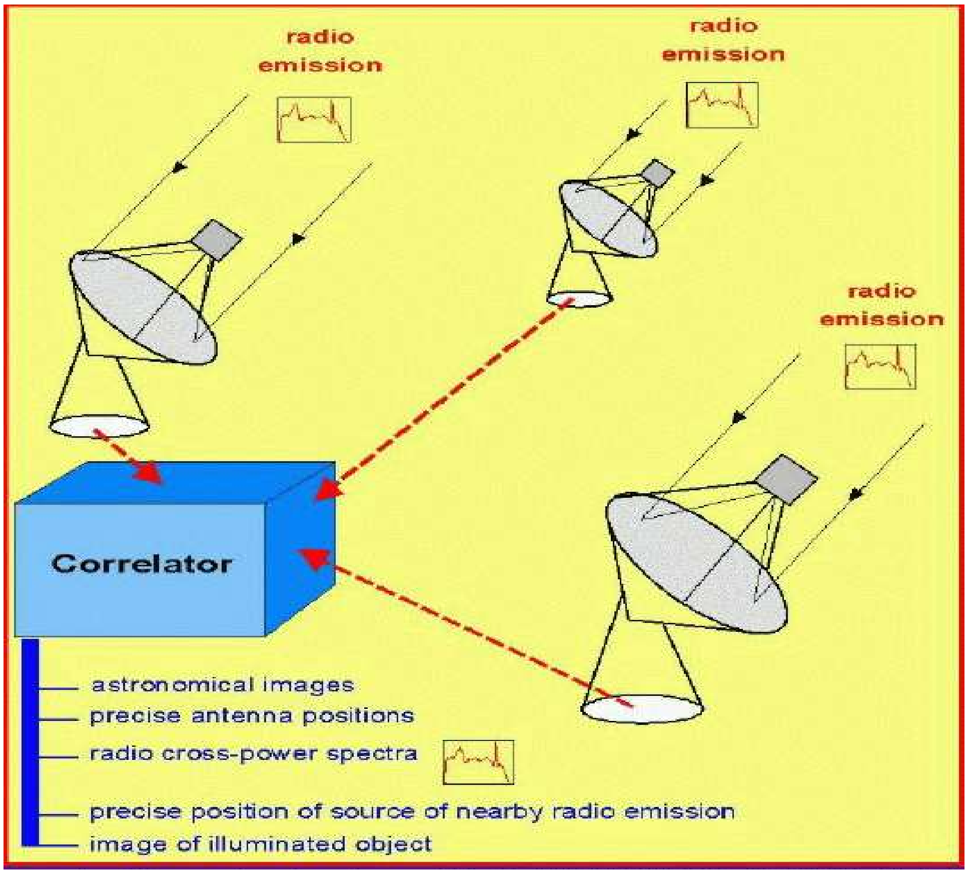

Figure 2: In VLBI two or more stations are used in an array, data is postprocessed at a correlator. (source: Dominion Radio Astrophysical Observatory, Penticton, BC, Canada. (http://www.drao.nrc.ca/))

The techniques of VLBI, GPS and SLR further the scientific understanding of Earth dynamics, earthquake mechanisms and tectonophysics. These techniques find application (amongst others) in the following areas:

(1) Studies of the Earth's variable rotation, this includes the motion of the Earth's rotation axis with respect to the Earth as shown by polar motion and the angular position around the Earth's rotation axis describing universal time (UT1).

(2) Studies of angular momentum transfer from the atmosphere and its effect on the rotation of the Earth.

(3) Crustal dynamics - e.g. tectonic motion and monitoring of active regions.

(4) Global studies of true variation of ocean levels by linking tide gauges to fundamental GPS, VLBI and SLR sites.

(5) Geophysical studies - e.g. VLBI has significantly improved our knowledge of the shape of the core-mantle boundary.

(6) Geomorphological studies - e.g. global and tectonic geomorphology.

(7) Geopotential field measurements - SLR data from LAGEOS is very important to enable measurement of long wavelength temporal components of the gravity field.

(8) SLR allows special tests of the theory of General Relativity.

(9) Using SLR, sub-nanosecond global time transfer is possible.

(10) Precision orbit determination for spaceborne radar altimeter missions.

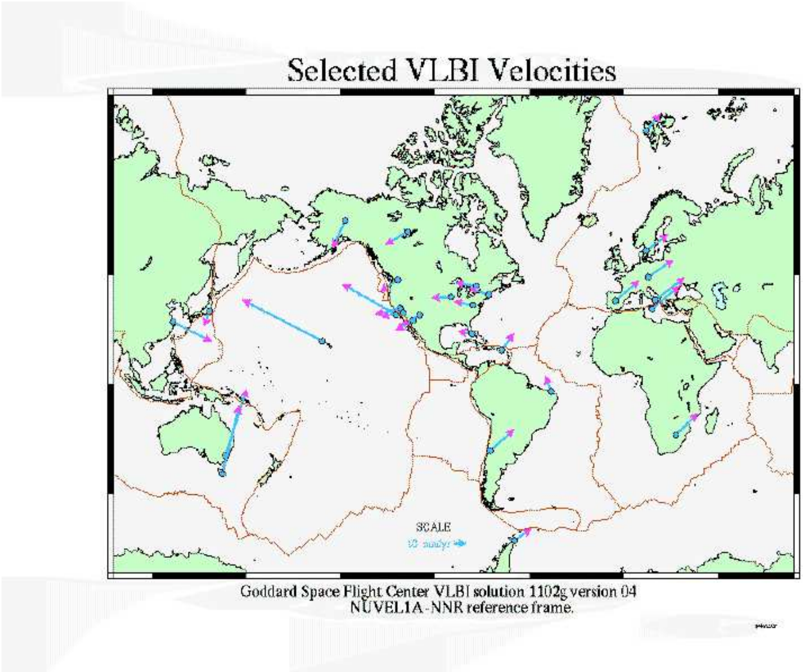

Figure 3: Depiction of global VLBI station velocities. (Ma and Ryan 1998)

Basic Principles of Geodetic VLBI

In general, the travel time of a wavefront between the antennas at two or more sites is measured by maximising the cross-correlation function of the different signals received at the antennas. The difference in travel time (group delay) is a function of the geometry of the participating stations, the spatial distribution of the radio sources, the effects of the propagation medium and instrumental effects (Kolaczek 1989). The latter includes clock drifts and the offset of the antenna axis which is by definition the distance between the Hour Angle (HA) rotational axis and the Declination (DEC) rotational axis. The group delay is one of the parameters which allows solving for the baseline coordinates. If the antennas in an array are separated by relatively short distances, phase-synchronized local oscillators can be used and the antennas can feed a correlator directly. If the antennas are situated on different continents they cannot be connected in real time at present. Instead hydrogen MASER atomic clocks are used to sinchronize the signals from the antennas and the signals from the radio sources are stored on very high density magnetic tape. This technique requires specialised recording equipment and a correlator system (see figure 2), but the antennas can be located far apart, allowing the measurement of inter-continental baselines.

Geodetic VLBI Applications

Geodetic VLBI allows one to accurately determine the relative positions of the radio antennas in an array. These relative positions can then be used to study motion of the continents on which the antennas are located as well as the motion of the Earth itself. The basic concept of plate tectonics is that the lithosphere, i.e. the crust and uppermost mantle which is of the order of 100 km thick, is divided into a small number of nearly rigid plates, which are moving over the astenosphere. Apart from plate tectonics, the earth undergoes dynamic processes such as rapid and complex rotation about its axis. The lithosphere behaves elastically on a geological time scale, so there is also a gradual rebound of the land after the retreat of continental glaciers. It is only by careful investigation of all the complex dynamical processes that a deep enough understanding can be had of the physics of the earth which will enable us to predict earthquakes and monitor global changes. (Figure 3) (Ma & Ryan 1998) depicts VLBI station velocities on a world map. These VLBI plots are results from NASA Goddard Space Flight Center's VLBI terrestrial reference frame solution number 1102g, 1998 August. (Figure 4) (Ma & Ryan 1998) is a time series plot of HartRAO, the time baseline is more than ten years. It is interesting to compare this with our GPS solution(Figure 6), which has a time baseline of about a year. Note when comparing that the VLBI solution has the up component on the top part of the figure, followed by the east and north component, whereas the GPS solution has the sequence reversed.

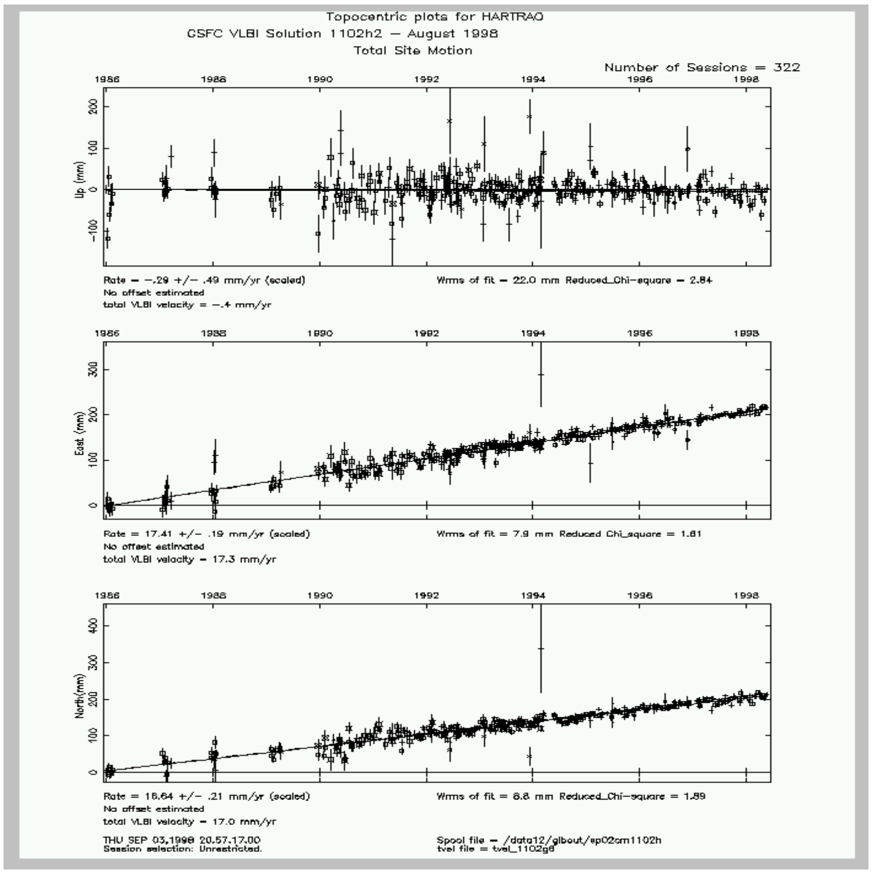

Figure 4: Time series of the HartRAO Geodetic VLBI station. (Ma and Ryan 1998)

HartRAO Geodetic VLBI Participation

The number of geodetic VLBI experiments conducted at HartRAO have increased since 1995 (38) to 1998 (44). A substantial increase in number has been allocated for 1999 (57). The experiments are each of 24 hour duration. The Space Geodesy Programme currently participates in the following projects:

(1) IRIS

(2) Core-A (Earth Orientation Parameters)

(3) SYOWA

(4) CRF

(5) CORE-OHIG

(6) RDV/VLBA

The bulk of these experiments are the IRIS and Core-A experiments. The IRIS-S sessions continue the series of measurements for the determination of earth rotation parameters. These experiments are set up to provide baseline components, all earth orientation parameters (UT1, polar motion, and nutation), as well as positions of extragalactic radio sources. The standard configuration of the monthly observed IRIS-S (South) experiments consists of four stations. A station each in the United States (Westford), South Africa (HartRAO), Europe (Wettzell,Germany) and one radio telescope in South America (Fortaleza,Brasil). Since January 1997 the network has been augmented by station Fairbanks (Alaska). During the O'Higgins occupations two more stations located in the southern hemispere are added to this network. With O'Higgins (Antarctica) and Hobart (Tasmania) there are seven stations in this network.

The purpose of Core-A (Continuous Observations of the Rotation of the Earth) is to validate the CORE concept of measuring EOP continuously using different networks. The network for CORE-A includes Fairbanks (Alaska), HartRAO (South Africa), Algonquin (Canada), Westford (USA), Matera (Italy), Medicina (Italy), Tsukuba (Japan), and Hobart (Tasmania). This set of 8 stations includes two geographically paired stations: Algonquin/Westford and Matera/Medicina. More detailed information can be had from the CORE white paper (http://lupus. gsfc.nasa.gov/core/final1.html).

Present Geodetic VLBI Status

The VLBI terminal has been upgraded to MKIV and the tape recorder to thin tape. The MKIV has the following characteristics:

- Maximum data rate of 1024 Mbits/sec, which can be expanded to 2048 Mbits/sec.
- Supports up to 16 video convertors, with a maximum channel bandwidth of 16 MHz.
- Maximum sampling rate of 32 Msamples/sec, using either 1 or 2 bits per sample.
- Up to 64 simultaneous tracks (using 2 headstacks) can be written on tape at a maximum of 18 Mbits/sec/track (not including parity bits), expandable to 128 simultaneous tracks.
- Track-data format is compatible with MKIII.
- Channelisation modes and data-multiplexing are fully compatible with all Very Large Baseline Array (VLBA) modes.
- By using thin tape (16 micron thickness) recording speeds to 320 ips at linear bit densities of up to 56 000 bpi/track are supported.
- MKIV is compatible with existing thick MKIIIA tapes for all tape speeds up to 270 ips and linear bit densities up to 33 000 bpi/track.

Apart from the VLBI equipment, further upgrades to the telescope are also in progress. We have converted the telescope from hydraulic to electric drive and are in the process of upgrading the telescope surface from a perforated aluminium surface to a more accurate solid surface. This will increase dish efficiency at VLBI frequencies and allow operation at higher frequencies for astronomical purposes.

The thin tape and MKIV upgrades were necessary to continue our participation in global geodetic VLBI experiments as the CORE experiments require thin tapes to achieve the targeted sensitivity. We are therefore committed to participate with a high standard and will continue to upgrade and maintain our equipment to ensure this standard. The upgrades have also allowed us to participate in astrometric/geodetic experiments. These are bi-monthly experiments coordinated by the geodetic VLBI programs of the United Sates Naval Observatory (USNO), NASA, and the National Radio Astronomy Observatory (NRAO). The same data set may be used by each agency for its particular application.

USNO will perform repeated imaging and correction for source structure with the aim to establish a set of core reference sources with known structure and precisely known positions. This will allow evaluation of the long term stability of the radio reference frame and the ultimate accuracy of wide angle astrometric measurements of extragalactic radio sources using VLBI.

NASA will use the data to determine a high accuracy terrestrial reference frame. The data will incorporate the Very Large Baseline Array (VLBA) stations into the VLBI reference frame through the inclusion of other geodetic stations for which long histories are available. The data will also lead to the most accurate Earth rotation results ever to be produced. NASA will also use these data to make accurate absolute measurements of UT1.

NRAO will use these sessions to provide high quality positions for small numbers of sources. Additional time and effort for observing and data reduction will be minimal because such sources can be incorporated into a session of the regular geodetic observations, instead of requiring special observations.

GPS

Introduction

The Global Positioning System (GPS) was developed by the USA Department of Defence to provide instantaneous positioning and velocity determination data for its armed forces. To ensure that four satellites are always visible to a receiver, a system was developed whereby 21+3 evenly spaced satellites placed in 12-hour orbits inclined at 55° to the equatorial plane would provide the required coverage most economically. Currently there are 27 operational satellites in orbit. GPS is now used for many more applications than it was originally intended for and is successfully used in high precision geodetic research. We routinely achieve 10-15 ppb repeatability per 24 hour data set in our weekly GPS analyses. This is a precision of about 10 mm in 1000 km.

HartRAO GPS Activities

During the 1995-1998 period HartRAO assisted IfAG (Institute for Applied Geodesy) of Germany in the Geodetic Antarctic Project (GAP95) which fall within the SCAR (Scientific Committee for Antarctic Research) program to establish a precise geodetic network in the Atlantic sector of Antarctica (Dietrich 1996). The 1998 GPS observations at HartRAO were conducted in cooperation with the Alfred Wegener Institute for Polar and Oceanic Research which had taken over the responsibility from IfAG after their transformation to the BKG (Bundesamt fuer Kartographie und Geodaesie). Several other GPS related projects were undertaken during this period. We developed a method to determine the VLBI antenna axis offset and reference point using GPS (Combrinck & Merry 1997) which allows simultaneous eccentricity determinations between geodetic reference points occupied by different measuring systems. A footprint survey of the HartRAO site was initiated during 1997 to determine local crustal and monumentation stability. High precision measurements were done for the Council for Scientific and Industrial Research (CSIR) using GPS. An ITRF96 reference point was determined for a GPS/GLONASS timing receiver, a metrology test range was calibrated and ITRF96 coordinates were obtained for a newly installed KU/KA satellite ranging antenna.

HartRAO IGS Participation

The International GPS Service (IGS) in cooperation with a multinational membership of organisations and agencies, provides precise GPS orbits, tracking data, and other high-quality GPS data and data products to meet the objectives of a wide range of scientific and engineering applications and studies. GPS stations which meet certain criteria can be included in the IGS network. During September 1996 HartRAO installed an IGS station (HRAO) which is currently equipped with a ROGUE SNR12 RM receiver and Dorne Margolin choke ring antenna (IGS 1996 Annual Report). A Hydrogen MASER is used as clock reference. The monumentation is tied to bedrock. The use of a Hydrogen MASER as reference has allowed HRAO to be included in a small network of globally distributed GPS receivers equipped with precise time references. This special network is used to estimate GPS clock parameters every 30 seconds. The accuracy obtained allows post-processing of high-rate single receiver kinematic GPS data with few-cm-level precision when used with precise GPS orbits (Zumberge et.al. 1998).

Towards the end of 1997 HartRAO installed an IGS station (SUTH) at the Sutherland site of the South African Astronomical Observatory (SAAO). The station is equipped with a ROGUE SNR8000 and Dorne Margolin antenna. Monumentation for a future IGS site (NAMI) at Windhoek, Namibia was installed during November 1998 at the location of the Surveyor General's office of Namibia. It is envisaged that this site will become an IGS station during the later part of 1999 after an equipment upgrade. The equipment for the IGS sites are provided by the Jet Propulsion Laboratory (JPL) of NASA.

From April 1999 HartRAO has officially commenced to function as an IGS Regional Data Center. In this function we gather data from various operational data centers and maintain an archive for users interested in stations in the Africa region. This reduces electronic network traffic and allows local users to obtain IGS products and data more timeously. Currently we archive data for 10 IGS stations and one regional station (NAMI). This data can be downloaded from our webpage: (http://www.hartrao.ac.za/geodesy/geodesy_index.html).

Regional GPS Network

With the co-operation of Scripps Orbit and Permanent Array Center (SOPAC) located at the Scripps Institute of Oceanography, La Jolla, we have started to process an eleven station network (figure 5) in the southern hemisphere using the GAMIT software package. The reference frame is maintained through the IGS orbit and IERS Earth orientation values using HRAO as origin. These stations are located on the African and Antartica tectonic plates. Preliminary results are shown in the form of a time series plot (figure 6) for HRAO. The north

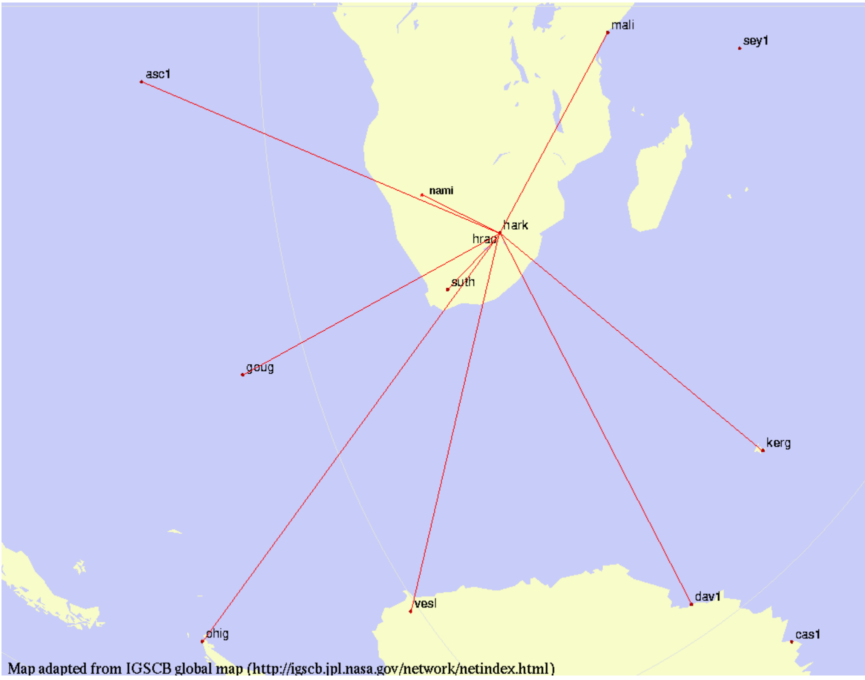

Figure 5: HartRAO regional GPS network. It is obvious that the network requires strengthening towards the north. Densification of the IGS network in Africa will benefit global geodesy.

and east components show close agreement with the VLBI results, even though the time baseline is much shorter. The vertical component is weaker, but is showing closer agreement every time more data is added. There is a noted improvement in the GPS timeseries at about 1998.3 due to the addition of the the Sutherland IGS station (SUTH) which strengthened the network and subsequently reduced the rms noise level. We plan to expand this network by establishing IGS stations north of South Africa as there is an obvious gap in the distribution of GPS stations in Africa. Adding stations will not only improve our regional network, but will densify the the global IGS network to the benefit of all IGS product users. Currently we archive data for 10 IGS stations, and 1 regional station (NAMI). The archive covers the period from January 1998 to present. The stations are:

- HRAO (HartRAO, Hartebeesthoek, South Africa [HRAO/JPL])
- HARK (SAC, Hartebeesthoek, South Africa [CNES])
- SUTH (SAAO, Sutherland, South Africa [HRAO/JPL])
- ASC1 (Ascension Island [JPL])
- MALI (Malindi, Kenya [ESA/ESOC])
- OHIG (O'Higgins, Antarctic Peninsula [BKG])
- DAV1 (Davis, Antarctica [AUSLIG])
- KERG (Port aux Francais, Kerguelen Islands [CNES])
- VESL (SANAE IV, Antarctica [AWI])
- GOUG (Gough Island [AWI])
- NAMI (Windhoek, Namibia [HRAO/JPL])

GPS users in southern Africa can easily download this data for postprocessing with their own measurements for the purpose of improved accuracy from our website. The data has been used by local and other users for various purposes, from local cadastral mapping to clearing minefields in Mozambique.

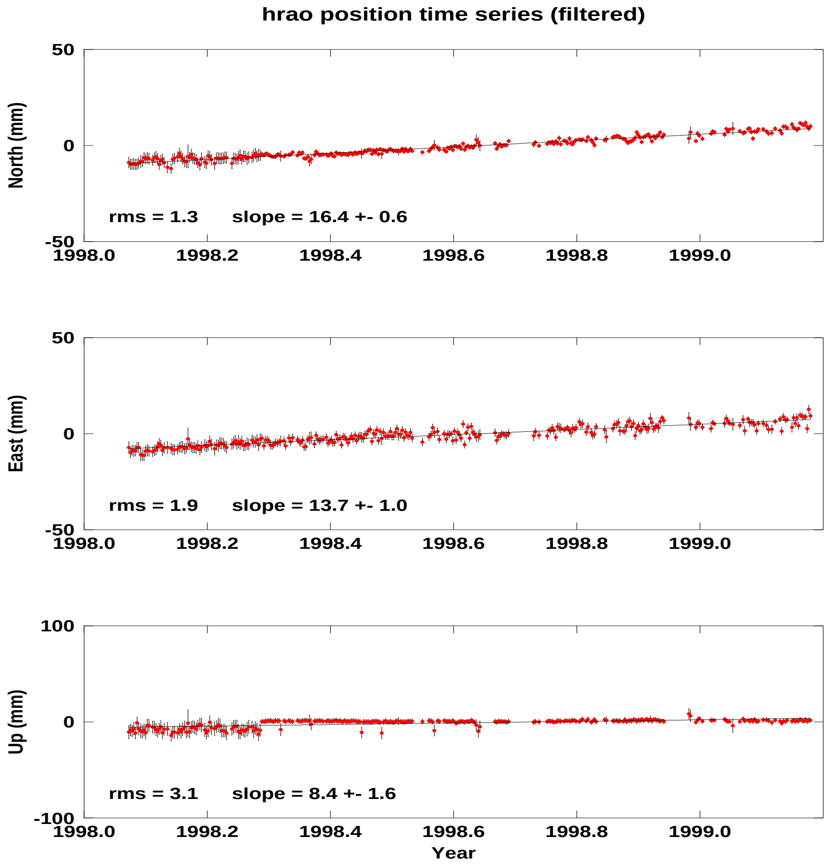

Figure 6: Time series of the HartRAO IGS station , HRAO. The nort and east components are showing good agreement with VLBI results.

SLR

Introduction

A Satellite Laser Ranging (SLR) station can be regarded as an optical radar. This technique makes very precise measurements of the range and rate of motion between an SLR station and an orbiting satellite (Figure 7). The satellite needs to be equipped with special mirrors called retroreflectors which reflect the laser light back to the SLR station. There are about 45 SLR stations in operation worldwide, but even more so than with GPS and VLBI, the African continent is not covered as clearly shown in Figure 8. This lack of an SLR in Africa has resulted in a large gap in the coverage for many geodetic and remote sensing satellites. This gap is affecting scientific results in an adverse way and establishing an SLR at HartRAO would fill this gap to a large extent.

Early in 1993, NASA and IfAG (now BKG) expressed an interest in establishing a satellite laser ranging system in South Africa. HartRAO proceeded to construct an SLR pad for the German Modular Transportable Laser Ranging System (MTLRS) which subsequently occupied the SLR pad in June 1993. Unfortunately the MTLRS never re-occupied the SLR pad, but very satisfactory results were obtained for the SLR pad reference point. Afterwards the MTLRS was moved to occupy an SLR pad at Sutherland, at the site of the South African Astronomical Observatory (SAAO). At the time of writing, we are making preparations to bring a MOBLAS6 SLR unit to HartRAO in collaboration with GSFC. We hope to have this station operational by the end of this year. The addition of this station to the global network will improve scientific results over a wide range of applications. There should be a positive contribution towards all parameters which enter into the establishment and maintenance of the International Terrestrial Reference Frame (ITRF).

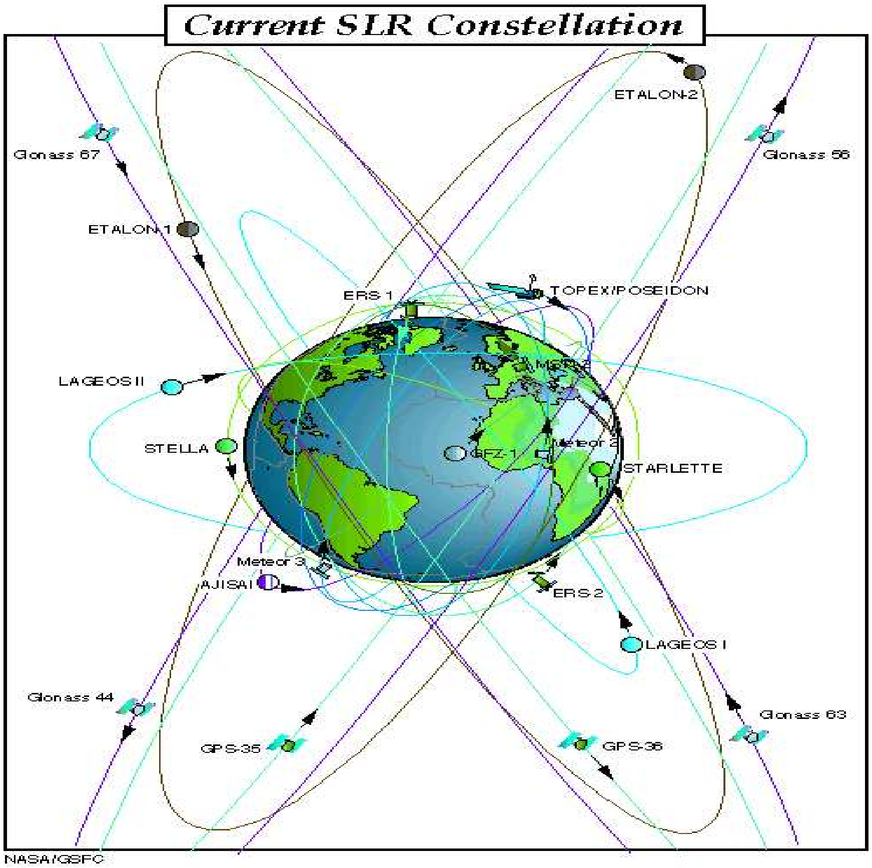

Figure 7: Constellation of satellites tracked by SLR. (source NASA, CDDIS, http://cddis.gsfc.nasa.gov)

The ITRF is realised by a set of positions and velocities derived from combining results from VLBI, GPS and SLR. These techniques complement each other and the combination of results leads to an improved ITRF. The unique contributions to the ITRF (Ma et.al. 1994) of each technique are:

SLR:

- centre of mass
- longest pole and length of day series
- scale

VLBI:

- tie to inertial frame
- stable pole, UT1, nutation series
- precision/accuracy
- site velocities

GPS:

- daily measurements of position
- pole densification

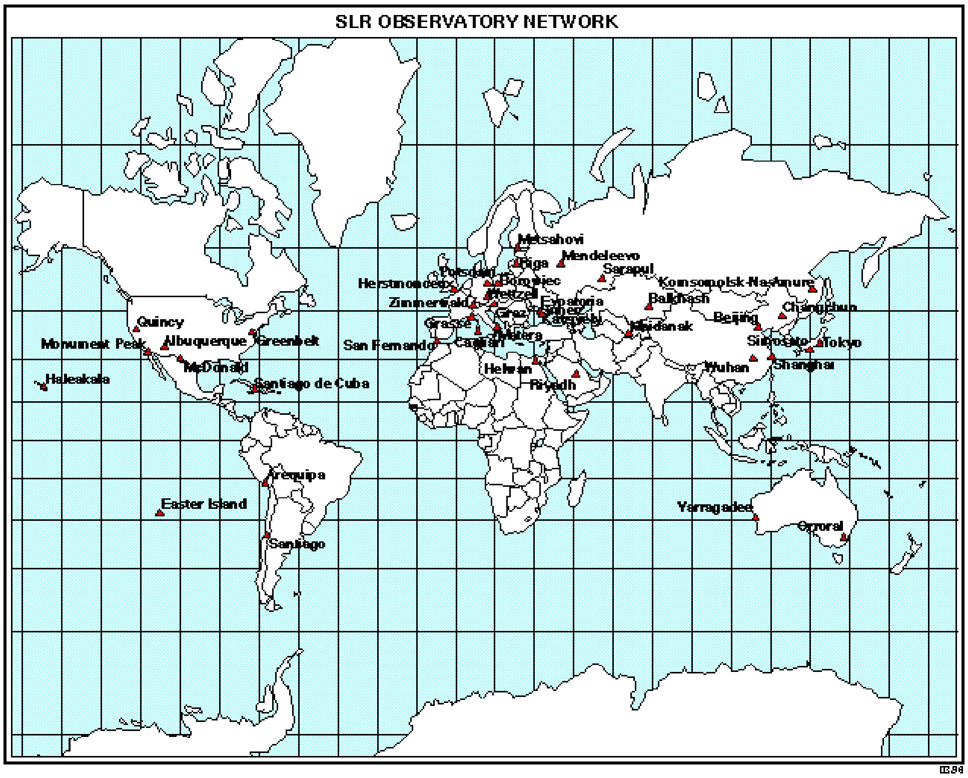

Figure 8: World map showing current distribution of SLR sites. (source NASA, CDDIS, http://cddis.gsfc.nasa.gov)

Summary

The Geodesy Programme at HartRAO is actively involved in and contributes to space geodesy using the techniques of VLBI, SLR and GPS. We are expanding our activities to enable us to make a more worthwhile contribution to geodesy not only in a local context, but to the international geodetic community. Participation in international experiments and active involvement in data analysis and interpretation will provide us with the necessary expertise and technological exposure to contribute to science in a field where there is still much to be done. We invite other institutions, universities and interested parties to make use of our regional database and invite all forms of scientific or educational collaboration within the scope of our institution.

Biographical Note

The author is currently at HartRAO and manages the Geodesy Program. He holds an MSc from the University of Cape Town and is currently registered for a PhD at the same university, under the leadership of Prof Charles Merry of the Department of Geomatics, Faculty of Engineering.

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