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Comparison of site velocities derived from collocated GPS, VLBI and SLR techniques at the Hartebeesthoek Radio Astronomy Observatory (Comparison of site velocities)

Abstract: Space geodetic techniques provide highly accurate methods for estimating bedrock stability at sub-centimetre level. We utilize data derived from Satellite Laser Ranging (SLR), Very Long Baseline Interferometry (VLBI) and Global Positioning Systems (GPS) techniques, collocated at the Hartebeesthoek Radio Astronomy Observatory, to characterise local plate motion and compare the solutions from the three techniques. Data from the GNSS station were processed using the GAMIT/GLOBK (version 10.4) software, data from the SLR station (MOBLAS-6) were processed using the Satellite Laser Ranging Data Analysis Software (SDAS) and the VLBI data sets were processed using the Vienna VLBI Software (VieVS) software. Results show that there is a good agreement between horizontal and vertical velocity components with a maximum deviation of 1.7 mm/yr, 0.7 mm/yr and 1.3 mm/yr between the North, East and Up velocity components respectively for the different techniques. At HartRAO there is no significant trend in the vertical component and all the techniques used are consistent with the a-priori velocities when compared with each other. This information is crucial in monitoring the local motion variations since geodetic instruments require a very stable base to minimise measurement errors. These findings demonstrate that station coordinate time-series derived with different techniques and analysis strategies provide comparable results.

Keywords: Global Positioning Systems, Site velocities, Satellite Laser Ranging, Very Long Baseline Interferometry

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1 Introduction

Prior to the development of space based techniques such as Satellite Laser Ranging (SLR), Very Long Base Interferometry (VLBI) and the Global Positioning System (GPS), determination of plate motions and directions were derived from relative plate motion models such as the NUVEL-1 model (DeMets et al., 1990), which were developed using data from plate boundaries (Stein 1993) and through geological observations. Global Navigation Satellite Systems (GNSS) is a collective term for the various navigational satellite constellations, of which GPS is a component. Other systems which are being developed include the Russian Federation GLONASS and the European Union GALILEO systems. At present, space geodetic techniques provide accurate methods of estimating tectonic plate motion in near-real time. This study utilises SLR, VLBI and GPS techniques (pictured in Fig. 1) which are collocated at the Hartebeesthoek Radio Astronomy Observatory (HartRAO) to study local motion variations and compare the solutions from the three techniques.

The GPS technique is based on a microwave signal modulated with a unique Gold Code per satellite. The antenna receives a mixture of signals from different satellites and noise then cross-correlates it with locally generated Gold Codes. Using cross-correlation the travel time to each satellite in sight can be estimated. To solve for the receiver position, at least four satellites have to be visible,



Fig. 1. Geodetic instruments collocated at HartRAO, South Africa. In the distance, 15 m VLBI antenna, 26 m VLBI antenna, SLR (MOBLAS-6) station (centre-right) and IGS station HRAO choke-ring antenna (front centre).

since three coordinates and one receiver clock error has to be estimated. The U.S. Department of Defense (DOD) originally designed the satellite-based navigation system for military purposes. It has a constellation of at least 24 satellites orbiting at about 20 000 km in altitude, with an orbital period of 24 hours, in six different planes, with approximately four or more satellites on each plane (Yu et al., 1997). These satellites are specially arranged to allow positioning anywhere in the world at any time. Applications of GPS have tremendously expanded since the mid-1980s (Erdogan et al., 2009). Principal applications of GPS include quasi-static applications, where there is a relative motion between the points being measured; continental plate motion and local crustal movement reside under these applications (Robaudo and Harrison 1993).

The SLR technique measures the round trip time-of-flight of ultra-short pulses of laser light to satellites that are equipped with special corner cube reflectors. The two-way range provides centimetre to several millimetre levels of precision and these data can be used for very accurate measurements of crustal dynamics on intercontinental scales. The tracking of satellites using the SLR technique was pioneered in the early 1960s (Combrinck, 2010). The first successful SLR experiment was reported on 3 December 1964 (Smith 1964). The Explorer-22 (also known as Beacon-B) satellite was successfully tracked for ten sessions during 11 October to 13 November 1964. The expected range accuracy was about 3 m (Combrinck, 2010). Since then, the SLR technique has greatly improved in accuracy (1-2 cm), and different applications are routine; these range from geodynamics, geophysical studies and tests of the General Theory of Relativity (Gendt et al., 1993; Combrinck et al., 2011).

Originally VLBI was developed by astronomers to determine accurate positions and spatial structure of radio sources in space. The technique achieves high angular resolution and therefore can be used to determine precise source positions and the orientation of the Earth in space. A VLBI network has roughly the same angular resolution as a telescope of the networks' size. Building on the early developments of VLBI for astronomers, the ability to compute very long-baselines with high accuracy was then used by the geodetic VLBI community to determine a variety of Earth's parameters. A network of geodetic radio telescopes determines accurate baselines and can therefore measure the position, deformation and movement of the station on Earth. Most of the time extragalactic sources, called quasars, are observed, but also radio frequency emitting satellites have been used. The VLBI technique is the only space geodetic technique that is able to observe the full set of Earth Orientation Parameters (EOPs). It is also the only technique that allows the precise measurements of nutation and dUT1 (UT1 - UTC). It contributes to the International Terrestrial Reference Frame (ITRF), in particular the scale is defined by VLBI, and it helps to maintain the International Celestial Reference Frame (ICRF) (Schuh and Böhm 2013).

2 Data and space geodetic analysis strategies

2.1 Network configuration for GPS, SLR and VLBI

In Fig. 2, the global distribution of space geodetic techniques are depicted. The GPS stations from the International GNSS Services (IGS) network and local stations were included during processing of the GPS data to create a robust network and to minimise network effects (Bruyninx et al., 2009). A data time-series from 2000 to May 2012 was processed in the International Terrestrial Reference Frame (ITRF2008) (Altamimi et al., 2011).

The VLBI sub-networks are usually designed with different purposes e.g. IVS-R1/IVS-R4 (where, IVS stands for International VLBI Service, "R" stands for rapid turnaround which means that VLBI results from these sessions should be available as fast as possible and a number ("1" and "4") at the end indicates the day of the week (Monday and Thursday respectively) sessions to estimate EOPs, INT (intensive) session for rapid dUT1 (The difference between UT1-Universal Time and UTC-Coordinated Universal Time) estimation, etc. Hence data availability for

VLBI stations to compute station coordinates is limited. The VLBI telescope at HartRAO has contributed to geodetic VLBI since 1986; it has the longest available time series (of the geodetic techniques) at this site.

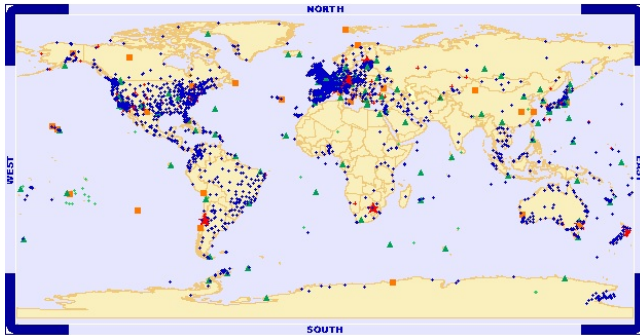


Fig. 2. Map illustrating distribution of space geodetic techniques (Source: <http://itrf.ensg.ign.fr/GIS/>).

Data from LAGEOS 1 spanning four years (2006 to 2010) were processed. The distribution of SLR stations, according to the International Laser Ranging Service (ILRS), are depicted in Fig. 2. Only two SLR stations are located on the African continent. One station is located in Egypt (Helwan SLR station) and the second one is located at HartRAO (MOBLAS-6 SLR station).

These stations contribute to different scientific products, such as the International Terrestrial Reference Frame (ITRF) and the determination of satellite orbits. Therefore, these stations are of importance to Africa despite poor geographical coverage in the Southern Hemisphere. Stations that were included in the estimation of the MOBLAS-6 coordinates were Yarragadee, Zimmerwald, Graz, Wettzell, Monument Peak, Herstmonceux, Matera_MLRO, Hartebeesthoek, Greenbelt, McDonald, Beijing, and Arequipa. The stations were selected based on data volume and data quality criteria for the LAGEOS 1 satellite.

2.2 GPS data processing

The GAMIT/GLOBK software (version 10.4) package developed at Massachusetts Institute of Technology (MIT) (King and Bock, 1995; Herring, 1997; Herring et al., 2010) was used to estimate daily station coordinates for HRAO GPS station in the ITRF2008. Data from 2000 to 2012 were analysed using the GAMIT module to produce loosely constrained daily solutions with associated covariance matrices (see Fig. 3). The GLOBK module uses a Kalman filter to combine the loosely constrained solutions (or quasi-observations) and their associated covariance matrices,

Earth Orientation Parameters (EOP) (or orbital parameters) to estimate 3-D velocities and coordinate solutions and satellite state vectors (King and Bock, 1995; Herring, 1997).

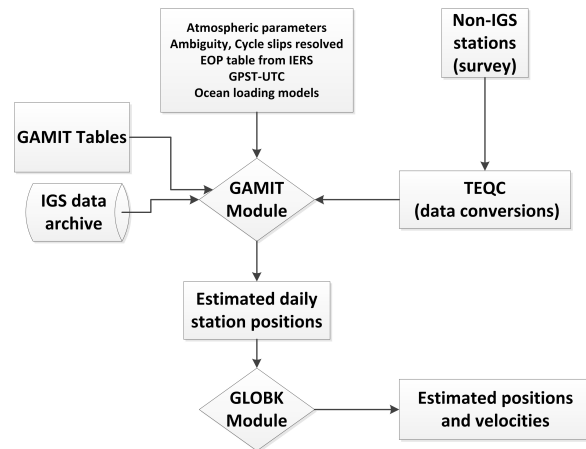


Fig. 3. Simple flow chart of the GAMIT/GLOBK (version 10.4) software.

2.3 VLBI data processing

As a first step, all sessions where HartRAO participated were selected and processed, using a simple parameterisation. The primary function of the first processing step is to find corrupted sessions. Also outlier files were created and used in further processing. The VLBI reference frame 2008 (VTRF2008) was used, which is derived from VLBI observations before 2008. Station coordinates were estimated using the "No Net Rotation" and "No Net Translation" approach.

Not all sessions are suitable for estimating station parameters, thus certain exclusion criteria have to be found. By examining the previously processed files, the following exclusion criteria were found:

- the session must at least include 3 stations.
- the number of observations must be greater than 250.
- the a-posteriori standard deviation of unit weight chi-square must be smaller than 2.5.
- session without HartRAO.

Stations that are either corrupted or not suitable were excluded from the processing list. Final processing was conducted using all the suitable stations.

The basic principle of every VLBI data analysis software package is shown in Fig. 4. It can be seen that the flow diagram contains two basic streams. In the left stream the

actual observations are represented, which are reduced by environmental factors (e.g. ionosphere, troposphere, source structure) and by instrumental factors (e.g. instrumental calibration, axis offset). The right stream contains the theoretical models and a-priori station coordinates, EOP and source coordinates.

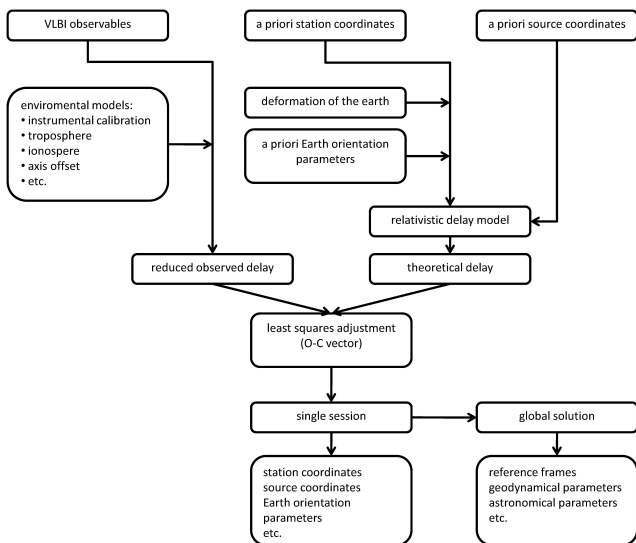


Fig. 4. Flow chart of VLBI analysis model (modified from Schuh and Böhm, 2013).

The two streams merge and create the observed-minus-computed vector (O-C). The parameters are estimated by means of a least squares adjustment. With single sessions, parameters such as station coordinates, EOPs and the troposphere can be estimated. If more than one session is merged into a global solution, reference frames, geodynamical parameters and astronomical parameters can be estimated (Schuh and Böhm 2013).

The Vienna VLBI Software (VieVS) software was written by the Institute of Geodesy and Geophysics (IGG), Vienna University of Technology. It includes state of the art models that coincide with the latest International Earth Rotation and Reference Systems Service (IERS) conventions. It is written in Matlab (version 7.6 (R2008a) or later as required), which has the advantages of being easy to handle, and source code changes can be applied easily. Unfortunately Matlab is expensive and is not as fast as C++ or FORTRAN, but Matlab is widely used, hence many research facilities are already in possession of a licence, the slower speed is not a big disadvantage, since today's computer hardware is fast enough for normal usage of the software (Nilsson et al, 2011).

2.4 SLR data processing

The data sets were analysed using the SLR Data Analysis Software (SDAS) package (written in C++), developed at HartRAO. The SDAS software is currently configured to: generate initial setup files to compute station positions and velocities; estimate orbits and parameter adjustments; allow selection of various Earth gravity and solid Earth tide models.

The output solution from the SDAS software include: O-C RMS residuals, the mean and standard deviation of the O-C residuals; station positions and velocities; estimated coefficients for atmospheric drag, solar radiation pressure, Earth's elasticity, Earth's albedo (shortwave radiation), once-per-cycle per revolution empirical parameters and coefficients of un-modelled components (Combrinck and Suberlak, 2007; Botai, 2013). The schematic diagram in Fig. 5 illustrates the processing procedure used in the SDAS software. The data sets from the CDDIS archive are loaded into the SDAS package, which incorporates the different models and parameters to accurately estimate station positions and velocities (Combrinck, 2011).

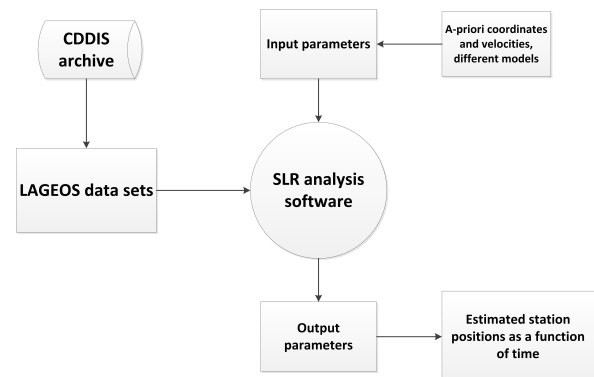


Fig. 5. Schematic representation of SDAS software (modified from Botai, 2013).

3 Results and Discussions

Time-series plots presented here represent positions derived from the MOBLAS-6 SLR station, the 26 m VLBI station and IGS station HRAO. Since the geodetic instruments (pictured in Fig. 1) are attached to the same bedrock, they should exhibit the same global plate motion. If, however, different velocities are observed, then this is an indicator for local instabilities or errors in the data sets (Bastos et al., 2010).

It has to be noted that all the time series have significantly different time scales. The VLBI data goes back to the first observations in 1986 and lasts till 2012, GPS data, however, dates from 2000 to 2012 and SLR data, which has the shortest time span, stretches from 2005 to 2010. The data hasn't been cropped to get identical time spans, because the VLBI telescope had a two year failure from 2008 to 2010, which is exactly during the already short SLR time span. Note that outliers were eliminated by estimating the standard deviation with the Median Absolute Deviation (MAD) and using a 3σ -band.

3.1 GPS

Variation of estimated GPS positions over the period of 12 years is illustrated in Fig. 6. The North component had a jump between 2008 and 2009, this jump was not due to tectonic movement, but was due to misalignment of the antenna during maintenance. To correct for this offset, an offset was introduced, this however, had a slight effect on the East component. The velocities indicate a great degree of consistency i.e. within 1.7 mm/yr in all components when compared against a-priori velocities (17.11 mm/yr, 17.71 mm/yr and -0.81 mm/yr in the North, East and Up components respectively). The vertical components indicate seasonal variations (with peaks during mid-summer for HRAO), which can be linked to many geophysical processes such as the ground water recharge and discharge cycle, varying atmospheric processes (ionospheric cycles) and changing multi-path effects.

3.2 VLBI

The estimated and transformed coordinates are displayed in Fig. 6; a linear trend was fitted to the data points, in order to estimate mean velocities over time. It can be seen, as previously mentioned, that no data were recorded between 2008 and 2010. The estimated velocities from the VLBI data agrees within 0.1 mm with the velocities from the VTRF2008 (18.7 mm/yr, 18.2 mm/yr and 0.3 mm/yr in North, East and Up components respectively), which is a good indicator that the results derived by VLBI are trustworthy. The VTRF2008 uses all available data until 2008 to derive a priori coordinates. In this study, data from the beginning of geodetic VLBI observations (1986) until July 2012 were used. Since the data used to estimate the velocities overlap to a great extent (22 years) with the data used in the VTRF2008, the resulting velocities are very similar.

3.3 SLR

Estimated coordinates from the MOBLAS-6 SLR station are pictured in Fig. 6. The SLR data sets are the shortest compared to VLBI and GPS data sets, despite this, the solution agrees within 1.7 mm/yr for all the components when compared with the a-priori velocities from SLRF2005 (18 mm/yr, 18.1 mm/yr and 1.2 mm/yr in North, East and Up components). The results from the SDAS software package are very good and this is not surprising, the software incorporates recently developed models to take into account the effect of geophysical parameters such as Earth tide, pole tide, relativity etc. It was successfully tested by estimating gravity coefficient J_2 (which correspond to the Earth's oblateness), which were comparable with published values. It was recently used to evaluate Earth gravity field models, which indicated an improvement in gravity field models by at least a factor of 2 since 1990 (Botai, 2013).

3.4 Comparison

Velocities obtained from the IGS station HRAO, the MOBLAS-6 SLR station and the 26 m VLBI telescope are listed in Table 1. The velocities were derived using independent techniques, different processing packages and different processing strategies. A good agreement between GPS and SLR techniques was obtained with only about 1.7 mm/yr, 0.7 mm/yr and 0.7 mm/yr difference between the North, East and Up components respectively. The difference between velocities derived from VLBI and GPS techniques is only about 0.6 mm/yr, 0.7 mm/yr and 0.6 mm/yr in the North, East and Up components respectively. Velocities from the VLBI and SLR technique differ only about 1.1 mm/yr, 0 mm/yr and 1.3 mm/yr in the North, East and Up components respectively. This validates that the SDAS software developed at HartRAO produces good quality results that compare favourably with other techniques.

In Table 1, computed standard deviations of the VLBI, SLR and GPS residuals are listed. The VLBI technique indicates higher standard deviations in all the components compared with the other techniques. Higher standard deviation of the GPS technique in the East component is most likely to be related to the slight shift of the residuals caused during the process of correcting for the North component jump as discussed in the results and discussions section for GPS. The solution from the SDAS software package however, performed better compared with the GPS and VLBI techniques.

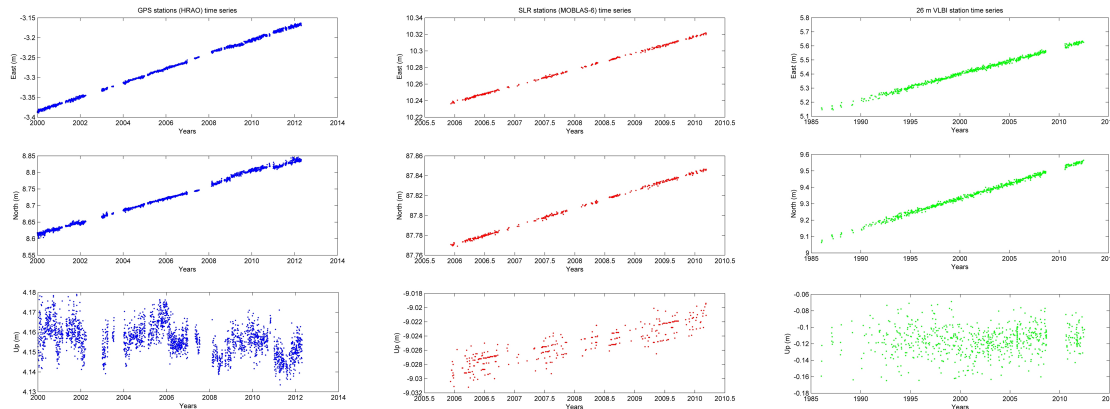


Fig. 6. Time series for the GPS station HRAO, the SLR station MOBILAS-6 and the 26 m VLBI telescope. The coordinates are not in the same coordinate system, they are arbitrary plotted to illustrate velocity trend for each technique.

Table 1. Comparison of VLBI, SLR and GPS velocity solutions (V_n , V_e and V_u) with the associated standard deviation (S_n , S_e and S_u) and their differences.

Technique	V_n [mm/yr]	S_n [mm/yr]	V_e [mm/yr]	S_e [mm/yr]	V_u [mm/yr]	S_u [mm/yr]
VLBI	18.6	7.6	18.1	6.8	0.3	1.63
SLR	19.7	0.6	18.1	0.8	1.6	1.1
GPS	18	1.9	18.8	4.3	-0.9	6.8
VLBI-SLR	1.1		0		1.3	
VLBI-GPS	0.6		0.7		0.6	
GPS-SLR	1.7		0.7		0.7	

The differences between VLBI, SLR and GPS velocity solutions could be partially due to the different reference frames utilized for different techniques (i.e. the VTRF2008, ITRF2008 and SLRF2005 reference frames were used for VLBI, GPS and SLR respectively). However, as these reference frame are essentially the same at the 1 mm or better in terms of velocity (Altamimi et al., 2011), the difference will mostly be due to technique dependent errors). Different data time spans for the techniques used might also explain the deviations that are evident in Table 1. Other possible explanations for the different velocity estimations are: different network geometry, environmental effects and different a-priori empirical models. The SLR technique had the shortest time span compared with other techniques, this might explain the weaker estimated North component as it indicates higher deviations when compared with other techniques (see Table 1). It is envisaged that as more data becomes available for MOBILAS-6, the North component will improve.

In space geodesy, one requires external validation methods. In this case, three different techniques were utilized to estimate local motion at HartRAO. The results indicated that at HartRAO there is no significant trend in the

vertical component (all measurements are basically within the error limits) and all the techniques used are consistent with the a-priori velocities when compared with each other. This information is crucial in monitoring the local motion variations since geodetic instruments such as SLR require a very stable base to minimise measurement errors during tracking of the satellites. This also validates that the SDAS software gives reliable results. This study also contribute towards the Global Geodetic Observing System (GGOS) of the International Association of Geodesy (IAG) (see www.ggos.org) by integrating different space geodetic techniques to better understand the Earth system.

4 Conclusions

The approach used in this study for independently determining position time-series from VLBI, SLR and GPS using independent software packages and processing strategies, has made it possible to study station velocities and evaluate the SDAS software which is currently being developed at HartRAO. The GAMIT/GLOBK, SDAS and VieVS software packages were utilized to analyse and process GPS, SLR

and VLBI data sets. Usually space-based techniques require external validation methods to validate observations made by one technique. In this case, a good agreement between velocities derived from VLBI, GPS and SLR techniques was obtained with less than 1.7 mm/yr difference in all the components. No significant local vertical motion was observed from the three techniques. The close agreement found for global plate velocities using independent techniques and software packages indicates that the different techniques produce accurate and reliable results. Our velocity results compare favourably with those of published reference frames for the different techniques used.

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