Introduction to joint analysis of SLR and GNSS data

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Abstract. The paper presents models, parameters and assumptions concerning Satellite Laser Ranging (SLR) and Global Navigation Satellite System (GNSS) data processing, which will be conducted in the frame of a project concerning comparison of the site coordinates determined using these two techniques. The analysis will be performed by two research units: the Space Research Center (Polish Academy of Science) and the Center of Applied Geomatics (Military University of Technology) and will take into account the data from all global stations adopting SLR and GNSS techniques that were operating in the same time (from 1996 to 2011). The main goal is to obtain exact coordinates and their changes in time (velocities) on the basis of both techniques and to compare the results. The stations' coordinates will be determined for the common reference epoch - for the first day of each month. According to the recommendations of the Global Geodetic Observing System (GGOS), the same models and parameters from IERS Conventions 2010 will be used in both processing strategies (if possible). Monthly orbital arcs for laser observations will be created on the basis of solutions from several SLR sites providing best quality results and the highest number of observations. For GNSS coordinates determination of about 100 sites belonging to International GNSS Service (IGS) will be selected: 30 with local ties to SLR sites and others chosen on the basis of their localization and quality of time series.

Keywords: satellite geodesy, GNSS, SLR, local ties, GGOS, data processing

1 Introduction

The Global Geodetic Observing System (GGOS) is currently one of the main concerns of the International Association of Geodesy (IAG).

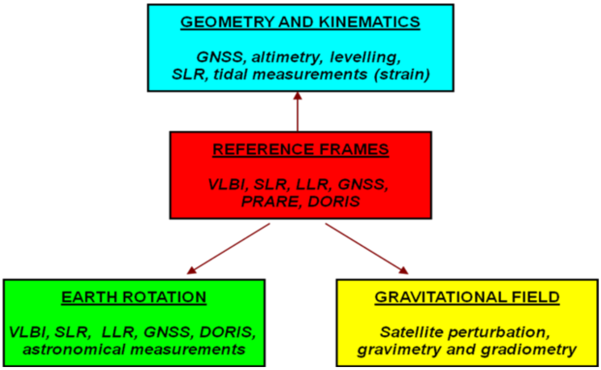

Figure 1. *GGOS scheme based on Plag and Pearlman, 2009*

It plays a crucial role in the implementation of the Global Earth Observing System of Systems (GEOSS), which links different systems of observation. The main aim of GGOS is to deliver geodetic products for Earth monitoring (e.g. for climate changes investigation) and to create one coherent observation system divided into three main parts (called pillars) of modern geodesy: gravitational field, Earth rotation and geokinematics. Such a system would integrate various geodetic techniques, models and data processing strategies and would deliver solutions which would provide a stable and accurate reference frame determination. Reference frames have a crucial role here, because they link different techniques and measurement methods by combining all three GGOS pillars (Fig. 1).

International Terrestrial Reference Frame (ITRF), as a practical realization of the International Terrestrial Reference System (ITRS) is determined on the basis of long-term observations by the following four techniques: Global Navigation Satellite System (GNSS), Satellite Laser Ranging (SLR), Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) and Very Long Baseline Interferometry (VLBI). Each technique has its own specific character, so each one delivers different products and brings a different contribution to ITRF (e.g. the origin of ITRF2008 was determined on the basis of SLR observations, the scale was obtained by using SLR and VLBI methods and the orientation was a result of all four techniques).

Joint analysis of the data delivered by different techniques provides a stable reference frame determination, because the use of different methods of measurement increases the solutions reliability and, above all, permits additional control of the results. According to Altamimi *et al.*, 2011, improvement in further ITRS realizations requires an increase in the agreement between the local ties used in particular techniques (ground as well as space - between satellites) and improvement in the geometry of co-location network. Ground local ties are calculated from the data provided by the stations applying different observation techniques (Fig. 2). Their mutual localization can be precisely determined using classic geodetic measurements or GNSS. Up-to-date investigation is mostly aimed at common processing of the data obtained by various techniques. Analysis of GNSS and SLR observations in the context of TRF determination was described e.g. in (Thaller *et al.*, 2011), but it concerned especially SLR observations of GPS (Global Positioning System) and GLONASS (*Globalnaja Nawigacionnaja Sputnikowaja Sistiema*) satellites, which are equipped with laser reflectors.

The authors' main goal is to process GPS and SLR (LAGEOS-1 and LAGEOS-2 satellites) data using the most coherent and compatible strategies as possible and to compare the results, i.e. the sites coordinates and velocities. The study is a continuation of the investigation performed in 2006-2009, based on a comparison of SLR solutions determined by the Astrogeodynamic Observatory of Space Research Centre in Borowiec with GPS solutions received from various sources (databases). The use of different GPS solutions caused incoherence of the results, which led to the idea of joint analysis which will include solutions obtained by the Centre of Applied Geomatics (Military University of Technology) using the well-known processing strategy with the same models and parameters as SLR data processing. CAG MUT is going to perform these calculations on the basis of the experience gained during processing the regional (EUREF Permanent Network) and national (Active Geodetic Network – European Position Determination System) GNSS networks. The strategy of SLR data processing requires also some changes following especially from the appearance of

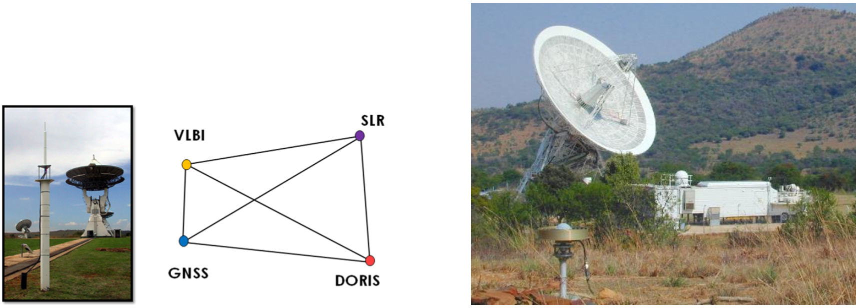

Figure 2. *Local ties of various geodetic techniques on the example of Hartebeesthoek observatory in South Africa* (`http://www.evlbi.org`)

new models developed since the previous investigation. This paper specifies problems which appeared on settlement of the common processing strategy.

2 Strategy of SLR data processing

Strategy of SLR data processing will be based on the latest version of the NASA Goddard's GEODYN-II orbital program (Pavlis *et al.*, 1998). The coordinates of the stations presented in Table 2 will be determined for each month from the results of LAGEOS-1 and LAGEOS-2 satellites. The SLR data has been downloaded from Eurolas Data Centre (EDC) database in the form of 120 sec normal points in the ILRS NP or CRD format (monthly files). All these data have been sorted according to time and changed to MERIT-II data format (GEODYN-II SLR data format).

The computations will be performed using the IERS 2010 Conventions (Petit and Luzum, 2010) models and parameters: Earth gravity field model EGM2008, ocean tides model FES2004 etc. (Table 1). The satellites arcs will be reduced using the observation data from the about 15 the best in given year ILRS (Pearlman *et al.*, 2002) stations in ITRF2008 (Altamimi *et al.*, 2011). The SLR station coordinates will be determined from the normal equations for the LAGEOS-1 and LAGEOS-2 satellites combined. Orbits of LAGEOS satellites will be computed with empirical acceleration coefficients in along-track, cross-track and radial directions determined every 5 days. Mendes-Pavlis tropospheric refraction model will be used.

The following criteria will be used for rejection of normal points:

- normal points with orbital residuals larger than 5 sigma,
- normal points lower than 10° above the horizon.

The process of the station coordinates determination will be performed by the following method (Lejba and Schillak, 2011):

- the geocentric coordinates (X, Y, Z) only for one station in each arc will be determined with the initial a priori position, all other stations will be fixed in ITRF2008 for epoch 2005.0,
- the geocentric station positions will be transformed into topocentric positions (North-South (N), East-West (E), Up (U)) with reference to ITRF2008 (Borkowski, 1989),
- the station velocity will be computed by linear regression analysis as inclination of the position vs time,
- the positions will be transformed to the epoch 2005.0 with the help of ITRF2008 velocity,
- this process will be repeated for all arcs of another station.

The SLR results will be in the following form:

- an average of N, E, U components in reference to ITRF2008 and their stability,
- 3D station coordinates stability,
- 3D station velocity,
- horizontal station velocity and azimuth,
- vertical station velocity.

These results will be compared with GNSS results.

3 Strategy of GNSS data processing

Strategy of GNSS data processing will be based on that applied to the EPN re-processing performed in the CAG (MUT) (Figurski *et al.*, 2009). The processing will be made using the latest version of Bernese software (Beutler *et al.*, 2007). Besides the GNSS

Table 1. *GEODYN II – force models and parameters*

Force Model	Earth gravity field: EGM2008 20x20 Ocean tides: GOT99.2 or FES2004 Third body gravity: Moon, Sun and all planets – DE403 Solar radiation pressure: CR coefficient 1.13 Earth albedo Dynamic polar motion Relativistic correction Earth gravity field: EGM2008 20x20
Constants	Gravitational constant times the mass of the Earth (GM): 3.986004415x1014 m3/s2 Speed of light: 299792.458 km/s Semi-major axis of the Earth: 6378.13630 km Inverse of the Earth's geometric flattening: 298.25642
Reference Frame	Inertial reference system: true of date defined at 0h of the first day of each arc Stations coordinates: ITRF2008 Precession and nutation: IAU 2006/2000 Polar motion: C04 IERS Tidal displacement: Love model H2 = 0.609, L2 = 0.0852 Pole tide
Estimated parameters	Satellite state vector Station geocentric coordinates Acceleration parameters along-track, cross-track and radial at 5 days intervals
Measurement Model	Observations: 120 seconds normal points from Eurolas Data Center Laser pulse wavelength: 532 nm (Zimmerwald 423 nm) Tropospheric refraction: Mendes-Pavlis model Editing criteria: 5σ per arc cut-off elevation 10 degrees for all satellites station coordinates ¡ 50 normal points per station per arc
Numerical Integration	Integration: Cowell's method Orbit integration step size: 120 sec Arc length: 1 month

sites with local ties to SLR, also the IGS sites were selected on the basis of the criteria of their localization and quality of data (http://igscb.jpl.nasa.gov/). The GNSS data were already downloaded from CDDIS (Crustal Dynamics Data Information System) database in RINEX format (daily files).

Double differences (ionosphere-free linear combinations for ionosphere delay elimination) will be used as modelled observables. An absolute model of ground and satellite antenna phase centre calibrations will be also implemented. Elevation angle cutoff will be set to 3 degrees and elevation dependent weighting using $\cos(z)$ will be applied. During the processing, Saastamoinen-based dry component mapped with the Dry-Niell mapping function will be used as an priori model. The Wet-Niell mapping function will be employed to map the wet component (without using the priori model). Estimation of zenith delay corrections will be made at 1-hour intervals for each station and horizontal gradient parameter will be estimated for each station per day without a priori constraints. Bad quality observations related to particular sites and satellites will be excluded from analysis (e.g. daily RINEX observation files containing less than 50 percent of possible observation epochs). The method of ambiguity determination usually depends on the length of a baseline. For baselines up to 1300 km length, QIF strategy using CODE (Center for Orbit Determination in Europe) global ionosphere models will be used (to increase the number of resolved ambiguities). For baseline lengths shorter than 200 km the L5/L3 approach will be employed and for baselines shorter than 20 km - the L1/L2 approach will be used. In the data processing the authors will have to handle determination of many very long baselines between global IGS sites. Orbits and Earth Orientation Parameters will be taken from IGS re-processing. To permit reliable comparison of GNSS and SLR solutions, processing of the data provided by both techniques should make use of the same (if possible) models. To model the Earth's gravity field EGM2008 will be used, planetary ephemeris will be taken from DE405. Solid tides will be modelled according to IERS Conventions 2003, ocean tides using OT_CSRC and FES2004 will be used for ocean loading. The IERS subdaily pole model and the IAU 2006/2000 nutation model will be also applied.

Realization of a reference system will be carried out using selected GNSS sites with the most stable solutions with minimal constraints approach, i.e. by adding conditions on Helmert transformation parameters (translation). Geocentric XYZ coordinates will be determined for the beginning of each month (according to SLR strategy) and then transformed to the epoch 2005 using site velocities in ITRF2008. The XYZ coordinates time series will be converted into topocentric NEU coordinates in reference to ITRF2008 to permit better analysis of the results. Velocities will be calculated by the means of linear regression separately for each component.

The procedure of GNSS processing described above is differential, which means that it is based on determination of baselines between sites. Coordinates are calculated during adjustment. It is possible that problems that may occur in one site can affect the coordinates of another site. This is in opposition to the SLR method, because the coordinates obtained using this technique are referred only to the centre of the Earth, so the next step could be the use of PPP (Precise Point Positioning) method to determine the GNSS sites' coordinates.

4 Main difficulties in the joint analysis of SLR and GNSS data

The main problem concerning joint analysis of SLR and GNSS data is the inconsistency of some of the models used in previous studies. To unify the processing, the authors will implement suitable models in GEODYN-II and Bernese software (if possible). In further part of the project the authors plan to use the NAPEOS (NAvigation Package for Earth Observation Satellites, http://www.positim.com) software distributed by ESA (European Space Agency), which enables processing of both techniques data using the same models and parameters (it gives a possibility to combine the data on the observations normal equations level).

The selection of stations (Fig. 3) depends mostly on the SLR sites localization (there are fewer SLR sites than GNSS ones). The data

Table 2. *List of the stations, which gathered both types of observation data in the same period*

Localization of the site	SLR site	GNSS site	Beginning of joint observation	End of joint observation
Kiev, Ukraine	1824	GLSV	2001.1	2012.0
Lviv, Ukraine	1831	SULP	2002.4	2009.9
Simeiz, Ukraine	1873	CRAO	2000.3	2012.0
Riga, Latvia	1884	RIGA	1999.2	2012.0
McDonald, Texas, USA	7080	MDO1	1993.4	2012.0
Yarragadee, Australia	7090	YAR1	1992.5	2002.3
	7090	YAR2	1998.0	2012.0
Greenbelt, Maryland, USA	7105	GODE	1993.4	2012.0
Quincy, California, USA	7109	QUIN	1993.0	1997.4
Monument Peak, California, USA	7110	MONP	1994.2	2012.0
Tahiti, French Polynesia	7124	THTI	1998.4	2012.0
Haleakala, Hawaii	7210	MAUI	1999.0	2004.5
	7119	MAUI	2006.9	2011.2
Wuhan, China	7231	WUHN	1996.1	1998.8
	7236	WUHN	2000.3	2005.0
Beijing, China	7249	BJFS	1999.8	2012.0
Arequipa, Peru	7403	AREQ	1994.2	2012.0
Concepcion, Chile	7405	CONZ	2002.4	2010.7
Hartebeesthoek, RSA	7501	HRAO	2000.5	2012.0
Metsahovi, Finland	7806	METS	1992.4	2005.2
Zimmerwald, Switzerland	7810	ZIMM	1993.0	2012.0
Borowiec, Poland	7811	BOR1	1994.7	2010.2
San Fernando, Spain	7824	SFER	1996.2	2012.0
Grasse, France	7835	GRAS	1995.2	2005.6
	7845	GRAS	1997.9	2012.0
Potsdam, Germany	7836	POTS	1994.8	2004.6
	7841	POTS	2003.1	2011.3
Shanghai, China	7837	SHAO	1995.0	2005.3
	7821	SHAO	2005.9	2012.0
Graz, Austria	7839	GRAZ	1992.5	2012.0
Hertsmonceux, UK	7840	HERS	1992.2	2012.0
Orroral, Australia	7843	TIDB	1994.5	1998.8
Mt Stromlo,Australia	7849	STR1	1999.5	2003.1
	7825	STR1	2004.6	2012.0
Matera, Italy	7939	MATE	1992.3	2000.9
	7941	MATE	2001.5	2012.0
Wettzell, Germany	8834	WTZR	1995.7	2012.0

Figure 3. *Global distribution of the stations with GNSS and SLR sites related using local ties*

from all stations running the observations by by both techniques (from the same period of time) will be taken into consideration. Table 2 presents these sites. Additionally, the network of sites will be strengthened with several globally distributed IGS sites. In the GNSS data processing very long baselines will be analysed, so some difficulties concerning ambiguities determination can appear. It can force some changes in the strategy assumed. The main problem is to build a network of sites ensuring reliable solutions between 1996 and 2000, because of the lack of GNSS sites on some parts of the globe (especially in Africa) at this time. In the beginning it was planned to process also the GPS data gathered between 1993 and 1996, but the tests proved that the results would be unreliable as the dispersion of the solutions (coordinates) would be too high.

As mentioned above, SLR delivers solutions (coordinates of individual sites) referred to the Earth's centre of mass. Observations performed at one SLR site do not affect those made on other sites. GNSS processing concerns a network of sites (it is differential). In the first step baselines between sites are calculated, then in the adjustment process the coordinates of the sites (and other parameters) are determined. Such a procedure can lead to error mitigation in the network. In further part of the project the authors plan to use PPP approach to eliminate this problem.

5 Solutions of the common SLR and GNSS analysis

Up to now, the authors have agreed on the processing strategies and collected all the data necessary for calculations (both GPS and SLR observations for the period 1996-2011). A test GPS processing has been made for the year 1996, as this year is supposed to be the most problematic, because of the small number of GPS stations. The next step is to process the data obtained by both techniques using the settled strategies and models. This part of the project is planned to be finished in the middle of 2012. As a result of the SLR and GNSS observations processing, geocentric and topocentric coordinates of all analysed sites will be determined. They will be expressed for the first day of every month separately for both techniques. Such time series will be analysed in order to verify the agreement between the data provided by both techniques. Besides, the coordinates of all sites in ITRF2008 for the epoch 2005.0 (with their standard deviation) will be calculated. Stability of sites positions and deviation of their coordinates from ITRF2008 values will be investigated. Velocities of all sites in ITRF2008 (for all components) and topocentric NEU frame (vertical and horizontal component) will be determined separately for SLR and GNSS to compare both solutions.

Another interesting future aspects of the analysis will be a combined orbit determination (when using NAPEOS software) and independent control of local ties.

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