

Analysis of 04 years (2002-2005) of laser data on Starlette, Stella and LAGEOS-I/II satellites for stations coordinates and Earth Orientation Parameters (EOP)

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ملخص : يتمحور هذا المقال على حساب إحداثيات محطات ليزر و معايير دوران الأرض EOP، المرتكزة على مقاييس السوائل ذات ارتفاع منخفض مثل: ستارلت (STA) و ستيللا (STL). تعتبر مدارات هذه السوائل أقل دقة من سواتل لاقوس (عادة ما تستعمل في الحساب الدقيق) لأنها أكثر تأثراً بقوى الجاذبية و الغير الجاذبية. الهدف منها هو تحقيق أفضل جودة في المنتوجات الجيوديزية من خلال الربط بين السواتل لمعطيات ستارلت و ستيللا سويا إلى معطيات لاقوس-I (LA1)، و لاقوس-II (LA2). نقوم بحساب المدار من خلال برنامج GINS (GRGS / فرنسا). تتم معالجة مقاييس الليزر بواسطة برنامج MATLO (OCA, IGN / فرنسا) مع الأخذ بعين الاعتبار استعمال نموذج حقل الجاذبية (Eigen-Grace-03s) للسواتل GRACE في مدة أربع سنوات (ما بين جانفي 2002 و ديسمبر 2005).

تعرض النتائج فيما يخص السلاسل الزمنية على العلامة المرجعية ITRF 2000، من خلال برنامج CATREF (IGN / فرنسا)، أين يتم التحصل على معايير التحول Helmert. و قد قمنا بمقارنة حلين : LA2+LA1 (LL) و STA+STL+LA2+LA1 (LLSS) في شكل جودة السلاسل الزمنية للمواقع المتبقية للمحطات، لتغيرات EOP و الجيومركز. تبين النتائج أن المعطيات المتحصلة عليها من خلال السواتل ذات ارتفاع منخفض مثل ستارلت و ستيللا، يمكن استعمالها بنجاح للتحديد الدقيق للمنتوجات الجيوديزية الليزرية.

الكلمات الأساسية : تلمتريه الليزر على الساتل (SLR)، ستارلت، ستيللا، لاقوس-I/II، LEO، EOP، جيومركزية.

Résumé : Le présent article porte sur le calcul des coordonnées des stations Laser et des paramètres de rotation de la Terre (Earth Orientation Parameters : EOP), basé sur les mesures des satellites à basse altitude, tels que Starlette (STA) et Stella (STL). Les orbites de ces satellites sont moins précises que celles des satellites LAGEOS (usuellement utilisés pour un calcul précis), car ils sont plus affectés par les forces gravitationnelles et non-gravitationnelles. L'objectif est d'atteindre une bonne qualité sur les produits géodésiques par une combinaison inter-satellitaire des données des satellites Starlette et

Stella conjointement à celles de LAGEOS-I (LA1) et LAGEOS-II (LA2). Le calcul d'orbite de ces satellites est effectué par le logiciel GINS (GRGS / France), le traitement des mesures Laser est réalisé par le logiciel MATLO (IGN, OCA/France), en considérant l'utilisation du modèle du champ de gravité (Eigen_Grace-03s) du satellite GRACE, sur une période de 04 ans (entre Janvier 2002 et Décembre 2005). Les résultats en termes de séries temporelles sont projetés sur le repère de référence ITRF2000, par le logiciel CATREF (IGN/France), où les paramètres de transformation d'Helmert sont obtenus. Deux solutions ont été comparées: LA1+LA2 (LL) et LA1+LA2+STL+STA (LLSS), en termes de qualité des séries temporelles des positions résiduelles des stations, des variations des EOP et du Géocentre. Les résultats montrent que les données obtenues à partir des satellites à basse altitude tels que Starlette et Stella peuvent être utilisées avec succès dans la détermination précise des produits géodésiques Laser.

Mots clés : Télémétrie Laser sur Satellite (SLR), Starlette, Stella, LAGEOS-I/II, LEO, EOP, Géocentre.

Abstract : The present paper deals with the computation of Laser stations coordinates and Earth Orientation Parameters (EOP) based on measurements of low Earth orbit (LEO) satellites, namely Starlette (STA) and Stella (STL). The orbits of these satellites are less accurate than those of the LAGEOS satellites (usually used for an accurate calculation), because they are more affected by gravitational and non-gravitational forces. The objective is to achieve a good quality on the geodetic products by inter-satellite combination of Low and High satellites data. The orbit computation of the different satellites is performed by the GINS software (GRGS/France) and the laser data processing is carried out by the MATLO software (IGN, OCA/France), considering the use of gravity field model (Eigen_Grace-03s) of GRACE satellite, over a period of 04 years (between January 2002 and December 2005). The results in terms of time series are projected onto the reference frame ITRF2000 by the CATREF software (IGN/France), where the

Helmert transformation parameters are obtained. Two solutions were compared: LA1 + LA2 (LL) and LA1 + LA2 + STL + STA (LLSS), in terms of quality time series of residual positions of stations, EOP and Geocentre variations. The results show that the data obtained from LEO satellites such as Starlette and Stella can be successfully used in the accurate determination of Laser geodetic products.

Key words : Satellite Laser Ranging (SLR), Starlette, Stella, LAGEOS-I/-II, LEO, EOP, Geocentre.

1. Introduction

Satellite Laser Ranging (SLR) is one of the main techniques of the determination of the International Terrestrial Reference Frame (ITRF). It contributes to the frame determination by providing time series of laser stations coordinates and Earth Orientation Parameters (EOPs). The laser observations of LAGEOS-I (LA1) and LAGEOS-II (LA2) are generally used for such determination. However, what is the contribution in this determination of other satellites like Low Earth Orbit (LEO) ones?

The twins Starlette (STA) and Stella (STL) satellites, orbiting at 800 km altitude, were launched by the CNES, on 1975 and 1993, respectively. The main tasks of these LEO satellites are the determination of Earth's gravity field coefficients, Earth rotation parameters, and investigation of Earth and ocean tides. So, the computation of the laser ranging stations coordinates on the basis of other data than LAGEOS-I/-II (orbiting at 6000 km altitude) observations is desirable for the following reasons: (1) significantly increases the number of observations used for determination of the stations coordinates and EOPs, (2) verification of results obtained from the LAGEOS-I/-II data, (3) determination of station coordinates that cannot range to LAGEOS satellites.

Interesting results of the stations coordinates determination were obtained for LEO satellite for short period of 01 year only [Lejba et al., 2008] & [Lejba et al., 2007]. The objective of our study is to check if the laser ranging observations of Starlette and Stella can be used for a precise determination of the laser ranging station coordinates and EOP, and to investigate the contribution of these LEO data for the geodynamic study of the stations behaviour, pole and Geocentre motions.

So, the work concerns the computation of a laser network, composed of 34 stations, based on both LAGEOS satellites measurements with those of Starlette and Stella over 04 years period (between January 2002 and December 2005), according to two data combination solutions, namely LA1+LA2 (LL) and LA1+LA2+STL+STA (LLSS).

The methodology adopted, in this work, comprises the following steps :

a. The orbit restitution of different tracked satellites is performed by the GINS (Géodésie par Intégration Numérique Simultanée, Geodesy by Simultaneous Numerical Integration, in English) software (GRGS/France), based on purely dynamical approach, see section 2.

b. The estimation of stations coordinates updates and of EOPs residuals is performed using the MATLO (MATHématiques pour la Localisation et l'Orbitographie, MAThematics for Localization and Orbitography, in English) software (OCA & IGN, France) [Coulot, 2005]. This estimation provides weekly time series of stations positions and daily time series of EOPs. In order to express these parameters in same reference frame, the parameters of transformation were computed using CATREF (Combination and Analysis of Terrestrial Reference Frames) software (IGN/France).

c. The analysis of SLR geodetic products time series based on (i) frequency analysis by FAMOUS (Frequency Analysis Mapping On Unusual Sampling) software (OCA/France) [Mignard, 2005], and (ii) noise estimation (type and level noise) by Allan variance method [Feissel-Vernier, 2007]. This analysis permits to study the geophysical behaviour of the stations positions, the Geocentre variations and the pole motion.

Finally, the preliminary results of 04 years combined SLR data analysis are presented and discussed in section 3.

2. Laser Data Processing

2.1 Orbit computation

The orbit restitution of different satellites used (LAGEOS-I, LAGEOS-II, Starlette and Stella) is performed with the GINS software, from a subset of SLR fixed stations well distributed on the Earth as reference frame for the orbitography. The dynamical models used for the orbit computations and for the stations positions and Earth Orientation Parameters (EOPs) determination, are described in table (1).

Table 1. Some of dynamical models used for the orbit computations.

Model	Description
<u>For Orbit:</u>	
Earth's gravity field	GRIM5_C1 (for LAGEOS-I/-II) EIGEN_GRACE03S (for Starlette & Stella)
Ocean tides	FES2002
Atmospheric pressure	ECMWF, http://www.ecmwf.int/
Solar radiation (Flux)	ACSOL2
Atmospheric density	DTM94
Planets	DE403
<u>For Station's position :</u>	
Terrestrial reference frame	ITRF2000
Celestial reference frame	ICRF
Atmospheric tides	ECMWF
Oceanic loading	LOAD_FES2002
Solid Earth tides	Model in [McCarthy and Petit, 2004]
Solid Earth pole tide	Model in [McCarthy and Petit, 2004]
<u>For EOP :</u>	
Pole	EOPC04 [Gambis, 2004]
Quasi-diurnal variations	Model in [McCarthy and Petit, 2004]
Precession	Model in [Lieske et al., 1977]
Nutation	Model in [McCarthy, 1996]

The quality of the positioning is directly linked to the accuracy of the orbits used (in addition to the data accuracy itself). For this reason high altitude geodetic satellites (LAGEOS-1 and LAGEOS-2) are used primarily by geodesists for SLR network computation (EOPs and stations coordinates). Indeed, these satellites have the advantage of being less sensitive to remaining uncertainties in the dynamical models than low altitude satellites like Starlette and Stella. It concerns gravitational and non gravitational effects. But since few years, global Earth gravity field models have greatly improved the accuracy of their coefficients notably thanks to the GRACE mission [Reigber et al., 2005]. As a consequence, empirical coefficients can be estimated along the orbit with more consistency than before; their role is to compensate part of the unknown non gravitational forces (constant and periodic). In this fact, we have used Eigen-Grace03s gravity field model for Starlette and Stella [Gourine et al., 2008].

2.2 Network and EOP computation

The processing of SLR stations coordinates and EOP parameters was carried out by MATLO software. It comprises two main steps. The first relates to the use of the loose constraints for the resolution of the weekly normal equations systems of the network

which are initially singular due the rank defect corresponding to three rotations, in case of the Laser ranging technique. For this reason, we have applied loose constraints of about ± 1 m for stations positions and ± 1 cm for range bias per station and per satellite. The results obtained are in terms of times series of weekly coordinate updates and daily Pole parameters updates which are considered as individual solutions. Each solution generates its proper terrestrial reference frame. The second step consists in applying minimal constraints on these solutions obtained from MATLO software and to project the individual solutions according to a combined and homogeneous terrestrial reference frame using CATREF software. This projection permits to obtain the seven parameters transformation (3 translations, 3 rotations and 1 scale factor) between the individual solutions and the combined one.

The processing results, illustrated hereafter, are expressed according to :

- parameters of transformation (translations, rotations and scale factor / ITRF2000);
- variations of pole coordinate (X_p , Y_p) and of Length Of Day (LOD) / EOPC04;
- topocentric coordinate (N , E , U) updates of some laser tracking stations.

3. Results Analysis

Table (2) shows that the orbits of the high satellites (LAGEOS-I/-II) have a better accuracy than those of the low satellites (Stella and Starlette), because they are less perturbed. This phenomenon is related to the difficulty of an accurate modelling of the physical forces, to which the satellites of low altitudes are more subjected.

Table 2. Length of arcs and weighted RMS of orbital arcs residuals

Satellite	Length of the arc (<i>days</i>)	WRMS (<i>mm</i>)
LAGEOS-1	7	11.1
LAGEOS-2	7	9.5
Starlette	3.5	16.1
Stella	3.5	15.5

The SLR time series of positions expressed in the local coordinates (NEH); from the LL and LLSS combinations; are projected on ITRF2000 reference system. The results revealed that these series are statistically equivalent, according to table (3).

The addition of the low satellites to the high satellites did not deteriorate the results quality, in particular for the estimation of Earth orientation and transformation parameters see table (4). In spite of the inaccuracy of the low satellites orbits (Starlette and Stella) due to the effects of the non-gravitational forces as well as the gravity field, it is now able to use them in complementary with the LAGEOS orbits; for two reasons : (a) The important quantity of the low satellites data which can contribute to well constraint the calculation of the ILRS network; (b) The good quality of the recent dynamical models (gravitational and non-gravitational) which allows an improvement of the low satellites orbits. Hereafter, we summarise some results in the following tables.

Table 3. Mean and weighted RMS of coordinates updates, expressed in topocentric coordinates (N, E, U), of 34 Laser stations

Combination	N (<i>mm</i>)	E (<i>mm</i>)	U (<i>mm</i>)
LL	-20±35	21±23	-6±26
LLSS	-21±36	20±21	-5±28

Table 4. Statistics the pole coordinate updates (Xp, Yp) and the transformation parameters time series.

Solution	Xp (<i>mas</i>)	Yp (<i>mas</i>)	TX (<i>mm</i>)	TY (<i>mm</i>)	TZ (<i>mm</i>)	RX (<i>mas</i>)	RY (<i>mas</i>)	RZ (<i>mas</i>)	Δ (10^{-9})
LL	-0.12±0.32	0.30±0.32	-1±6	1±5	1±7	-0.13±0.41	0.01±0.36	-0.18±0.19	-0.37±1.03
LLSS	-0.10±0.30	0.33±0.32	0±6	1±5	1±7	-0.13±0.46	-0.01±0.49	-0.21±0.16	-0.31±0.93

3.1 Pole motion

The figure (2) illustrates the time series residuals of pole coordinates (Xp, Yp) and of the Length of Day (LOD). These times series were processed, for LL and LLSS solutions, with respect to the standard solution EOPC04 of IERS, and expressed according to a coherent reference frame with ITRF2000. It shows that the two solutions are similar,

by consequence the contribution of the Starlette and Stella data do not perturb the determination of the EOP updates. In fact, according to the table 4, the values of pole coordinates and their RMS, according to LL and LLSS solutions are practically the same. In addition, the estimation of pole parameters is satisfactory for the SLR technique and the obtained values are coherent with published values of IERS [Gambis, 2004].

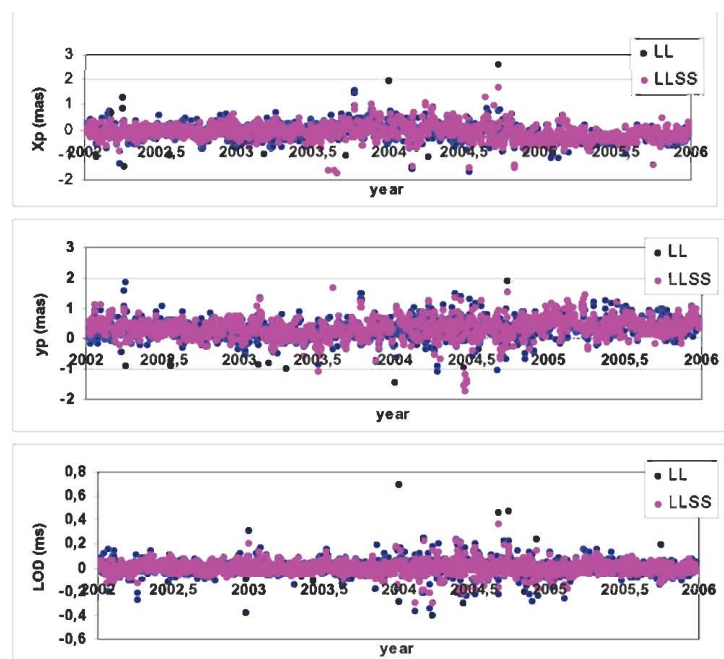


Fig. 2 Parameters of pole motion according to LL and LLSS combinations.

Table (5) shows the results of frequency analysis of pole time series, using FAMOUS software. The periodic signals are decomposed, with respect to three periods: inter-annual, annual and short periods (from few days to few months < 100 days). The choice of this decomposition is based on the periods of the geophysical phenomena causing the variations in the pole motion. These phenomena are mainly due to the redistribution of masses in the Earth, Oceans and Atmosphere [Frède, 1999],

and were taken in account in our computations. The amplitude values of pole coordinates, according to LL and LLSS combinations, are much closed, because the maximal difference does not exceed $22 \mu\text{as}$ (i.e., 0.7 mm). In other hand, the amplitudes are small of about few mm. For the LOD, the average amplitude is around $10 \mu\text{s}$ (i.e., 5 mm). Generally, these values remain very small because they describe the residual signals of the geophysical phenomena.

Table 5. Periodic signals of the pole residual parameters.

* : corresponds to the semi-annual term.

Parameter	Term	LL	LLSS
X_p (μas)	Interannual	146.9	125.2
	Annual	81.7, 48.1*	54.0*
	Short period	43.7 – 68.3	48.5 – 61.0
Y_p (μas)	Interannual	—	—
	Annual	—	69.8*
	Short period	42.7 – 54.6	50.9 – 72.3
LOD (μs)	Interannual	—	—
	Annual	12.6*	10.7, 10.0*
	Short period	9.1 – 10.0	6.7 – 8.9

The study of the noise, affecting the pole time series, has provided the level and the type of the noise. These two parameters are described in [Feissel-vernier, 2007] as, (i) the noise level is measured by Allan deviation for one year sampling time of the non-linear and non-seasonal time series (ii) the noise type is measured by slope of Allan graph, describing the log-log relationship of the the Allan variance of

the time series with the corresponding sampling time τ . According to Figure (3), the dominant noise, for LL and LLSS solutions, is the flicker noise with a slope of the Allan diagram of -0.4 and -0.6, respectively. The noise level is of about 106 - 115 μ as or 3mm, for pole coordinates and it is around 11 and 16 μ s (6 and 8mm), for LOD, according to LL and LLSS, respectively.

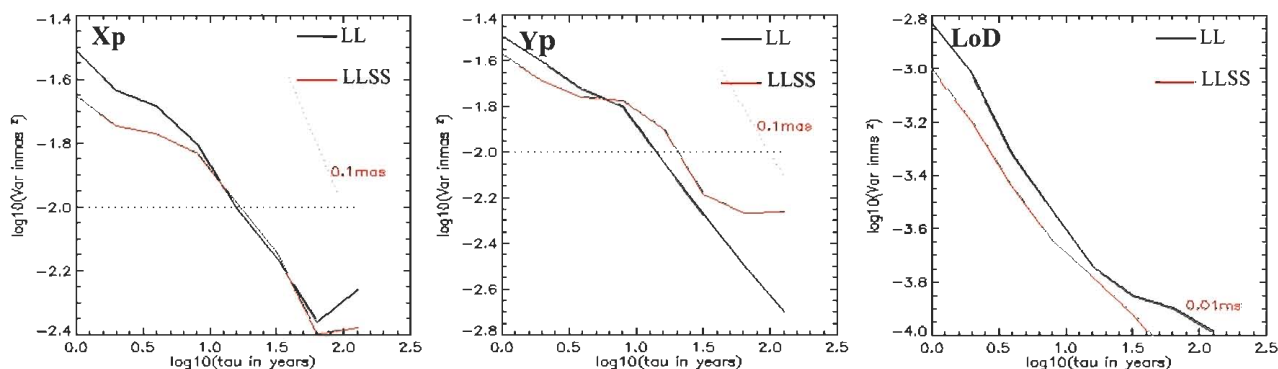


Fig. 3 Allan variance diagram of the pole parameters, according to LL and LLSS solutions.

3.2 Transformation parameters variations

Among the weekly transformation parameters computed between the terrestrial reference frames (TRFs) and the ITRF2000, the translation parameters have a particular importance. Indeed, they permit to highlight the Geocentre variations. This is a topic of crucial importance in the Earth deformation theory as well as in the definition and maintenance of the ITRF.

Figure (4) illustrates the time-series of weekly transformation parameters according to LL and

LLSS solutions. The RMS estimated on the components of Geocentre are about 5-7 mm.

Usually, the variations of the reference frame scale are affected by the determination errors of stations vertical coordinates [Coulot, 2005]. So, range biases and errors of the radial components due to the orbit residual errors affect also the scale variations. According to the table (4), the results about the scale factor are at the same level for the two solutions (LL and LLSS). The average RMS is about 6mm for both solutions.

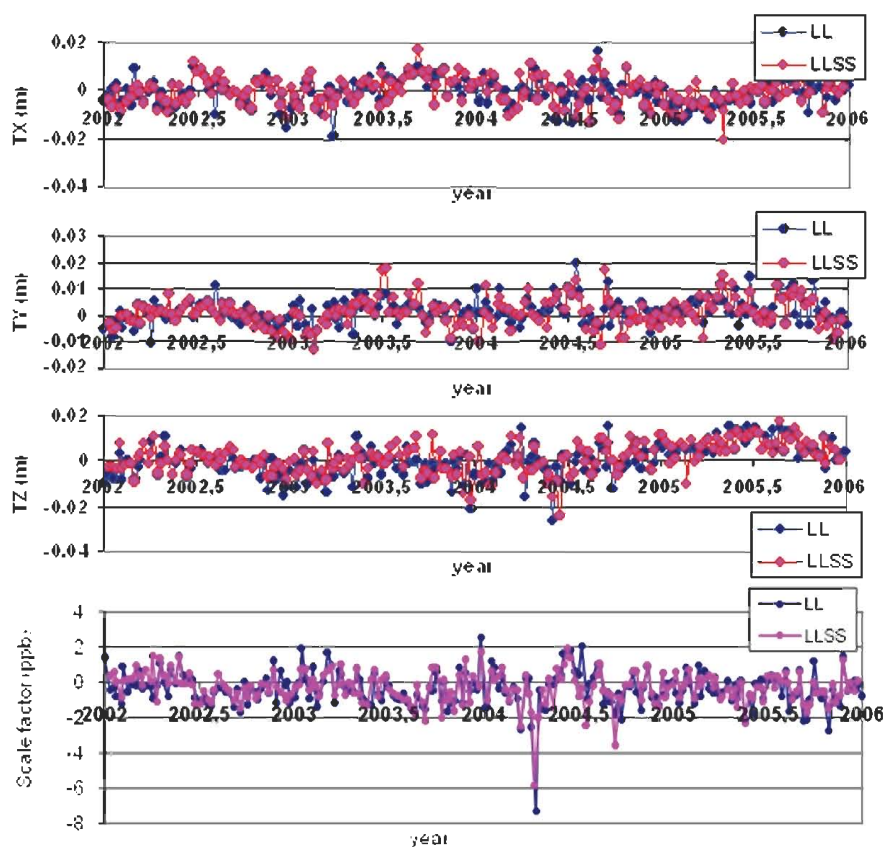


Fig. 4 Time series of translations and scale factor variations, according to LL and LLSS combinations.

The Geocentre variations are mainly due to the redistribution of masses in atmosphere, in oceans and also in hydrological reservoirs. In general, they present two principal periodic components: annual and semi-annual terms. Table (6) displays the values of amplitudes and phases of annual terms of our solutions, and of two geodynamic models of [Dong et al., 1997] and [Chen et al., 1999], computed taking

into account atmospheric pressure data, ocean tides and surface water data. We can observe equivalent amplitude values of TX and TZ, for the LL and LLSS solutions. There is coherence in amplitude between our solutions and geodynamical models, for TX and TY. However, a difference of about 1-2mm exists for TZ.

Table 6. Annual terms of the Geocentre variations components according to LL and LLSS combinations.

		LL	LLSS	Dong et al. 1997	Chen et al. 1999
TX	A	2.9 ± 0.8	2.6 ± 0.8	4.2	2.4
	φ	139 ± 15	131 ± 18	224	244
TY	A	2.3 ± 0.5	4.1 ± 0.6	3.2	2.0
	φ	168 ± 22	183 ± 16	339	270
TZ	A	2.3 ± 2.6	1.9 ± 2.1	3.5	4.1
	φ	246 ± 67	218 ± 71	235	228

The spectral behaviour of the Geocentre motion, described by Allan variance method, is illustrated by the figure (5).

The white noise is the dominant noise for the X and Y Geocentre components, with noise

level of about 1.8 mm (according to the LL and LLSS combination but it is about 2.3 mm for Y-component of LLSS solution). However, the Z-component is affected by a flicker noise at level of 2.8 mm.

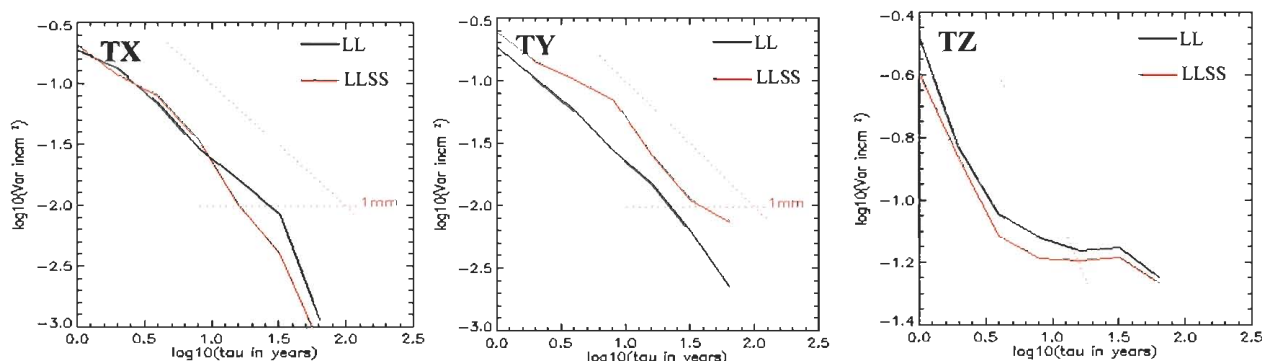


Fig. 5 Allan variance diagram of the Geocentre variations, according to LL and LLSS solutions.

3.4 Coordinate updates of SLR stations

Figure (6) shows the geographical distribution of the 34 SLR stations considered in this study.

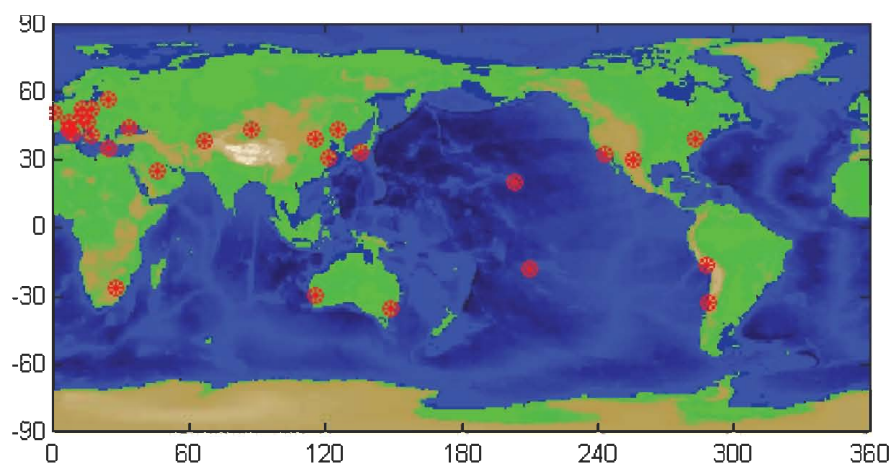


Fig. 6 SLR Network considered in this study.

The following figure shows the average RMS of topocentric coordinates (North, East and UP) of 34 SLR Stations over four years (2002-2005), according to the LL and LLSS combination solutions.

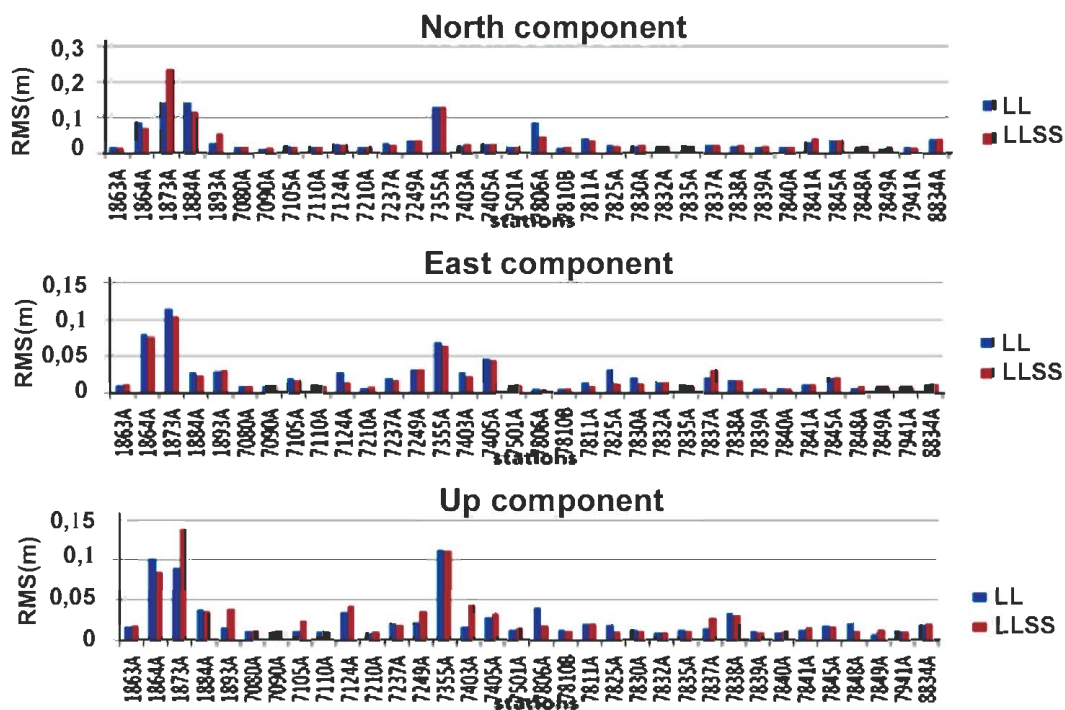


Fig. 7 RMS of topocentric coordinates of 34 SLR stations, according to LL and LLSS solutions.

The following figure shows an example of the position time series of two stations (7080-McDonald, USA) and (7090-Yarragadee, Australia).

These stations are among the best stations which provide good quality of observation results and large number of normal points.

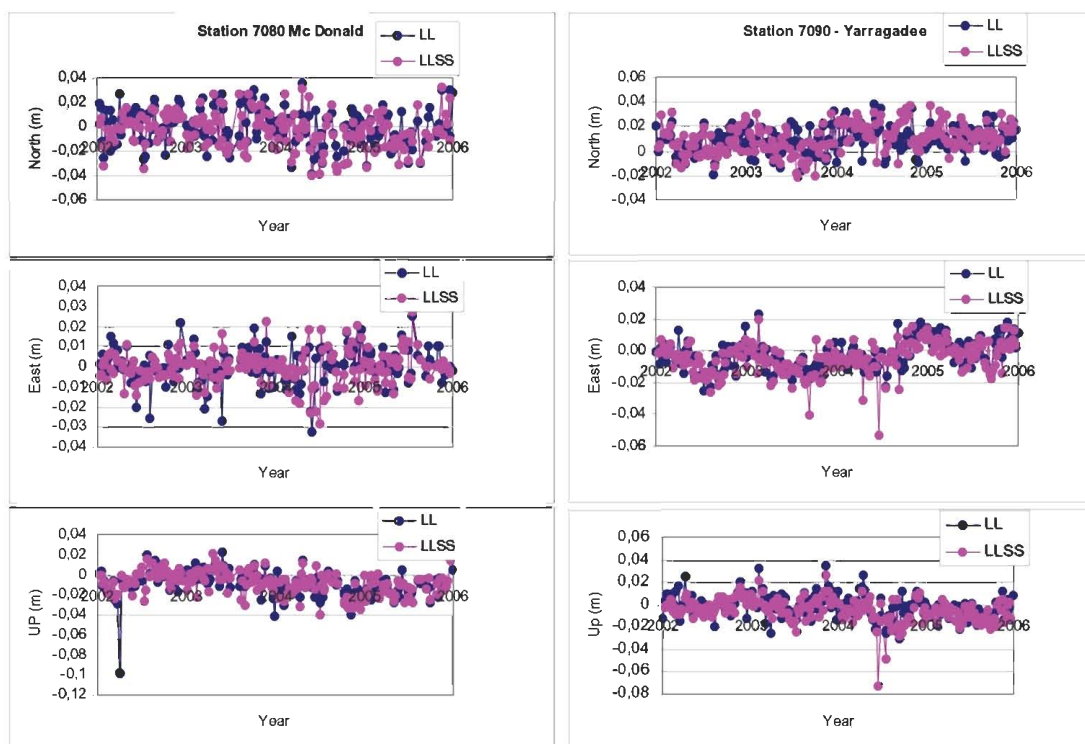


Fig. 8 Time series of McDonald (7080) and Yarragadee (7090) stations.

The interest of the time series of the stations coordinates calculated in a homogeneous reference frame is to enable us to highlight residual signals compared to the a priori signals used in modelling (geophysical signals). We focused on vertical component because it is important for the geodynamical studies since it holds amplitude 2/3 of signals acting on the station motion [Coulot, 2005]. In this context, one carried out a frequency analysis on vertical component series by FAMOUS software. Seasonal signals with amplitudes of about few mm were estimated. Since, the effects of ocean loading were considered in the model a priori of restitution, the signals detected are probably related to residual loading effects, which typically have amplitudes of mm level.

4. Conclusion

This study showed that good quality on SLR geodetic products (stations coordinates, EOP, Geocentre) can be achieved by inter-satellite data combination of LEO satellite such as Starlette and Stella with high satellite as LAGEOS1 & LAGEOS2, thanks to use of good dynamical models as gravity field model (Eigen_Grace03s). The positions of 35 stations are estimated with the same RMS of about 3cm, 2cm and 3cm, for local coordinates (N, E, U), respectively, considering the two solutions (LL and LLSS combinations). The analysis methodology, developed in this context, which is based on the frequency analysis by FAMOUS software and noise estimation by Allan variance method, revealed that for both solutions:

- The quality on EOP time series is the same and coherent with published values of IERS [Gambis, 2004]. Small amplitudes were estimated on pole coordinates updates (Xp, Yp) and LOD. The flicker noise is the characteristic noise of the EOP with level of about 3mm level for pole coordinates and 8 mm for LOD.
- The amplitudes of annual signals estimated on Geocentre variations are equivalents and are coherent with geodynamic models ones. The white noise is the dominant noise for the X and Y Geocentre components at level of about 2mm; however, the Z-component is affected by a flicker noise at level of 3mm.

It will be interesting, for extending this work, to consider more observations of LEO satellites (such as, Ajisai, TopexPoseidon, Jason-1&-2, with Starlette and Stella), during a long period.

Acknowledgements

The author thanks the Prof. Exertier and his research team (GMC/GEMINI/OCA) for their scientific and technical support and their help for the use of GINS, MATLO, FAMOUS and CATREF softwares.

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