SLR Contribution to Investigation of Polar Motion*

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Abstract

SLR technique has being used for determination of ERP during over twenty years. Most of results contributed to IERS are based on analysis of observations of Lageos 1&2 satellites collected at the global tracking network of about 40 stations. Now 5 analysis centers submit operative (with 2-15 days delay) solutions and about 10 analysis centers yearly contribute final (up to 23 years) ERP series. Some statistics related to SLR observations and analysis is presented and analyzed. Possible problems in SLR observations and analysis and ways of its solution are discussed.

1 Introduction

Laser ranging to Earth artificial satellites (SLR) was initiated in 1964 after launch of the first geodetic/geodynamical satellite Beacon-B.

Since that time satellite laser ranging (SLR) technique have being widely used for geodynamical and geophysical researches. The primary fields of investigations used SLR observations are Earth rotation, maintenance of the Terrestrial Reference Frame, tectonic motion, Earth crust deformations, geopotential with its spatial and temporal variations, tides, movement of geocenter, support of satellite geophysical missions (such as satellite altimetry), global time transfer, and others. Detailed analysis of SLR contribution to Earth sciences can be found in (Tapley et al. 1993).

After the launching of the Lageos satellite in May 1976, SLR became one of the main techniques for investigations of the Earth rotation, and during over twenty years SLR technique have been used for determination of ERP. Most of results contributed to IERS are based on analysis of observations of Lageos 1&2 satellites collected at the global tracking network of about 40 stations. SLR provides high precision series of Xp, Yp, and LOD. Some analysis centers compute also UT that allow to densify Universal Time series in combination with VLBI data.

Importance of ILRS as one of the main method to study the Earth led, naturally, to the establishment of the International Laser Ranging Service (ILRS) in 1998 that coordinates now scientific activity SLR (and LLR), chiefly in the framework of IAG and IERS projects.

In this paper we will focus only on SLR contribution to investigation of polar motion in accordance with topics of the conference.

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2 Contribution of SLR PM series to the IERS

SLR observations of Lageos and ERP derived from these observations are available from May 1976. However, only in 1980–81 after significant improvement of range technique SLR ERP series achieved accuracy required for investigation of Polar motion (PM). Figure 1 summarizes information from IERS Annual Reports for 1978–1997 concerning use of submitted SLR series in IERS yearly solutions. One can see that beginning from 1983 SLR ERP series is regularly used for IERS combination. It’s also seen that the Center for Space Research, University of Texas at Austin (CSR) provides most long-time spanned and stable PM series.

At present 5 analysis centers submit operational solutions with 2-15 days delay, and about 10 analysis centers yearly contribute final (up to 23 years) ERP series. Most long series available for analysis are listed in Table I

3 Accuracy of SLR PM series

During long history of using SLR technique to study PM drastic improvement in range precision was achieved. It’s interesting to see how this technology development affected accuracy of PM series obtained from SLR observations. Figure 2 shows differences between SLR series obtained at the CSR and the Institute of Applied Astronomy, St.Petersburg (IAA) and IERS combined solution EOP(IERS)C04.

One can clearly see in Figure 2 that replacement of the first generation ranging equipment by the second generation one about 1980 and its further replacement by the third generation units led to significant improvement of accuracy of PM solution. However, in spite of
Table 1: Longest series.

| Solution | 1976 | 1980 | 1983 | 1983 | 1985 | 1988 |
|----------|------|------|------|------|------|------|
| CSR      |      |      |      |      |      |      |
| GSFC     |      |      |      |      |      |      |
| DUT      |      |      |      |      |      |      |
| GAOUA    |      |      |      |      |      |      |
| IAA      |      |      |      |      |      |      |
| CGS      |      |      |      |      |      |      |
| BKG      |      |      |      |      |      |      |

Table 2: Agreement of series with C04, mas.

| Solution | Xp  | Yp  |
|----------|-----|-----|
| GPS      | 0.11| 0.11|
| SLR      | 0.11| 0.12|
| VLBI     | 0.16| 0.15|

Table 3: Statistics of operational solutions based on USNO data for Sep 1998 – Sep 1999.

| Center        | Delay, days | Error in PM, |
|---------------|-------------|--------------|
|               | min | mean | mas |
| NEOS VLBI     | 6.3 | 12.0 | 0.10 |
| IAA VLBI      | 13.3| 22.5 | 0.12 |
| CSR SLR       | 2.3 | 9.2  | 0.36 |
| TUD SLR       | 4.6 | 7.8  | 0.36 |
| IAA SLR       | 1.6 | 3.1  | 0.20 |
| MCC SLR       | 7.6 | 11.1 | 0.21 |
| IGS Final     | 10.1| 14.8 | 0.02 |
| IGS Rapid     | 1.1 | 1.4  | 0.06 |

Figure 2: Differences between SLR and IERS PM series.
improvement of ranging technique and implementation the fourth generation equipment, precision of PM series derived from SLR observations remains the same during last 10–12 years. We will try to discuss the problem below.

In 1998 IERS Central Bureau had derived final IERS combination in two step: on the first stage combined VLBI, SLR, and GPS series was computed and then these was used for final IERS combination. Table 2 copied from the 1997 IERS Annual Report shows that precision of SLR and GPS combinations is practically the same. Unfortunately, this is not so for operational solutions.

Table 3 compiled on basis of gpso1.asc files produced by USNO along with Bulletin A issues contains statistics of series used for IERS Rapid Service. Of course, errors in PM obtained there depend on weighting applied to combined series, but it already clear that accuracy of individual SLR series is worse than VLBI and GPS ones, and delay of SLR contribution is much worse than GPS one. Nevertheless, one can see that at least two centers can produce operational solution with delay about 2 days. If all SLR analysis centers would provide such a solution on regular basis, it will allow to have, in principle, combined SLR solution with accuracy 0.1–0.15 mas and delay 1.5–2 days.

4 Factors limited quality of the SLR ERP solutions

During long time SLR was the one of the main methods of determination of PM and densification of PM series based on VLBI observations. However, lately SLR ERP series are inferior to GPS ones in quality (accuracy, density, delay of operational solution) of results. It would be very important to understand existing problems in SLR observations and analysis procedures and discuss possible ways to solve them.

4.1 Observations

The first problem with SLR observations is that SLR technique is an 'one-object' one. This means that, unlike GPS, SLR station can observe only one object in time. Hence, planning of observations and priority politics plays substantial role in acquisition of observations of satellites on which PM determination is based, especially keeping in mind that SLR observations are rather expensive and number of ranging units are limited.

At present four operational satellites seem most suitable for investigation of Earth rotation (as well as tectonic motion and long-term temporal variations in various geophysical parameters) — two Lageos satellites and two Etalon satellites. Both Lageos and Etalon satellite was launched to long-time stable orbits and have a low area to mass ratio. Their description is presented in Figure 3.

Figure 4 shows number of observations of these satellites during last 12 years and ILRS priorities. One can see that number of observations of Lageos satellites remains approximately the same during these years and number of observations of Etalon satellite is too small to contribute seriously to analysis.

Let us see in more details distribution of SLR observations in stations and time. Figure 5 shows distribution of observations in stations for the period from Sep 1983 till Aug 1999. Table 4 contains list of stations contributed more than 2% of total number of observations.
The first impression is that stations are distributed quite uniformly along of satellite orbit. However, if we recall that SLR observations are weather-dependent, it would be evident that Australia – West Asia region need at least one more active station. Fortunately, several new stations was put into operation in China and Japan during the last years but they are still not active enough. So, problem of more uniform distribution of observations in stations evidently still exist. Besides, as usually, most of stations are located in the Northern hemisphere and at least two active stations would be very desirable in the Southern hemisphere (in South America and South Africa).

Distribution of observations in months is more or less uniform, with small decrease in November and December (sharp dip in Christmas days!). But distribution in days of week (Figure 6) is not so good. One can see that number of observations on several most active stations is about twice lesser than during workdays. This is statistics for whole interval from Sep 1983 till Aug 1999. For the last year distribution is a little bit more uniform - maximum number of observations was made in Wednesday (16.2%), minimum in Sunday (11.6%), but still far from ideal.

### 4.2 Analysis

Though, in my opinion, the only real way to improve quality of SLR ERP series is to increase number of observations and, especially, number of satellites involved in determination of ERP, analysis strategy can also be advanced.

Modern tendency is to use combined VLBI, GPS, SLR series for final IERS combination. Unfortunately, PM series produced by SLR analysis centers are not unified enough which makes difficult their comparison and combination. The main problems in individual SLR series are:

| Satellite | Satellite parameters | Orbital parameters |
|-----------|----------------------|-------------------|
| Lageos 1,2 | D, m: 0.6 M, kg: 407 A/M, m^2/kg: 0.00070 | a, km: 12300 h, km: 5900 T, h: 3.76 i, deg: 110, 53 |
| Etalon-1,2 | D, m: 1.3 M, kg: 1344 A/M, m^2/kg: 0.00098 | a, km: 25500 h, km: 19100 T, h: 11.26 i, deg: 65 |

Figure 3: Satellites Lageos and Etalon.
• Sparse time series (3-5 days for most solutions, 1 day needed).

• Large delay of operational solutions (5-10 days for most solutions, 1-2 days needed).

• Non-unified TRS.

• Dependence on a priory values of EOP.

Analysis of methods used for determination of ERP from SLR observations shows that not all possibilities for improvement and unification of SLR ERP series are exhausted. What can we do to make SLR series more efficient? Existing experience shows that significant improvement could be achieved if we would:

• Produce daily EOP series.

• Produce operative solution with delay about 2 days.

• Advance strategy for determination UT.

• Use the same TRS for all solutions (ITRF seems most suitable for this purpose).
Table 4: Distribution of observations in stations.

| CDP     | Station          | %   | CDP     | Station        | %   |
|---------|------------------|-----|---------|----------------|-----|
| 7110    | MONUMENT PEAK    | 9.6 | 7843    | CANBERRA       | 3.0 |
| 7090    | YARRAGADEE       | 9.3 | 7403    | AREQUIPA       | 2.7 |
| 7840    | HERSTMONCEUX     | 8.2 | 7810    | ZIMMERWALD     | 2.4 |
| 7210    | MAUI             | 5.4 | 7838    | SIMOSATO       | 2.4 |
| 7835    | GRASSE           | 5.3 | 7907    | AREQUIPA       | 2.0 |
| 7109    | WASHINGTON       | 5.3 | 7836    | POTSDAM        | 1.7 |
| 7839    | GRAZ             | 5.0 | 1884    | RIGA           | 1.5 |
| 7109    | QUINCY           | 4.8 | 7237    | CHANGCHUN      | 1.2 |
| 7939    | MATERA           | 4.6 | 7811    | BOROWIEC       | 1.0 |
| 8834    | WETTZELL         | 4.0 | 7849    | MOUNT STROMLO  | 0.8 |
| 7080    | FORT DAVIS       | 3.3 | 7845    | GRASSE         | 0.6 |

Total about **130** stations including mobile occupations
- **5** stations provided **38%** of total number of observations
- **7** stations provided **48%** of total number of observations
- **10** stations provided **62%** of total number of observations
- **15** stations provided **75%** of total number of observations
- **22** stations provided **85%** of total number of observations
An analysis of these problems and some proposals on their solution was presented in (Malkin 1998). Below proposed methods tested in the IAA during last three years are briefly described.

The first serious problem is how to compute daily ERP series without loss of accuracy. There are two main ways to compute daily series. The first is to use daily arc solutions (i.e. use one day arcs). But this leads to degradation of accuracy of solution. The second one is to use overlapping arcs with appropriate length and one day shift between arcs. Such a solution produces dependent results for neighbor arcs, but significant improvement in precision can be considered as sufficient compensation. Table 5 shows accuracy of ERP solution with various length of arc.

So, experience shows that using overlapping arcs yields more precise ERP series than using one day arcs.

It would be very desirable to have strictly daily series for all analysis centers, i.e. series with epochs equal to 0\(^{h}\). This can be achieved by two methods - determination of Pole coordinates with their rates and a posteriori interpolation to 0\(^{h}\). Numerous test showed that including Pole coordinates rates into parameter model lead to small degradation of accuracy of PM, evidently due to degradation of normal system matrix condition. A posteriori inter-
Table 5: Dependence of errors in ERP on length of arc (RMS of EOP(IAA)L – EOP(IERS)C04 after removing trend).

| ERP        | Length of arc, days |
|------------|---------------------|
|            | 1  | 3  | 4  | 5  | 7  |
| $X, 0.001''$ | 0.40 | 0.23 | 0.20 | 0.18 | 0.16 |
| $Y, 0.001''$ | 0.34 | 0.22 | 0.21 | 0.18 | 0.15 |
| $LOD, 0.0001s$ | 0.44 | 0.16 | 0.15 | 0.12 | 0.09 |

Table 6: Effect of interpolation of SLR ERP series (RMS of EOP(IAA)L – EOP(IERS)C04 after removing trend).

| EOP        | Series    | Raw     | Interpolated |
|------------|-----------|---------|--------------|
| $X, 0.001''$ |           | 0.154   | 0.155        |
| $Y, 0.001''$ |           | 0.171   | 0.171        |
| $LOD, 0.0001s$ |           | 0.154   | 0.168        |

Interpolation of ERP to 0th epochs gives better result. Linear interpolation was found as most suitable for this purpose.

Table 6 shows dependence of results on effect of interpolation of raw ERP series. One can see that use of linear interpolation don’t lead to visible degradation of accuracy. Special tests showed that strictly daily series obtained with interpolation is more accurate that series obtained with including Pole coordinates rates in parameterization.

It should be mentioned also that producing daily solution (independently which method id used) provide operational solution with steady delay about 2 days, which solves the second problem mentioned above.

Other serious problem is determination of UT from SLR (and other satellite observations). It is well known that UT1 cannot be separated from longitude of node of satellite orbit during parameter solution. Three methods are being used to solve this problem:

- Fixing longitude of node during parameter solution (usually, during last iteration).
- Analysis of node longitude series, forecasting it and use predicted values for operational solution.
- Integrating LOD series to obtain independent free-running UT series with its possible correction for high-frequency variations from comparison with VLBI series.

Evidently, only the latter method can provide (in principle) independent result. Since that is not a subject of this paper, we will not stay on detailed analysis of this problem. However, It is worth to mention here that significant improvement of SLR UT series is also impossible without increasing of number of satellites involved in determination of ERP.
At last, use the same terrestrial reference frame for all SLR solutions seems evident to achieve uniform solutions for combination. Use of ITRF as terrestrial reference frame for by all analysis centers for their SLR solutions provides more homogeneous series for SLR combined solution.

Realization of this or alternative analysis strategy could provide more uniform, accurate and operative SLR ERP series. After that, combining of all submitted series to final ILRS SLR product seems reasonable and useful for further use for IERS and other purposes.

We have not mention here such a serious problem as dependence of SLR ERP results on a priori values. This is worth to perform special investigation for each method used for computation of ERP at various analysis centers.

5 Conclusion

Satellite laser ranging technique made and make a very valuable contribution to Earth dynamics. In particular, very valuable contribution was made in investigation of PM. During many years SLR was one of the main methods of determination of polar motion and main method of densification of ERP series obtained with VLBI. At present 5 analysis centers submit operational solutions with 2-15 days delay, and about 10 analysis centers yearly contribute final (up to 23 years) ERP series.

However, due to principal peculiarity of this method (relatively expensive experiment, limited number of units, lack of capability of multi-satellite ranging, etc.) quality of SLR ERP data remains the same during the last decade in spite of ranging precision improved by a factor of a thousand from a few meters to a few millimeters since the first SLR experiments (and by factor of about 10 during last 10-12 years). This leads to decreasing of weight of SLR solutions in the combined IERS EOP series.

It is evident that only substantial increasing of number of observations and satellites involved in investigation of Earth rotation and improvement of distribution of observations in stations and time can help in improvement of the SLR ERP accuracy. However, capacity of tracking network is practically exhausted.

On the other hand, in spite of GPS provides determination of ERP with impressive accuracy and delay, SLR results are very important for combined IERS solution for improvement of systematic accuracy of the final IERS product. Analysis of precision of individual SLR series shows that its combination can provide combined SLR much more accurate and rapid series. To achieve highest accuracy of combined SLR ERP product is necessary to solve problems discussed in section 4.2.

Realization of this opportunities by ILRS would be very important for investigation of Earth rotation because allow to save independent method of determination of PM and velocity of the Earth rotation.

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