NETWORK PERFORMANCE AND RESULTS SESSION SUMMARY

C. Luceri and M. Torrence, co-chairs

This workshop session was a forum for the assessment of network data production, quality, and ILRS products.

The regular quality control assessments performed by several ILRS analysis centers was discussed by R. Noomen. He showed range bias estimates for LAGEOS 1 and 2 improved in consistency from 2004 through 2006 from 30 to 20 mm level. Other analysis centers contributions to regular and rapid data quality analyses will help the overall assessment of the results as there are, as of this writing, only two AC contributing to this effort. T. Otsubo showed that characterization of possible intensity-dependence station effects should be considered to achieve mm level data accuracy and calibrations may show possible correlations with seasonal loading effects. M. Torrence showed examples of plots of station's data as a function of local time and range measurement.

J. Luck reported on upgrades to the WPLTN sites and reported the data yield from southern hemisphere tracking sites has increased to 40% of the total data available data with the quality generally comparable with the data from the northern hemisphere. Luck also commented that all stations should pay close attention to their system delay and calibrations. A report on mm level bias due to measurement characteristics of the Stanford counter in the data from Herstmonceux was given by P. Gibbs, with the suggestion that all Stanford counters should be characterized. F. Pierron showed results of the FTLRS occupations at the Ajaccio site, achieving stable position estimation from multi-satellite data analyses using the Eigen-Grace03s gravity model for the two occupations (2002 and 2005).

E. Pavlis discussed the global SLR network and the origin and scale of the TRF in the GGOS era and an SLR-based evaluation and validation studies of candidate ITRF2005 products. An assessment of the ILRS-A standard product was presented by G. Bianco. This routine production process is stable and reliable and those ILRS standard products allow monitoring of site coordinates and EOPs. Additionally, the geocenter motion, geometrically derived from the weekly solutions, could be included among the future ILRS standard products. R. Govind showed results of a simulation to evaluate the contribution of an additional SLR station in northern Australia to the Earth center-of-mass determination.

The session concluded with a light-hearted presentation by P. Shelus on "Evolution of SLR/LLR in Response to Mission Needs." From the summary slide: "As scientific experiments become more complicated, greater pressures are placed upon operational logistics in order to perform necessary operations, and yet retain personnel safety and instrumental integrity. Thorny logistical problems have been solved by a combination of computer power, internet communications, orbital dynamics and precisely defined inter-relationships among several reference frames."

There were several posters presented for this session. C. Noll described the laser ranging archive available at the ILRS data centers and plans for future enhancements. J. Luck showed the result of a minico system delay for the Mt. Stromlo site. C. Moore presented a summary of the observations of GioveA taken from Mt Stromlo SLR Station, the identified patterns that have impacts on tracking productivity and the use of Giove A data for an empirical analysis of link budget requirements for potential gain in tracking GioveA, Galileo and similar satellites. T. Otsubo showed plots of intensity-dependent effects for all stations. M. Torrence displayed plots of data as function of local time and range for all stations.

The SLR network from a QC perspective

R. Noomen[1]

1. Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands.

Contact: r.noomen@tudelft.nl / Fax: +31-15-2785322

Abstract

Although it can be considered as a traditional if not classical technique, Satellite Laser Ranging (SLR) (still) plays a crucial role when it comes to assessing and monitoring a number of global aspects of System Earth: scale and origin of the terrestrial reference frame. A proper and timely monitoring of the performance of the network of laser stations is a prerequisite to provide an optimal contribution to the space geodetic community. In order to detect possible data problems at an early stage, a number of analysis centers perform a regular quality control (QC) of the SLR measurements on a variety of satellites. This paper addresses a number of issues relating to that: the development of the global network in terms of stations and their distribution, and the development of the (raw) data quality. The quality and consistency of reported range biases will be studied in this paper as well. Although the analysis done here covers the years 2004-2006 only, the results show an improvement in consistency for most of the QC centers, from about 30 mm in 2004 to about 20 mm in 2006 (total network) or from 25 mm to 15 mm (AWG core network). Two points of concern are the global coverage of the network of SLR stations and the decrease in the number of QC centers.

Introduction

With its highly accurate absolute distance measurements between satellites and ground stations, the International Laser Ranging Service (ILRS) supports a wide range of space geodetic missions: gravity field missions, altimetry missions, missions aimed at the assessment and monitoring of the terrestrial reference frame, and others. To obtain the best possible contribution from such SLR observations, a good global coverage of the network of ground stations, a good production rate and a high quality of such observations are prerequisites.

In this paper, both network geometry and data quality aspects are addressed. In particular, the overall development of the network in terms of geometry, data yield and data precision is described. Also, the various possibilities to monitor the quality of these observations and to alert stations in case of systematic errors (range biases) are examined. The paper compares a number of QC institutes, and derives recommendations for the threshold at which a reported bias can be considered to be real. This is primarily done by comparing independent bias estimates for common passes on LAGEOS-1 and on LAGEOS-2.

SLR network development

Figure 1 shows the number of stations that have tracked the satellites LAGEOS-1 and/or LAGEOS-2, during a particular year. Considering the central role of these two spacecraft, an inventory of the data acquisition on either of these satellites can be considered as a direct measure for the amount of stations that were active in a particular year. It is clearly visible that the number of stations in the global network has increased from about 30 in the mid-1980s to about 40 now; variations and developments in this number are typically related to the operations of transportable SLR stations, and the installation of new stations at various places around the world.
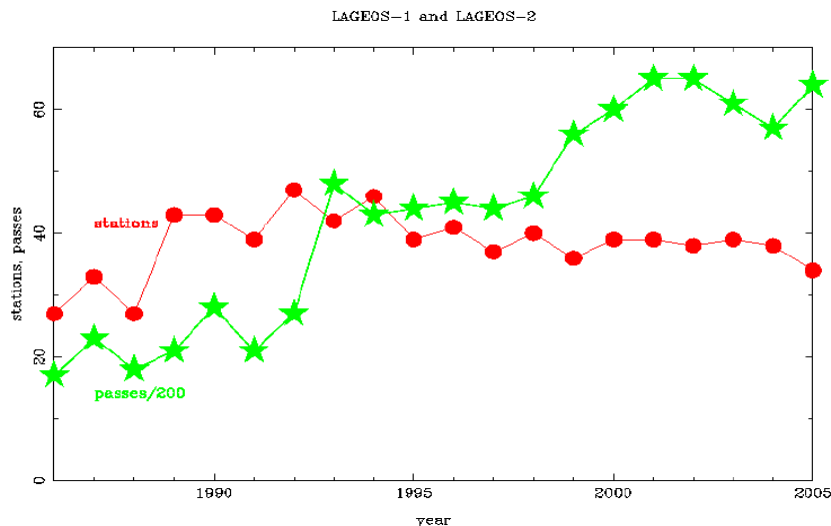
Figure 1. *The yearly number of stations that tracked LAGEOS-1 and/or LAGEOS-2, and their production in terms of number of passes.*

In spite of the reasonable stability of this number over the past decade, the plot shows a remarkable reduction from a recent maximum of 39 in 2003 to 34 in 2005. This will be discussed further shortly.

The figure also shows the total number of passes (on LAGEOS-1 and LAGEOS-2) that have been taken during the same year. In spite of the reduction of the number of stations, the total number of individual passes has been stable if not on the rise: in 2005, about 13,000 passes were obtained, or almost 400 on average per station. Clearly visible is the increase of this number of passes in 1993, the first full year after the launch of LAGEOS-2, on October 25, 1992. Contrary to the decline in number of stations in the past few years, the total data yield of the network appears to be stable (if not increasing). This can be attributed to a higher level of efficiency (automation), improvements in scheduling and increasing number of shifts.

The geometry of the SLR network is illustrated in Figure 2. Here, the tracking network in 2003 is compared to that in 2005; note that no allowance for the number of passes is made. It is clearly visible that the majority of the network has been in operation permanently, whereas a relatively small number of stations (Hawaii, Arequipa/Peru, Chania/Crete and Komsomolsk-na-Amure/Russia; open red circles) did not range in 2005 whereas they did in 2003. New stations in 2005 (or 2004, at least w.r.t. 2003) are Ajaccio/France and Tanegashima/Japan. The plot shows that the distribution of stations has a preference for the Northern Hemisphere, and that the termination of activities in Hawaii and Arequipa has dramatic consequences for the coverage in particular in the Pacific region. In view of the important role of SLR in its unique determination of global parameters of System Earth like geocenter and scale, such flaws in station distribution are an absolute point of concern. Fortunately, the situation has improved again with the installation of new stations in San Juan/Argentina, Hawaii and Arequipa in mid-2006.

To get an idea of the advancement of the technical quality of the network, Figure 3 gives a comparison of single-shot precision values of raw SLR observations. It is clearly visible that these values have improved dramatically in 2002 when compared to 1997. These numbers are to be considered as representative for the current network of stations: on average, the single-shot precision is at the level of a few mm for the major part of the network.
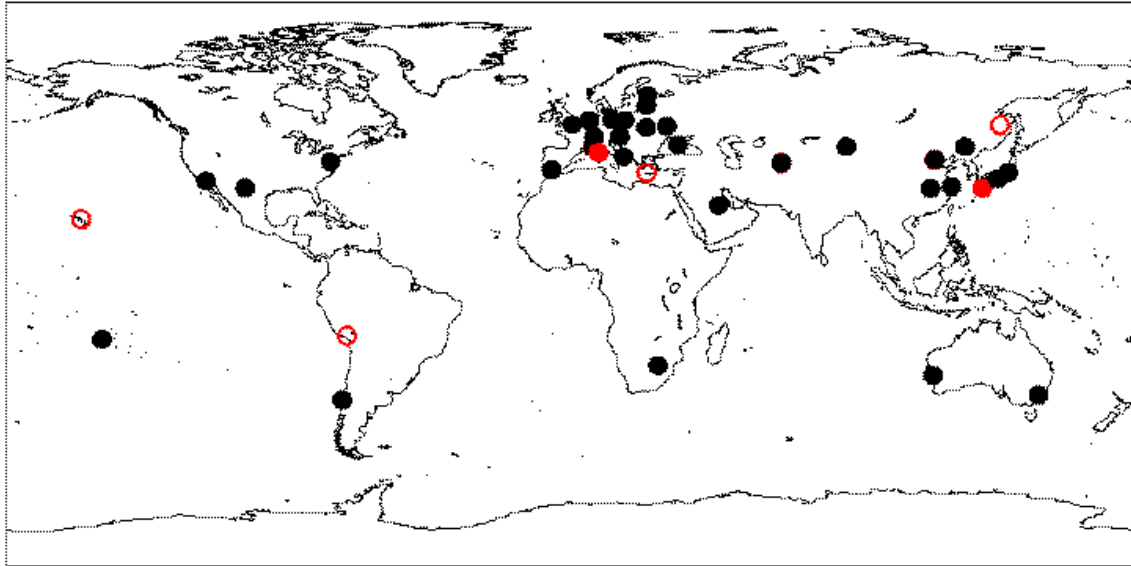
Figure 2. *The global network of SLR stations, Black circles indicate stations that have been active in both 2003 and 2005. Open red circles represent stations that were active in 2003, but not in 2005. Solid red circles represent stations that were active in 2005, but not in 2003.*
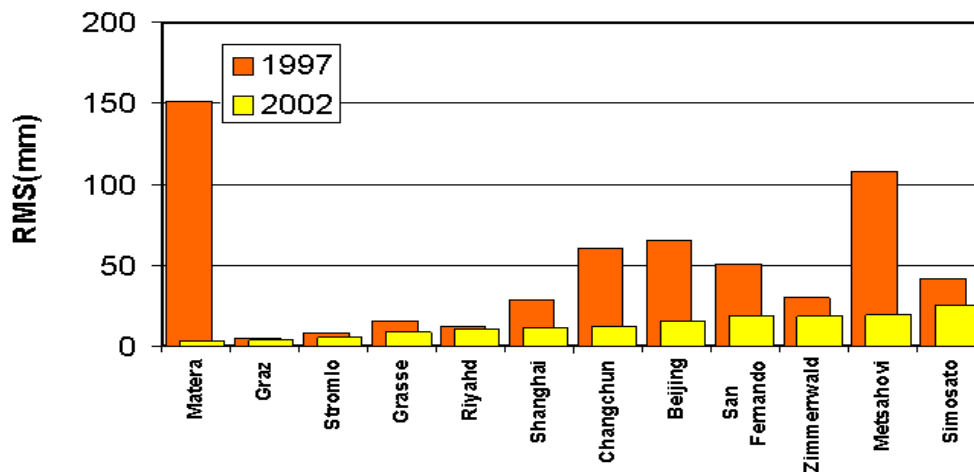

Figure 3. *A comparison of the single-shot precision of a number of representative SLR stations, in 2002 as compared to 1997 (courtesy Van Husson).*

Bias detection capability

SLR observations are reputed for their absolute, unambiguous value, and therefore they play an essential role in the determination of the origin and scale of the International Terrestrial Reference Frame (ITRF) (*e.g.* [Altamimi *et al*., 2002]). In order to do so properly, it is of utmost importance to monitor the quality of the observations taken by the SLR stations, not only on a precision level (*i.e.* in terms of internal consistency) but especially on absolute accuracy. To this aim, possible systematic errors (range biases) need to be computed and evaluated on a pass-by-pass basis and scrutinized constantly. To do so, a number of options exist. First, one can do so at the tracking station itself; actually the monitoring of such items is already being done, on the basis of orbit predictions and/or short-arc, rapid-return orbit solutions.

Although the capabilities are limited, the stations and analysis centers involved in this are encouraged to continue to do so. The second option is to derive such biases from the official ILRS product; here, a group of 6 analysis centers cooperate in a concerted effort to generate a weekly solution for station coordinates and Earth Orientation Parameters (EOPs) [ILRS, 2006]. A drawback of this technique is that station position and biases become highly correlated below a certain level, and the possibility to monitor range biases at the level of a few mm is therefore not possible. Also, by virtue of the (inherent) scatter in the weekly coordinates solutions for an arbitrary station, the corresponding range biases would also reflect this scatter to say the minimum. The third option is most attractive: a dedicated analysis in which the satellite orbit and related parameters are estimated to come to a most accurate description of the relevant elements of our system, but in which the position of the stations is kept fixed at a highly accurate model value (of course, allowing for temporal effects like crustal deformation, tidal motions, and ocean and atmospheric pressure loading deformation). This paper focuses on results obtained by the latter techniques.

An overview of the analysis centers active in such analyses (not necessarily exhaustive) is given in Table 1. In order to assess the quality of the bias values as reported by these groups on a regular (daily, weekly) basis, only values reported for the satellites LAGEOS-1 and LAGEOS-2 will be treated further here.

Institute	Altimetry, gravity missions	LAGEOS-1, -2	Navigation missions
Astronomisches Institut Universität Bern, Switzerland			X
Center for Space Research, Texas, USA		X	
Deutsches Geodätisches Forschungs Institut, München, Germany		X	
Delft University of Technology, Netherlands		X	
Mission Control Center, Moscow, Russia		X	
National Institute of Information and Communications Technology, Kashima, Japan	X	X	
Shanghai Astronomical Observatory, China		X	

Table 1. *Overview of the dedicated QC efforts done by various SLR analysis groups.*

Although Table 1 shows that quite a number of analysis centers are involved in the operational QC assessments, and might suggest that the results are consistent, a simple illustration (Figure 4) shows that this is not necessarily the case: differences in the "verdict" for individual passes of up to several tens of millimeter can easily be present, sometimes even exceeding decimeter values. This aspect has been known for quite a number of years already [ILRS, 1999]. One of the main reasons for this is the modeling of the ground station positions: differences in this analysis component will immediately show up as consistent bias differences. To remedy this (aspect of the) situation, QC centers have been urged to use a common representation, which has been put into practice during the last years with reasonable success: at this moment, almost all QC centers use the ITRF2000 [Altamimi *et al*., 2002] model, with just a single exception: MCC still uses its own set of station coordinates (status October 2006).

The consistency of the reported bias values is the subject of the remainder of this paper. The results as they are included in the weekly so-called ILRS Combined Range Bias Reports [Gurtner, 2006] are used as input for this evaluation. These reports basically merge the information from a number of individual bias reports, and have been available since 2004. An example of (a few lines from) such a report is given in Table 2, for one (arbitrary) station only.

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-------------------------------------------------------------------------------
1864 MAIL Maidanak              CSR      DGFI      DUT      MCC      NICT     SAO
                    sc   wl    rb  pr    rb  pr    rb  pr    rb  pr    rb  pr    rb  pr
-------------------------------------------------------------------------------
1864 2005-11-30 19:49 L2  532    -8   6   -72  12              5   5   -27  12    -2   3
1864 2005-11-30 21:03 L1  532   -18   5   -49  23            -14  10   -28  16    13  20
1864 2005-12-01 17:43 L2  532    29  14   -36  11   -10  15   48   6    13  11    23   1
1864 2005-12-01 19:41 L1  532     4  11   -27  12   -54  11    8   5   -15  12    30  12
1864 2005-12-02 19:40 L2  532   -35   0   -91  11    82   4    *   *   -81   5   171   4
1864 2005-12-05 18:10 L2  532   -31   7    29   8   -62   7            -38   7
1864 2005-12-05 21:07 L1  532   -50  15    19  14   -16  18             -2  16
1864 2005-12-05 22:19 L2  532   -40   5     4   9   -64  12            -74   6
1864 2005-12-06 16:15 L2  532     4   7    50   9   -36   6            -17   7
1864 2005-12-06 16:29 L1  532    12   4   -52   4   -12   3             -6   3
1864 2005-12-08 14:03 L1  532   -16  13   -55  12   -64  12            -53  13
1864 2005-12-08 16:35 L2  532    -5   9    10  15   -70  21            -56  13
1864 2005-12-08 17:12 L1  532    28   1   -80   6   -32   0            -49   9
1864 2005-12-08 20:36 L1  532     3  10    -3   9    -5  10            -32  10
1864 2005-12-08 20:42 L2  532     8   7    26  10   -24  11            -27  11
1864 2005-12-09 16:02 L1  532    10   5   -61   9   -59   9            -29   9
1864 2005-12-10 14:29 L1  532    22  13   -13  12    -7  12             12  13
1864 2005-12-10 16:39 L2  532    -5  11    40  27   -54  28            -27  20
1864 2005-12-10 17:58 L1  532    -5  16   -29  15   -39  15            -28  16
-------------------------------------------------------------------------------
1864 Average         532    -4   8   -20  12   -38  11   11   6   -29  11    47   8
-------------------------------------------------------------------------------
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Table 2. *An example of en entry in the ILRS Combined Range Bias Report [Gurtner, 2006], for station Maidanak in December 2005. All values are in mm.*

To compare the reported biases in a useful fashion, statistics on a large number of values will be derived. In principle, one can do so in two ways. First, it is possible to do a covariance analysis (cf. Figure 5), where common biases from an arbitrary pair of QC centers are plotted against one another and trend line(s) and correlation coefficients are computed. The advantage of this method is that it allows/eliminates systematic differences between the two series. However, the results can be interpreted with either of the two series as a reference, so this comparison technique will not yield unambiguous results. Instead, a direct comparison is opted for here, where the bias values reported for common passes as reported by an arbitrary QC center pair will be subtracted (cf. Figure 4) and simple, straightforward statistics will be computed. It should be noted that the QC centers may have developed/refined their analysis procedures over the course of time, and therefore allowance will be made for time-depending answers, reflecting differences in quality. An indication of this is shown in Figure 6, which gives the rms-of-fit of orbital solutions on LAGEOS-1, as obtained by Delft University of Technology over the period 1985-2005; improvements in the quality of the orbital fit and therefore also in the bias detection capabilities are clearly visible.

Results

A summary of these computations is given in Table 3: the rms values of the differences. Typically, some 20,000 common LAGEOS-1 and LAGEOS-2 passes went into the computation of a single entry in this table. It should be noted that individual biases of 100 mm and larger (in absolute terms) were ignored here for

various reasons: (*i*) they may be real in some cases, but not representative for a normal situation; (*ii*) they may be very weak because of a small number of observations during such a pass; and (*iii*) they may reflect problems with the model
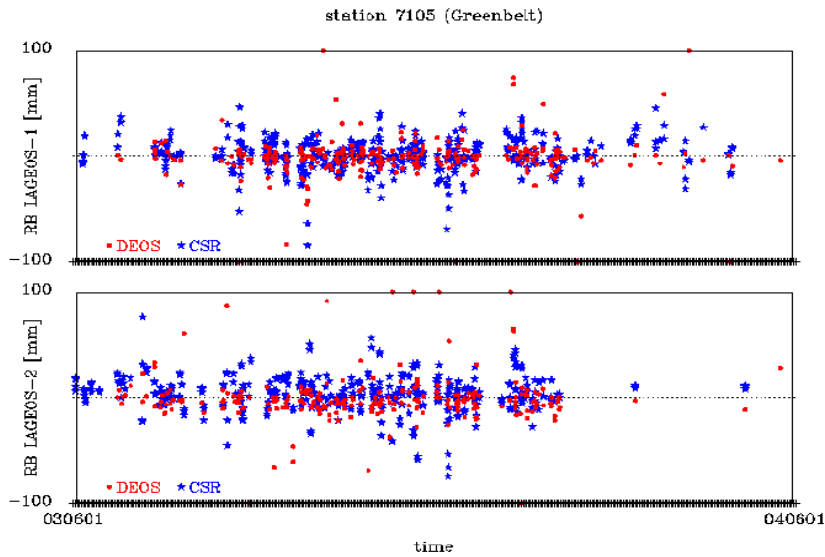

Figure 4. *A comparison of bias values reported for common LAGEOS-1 passes over station Greenbelt by QC centers CSR and Delft, as an illustration of the scatter and uncertainties in these values (direct comparison).*
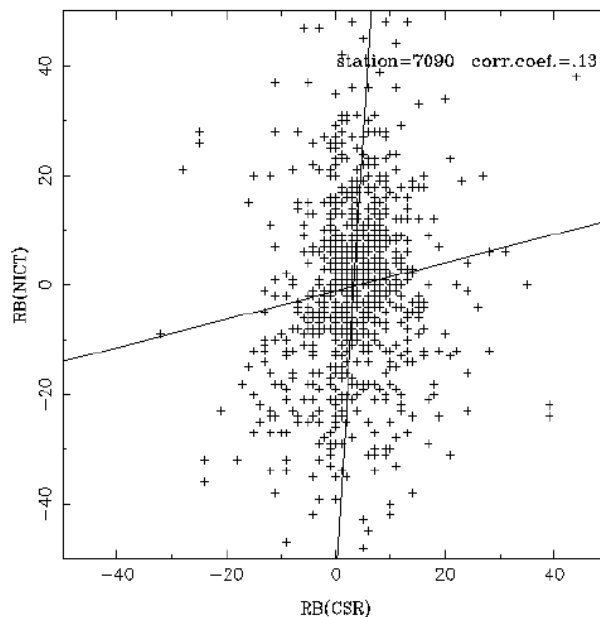

Figure 5. *A comparison of bias values reported for common LAGEOS-1 passes over station Yarragadee by QC centers CSR and NICT, as an illustration of the scatter and uncertainties in these values (covariance-style comparison).*

for station coordinates for the pertinent QC center. However, this represents a very small fraction of the total number of common passes. Another aspect to be noted is that the statistics have been computed in an unweighted fashion. Although passes with a relatively large number of normal points will lead to more stable (consistent) bias values, it is expected that this actually will average out, and straightforward statistics are given here only. After all that is what a station operator or manager is confronted with when reviewing the various bias reports.

As reported, the values have been computed for various periods: the years 2004 (when the Combined Bias Reports were initiated), 2005 and 2006. To better illustrate any trend, the rms differences are also shown in a graphical form: Figure 7.
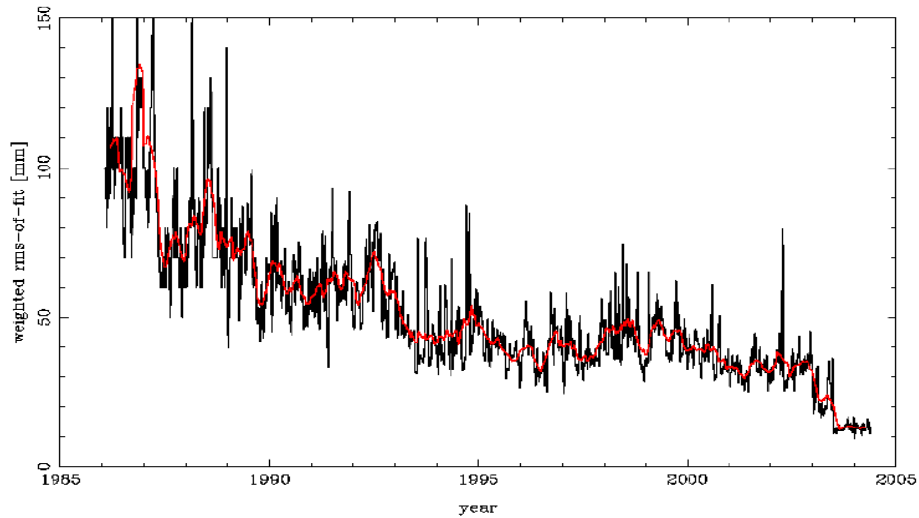
Figure 6. *Overview of the LAGEOS-1 rms-of-fit of the weekly orbital computations as done by Delft University of Technology.*

	DGFI	DUT	MCC	NICT	SAO
CSR	- / 26 / -	25 / 22 / -	28 / 25 / -	29 / 18 / -	34 / 21 / -
DGFI		- / 28 / 34	- / 29 / -	- / 29 / 28	- / 30 / 32
DUT			22 / 22 / -	25 / 22 / 21	24 / 22 / 22
MCC				26 / 25 / -	28 / 25 / -
NICT					32 / 26 / 21

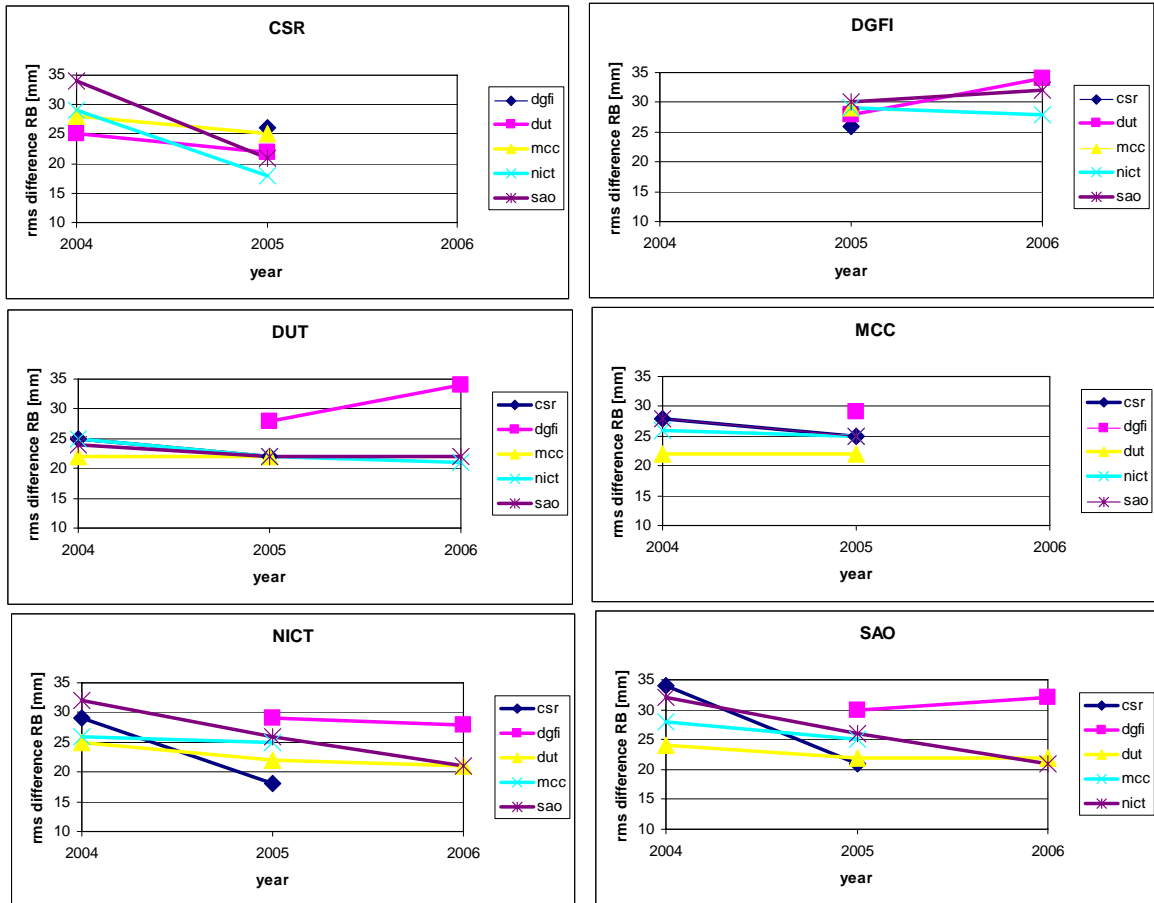**Table 3.** *Statistics of the differences between bias values for common LAGEOS-1 and LAGEOS-2 passes observed by the global network of SLR stations, as reported by various pairs of QC centers. Entries are for 2004, 2005 and 2006, respectively. All values are in mm.*

The discussion of the results is postponed until the next section. It is an unfortunate but real fact that the quality of the global SLR network is quite diverse: it is a mixture of top-quality stations and stations that do a little bit less in terms of performance. This might lead to the situation where the numbers reported in Table 3 and Figure 7 are indeed representative for the global network, but do not reflect the bias detection capabilities for the state-of-the-art stations properly. To that aim, the consistency computations have been repeated, but now for a subset of stations which has been given a preferential role in the derivation of the weekly official ILRS product on station coordinates and EOPs only: Graz, Greenbelt, Hartebeesthoek, Herstmonceux, McDonald, Monument Peak, Mount Stromlo, Riyadh, Wettzell, Yarragadee and Zimmerwald. These stations excel in terms of data quantity and quality, and it is expected that the bias values reported for these stations are more consistent than the values reported for the overall network. Results are presented in Table 4 and Figure 8, with similar definitions.

Discussion

The numbers as reported in Tables 3 and 4 and illustrated in Figures 7 and 8 give a very clear message: on average, the reported range bias values are consistent at the level of about 20 mm when considering the total network of SLR stations, and at the

level of about 15 mm when considering the so-called AWG core stations only. If these numbers were to be reduced to an average quality verdict on a bias value reported for an individual pass in an individual analysis report, these numbers can be divided by √2 (first order; one can argue about the level of formal correlation between the pairs of numbers).

Figure 7. *Statistics of the differences between bias values for common LAGEOS-1 and LAGEOS-2 passes observed by the global network of SLR stations, as reported by various pairs of QC centers. Entries are for 2004, 2005 and 2006, respectively. All values are in mm*

The plots in particular show that the general trend of the agreement between QC center pairs is positive: the consistencies become better with time for most of them. A good illustration of this trend are all statistics involving NICT, where the level of agreement has gone down from about 30 mm (2004) to about 20 mm (2006) (Figure 7, all stations). Similar observations can be done for the AWG core stations only.

	DGFI	DUT	MCC	NICT	SAO
CSR	- / 22 / -	20 / 15 / -	20 / 15 / -	25 / 15 / -	29 / 17 / -
DGFI		- / 24 / 32	- / 26 / -	- / 26 / 25	- / 28 / 30
DUT			17 / 15 / -	22 / 18 / 14	22 / 18 / 18
MCC				23 / 19 / -	22 / 18 / -
NICT					29 / 23 / 18

Table 4. *Statistics of the differences between bias values for common LAGEOS-1 and LAGEOS-2 passes observed by the so-called AWG core stations, as reported by various pairs of QC centers. Entries are for 2004, 2005 and 2006, respectively. All values are in mm.*
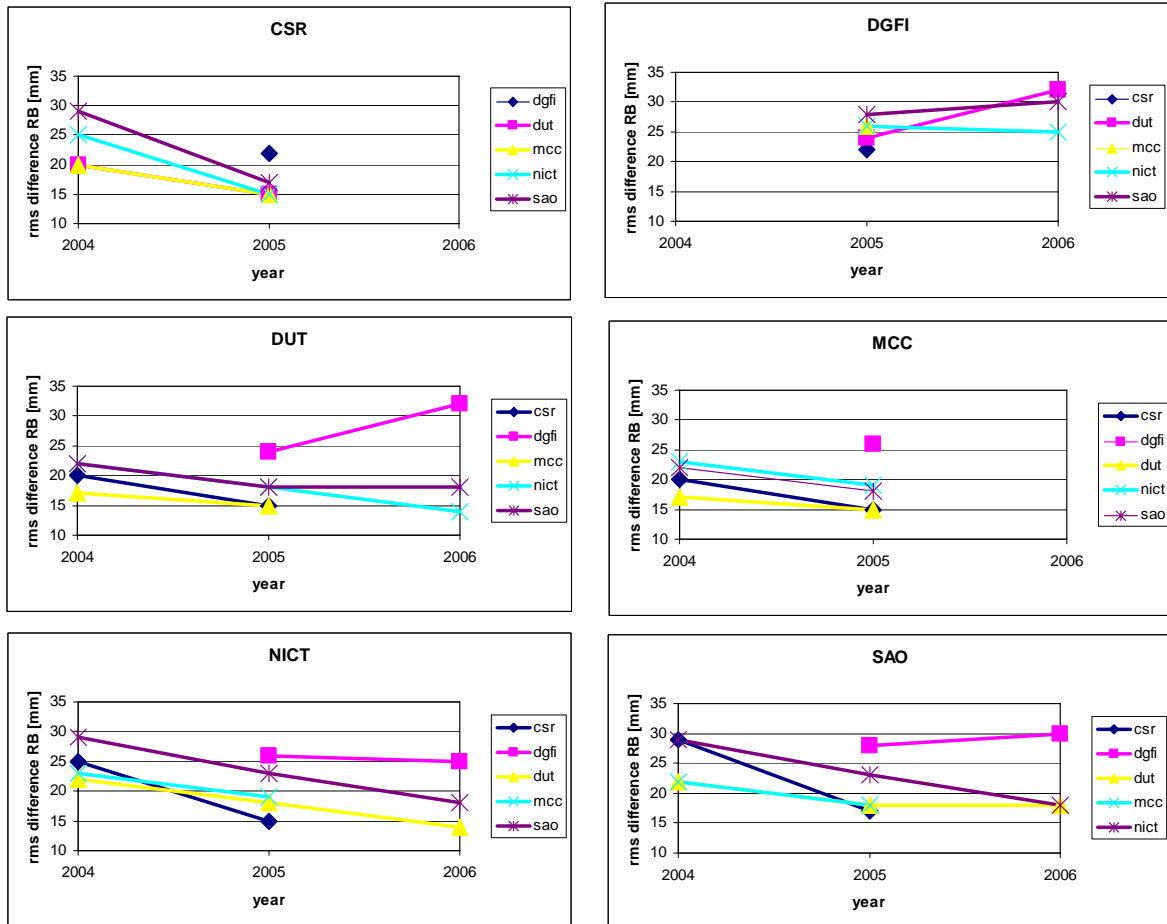
Figure 8. *Statistics of the differences between bias values for common LAGEOS-1 and LAGEOS-2 passes observed by the so-called AWG core stations, as reported by various pairs of QC centers. Entries are for 2004, 2005 and 2006, respectively. All values are in mm.*

Two points of concern remain: first of all, it is clear that the number of analysis centers involved in such analyses fluctuates quite a bit over time. In particular, the situation has become quite worrisome for 2006, with CSR and MCC not contributing anymore (and, although not visible, DUT in a similar situation since mid-2006) for various reasons. Every effort should be undertaken to improve this situation. Secondly, the plots also show that the trends are not so favorable for every QC center involved, and the consistency numbers get worse with time. This holds in particular for DGFI, and an effort should be started to remedy this.

Finally, coming back to the subject of the first part of the paper, the SLR network itself remains a continuous point of attention: only if the laser stations are distributed evenly on a global scale, can the space geodetic (and geophysical) community really take benefit from the unique capabilities of the technique to its fullest.

References

[1] Altamimi, Z., P. Sillard and C. Boucher: A new release of the International Terrestrial Reference Frame for earth science applications, *J. Geophys. Res.*, *107*(B01), 2214, doi:10.1029/2001JB000561, 2002.

[2] Gurtner, W., ILRS Combined Range Bias Report, http://aiuas3.unibe.ch/ftp/slr/summary_report.txt, 2006

[3] ILRS, http://ilrs.gsfc.nasa.gov/working_groups/awg/awg_activities/awg_min_florence1999.html, 1999.

[4] ILRS, ftp://cddis.gsfc.nasa.gov/pub/slr/products/pos+eop/, 2006.

The ILRS Standard Products: A Quality Assessment

G. Bianco[1], V. Luceri[2], C. Sciarretta[3]

1. Agenzia Spaziale Italiana, Centro di Geodesia Spaziale, Matera, Italy
   giuseppe.bianco@asi.it / fax: +39-0835-339005

2. e-Geos S.p.A., Centro di Geodesia Spaziale, Matera, Italy

3. Telespazio S.p.A., Roma, Italy

Abstract

In June 2004 the Space Geodesy Center (CGS, Matera, Italy) of the Agenzia Spaziale Italiana (ASI) has been selected by the International Laser Ranging Service (ILRS) as its Primary Official Combination Center for station coordinates and Earth Orientation Parameters.

From the beginning, the CGS has been providing the weekly operational combined ILRS solutions (SSC/EOP), also supporting the IERS B Bulletin production; moreover, CGS has produced the official ILRS contribution to ITRF2005, by combining the weekly solutions, from 1993 to 2005, submitted by the contributing ILRS Analysis Centers.

The CGS combination methodology relies on the direct combination of loosely constrained solutions. This methodology has been implemented and tested to handle site coordinates, site velocities, EOP, LOD coming from the same and/or different techniques.

The whole set of weekly combined solutions, those produced in support of ITRF2005 as well as the operational ones, is analyzed in detail in this contribution, to show the coherence and robustness in terms of global parameters as well as station coordinates.

Introduction

Soon after the establishment of the ILRS a strong need was felt to coordinate the work and combine the results of the various SLR data Analysis Centers (AC's) in order to define and distribute a series of "certified" ILRS products to the users community.

In 1999 the ILRS Analysis Working Group, chaired by Ron Noomen (TU Delft), outlined two Pilot Projects for the estimation of site coordinates and EOP, separately, from different AC solutions; the year after the two Pilot Projects were joined and the first results discussed. In 2003 the ILRS issued a formal Call for Participation for the generation of ILRS products,

In 2004 the ILRS AC structure was finalized and official delivery of standard products started; the CGS was selected as the Primary Official Combination Center, referred to as ILRSA, while DGFI was selected as Backup Official Combination Center or ILRSB.

In 2005 the ILRS contributed to the definition of ITRF2005 with its official time series.

The ILRS Standard Products

Presently, the following six AC's regularly contribute to the production of the ILRS standard products by means of weekly solutions:

ASI, Agenzia Spaziale Italiana, I

BKG, Bundesamt fuer Kartographie und Geodaesie, D
DGFI, Deutsches Geodatisches Forschungsinstitut, D
GFZ, GeoForschungsZentrum Potsdam, D
JCET, Joint Center for Earth System Technology, USA
NSGF, NERC Space Geodesy Facility, UK

Those ACs have been recognized after passing the benchmark tests as requested by the AWG. Other institutes are now under test and on the way to become official ILRS Analysis Centers.

The standard weekly ILRS combined solutions (either the primary and the backup) are made available each Wednesday at CDDIS and EDC, together with the single contributing AC solutions. The complete time series, starting from 1993, is available at CDDIS and EDC. A backwards extension of the time series, back to 1980, in now under construction.

A complete description of standards and methods adopted in the combination is given in [Bianco et al, 2003].

The ILRS coordinate solution in the ITRF 2000 and ITRF 2005

The first quality assessment has been done comparing the ILRS coordinate solution with the ITRF2000 as well as with the newly issued ITRF2005.
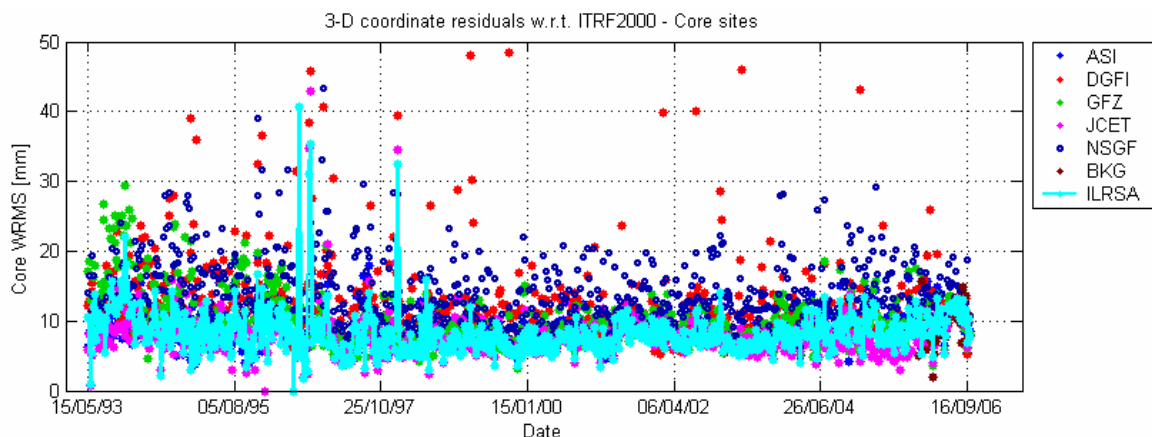
Fig 1 Time series of weekly 3-D coordinate residuals w.r.t. ITRF2000 for ILRS core sites from individual AC solutions as well as from the combined ILRSA solution.

Generally speaking, the plot in Fig. 1 shows that the combined solutions represents a real improvement, in terms of consistency and dispersion, with respect to the individual AC solutions. The average 3-D residuals with respect to ITRF2000 are consistently at or below the 1 cm level, as confirmed by the plot in Fig. 2, which shows the 3-D coordinate residuals WRMS as a function of time.

It shows very clearly the fundamental role of the so called "core" sites (i.e., SLR stations with a consolidated tracking history in terms of data quantity and quality). The behavior of the total network worsens after year 2000 due to the introduction of several new observing sites which are not properly modeled in ITRF2000.

As expected, the situation improves with the ITRF2005, as shown if the plots in Figures 3 and 4 below. In particular, the new stations appear properly accounted for; moreover, the 3-D coordinate residuals for the "core" stations behave remarkably well, with an average value constantly below the 1 cm level.
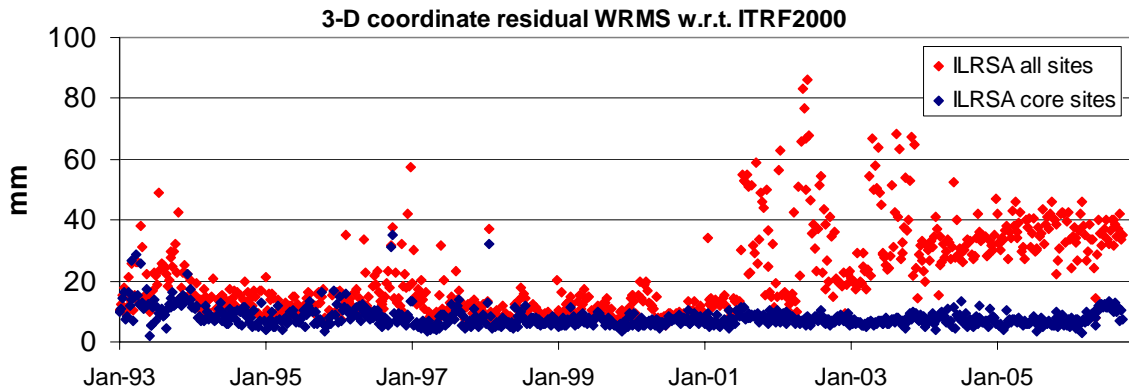
Fig. 2 *Time series of weekly 3-D coordinate residuals WRMS with respect to ITRF2000*
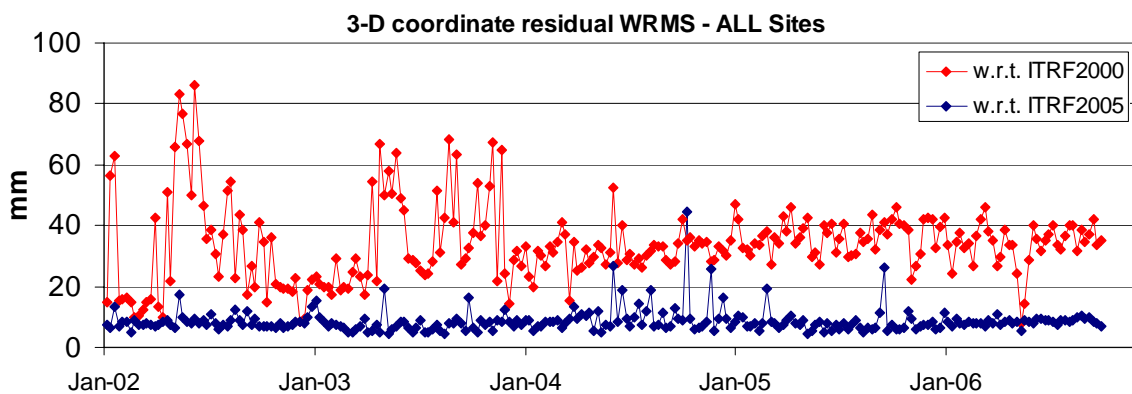

Fig. 3 *Time series of 3-D coordinate residual WRMS for all ILRS sites with respect to ITRF2000 and ITRF2005, as computed in the ILRSA combined solution*
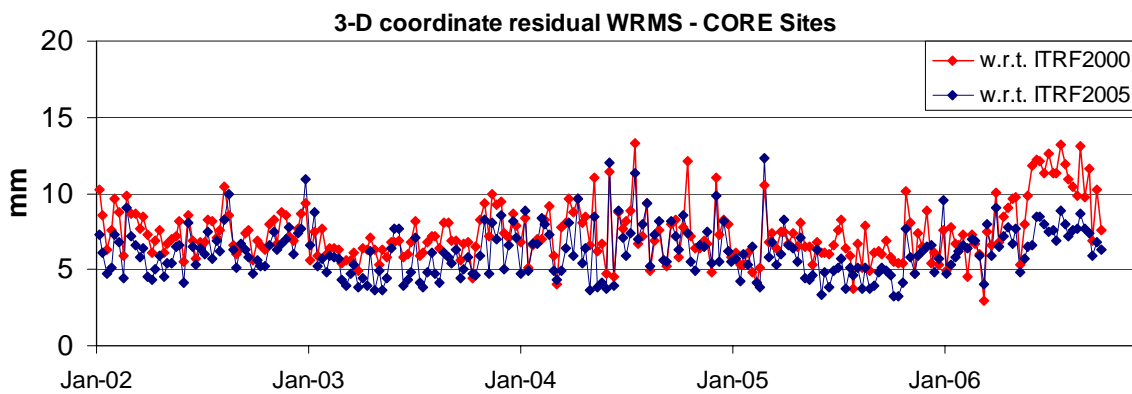

Fig. 4 *Time series of 3-D coordinate residual WRMS for ILRS "core" sites with respect to ITRF2000 and ITRF2005, as computed in the ILRSA combined solution*

ILRS TRF origin with respect ITRF 2000/2005 origins

Another quality assessment has been done by looking at the time series of the 3-D distances of the ILRS Terrestrial Reference Frame origin with respect to another ITRF origin. Each TRF realized by the SLR stations in a loose solution places naturally its origin in the center of mass of the Earth: its Cartesian coordinate offsets from a conventional origin describe the geocenter location. This time series, often referred to as "geocenter motion", is particularly interesting since it can be proposed as a new standard ILRS product.

The plots in Fig. 5 represent respectively the X, Y and Z components of the distance between the ILRS weekly origin with respect to the ITRF2000 and ITRF2005 origins, computed by roto-translations ("geometric" method) in the period 2002-2006. A clear annual signature is visible in all three components. The two series look pretty similar, with a slightly more evident drift in the Z component with respect to the ITRF2005 origin.
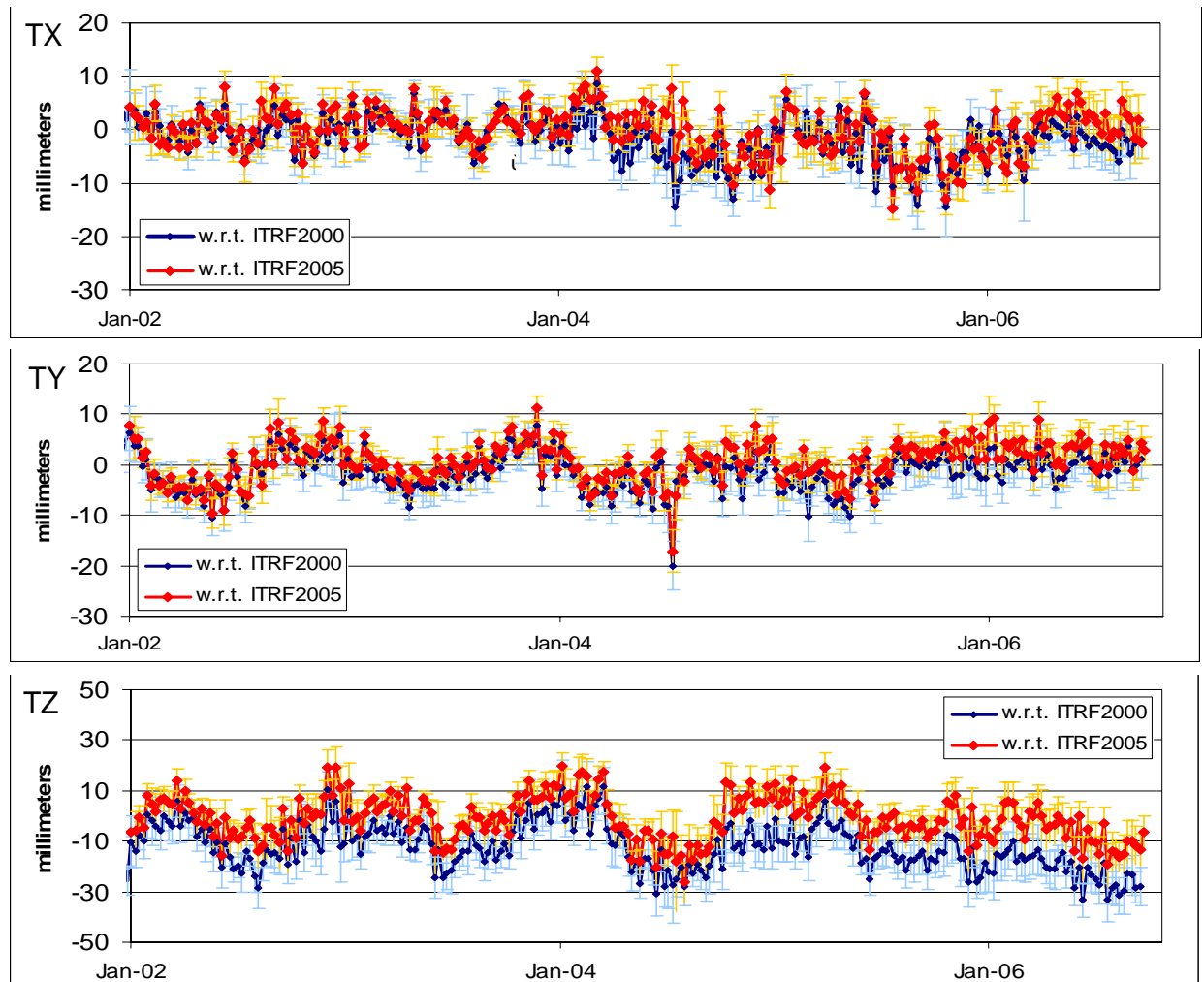
Fig. 5 *Time series of distance between the ILRSA geometric origin and the ITRF2000 and 2005 origins*

The translations of the ILRS TRF origin can also be obtained with a more rigorous data analysis strategy: through the estimates of the C_{10}, C_{11}, S_{11} geopotential coefficients, ("dynamic" method).

The plots in Fig. 6 show a direct comparison between the geometric and the dynamic ILRS TRF origin translations, with the latter obtained via the dynamic solution done by ASI. The behavior of the two time series is remarkably similar; the dynamic origin evolution looks smoother but the main features are present in both series.

This confirms that the geometric offsets, as defined by the standard ILRS combined solution, could be used to properly represent the geocenter motion.
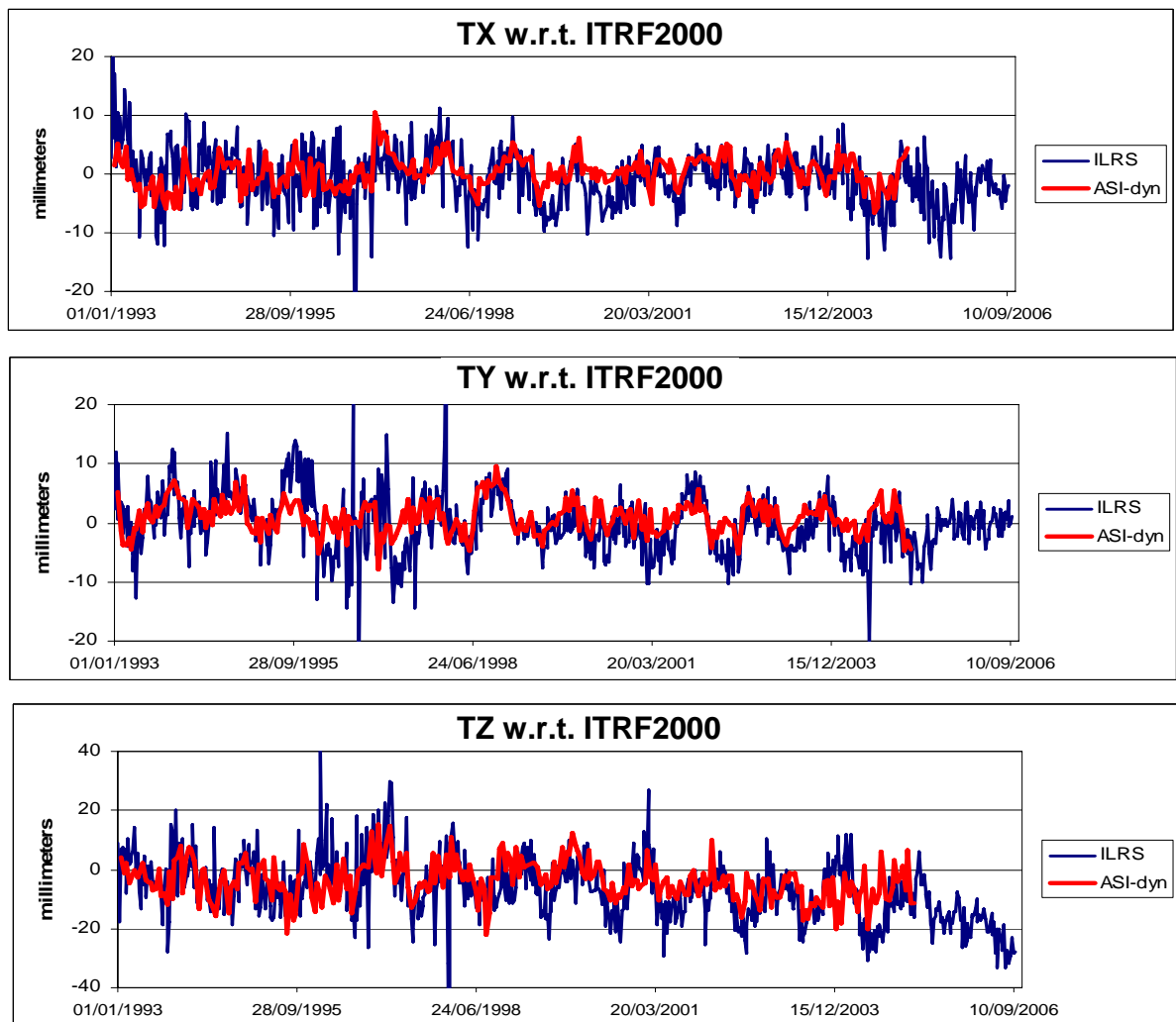
Fig. 6 ILRSA geometric vs ASI dynamic geocenter motion.

The scale factor

Much debate has been generated soon after the publication of the ITRF2005, whose scale has been defined without taking into account the ILRS contribution, due to an apparent strange behavior of the ILRS scale itself.

However, based on our work, we do not find evidence of any strange effect in the ILRS scale, as shown in the plots hereafter, covering the period January 2002 to mid 2006.

The ILRS scale with respect to the ITRF2000 is nicely flat, while a clear trend shows up in the scale time series with respect to the ITRF2005.

The selection of the core sites to be used when comparing different reference frames is crucial and can introduce artifacts.

Earth Orientation Parameters

In Fig. 8, ILRS X-pole, Y-pole and Length of Day (LOD) residuals with respect to the USNO "finals.daily" EOP time series, are plotted. The ILRS EOP products look pretty good and stable, with a WRMS of the residuals of the order of 0.25 milliarcseconds.

We've also made an external comparison between ILRS EOP's and those computed by other space geodetic services, namely IVS and IGS (CODE solution). The results for the Y component are shown in Fig. 9 below.
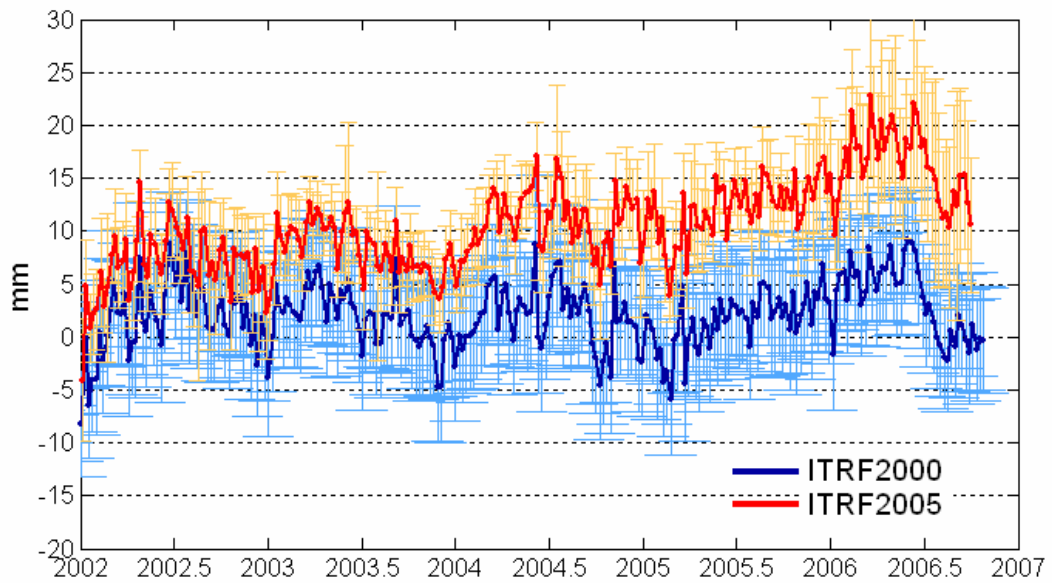
Fig. 7 *ILRSA scale with respect to ITRF2000 and ITRF2005*
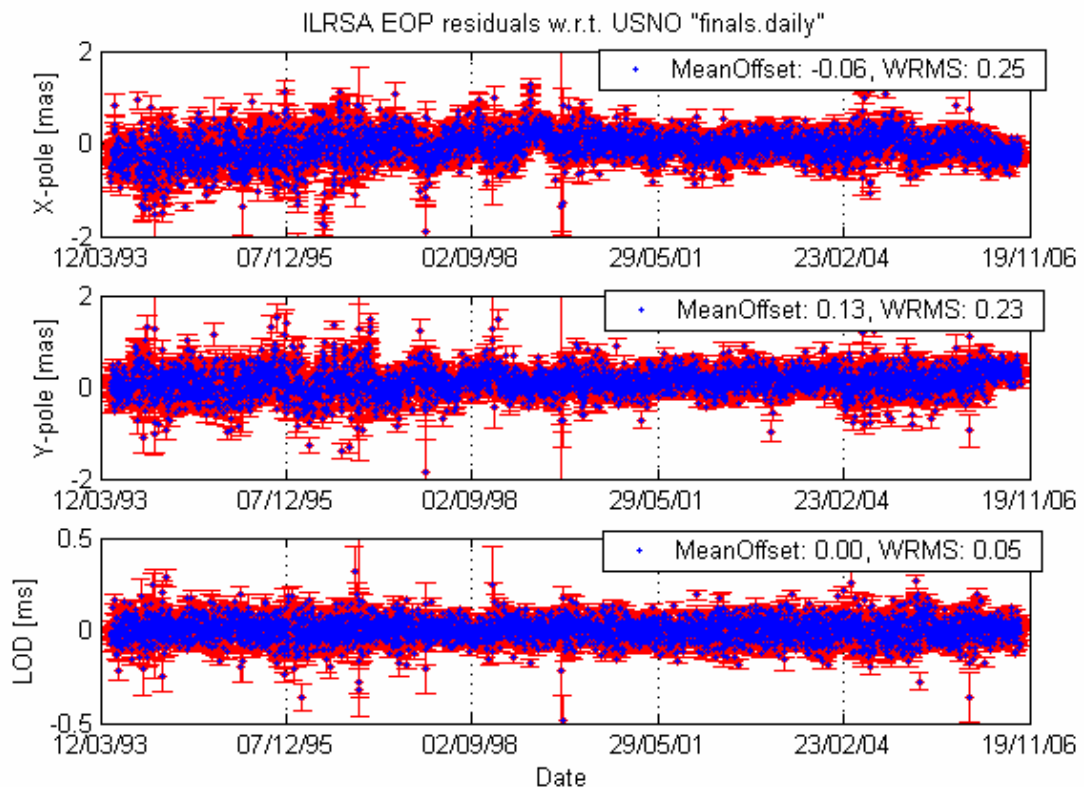
Fig. 8 *ILRSA EOP residuals with respect to USNO "finals.daily" EOP's*

EOP Y DIFFERENCES w.r.t. C04
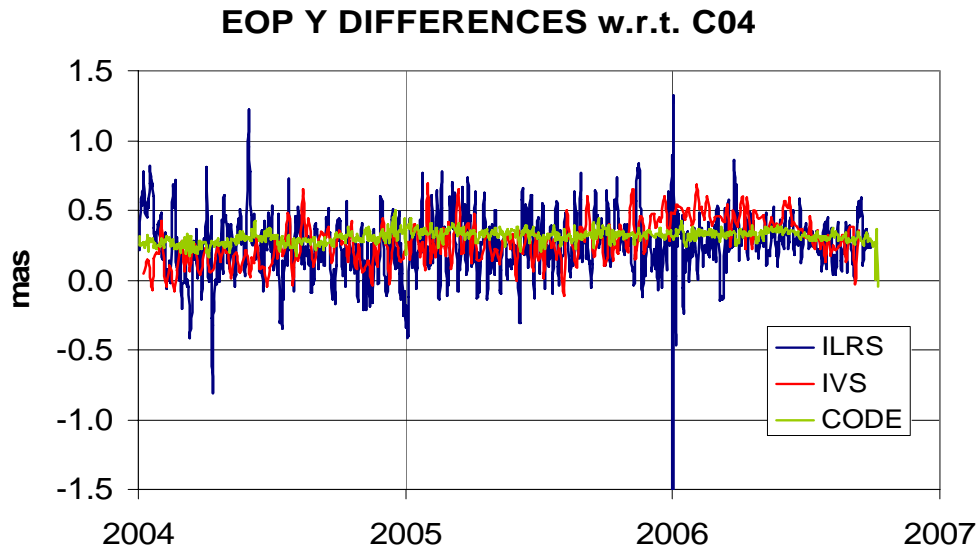
Fig. 9 ILRSA EOP differences with respect to IERS EOPC04

Conclusions

After two years of continuous operations, the routine ILRSA combination production process is stable and reliable. The processing chain has been made almost completely automatic and has already demonstrated a high degree of dependability.

Other than for the definition of origin and scale, almost unique to SLR, the ILRS standard products are a very valuable monitoring tool for site coordinates and EOPs, with a very fast response time.

This work has also shown that the geocenter motion, geometrically derived from the weekly solutions, is reliable enough to be included among the future ILRS standard products.

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Systematic range bias 2005-06

Toshimichi Otsubo[1], Naoko Obara[1]

1. Kashima Space Research Center, National Institute of Information and Communications Technology, 893-1 Hirai, Kashima 314-8501 Japan.

Contact : otsubo@nict.go.jp / Fax: +81-299-84-7160

Introduction

Most of modern laser ranging systems potentially have 1-millimetre-precision measurement ability in a normal-point basis. However, when it comes to 1-millimetre 'accuracy', it has not been fully achieved yet and it is still a challenge for the International Laser Ranging Service (ILRS) network.

At National Institute of Information and Communications Technology (NICT), Kashima, Japan, we check the quality of laser ranging data from the whole ILRS network, in two folds. One is routine automated quality check analysis which gives quick alarms for large and obvious anomalies, and the other is precise residual analysis for sub-centimetre systematic range biases.

Routine quality check analysis

We started the 3-satellite (two LAGEOS and AJISAI) routine bias report in 1997 (Otsubo and Endo, 1998) and enhanced it to the 7-satellite (plus STARLETTE, STELLA and two ETALON) analysis in 1999 (Otsubo, 2000). It was again significantly upgraded in May 2005 as follows.

Firstly, we further added satellites: ERS-2, JASON-1, ENVISAT, GPS-35, GPS-36, GLONASS-87, GLONASS-89 and GLONASS-95. Note that some of these satellites might be omitted from the analysis report in the case of failing a certain criteria in terms of data quality and quantity. Nevertheless, the analysis reports constantly include well more than 10 satellites. The increase of number of satellites and the variety of satellite altitudes will certainly help the ILRS stations easily point the problem and the cause.

We have switched the orbit analysis software from 'concerto v3' to 'concerto v4'. The new version is almost compatible to the physical models recommended in IERS Conventions (2003). The station coordinates basically unchanged to ITRF2000, but those of new or significantly improved stations after the year 2000 were readjusted. Therefore the quality of our analysis reports should be more accurate.

We now publish the report every day, which used to be a week interval before May 2005. The report timing was also improved from 48-hour delay to 24-hour delay. Every morning in Japanese Standard Time (around 0 to 1 hr UT), a report covering up to two days before is being released. Such a quick reporting scheme became possible thanks to the rapid submission (typically within a few hours after the observation) and the rapid archive service (at CDDIS and EDC) of normal point data. The daily reports are available at our website and also via email. See figure 1 for previous website page. New website is: http://www.science.hit-u.ac.jp/otsubo/slr/bias/ [ed].

The reports are distributed through the SLReport mailing list every Wednesday, and they are being sent to registered users even on a daily basis.
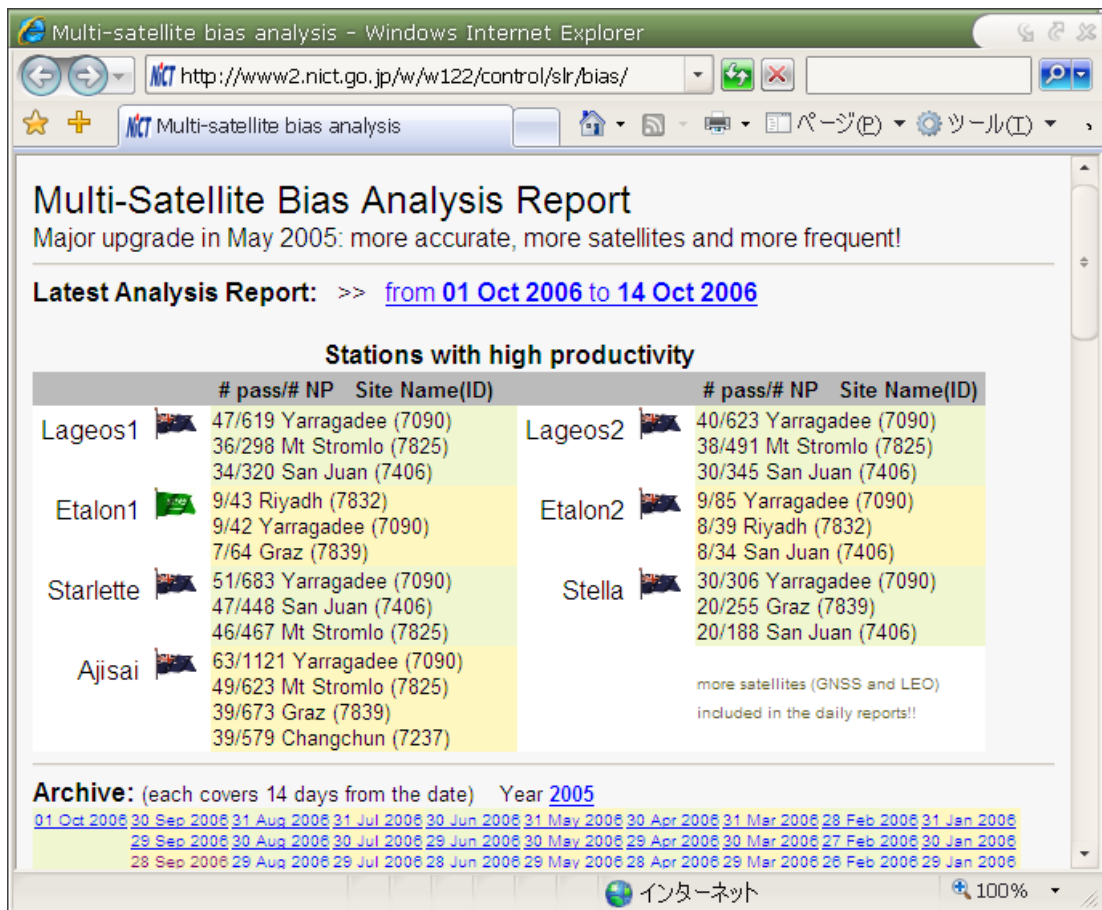
Figure 1. Multi-satellite bias analysis webpage at NICT.

Range bias vs intensity

We have proposed a quality assessment method for the intensity-dependent biases (Otsubo, 2000). The post-fit residual data were sorted by the number of single-shot returns per normal point bin which should be strongly related with the signal intensity into a detector. If the detection signal intensity varies, and if the detection timing is dependent on it, there will be intensity dependent bias. Our previous studies also pointed out it is also related to the so-called target signature effect, which is now the major error source of laser ranging technique due to the reflection from multiple retroreflectors on board. The range measurement can differ, at maximum, by 4 to 5 cm for AJISAI and ETALON, and 1 cm for LAGEOS (Otsubo and Appleby, 2003).

We applied the same procedure to the 2005-2006 data set. Three sets of satellite types were chosen: LAGEOS-1 + LAGEOS-2, AJISAI, and STARLETTE + STELLA. For each satellite, the worldwide laser ranging data for 360 days from September 2005 to August 2006 were used for orbit determination. Orbits were solved for every 5 days for LAGEOS satellites and 2 days for others. The station coordinates and range bias were adjusted for all stations. The post-fit residual weighted rms of normal points was 1.0 to 1.2 cm for LAGEOS satellites and 1.5 to 2.5 cm for others.

The intensity dependent tests were carried out for most productive 24 stations during the period. The whole results are available at:

http://www.nict.go.jp/w/w122/control/pod/bias-intensity-0506.pdf

Fig. 2 (a) to (c) shows the three typical samples of them. The first case of Herstmonceux is the station where the return signal energy is almost strictly controlled to single photoelectron. This observation policy successfully results in the flat trend, that is, no intensity dependence seen for this station, in Fig. 2 (a). The Yarragadee station in Fig. 2 (b) represents good MCP stations. There is no intensity dependence larger than a few millimeters either. The typical result of (C-) SPAD stations is shown by Mt Stromlo in Fig. 2 (c). As the target signature studies suggested the strong signal makes the range measurement shorter. The AJISAI case is the largest in most cases, but a number of stations show significant trend (mostly negative) even for LAGEOS and STARLETTE + STELLA.
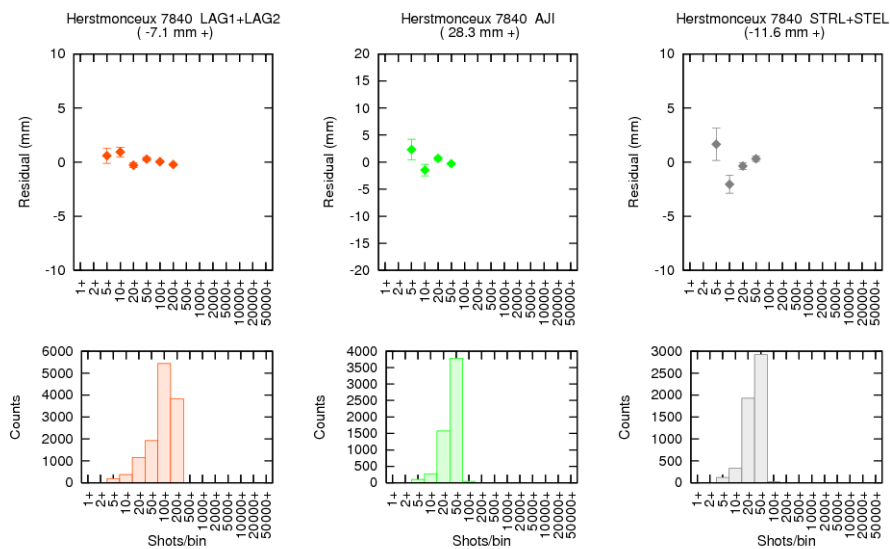
Figure 2 (a). Intensity dependence test. Single photon Herstmonceux station.
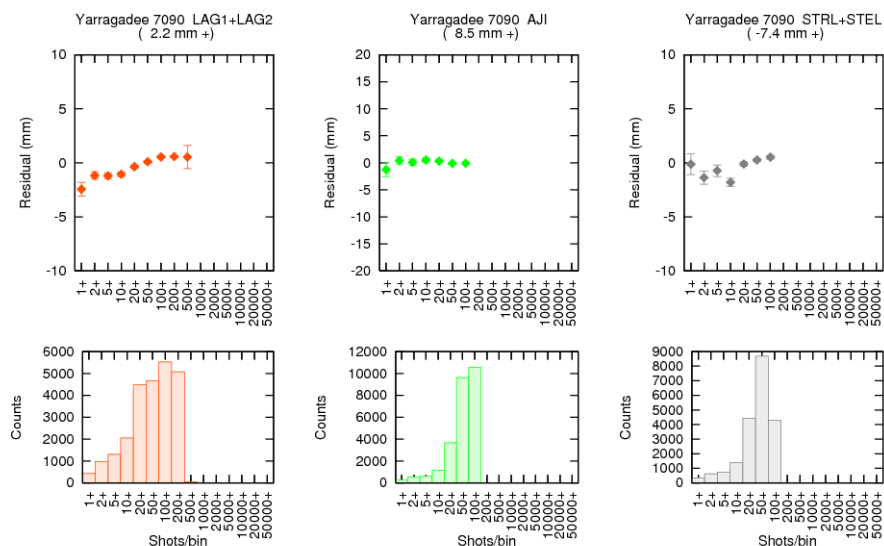
Figure 2 (b). Intensity dependence test. MCP Yarragadee station.

It is strongly recommended for every ILRS station to look into the result, and consider how the intensity dependent bias can be removed if it exists. As proven in previous
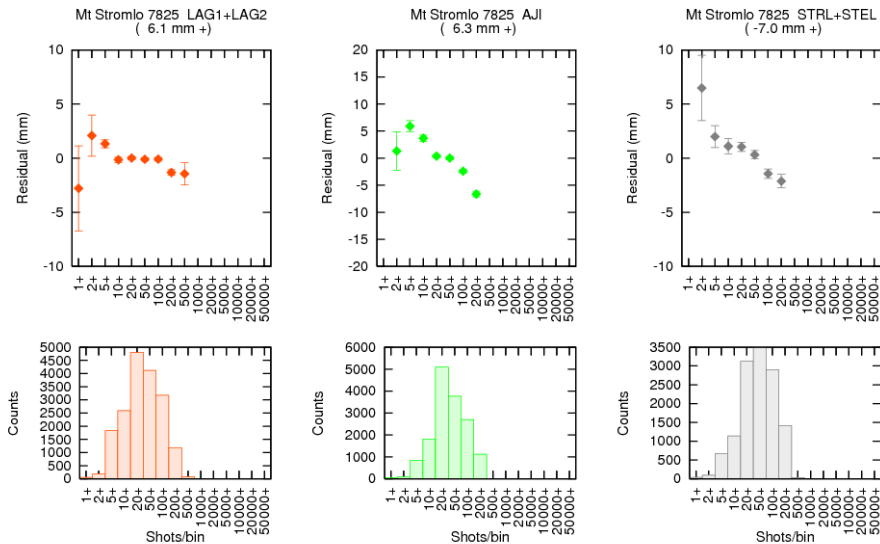
Figure 2 (c). Intensity dependence test. C-SPAD Mt Stromlo station.

studies (Otsubo and Appleby, 2004), the signal intensity is closely related to the elevation angle, and as a result the height component of station coordinates can be affected. This study probably underestimates the true intensity dependence. Note that the results from this study are just a guideline - it is the best to check the intensity dependence at each station, for example by inserting and removing the neutral density filter in front of the detector.

Range bias vs applied system delay

The alternative approach is the use of the applied system delay (given in the ILRS normal point format) as a sorting parameter.

The applied system delay is the value to be subtracted from the raw range observations, and it is not constant. Therefore it is to be regularly observed by ranging to terrestrial targets, what we call 'calibration'. There should not be any correlations between the range residuals and the applied system delay, in the ideal case. If there were, the station would have a systematic error in its ranging procedure to a terrestrial target or in its data processing stage.

We used the same set of the residual data as the previous section. At a number of stations, there have been jumps in the applied system delay itself probably due to some changes in optical or electronic path. Some stations seem to have multiple configurations (dual detectors, etc.) each of which gives different applied system delay. Such discontinuities themselves are not a problem at all as long as the reason is exactly known.

The bin size was set to the two-way range of 66 ps (1 cm in one-way distance). We applied the sorting procedure to the same 24 station as the previous section. The sorting procedure was chopped into a few portions for stations with large jumps. The graphs are also available at our website:

http://www.nict.go.jp/w/w122/control/pod/bias-delay-0506.pdf
(graphs for calibration dependent bias)

http://www.nict.go.jp/w/w122/control/pod/delay-0506.pdf
(auxiliary graphs for variation of applied system delay for the 1-year period)
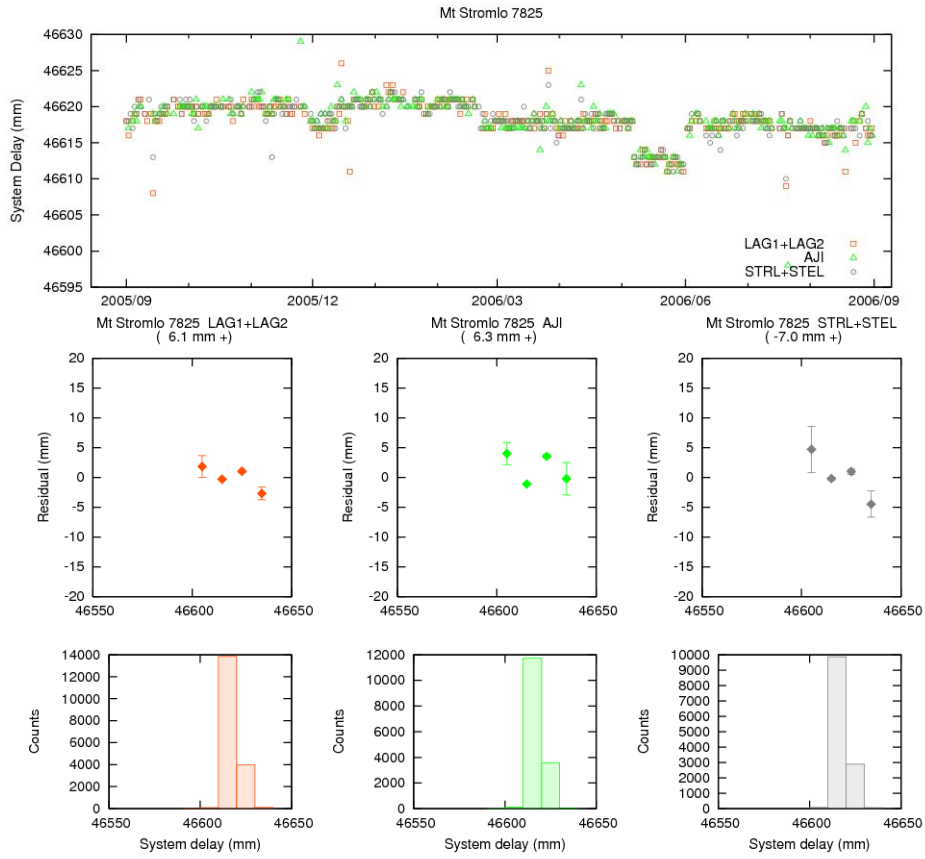
Figure 3 (a). *Calibration dependence test. Mt Stromlo station.*
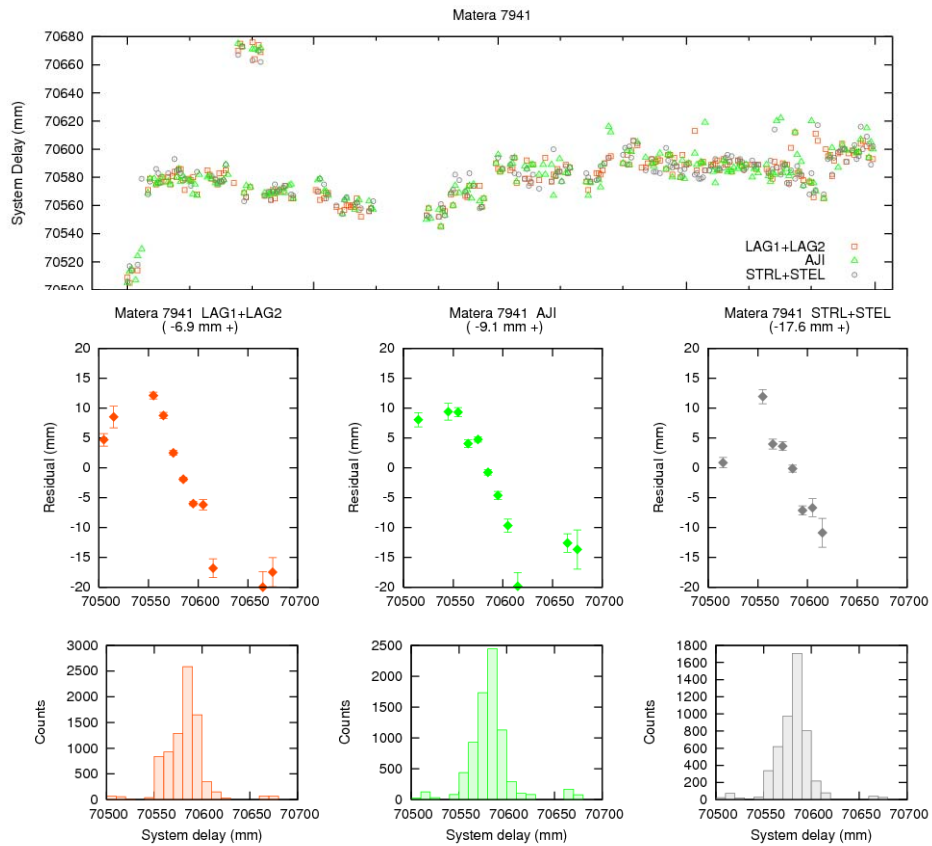

Figure 3 (b). *Calibration dependence test. Matera station.*

Two results are shown in Fig. 3 (a) and (b) among the 24 cases. The first case (Fig. 3 (a)) is probably the best one of all: Mt Stromlo. Its applied system delay has been very stable throughout the year, almost within ± 1 cm (top). There has been no significant calibration dependent bias (bottom). Such long-term stability of calibration ranging helps the long-term stability of satellite ranging. The next graph of Fig. 3 (b) shows those for Matera station. The stability of applied system delay is also good (± 3 cm) for this station. However, there is a steep negative trend for all three types of satellites. A possible reason is that a part of the variation in calibration ranging might not be true and therefore the raw observation would be 'wrongly calibrated' by the calibration procedure.

The long-term variation of terrestrial target ranging is hardly separable from the seasonal or secular variation of station height. Therefore, the result from this approach has a risk of sending a wrong alarm if the station coordinates experience unmodelled effects like loading displacement. It is strongly recommended for each station to understand why the calibration measurement varies and strive to reduce the variation.

Conclusions

In addition to the multi-satellite daily bias reporting system, we demonstrated the more precise ways for quality assessment of laser ranging data. We use the single shot returns per normal point bin, and the applied system delay, as a sorting parameter. Some correlations were found between the range data and these sorting parameters.

It is important to note that most of the information that is potentially useful to assess the quality is lost in the process of normal point generation. It is essential that each station performs extensive tests on site in order to eliminate any systematic bias and to keep the data quality stably high.

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A reassessment of laser ranging accuracy at SGF Herstmonceux, UK

Philip Gibbs[1], Graham Appleby[1] and Christopher Potter[1]

1. Space geodesy facility, Herstmonceux, East Sussex, UK.

Introduction

Gibbs et al (2007, these proceedings) reports on a major upgrade and expansion of capability at the Space Geodesy Facility, Herstmonceux, UK. A prerequisite of the laser ranging upgrade to kHz repetition rate is the in-house build of a ps-level precision event timer, based on Thales clock units and dubbed HxET. Extensive use has been made of HxET since it was completed during the summer of 2006 to calibrate the existing cluster of Stanford counters prior to making routine use of HxET. In particular, we are very interested in back-calibrating all the Herstmonceux data for the period 1994-present, during which time the Stanford counters had been exclusively used. In this paper we detail the results of this re-calibration, and also consider the effect the correction to our LAGEOS data will have on the published site coordinates in the ITRF.

Previous calibrations

Extensive tests on the linearity of the Stanford counters at satellite ranges, from a few to approximately 150ms were carried out by Gibbs (Appleby *et al*, 1999, Gibbs *et al*, 2002) using an early version of the Portable Pico Event Timer (P-PET, Hamal *et al*, 2007). The method used is to record start signals and subsequent noise events simultaneously by the P-PET and by the Stanford counter(s) that are under test. A hardware delay is used to move the average interval between start events and detected noise events from a few ms up to 150ms, the range encountered during real satellite ranging. For each event, comparison of the time interval as measured by each Stanford relative to that determined by the highly-linear P-PET, gives an estimate of the error in time interval determined by each Stanford. From this work, a correction table as a function of range was compiled and issued in SLRMail 0891 in 2002 January. The effective dates of application of the results are 1994 October to 2002 January and the magnitude of the corrections reaches 8mm. From 2002 February the corrections are applied at the station as part of pre-processing.

With the availability of HxET, these linearity tests were repeated during 2006 October; the results were found not to be significantly different from those determined in 1999 and 2001, confirming the ongoing validity of the correction table given in SLRMail 0891. The comparison between HxET and the three Stanfords in use at Herstmonceux (coded SRa, SRb and SRd) is shown graphically in Figure 1. The horizontal axis gives the time delay after which each set of measurement comparisons are made of 'flight time' as recorded by the Stanford counters and by HxET. The vertical axis records the mean difference of each Stanford-recorded flight time from that recorded by HxET. It is noted that SRd, the counter currently in use at the station, exhibits close-to linear behaviour over the entire time-range. Excursions from linearity of up to 100ps (15mm in range) are seen for the other two counters.

New Calibrations

The availability of HxET has meant that more detailed measurements of non linearity effects can be made on the Stanford counters. In particular, we are interested in the behaviour at close ranges, within the first few micro-seconds. Time constraints on our previous experiments with the PPET precluded such a detailed study, and errors in
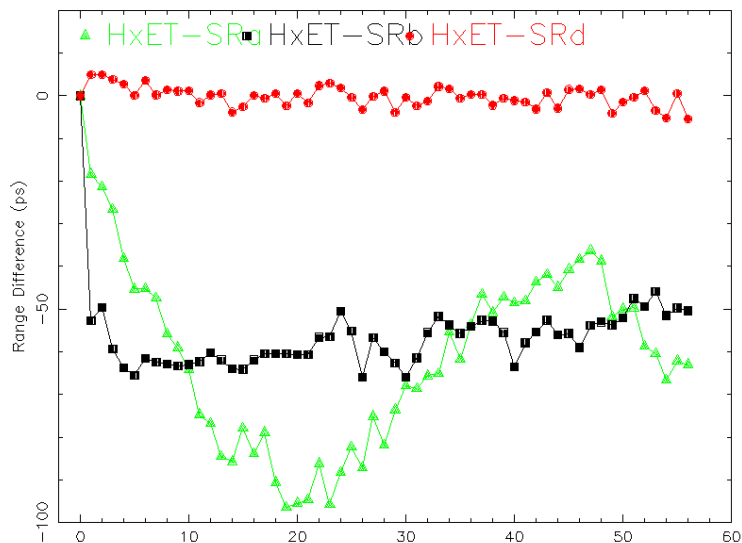
Figure 1 *SGF long-range linearity determination of three Herstmonceux*
Stanford counters relative to the event timer HxET.

this time-region will directly affect calibration ranging results and thus all satellite ranges from the station. We expect some significant effects in this region since the Stanford manual shows both high-frequency periodic signatures and more random departures from linearity in the critical range of about 1micro-second, the distance of the prime SGF calibration target. A figure from the Stanford manual is reproduced here as Figure 2, with the time-range locations of the calibration targets marked. We carried out our tests on the behaviour of SRa, SRb and SRd against HxET in this critical range of from zero to 5µs; the results are shown in Figure 3 below and are to be compared with the Stanford manual results reproduced here in the right-hand plot of Figure 2.

In the range of from zero to 2µs the measured behaviour of our three Stanford counters is close to that expected from the specifications, with maximum departure from linearity of from 50 to 100ps, at a range of 1µs. Beyond a range of 2µs, the behaviour of the counters diverges. A probable explanation for the inter-counter scatter evident in these results is the high-frequency periodic structure shown in the
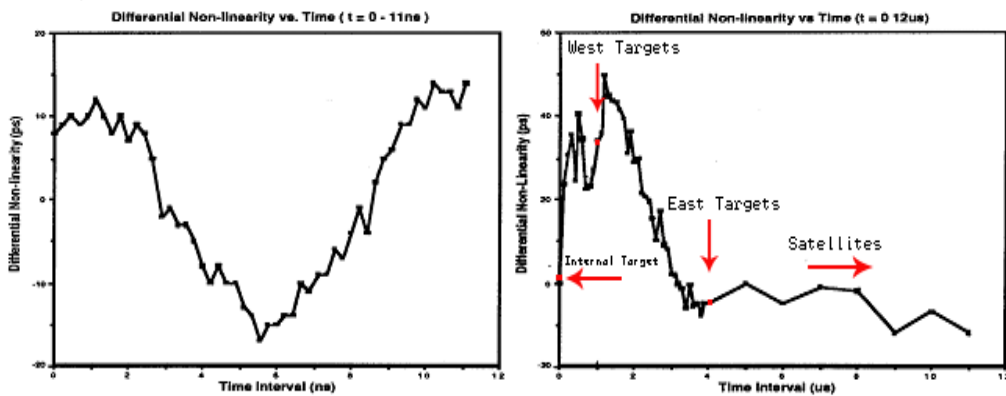
Figure 2 *Short-range non-linearity of Stanford counters as given in specification*

specification (Figure 2, left-hand plot) and in our high-resolution results shown in Figure 4 where we find 22ns periodic effects (cf 11ns expected from specifications) of amplitudes up to 20ps (~3mm). This final result places a limit to the accuracy with which we will be able to determine corrections to range measurements made with the Stanford counters.
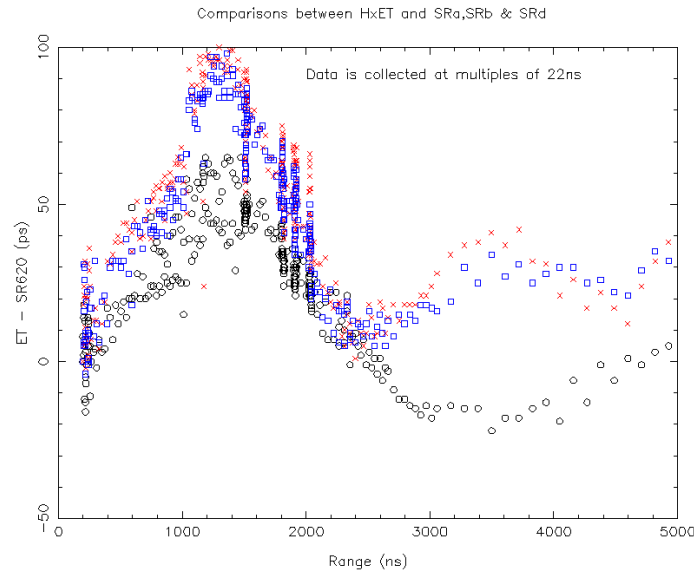

Figure 3 *SGF close-range linearity determinations of three Herstmonceux Stanford counters relative to the event timer HxET.*

In summary, at the effective range of the SGF primary calibration target (890-930ps, dependent on electronic set-up), the non-linearity of the counters imparts an average of ~50ps error into the observed range; this value is dependent on the range itself and the uncertainty of the value is ~20ps due to the observed 22ns periodicity in the non-linearity function.

Effect on LAGEOS data 1994-2006

We have taken from Figure 3 the results for the appropriate counter and also recovered the actual calibration range as given in the ILRS normal point header of
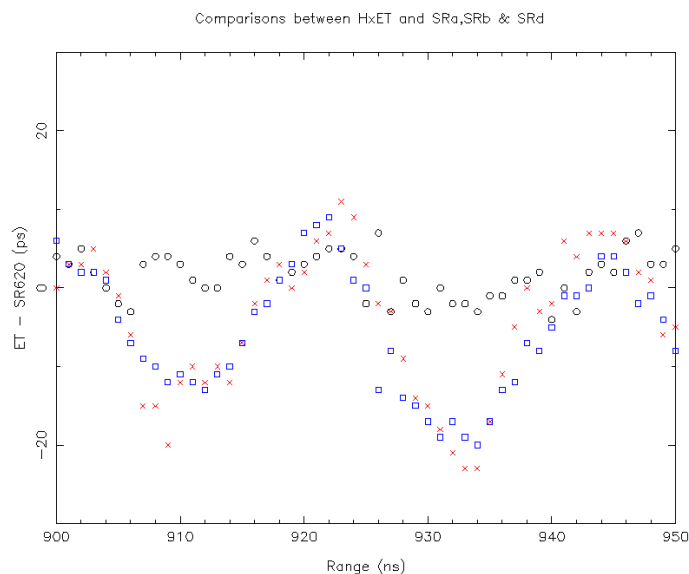

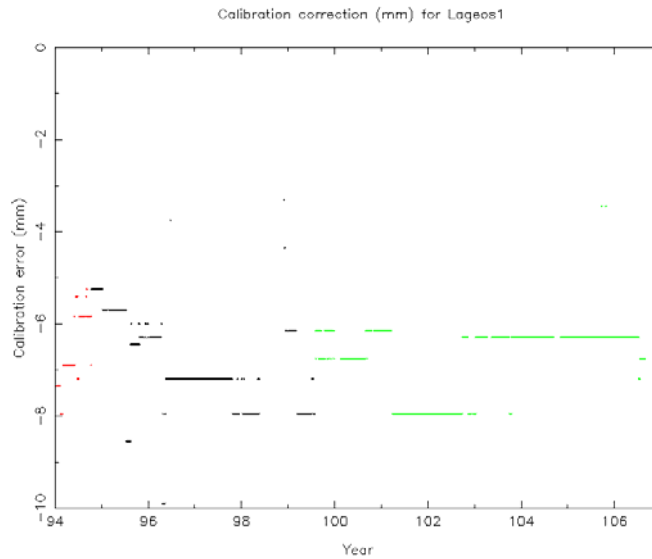***Figure 4*** *Observed periodic behaviour in Stanford counters' error functions.*

Figure 5 *Correction to calibration values used for LAGEOS during 1994-2006*

SGF LAGEOS data for the period 1994-2006. From these values we have estimated the corrections in mm to be applied to our calibrations taken over that period.The results are displayed in Figure 5, where it is apparent that errors of between 5 and 8mm have been made to the calibration values. However, given our estimate of the uncertainty of these average values, we finally derive an average calibration error of 7±2 mm, and in the sense that the calibration correction is too large by that amount. During this re-assessment we also discovered that no account had been taken for the effect on total delay of a glass neutral density filter that is placed in the optical path during calibration but not during satellite ranging. This correction amounts to 1.5mm, again in the sense that the calibration correction derived from target-board ranging is too long. Therefore our calibration corrections in the period 1994-date are too long by 8.5±2 mm and thus calibrated satellite ranges short by the same amount. This correction, which affects all satellite data equally, is of course in addition to the range-dependent correction discussed under 'previous calibrations' above and announced for the period 1994 October to 2002 January in SLRMail 0891 in 2002 January.

Assuming that the corrections presented in SLRMail 0891 have been made to the Herstmonceux ranges, it is interesting to look at the implications for and evidence in geodetic solutions of this newly-discovered correction of 8.5±2 mm. The centre-of-mass (CoM) correction for LAGEOS for 7840 Herstmonceux single photon data is 245 ± 1mm (Otsubo and Appleby, 2003). However, in computing ITRF2000, the Analysis Centres used the 'standard' 251mm CoM for all stations, thus effectively *increasing* Herstmonceux ranges by 6mm and nearly cancelling the bias of -8.5mm present since 1994. Thus the coordinates (height) of Herstmonceux in ITRF2000 should have only a small bias from the true value, given that a range bias (RB) affects primarily the solution for height. Indeed, the mean of Herstmonceux LAGEOS 1/2 residuals in our daily QC based on fixed ITRF2000 coordinates is currently -11 ± 2mm, close to the expected bias of -8.5mm. Thus it appears that the coordinates have not absorbed the range error and the full range bias remains. Further evidence comes from an analysis of LAGEOS 1/2 data between 1992 and 2006, where J Ries (personal communication, April 2006) finds a range bias of -10 to -12mm and a height change of ~7mm; from an analysis of LAGEOS 1/2 data in the period from 2001-

2005, Otsubo, Appleby, Gotoh and Kubooka (2006) find a range bias of -9mm, and a similar value for Etalon data.

For the ILRS combined product included in ITRF2005, the individual Analysis Centres used the correct value of 245mm for Herstmonceux's LAGEOS CoM, and did not solve for a bias for this station (AWG resolution at ILRS Fall Meeting, Eastbourne 2005). Thus it is likely that in particular station height will be in error in the ITRF2005. To test this, we apply the +8.5 mm range correction to LAGEOS 1/2 data for 2004, and solve simultaneously for correction to station coordinates as given in ITRF2005, and a range bias for 7840 Herstmonceux. On average, we find RB = +1 ± 2 mm and ΔH = -5 ± 1 mm, implying that station height in ITRF2005 had absorbed half the RB and is in error by +5mm.

Conclusion

All range data from 7840 Herstmonceux will from early 2007 be determined using HxET and will then be free of systematic error greater than 1 or 2mm. An SLRMail will announce the date and confirm that 8.5 mm should be *added* to all Herstmonceux satellite ranges from 1994 to that date, and re-iterate that the range dependent corrections given in SLRMail 0891 should also be applied for the period 1994 October to 2002 January. As a consequence of these counter problems, we estimate that the station height for 7840 Herstmonceux as given in ITRF2005 is approximately 5mm too large. We regret this long-term error that affects all laser data from Herstmonceux and encourage other stations, mostly among the EUROLAS sub-network, that use or have used Stanford counters, to investigate possible similar effects in their data. To this end, we will work with the ILRS Network and Engineering and Signal Processing Working Groups to calibrate the counters of all stations that are interested in collaboration.

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The Global SLR Network and the Origin and Scale of the TRF in the GGOS Era

E. C. Pavlis[1]

1. Joint Center for Earth Systems Technology (JCET), UMBC, Baltimore, MD, USA.

Contact: epavlis@umbc.edu / Fax: +1 410 455 5868

Abstract

Satellite Laser Ranging (SLR) data contribute to the realization of the Terrestrial Reference Frame (TRF), defining primarily its origin—geocenter, and in combination with VLBI, its scale. Both entities are fundamental in monitoring vital global change parameters, such as mean sea level, Earth rotation and orientation, etc. The Global Geodetic Observing System (GGOS), places the utmost importance on the development, maintenance and wide distribution of a TRF with very stringent attributes, an origin definition at 1 mm or better at epoch and a temporal stability of 1 mm/y, with similar numbers for the scale and orientation components. The stability, integrity and applicability of the TRF are directly related to the accuracy and fidelity with which mass redistribution can be observed or modeled during its development. Variations in the very low degree and order harmonics, produce geometric effects that are manifested as changes in the origin and orientation relationship between the instantaneous and the mean reference frame.

The unambiguous nature of SLR measurements and absence of significant biases, results in a very precise height determination, and thus the scale of the TRF. SLR has demonstrated millimeter level accuracy for weekly averages. Nevertheless, weather- or failure-induced changes in the network, and the small number and poor spatial distribution of the sites comprising the SLR network, generate additional signals aliased in the results. "Secular trends" seen in the recovered geocenter time series for example cannot be explained by any geophysical phenomena, and are primarily the result of these deficiencies of the present SLR network (poor geometry, lack of redundancy, N-S hemisphere unbalanced distribution, etc.). We investigate here through a number of alternate solutions the robustness of our results, using our SLR analyses spanning the past thirteen years.

Introduction

The Global Geodetic Observing System (GGOS), places the utmost importance on the development, maintenance and wide distribution of an International Terrestrial Reference Frame (ITRF) with very stringent attributes, an origin definition at 1 mm or better at epoch and a temporal stability of 1 mm/y, with similar numbers for the scale and orientation components (Pearlman et al., 2006). The stability, integrity and applicability of the TRF are directly related to the accuracy and fidelity with which mass redistribution can be observed or modelled during its development. Satellite Laser Ranging (SLR) data contribute to the realization of the Terrestrial Reference Frame (TRF), defining primarily its origin—geocenter, and in combination with VLBI, its scale. Both entities are fundamental in monitoring vital global change parameters, such as mean sea level, Earth rotation and orientation, etc., (Altamimi *et al.*, 2002). The motivation behind this contribution was to examine the robustness of the ILRS (Pearlman *et al.,* 2002) contribution to the ITRF in light of the forthcoming developments under GGOS and NASA's effort to upgrade and integrate the space geodetic networks of the future.
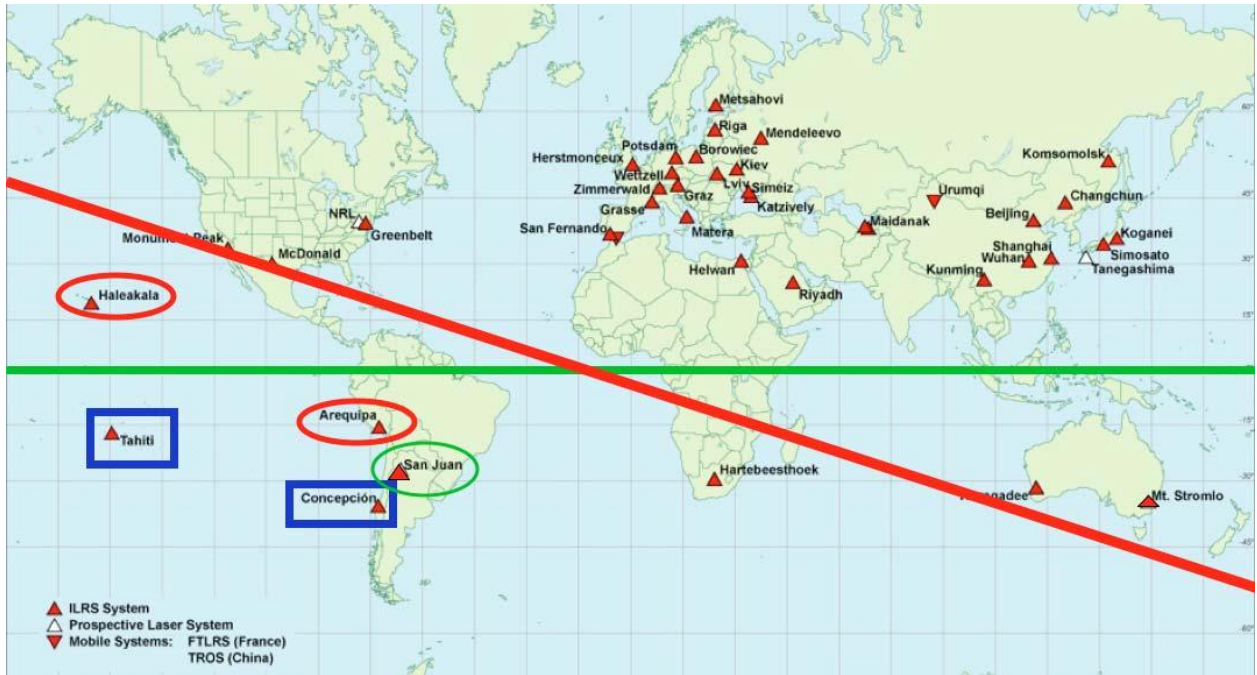
Figure 1*. The current ILRS network with mark-ups of sites that were recently established (green), poor-yield southern hemisphere sites (blue),and sites that were shut down in 2004 (red).*

SLR contribution to ITRF

The SLR network never achieved an optimal, uniform distribution of stations globally (Figure 1). Furthermore, the closing of two key-sites, Arequipa, Peru and Haleakala, Hawaii in 2004 led to a disastrous lopsided distribution, where one-half the globe is totally void of any SLR observations! This eventually manifested itself in the SLR products as a serious and systematic degradation of the network scale as realized through the SLR observations. Aside from this recent degradation (which is addressed with the re-establishment of the closed down sites and improved performance for the others), this network has produced valuable TRF contributions over the decades. ITRF2000, (Altamimi et al., 2002), was a product that for the first time included a vast number of sites around the world and input from all geodetic techniques with rather strict and rigorous editing in its development. Weekly "geocenter" monitoring with respect to that frame yields a significant and systematic motion in the z-axis, at a rate of ~ 1.7 ± 0.1 mm/yr! Most of this is eliminated in the new realization ITRF2005, but not all. In particular, our SSC (JCET) L 06 analysis resulted in the following rates for the three axes:

$$\Delta x = -6.55 - 0.0848 \times (t\text{-}2000) + periodic\ terms \qquad [mm]$$

$$\Delta y = 4.99 - 0.0898 \times (t\text{-}2000) + periodic\ terms \qquad [mm]$$

$$\Delta z = 0.91 + 1.6981 \times (t\text{-}2000) + periodic\ terms \qquad [mm]$$

The formal accuracy of these estimates is at 0.1 mm/y, however, without an independent estimate to compare, we have no sound way to calibrate this error. Interpreting these signals is even more difficult, since they can be caused by a number of different geophysical phenomena, none of which is easily or fully understood. Table 1 gives some estimates due the main sources that could cause such a systematic signal. It's worth noting that recently, Peltier (private communication), has been able to develop models

for Greenland and Antarctica melting in recent times that support this level of "geocenter" motion, especially in the axial component.

Table 1. Secular geophysical signals in the axial component of the "geocenter".

Source	Magnitude	Induced motion	Reference
Sea level	1.2 mm/y	0.064 ± 0.02 mm/y	[2]
Ice sheets (G)	2 mm/y	0.046 ± 0.20 mm/y	[2]
Tectonics	AMO-	0.309 ± 0.05 mm/y	[2]
Postglacial rebound	ICE-3G	0.2 - 0.5 mm/y	[1]

(1) Marianne Greff-Lefftz (2000)
(2) Yu. Barkin (1997)

Methodology

Our conjecture is that the remaining unaccounted-for motion is due to the evolving network, the uneven global distribution of the tracking sites with strong yields, and the poor coverage of some of the major tectonic plates. To test the effect of the "network evolution" we have performed a number of re-analyses of the data, defining TRFs from independent sub-sets of the data in various combinations. As for the effect of the lopsided distribution of the main tracking sites, a large-scale simulation is in progress, within a technique-wide coordinated effort to design the optimal space geodetic networks of the future. The initial results of this investigation will be available by late 2007. A third test involves the so-called effect of the "missing" historical SLR data, i.e. SLR data to LAGEOS prior to 1992. ITRF2000 contained that data, while ITRF2005 does not, due to its tight and firm release schedule. We have generated a TRF that includes the data obtained from LAGEOS since 1976. A comparison of this TRF to a similar one that does not include that data and spans exactly the same period with ITRF2005, should give some idea of whether the missing data contribute to the z-axis secular evolution or the scale difference observed between the SLR and VLBI contributions to ITRF2005.

The effect of the "missing" historical SLR data on the SLR-definition of the scale

To test whether the addition of the "historical" LAGEOS data (1976 to 1992) to the definition of the TRF would eliminate the differences seen between the ITRF2000 and ITRF2005 realizations, we simply reduced that data and added them to the 1993 – 2005 data, generating a new TRF and comparing that through a 14-parameter similarity transformation to the two realizations, ITRF2000 and ITRF2005. The results are tabulated in Table 2.

Our solution is identical to neither ITRF2000 nor ITRF2005, although very close to both. This is expected of course since this is a SLR-only TRF and not a combination product with input from other techniques. Examining the differences in the scale and its rate, we notice that in the case of ITRF2000, our TRF indicates the same level of disagreement as it was originally seen between the SLR-only contributed inputs to this model. Similarly, we see the same for ITRF2005, and the combined difference is exactly what is seen when comparing one ITRF to the other. The fact that a TRF that contains the historical LAGEOS data shows similar differences to the ITRF2005 as does the one without that

data, indicates strongly that the lack of that data cannot be the main reason of the observed differences.

***Table 2**. Similarity transformation parameters between SSC (JCET) L 06 and ITRF realizations.*

Parameter	SSC (JCET) L 06.97 vs. ITRF2000	SSC (JCET) L 06.97 vs. ITRF2005
D_x	-8.82 +/- 1.02 [mm]	1.25 +/- 0.91 [mm]
D_y	3.21 +/- 1.01 [mm]	8.37 +/- 0.91 [mm]
D_z	-5.65 +/- 0.95 [mm]	-6.59 +/- 0.86 [mm]
D_s	**0.52 +/- 0.15 [ppb]**	**-0.87 +/- 0.13 [ppb]**
R_x	-0.24 +/- 0.04 [mas]	0.05 +/- 0.04 [mas]
R_y	0.06 +/- 0.04 [mas]	-0.07 +/- 0.04 [mas]
R_z	0.15 +/- 0.03 [mas]	0.32 +/- 0.03 [mas]
$D_{x\text{-}dot}$	0.75 +/- 0.95 [mm/y]	-1.22 +/- 0.85 [mm/y]
$D_{y\text{-}dot}$	0.56 +/- 0.94 [mm/y]	1.37 +/- 0.85 [mm/y]
$D_{z\text{-}dot}$	3.10 +/- 0.73 [mm/y]	1.89 +/- 0.65 [mm/y]
$D_{s\text{-}dot}$	**-0.10 +/- 0.14 [ppb/y]**	**0.05 +/- 0.12 [ppb/y]**
$R_{x\text{-}dot}$	0.12 +/- 0.03 [mas/y]	0.12 +/- 0.03 [mas/y]
$R_{y\text{-}dot}$	-0.02 +/- 0.03 [mas/y]	0.02 +/- 0.03 [mas/y]
$R_{z\text{-}dot}$	0.02 +/- 0.03 [mas/y]	0.01 +/- 0.03 [mas/y]

In addition to the 'geometric' test of the scale implied by different spans of SLR data, we have also examined the dynamic definition of the scale, through the estimation of the GM_E constant from the different data sets. The SLR technique obtains the definition of the scale from the adopted speed of light in vacuum, v_c, however, because it involves satellite orbits, this scale should also be consistent with the size of the orbit as it is constrained by Kepler's third law. With v_c fixed, we can monitor any changes in the intrinsic SLR scale through the estimation of GM_E. The historical data were reduced in three different ways (arc-lengths), in order to verify that this is also not a factor in the development of the TRF: fortnightly (F), monthly (M), and quarterly (Q) arcs. With each expansion of the arc-length, any unaccounted systematic errors in the description of the site-motions is smoothed out by averaging, since more data from other, non-affected sites contribute to the definition of the TRF over that interval of time. Table 3 indicates that a comparison of the GM_E estimates from these solutions to the value that we obtain from the weekly-arc (W) analysis for the 1993- 2005 period, shows no systematic difference, and certainly no scale change larger than the calibrated uncertainty of the estimates.

***Table 3**. GM_E estimates from two SLR data spans: 1993 – 2005 and 1976 – 2005.*

Source of displayed GM_E	Value of GM_E
IERS Conventions 2003	398600.441500 x 10^9 [m^3/s^2]
SSC (JCET) L 06 W 1993 - 2005	398600.441659 x 10^9 [m^3/s^2]
SSC (JCET) L 06 F 1976 - 2005	398600.441634 x 10^9 [m^3/s^2]
SSC (JCET) L 06 M 1976 - 2005	398600.441633 x 10^9 [m^3/s^2]
SSC (JCET) L 06 Q 1976 - 2005	398600.441633 x 10^9 [m^3/s^2]

We can reach two main conclusions from the above table: (a) the effect of the historical data in the intrinsic definition of the scale in SLR is at most at the level of 0.1 ppb, and (b) the effect of the arc-length used in the reduction of the data on the scale is even less significant, less than 0.002 ppb. A calibrated estimate of the accuracy of these estimates at the 99% level of confidence is 0.2 ppb or approximately 1.3 mm.

Subset solution results

We investigated the effect of the "evolution of the network" with the development of a number of TRFs from independent sub-sets of the data in various combinations (Figure 2). With only some thirteen years of data to work with, we went as far as ¼ of the data, i.e. the smallest set of data spanned just over three years. This seemed to be marginally acceptable for a quality TRF, with six years being a comfortable minimum for a robust TRF product (specially for velocity estimates). We have two strategies in forming these subsets: (i) using similar amounts of data spanning the same period of time, and (ii) using the same amounts of data sampling totally different time periods. In the first case for example, we used ¼ of the data to generate four different TRFs, each based on the weeks that span the same time-period, every subset formed by choosing every 4th week from the ensemble of all weeks available. In the second case, we also have four TRFs formed on the basis of approximately ¼ the total data, but in this case we broke up the total interval in four equal-length intervals, so each TRFs is fit to data from a different period of time (and a different network with different conditions and performance).
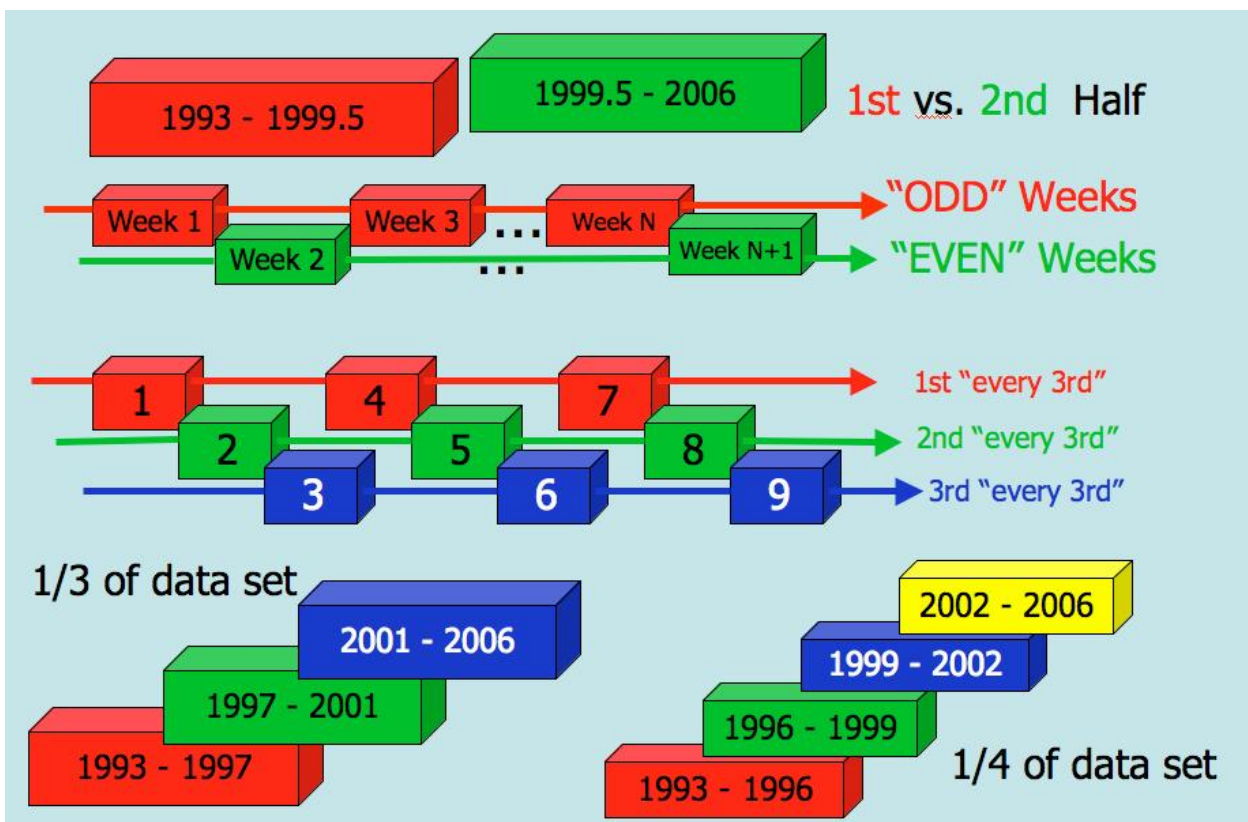
Figure 2*. The four groups of subset solutions used in this investigation*

Case	ΔX [mm]	σ_ΔX [mm]	ΔY [mm]	σ_ΔY [mm]	ΔZ [mm]	σ_ΔZ [mm]	3D |Δ| mm	σ_3DΔ mm
3 **Odd**	-8.37	±10.91	19.25	±10.78	-4.20	±10.32	21	± 17
4 **Even**	-12.62	± 8.93	5.15	± 8.82	-12.50	± 8.44	18	± 16
5 **@ 3rd**	-7.92	± 18.84	-3.87	±18.61	3.56	±17.82	10	± 31
6	-7.61	± 8.66	19.78	± 8.56	-15.33	± 8.19	26	± 16
7	-11.36	± 10.41	9.03	±10.28	-11.58	± 9.84	19	± 17
8 **@ 4th**	-15.62	± 21.76	43.27	±21.49	16.57	±20.57	49	± 36
9	-17.75	± 18.87	16.31	±18.63	-29.03	±17.84	38	± 33
10	-6.61	± 17.18	-5.50	±16.97	-11.56	±16.24	14	± 29
11	-16.72	± 12.01	1.32	±11.86	-9.92	±11.36	19	± 21
1 **1/2**	-41.20	±35.82	6.26	±35.38	-10.10	±33.86	43	± 61
2	1.74	± 6.76	8.06	± 6.68	7.28	± 6.39	11	± 11
12 **1/3**	-49.10	± 22.39	52.74	±22.11	2.73	±21.16	72	± 38
13	-3.07	± 8.21	-13.72	± 8.11	5.90	± 7.76	15	± 14
14	-16.95	± 14.20	5.72	±14.06	4.28	±13.40	18	± 24
15 **1/4**	-60.49	± 23.68	57.43	±23.39	7.48	±22.39	84	± 40
16	18.65	± 31.40	-57.81	±30.88	-6.19	±29.50	61	± 53
17	-0.27	± 18.01	-4.74	±17.79	15.72	±17.03	16	± 31
18	2.07	± 12.29	7.16	±12.18	1.73	±11.60	8	± 21

Figure 3. *The four groups of subset solutions used in this investigation*
(top cases: same time-span, and bottom cases: disjoint time intervals).

We will limit the discussion of our conclusions to two items of importance to the ITRF: the definition of its origin and its axial rate. The results are summarized in Fig. 3, in terms of the differences in each component Δx, Δy, and Δz, with respect to the solution obtained from the entire set of data. In order to facilitate their comparison we also formed a figure of merit, defined as the 3D positional difference, and formed as:

$$\Delta = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}.$$

We can draw several conclusions from this table:

- On average, each component is not determined to better than 6-8 mm (depends on time period)
- The 1993 to present data set is significantly non-uniform due to various factors
- There is a steady improvement over the years, however, we can see even 10-fold differences between different time-periods
- With the caveat that our calibrated error estimates are sufficiently realistic, and assuming that the second half of the 1993-2005 period is more representative of current network performance, we conclude that for a reliable definition of the origin of the TRF we need a data spanning more than ~6-7 years.
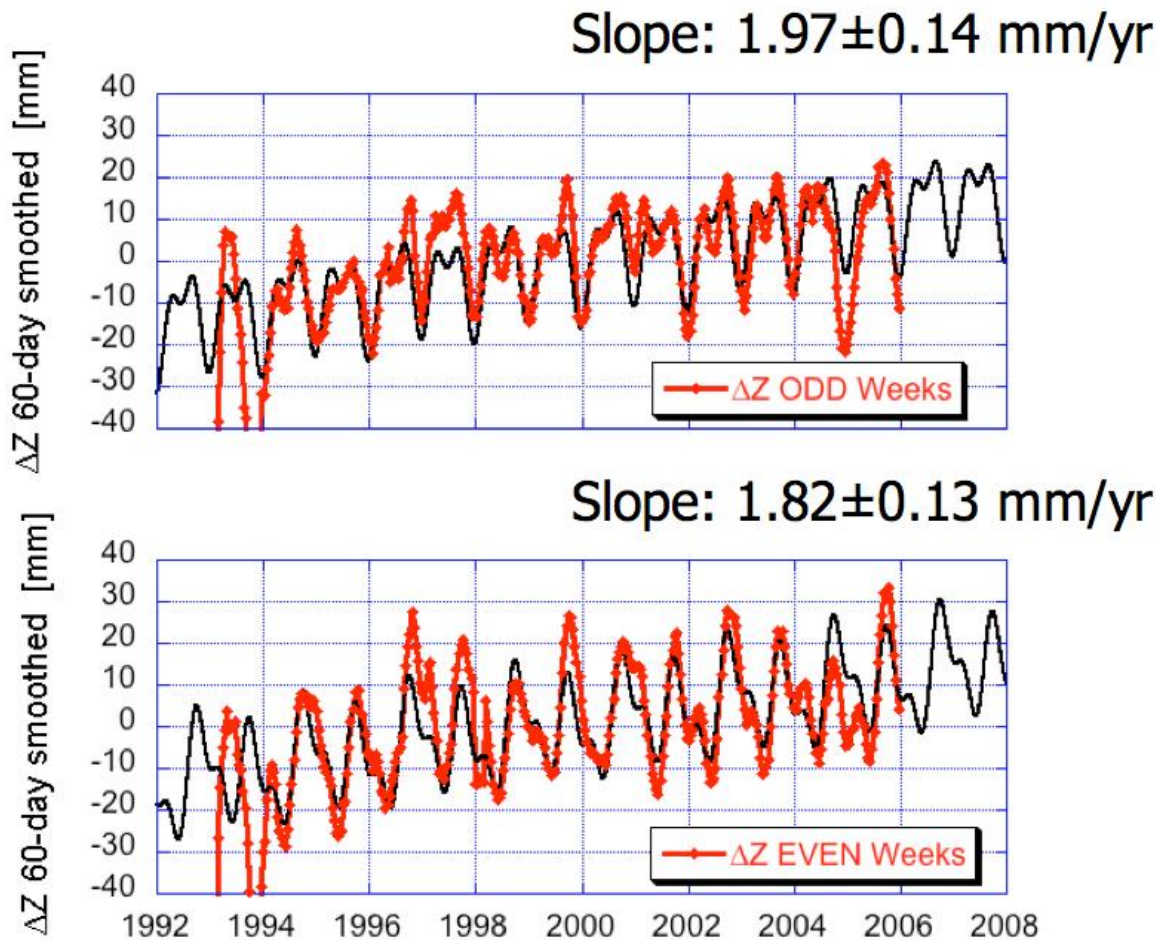
Figure 4*. The time series of Δz (axial component of geocenter) from two independent subset solutions, each spanning the period 1993-2005.*

With each subset solution we also obtained a time series of the weekly variations of the origin with respect to the geocenter. These were analyzed in a similar manner to the origin components themselves, i.e., in comparison to the series we obtain from our ensemble solution that spans the entire time period. The axial component is the only one that shows a significant secular trend, so we will use that in our example. Figure 4 gives an example of the recovered series and their fit to a model that includes a linear trend and three periodic terms, for the two subsets formed from the selection of the "even" and "odd" weeks (i.e. every other week used). The two subsets span the same time period with just one week "offset", but each set has about half the data of the entire data set. It is apparent from these two cases that the secular trend recovered here is statistically insignificantly different from what we obtained from the entire data set (cf. ~1.7 ± 0.1 mm/y). There are differences though in the periodic components' (not magnitude) and when we compare the results from subsets that span even smaller spans of data (less than half), then even the secular trend is not recovered correctly (sometimes we even get sign-reversals!). These observations lead us to the following conclusions:

- Secular trends from same size data span agree to 7-10%
- Secular trends from spans smaller than ~7 years and different periods of time can differ up to 100%, indicating a highly non-stable network (shape, performance or a combination of both)
- The magnitude of the seasonal variations is stable when recovered from various subsets of the entire data set, but the phases seem to be sensitive to

that choice

- For the robust definition of secular trends and seasonal variations simultaneously, it is recommended that more than a decade of data (preferably from a stable network) be used.

Summary and future plans

This study investigated the robustness of the definition of the origin and scale of the TRF from SLR data (only) and with the LAGEOS and LAGEOS 2 data available over the period 1993 to 2005. The conclusions we reached are that these data define the origin at epoch to no better than 10 mm. The monitoring of the secular motion of the origin depends strongly on the network evolution and its performance. For a robust estimate of temporal variations of the geocenter we need data sets that span a decade or more, with a stable network. In such cases, the secular trends can be estimated with an accuracy of about 10%.

For a complete rationalization of the observed error signatures and the performance of future networks, we need a set of very carefully controlled simulations (underway). Extension of this simulation to include the other techniques will give us the advantage to "negotiate" trade-offs between the techniques, since they all act in a complementary manner in the definition of the ITRF. This will allow better use of the available resources and full exploitation of the benefits from each technique.

References

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FTLRS Ajaccio campaigns : operations and positioning analysis over 2002/2005

F. Pierron[1], B.Gourine[2], P.Exertier[1], P.Berio[1], P.Exertier[1], P. Bonnefond[1], D.Coulot[3] and the Grasse/Ftlrs laser staff

1. Observatoire de la Côte d'Azur, GEMINI/UMR 6203-CNRS, Av N. Copernic, 06130 Grasse, France.

2. Centre National des Techniques Spatiales à Arzew (CNTS), Algeria

3. IGN, ENSG/LAREG, 6 et 8 Avenue Blaise Pascal, Cité Descartes, Champs-sur-Marne, 77455, France

Abstract

In the framework of JASON-1 project especially for Cal/Val aspects, Ftlrs has been deployed in Ajaccio for a six months campaign in 2005.

In the continuation of previous operations on the same site in 2002 the observations programs were carefully tuned to be pertinent on both aspects of scientific goals with new tools to optimize sky coverage for the data and technological issues like maintenance and operational costs.

In this paper, we'll present reports and results concerning station positioning with a very interesting combination of LAGEOS -1, -2, STELLA, and STARLETTE observations and comparison over 2002 and 2005 campaigns. An estimation of final accuracy will be discussed in such experiments of multi occupation site and operational issues will be commented.

1. Introduction and Operational issues for Corsica campaigns

The Ajaccio site is the main calibration site of the satellite altimeters in the Mediterranean area

Typical setup of the station (Corsica 2002 and 2005)

The SLR technique is the major contributor to the altimeter calibration: SLR data of the whole network are used to derive ultra precise orbit of altimeter satellites (in combination with DORIS and GPS data) and FTLRS conducts comparative laser distance measurements between the facility and satellite radar altimeters.

The objectives are the following :

- Absolute Sea level monitoring, altimeter calibration and orbit validation (CAL/VAL) of the Topex/Poseidon, Jason-1 and Envisat satellites from the Ajaccio site (Corsica-France)
- Estimation of the satellite altimeters biases and drifts

- Need for carrying out accurate SLR positioning from geodetic satellites observations

The FTLRS is a highly mobile Satellite Laser Ranging (SLR) system dedicated to the tracking of geodetic satellites equipped with retroreflectors. This instrument was developed by the Observatoire de la Côte d'Azur (OCA) and the Centre National d'Etudes Spatiales (CNES) in collaboration with the Institut National des Sciences de l'Univers (INSU) and the Institut Géographique National (IGN)

For these campaigns, Ftlrs system is deployed inside a French naval base near Ajaccio on a hill, close the sea and at some thirty kilometer from Senetosa Cape where are installed tide gauges and performed GPS buoys experiments near exact calibration point.
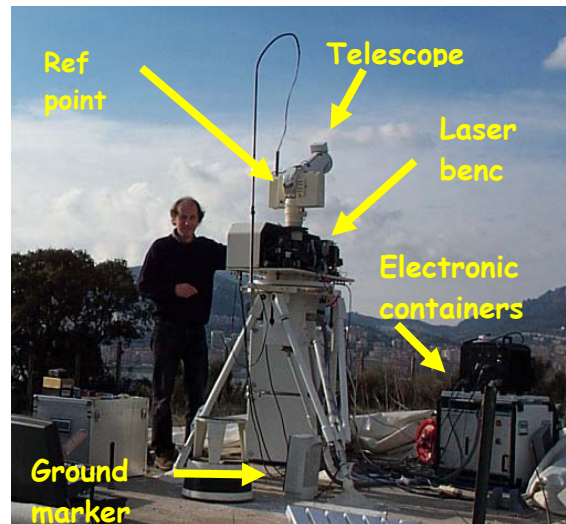
Two major campaigns have been organized at this site: January-September 2002 for 10 months and May-October 2005 for 5 months.

2. Jason1 absolute calibration/validation configuration :

- A geodetic site at Ajaccio with FTLRS settled for some months.
- An in-situ site at Senetosa cape under the track N°85.

Products used for the study:
- **T/P: M-GDR + TMR drift**
- **Jason-1: GDR**

Definition of altimeter bias calibration:
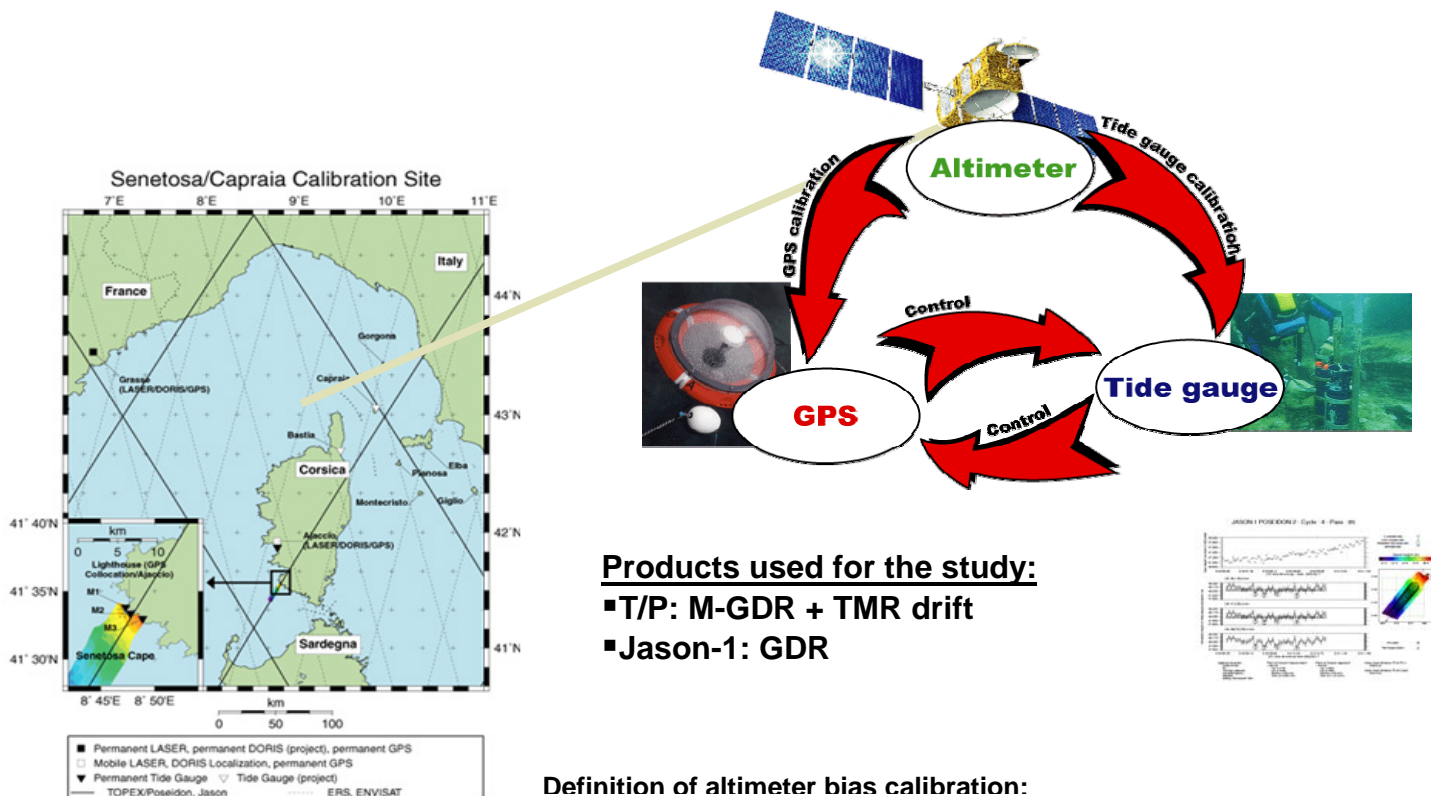
sea height bias = altimeter sea height - in situ sea height

Sea height bias < 0 meaning the altimetric sea height being too low (or the altimeter measuring too long)
Sea height bias > 0 meaning the altimetric sea height being too high (or the altimeter measuring too short)

The Senetosa site allows performance of altimeter calibration from tide gauges as well as from a GPS buoy.

At Senetosa POSEIDON-2 altimeter bias is +100 ±4 mm, based on the whole set of GDR-A products (135 cycles).

The large negative trend is due to JMR (Wet Troposphere) in GDR-A and has been solved in recent analysis works

Jason-1 Altimeter Calibration
Cape Senetosa: POSEIDON-2, GDR, CNES Orbit
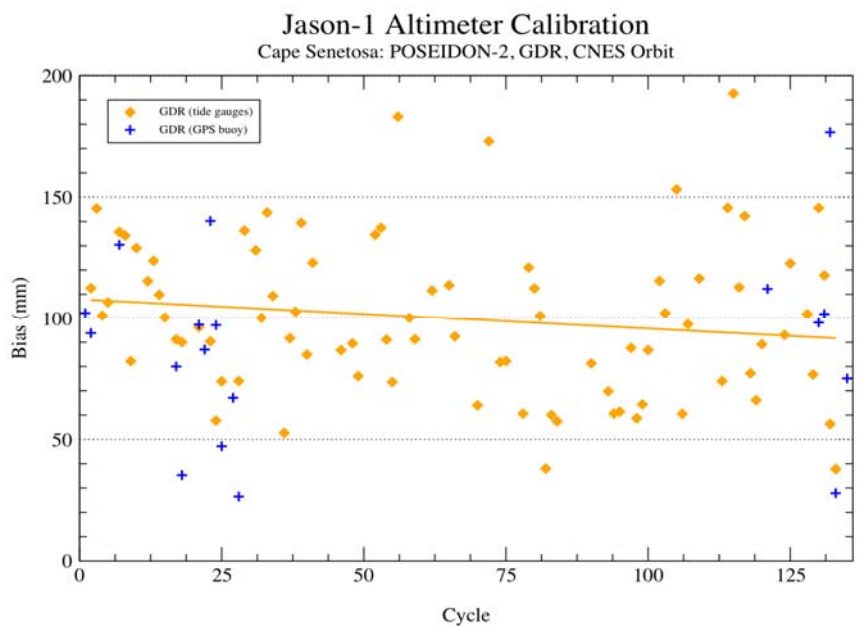
3. Scientific investigation for Positioning

➢ **Positioning with 4 geodetic satellites**

Lageos-1   **Starlette**
Lageos-2   **Stella**

➢ **Goals of this positioning :**

-To maintain geodetic accuracy of the FTLRS position in Ajaccio site (Corsica) between the two campaigns

-To provide high accuracy local orbits for the Jason-1 altimeter calibration

➢ **Main steps of the work methodology**

-Orbit computation
-Positioning of the FTLRS Station with Multi satellite combination.

Npts data on the sky for 2005 campaign :

• High Elevation Orbiting Satellites:
Few measurements on Lageos satellites, particularly at low elevation (40°), and irregular distribution of these data over the Ajaccio site

• Low Elevation Orbiting Satellites:
Ten times more range data on Starlette/stella relative to Lageos, and homogeneous distribution of the range data over the Ajaccio site

The quality of FTLRS positioning is very dependent on the accuracy of orbits, and Starlette and Stella are more sensitive to remaining uncertainties in the dynamic models (gravitational and non gravitational effects).
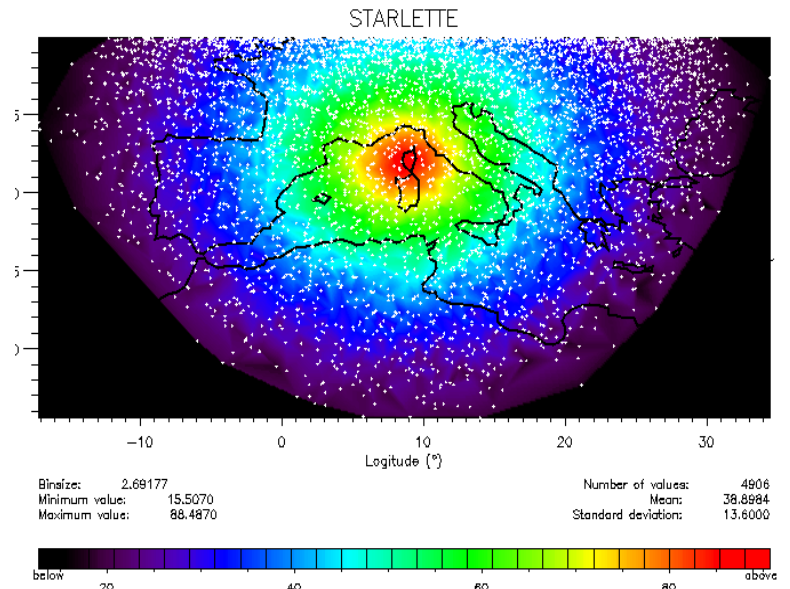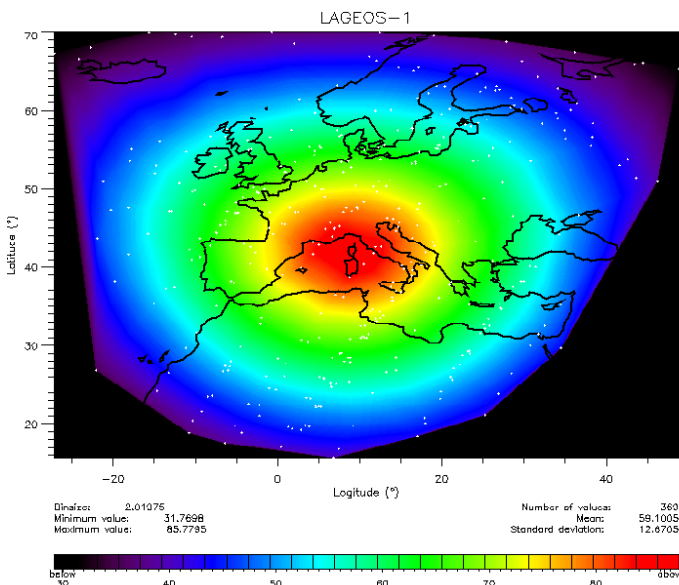
Maps of the range data distribution during the 2005 campaign (05 months) above Ajaccio site

Since few years, thanks to new space mission like Grace, the community got an improvement of the gravity field models. The method in our analysis is to use an accurate field gravity model for the LEO computation and a multi-satellite combination.

A. Parameters for orbit computation :

-Gins software (developed by CNES)

-Dynamical models used :

Model	Designation
Gravity field	*Grim5-c1* or *Eigen-Grace03s*
Atmospheric pressure	*ECMWF*
Solar flow	*Acsol2*
Atmospheric Density	*Dtm-94bis*
Ocean tides	*Fes-2002*
Planets	*De403bdlf.ad.ibm*
Earth Orientation Parameters	*Eop-c04*

-Terrestrial reference frame : ITRF 2000

-**Computation by successive** arcs (9 days for Lageos 1/Lageos 2 and 6,5 days for Starlette/Stella) with overlapping periods (1 day for Lageos 1/2 and 0,75 days for Starlette/Stella) allowing to control the orbits quality of successive arcs and to limit the "butterfly effect" on the arc computation.

-Effect of gravity field model :

On 32 arcs of Starlette/Stella in 2005, it appears that the Mediterranean area is less affected by a permanent effect.

Mean Radial orbit differences (m) geographically correlated of Starlette orbits
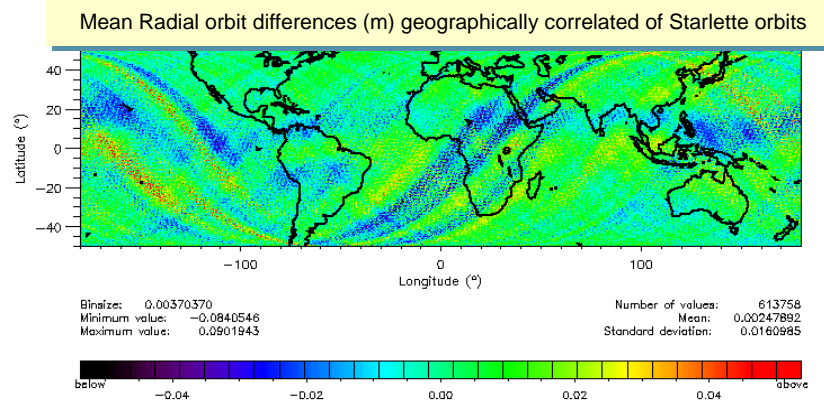
The lageos orbits are more precise and less affected by the change of gravity field model, but for Stella/Starlette, we have an improvement of orbit precision of +/- 5mm with Eigen-Grace03s model.

Satellite	2002 campaign		2005 campaign	
	GRim5-c1	Eigen-Grace03s	Grim5-c1	Eigen-Grace03s
LAGEOS-1	13	-	11	11
LAGEOS-2	10	-	10	09
Starlette	23	18	23	18
Stella	23	19	21	16

B. Positioning of Ftlrs station :
-Matlo Software (developed by OCA) (Coulot 2005)
This software dedicated to laser positioning (coordinates updates+ range bias/satellite) in a multi-satellite combination compute a global solution and Time series solution.

Range bias	B_{LAG-1} (mm)	B_{LAG-2} (mm)	B_{STAR} (mm)	B_{STEL} (mm)
Glob. Sol. (1)	+12.0	+12.2	-3.9	-6.4
Glob. Sol. (2)	+4.8	+4.6	-4.9	-4.9
7d. Sol. (1)	+11.7	+13.8	-4.6	-5.4
7d. Sol. (2)	+4.9	+3.3	-5.6	-4.3

Coordinate updates	$d\varphi$ (mm)	$d\lambda$ (mm)	dh (mm)	$\rho_{dh-Bias}$ (%)
Glob. Sol. (1)	+4.3 ± 0.6	-10.1 ± 0.6	+11.7 ± 1.8	94.4
Glob. Sol. (2)	+4.3 ± 0.5	-3.6 ± 0.4	+3.0 ± 1.4	94.4
7d. Sol. (1)	+4.4 ± 0.6	-8.6 ± 0.5	+13.8 ± 0.6	55.4
7d. Sol. (2)	+4.1 ± 0.4	-2.9 ± 0.4	+4.0 ± 0.4	55.4

The Main objective has been to reduce the correlation between the range bias and the vertical component. To do that, we compared a global solution (with coordinates and range biases estimated with the whole data) and 7 days solution (with bias/sat supposed constant remain estimated with the whole data). In the Global solution, the correlation remains to high between biases and dh, some parts of the bias may move to dh and vice versa.

In the 7 days solution, the correlation decreases significantly (55%), this solution is finally held

C. Results and Analysis: adjusted Ftlrs parameters over 2002 & 2005 campaigns:

with :

-Time series solution

-Eigen-Grace03s model

Coordinate updates	$d\varphi$ (mm)	$d\lambda$ (mm)	dh (mm)	$\rho_{dh-Bias}$ (%)
2002	-0.8 ± 0.7	+1.6 ± 0.7	+0.2 ± 0.8	55.8
2005	+4.1 ± 0.4	-2.9 ± 0.4	+4.0 ± 0.4	55.4

	Lageos-1 (mm)	Lageos-2 (mm)	Mean Lageos-1&2 (mm)	Starlette (mm)	Stella (mm)	Mean Starlette/Stella (mm)	Global mean (mm)
2002	-5	-7	-6	-13	-13	-13	-10
2005	+5	+3	+4	-5	-5	-5	0

- **The difference between Lageos and Starlette/stella biases** are probably coming from satellite signature and Ftlrs detection process.

- **adjusted values of Ftlrs range bias in 2002 campaign of -10 mm explained a posteriori:**
  - o Non linearity of Stanford chronometer not modelised at this epoch : -4.2 mm
  - o Geometrical path for external calibration not adjusted : - 3mm
  - ▪ **Total : 7.2mm**

- **The adjusted values of Ftlrs mean range bias for last campaign 2005 is very small and confirm agreement between analysis and technological corrections applied (Stanford non linearity, ground target measurements,..)**

D. Solved coordinates

<table>
<tr><td rowspan="2">**Coordinates differences**</td><td>$\Delta\varphi$</td><td>$\Delta\lambda$</td><td>Δh</td></tr>
<tr><td>(mm)</td><td>(mm)</td><td>(mm)</td></tr>
<tr><td>2002</td><td>$+0.5 \pm 0.7$</td><td>$+2.7 \pm 0.7$</td><td>-1.2 ± 0.8</td></tr>
<tr><td>2005</td><td>$+4.1 \pm 0.4$</td><td>-2.9 ± 0.4</td><td>$+4.0 \pm 0.4$</td></tr>
</table>

Geographical coordinates differences from (Exertier et al., 2004) solution:

Stability :

Campaign	Number of solution	$\sigma\varphi$ (mm)	$\sigma\lambda$ (mm)	σh (mm)	σ (mm)
2002	28	14.6	13.1	10.5	**12.**
2005	20	7.5	12.3	10.5	**10.**

-Global mean of bias (-5mm): very close to the published one (-7mm)

-Coordinate updates values for 2002 and 2005 are at 3mm level in average relatively to previous solution.

-Coordinates differences are very small at level of residuals errors in the ITRF2000 velocities

-No significant differences between 2002 and 2005 coordinates (at level of the tectonic movement): FTLRS point is locally stable.

4. Conclusion and Prospects:

➢ **Multi-satellite combination** has allowed to palliate lack of measurements on high satellites

➢ The improvement of the dynamical models, notably of the terrestrial gravity field (thanks to the GRACE satellite data (*Eigen-Grace03s*) has permitted a precise computation of the orbits, in particular for the low satellites, and so a more precise geographical positioning,

➢ **Interesting decorrelation (~ 40%)** is obtained between the range bias and the station vertical component, using the time series solution (MATLO),

➢ **The station position is stable** between the two observation campaigns,

➢ In conclusion, the FTLRS has allowed a **precise terrestrial positioning**. That confirms its importance for the absolute calibration process of oceanographic satellites.

SLR-Based Evaluation and Validation Studies of Candidate ITRF2005 Products

Erricos C. Pavlis[1,2], M. Kuzmicz-Cieslak[1] and D. E. Pavlis[3,2]

1. Joint Center for Earth Systems Technology (JCET), Univ. of Maryland Baltimore County, Baltimore, MD, USA

2. NASA Goddard Space Flight Center

3. SGT, Inc.

Contact: epavlis@umbc.edu / Fax: +1 410 455 5868

Abstract

The recent release of candidate solutions for adoption of the new ITRF2005 International Terrestrial Reference Frame (ITRF) initiated numerous tests and comparisons over the past months. This presentation focuses on the evaluation tests we performed with the ITRF2005P and ITRF2005D products, primarily with Satellite Laser Ranging (SLR) tracking data. Since over two decades now, SLR tracking data contribute to the definition of the TRF, primarily in defining its origin and scale. LAGEOS 1 and 2 are the main targets contributing to this, and we use their data, as well as a limited number of independent data to gauge the improvement gained by going from ITRF2000 to either of the two new candidate solutions. An easy and immediate observation is that either of them is only slightly different from ITRF2000, in contrast to what was observed during the release of ITRF2000. This seems natural though, since ITRF2000 dealt with many problems observed with its predecessor and used a uniformly high quality input from nearly all techniques. We concentrate here on the differences between the two and the impact of such factors as the improvements in the analysis methodology, the underlying models, the use of IERS Conventions 2003, and the latest improvements in modelling SLR observations.

Introduction

Since over two decades now, SLR tracking data contribute to the development of the ITRF, primarily in defining its origin and scale. The release of ITRF2000 in 2001 ushered a new era of TRF quality and performance (Altamimi *et al.*, 2002). The recent (mid-2006) release of candidate solutions for adoption of the new ITRF2005 initiated numerous tests and comparisons over the past months. This presentation focuses on the evaluation tests we performed with the ITRF2005P (from IGN) and ITRF2005D (from DGFI) products, primarily with SLR tracking data. In contrast to what was experienced during the release of ITRF2000, the release of the new models did not bring about order-of-magnitude changes, but rather small adjustments and corrections, either for sites that appeared 'after' the release of ITRF2000 or whose ITRF2000 estimates were based on too limited a set of data for meaningful results.

Initial tests for Precision Orbit Determination (POD)

As a first test of the two candidate models we looked at their performance on the LAGEOS and LAGEOS 2 data that were used in their development. From the initial tests on ITRF2005P, which was released first in early summer of 2006, it became obvious that the VLBI-consistent scale imposed on this model because of the observed scale discrepancy between SLR and VLBI, led to a TRF with inferior performance even on the SLR data that were used in its development.

When however we applied a scale adjustment to make it consistent with the intrinsic SLR scale or allowed for a scale adjustment in our tests, the two models performed very similarly, and only marginally better than ITRF2000, except for the few sites that either did not appear in ITRF2000 or had poor ITRF2000 estimates (Table 1).

Table 1. *Weekly RMS values from the weekly operational ILRS products in comparison to the old (ITRF2000) and new (ITRF2005P), ITRFs (results courtesy Cecilia Sciarretta/Telespazio, S.p.A.).*

Group RMS [mm]	ITRF2000	ITRF2005	ITRF2000	ITRF2005	ITRF2000	ITRF2005
	June 3, 2006		June 10, 2006		June 17, 2006	
All sites (24)	40	8	36	9	32	9.6
Core sites (16)	13	7	13	8	12	8

Several SLR analysts did similar POD tests and the main conclusion from all of these tests is that the new models perform very similarly, and not much different from ITRF2000, for the well-determined sites common to both TRFs. The POD tests we performed were limited to data from the period 2003 to 2006.5, and only for the sixteen (16) "Core SLR" sites as identified by the ILRS ACs' operational procedures. A summary of the RMS of fit per site for either of the two new models and ITRF2000 are shown in Tables 2 (for LAGEOS) and 3 (for LAGEOS 2).

A quick observation from Tables 2 and 3 is that overall, ITRF2005D performs slightly better than ITRF2005P does, especially in the case of LAGEOS 2. Note that unlike ITRF2005P, ITRF2005D ***does not*** require any adjustment to its scale or scale rate in order to achieve this performance. Despite this fact, absent any substantiated errors in the development of ITRF2005D, and ignoring all official objections by the International Laser Ranging Service (ILRS), (Pearlman *et al*., 2002), the final officially adopted model for ITRF2005 was a slightly modified version of ITRF2005P (without any changes with respect to the SLR-VLBI scale issue).

The scale difference between ITRF2005P and SLR

The scale difference between the new and old ITRF (about 1.4 ppb at 2000.0 or ~10 mm, and -0.15 ppb/y or -1 mm/y), intrigued all SLR analysts involved in the evaluation and validation of the new model. Several theories were formed and tested, all of them quickly eliminated following extensive and copious tests, in most cases cross-checked through repetition by more than one group. We list some of the more plausible ones here.

A possible error in the adopted value of GM_E was quickly discarded, since it would require an unreasonably large $\Delta GM_E \approx 0.0025 \times 10^9$ or an equally unreasonable change in the CoM value for the two LAGEOS (~20 mm). Next, the differences in the submitted SLR contributions to ITRF2000 and ITRF2005 were examined closely. The

Table 2. *LAGEOS POD: Core sites' RMS of fit using ITRF2000,
ITRF2005P and ITRF2005D, and differences. RMS in red (negative)
indicates ITRF2005P performs better than ITRF2005D.*

		ITRF2000 (IGN)		ITRF2005P (IGN)		ITRF2005D (DGFI)	
SITE NAME	**SITE ID**	RMS [mm]	ΔRMS [mm] 2000-2005P	RMS [mm]	RMS [mm] 2005P-2005D	RMS [mm]	ΔRMS [mm] 2000-2005D
BEIJING, PRC	7249	22.41	4.90	17.51	1.10	16.41	6.00
GRASSE, FRANCE	7835	10.45	2.54	7.91	-0.12	8.03	2.42
GFZ POTSDAM, DE	7836	13.11	2.60	10.51	-0.84	11.35	1.76
GRAZ, AUSTRIA	7839	9.46	1.48	7.98	-0.19	8.17	1.29
HALEAKALA, HI	7210	17.87	3.29	14.58	2.50	12.08	5.79
MLRO, MATERA, IT	7941	10.87	2.51	8.36	0.67	7.69	3.18
MLRS, TEXAS, USA	7080	13.54	2.00	11.54	1.11	10.43	3.11
YARRAGADEE, AUSTRALIA	7090	11.33	0.48	10.85	1.02	9.83	1.50
GGAO, WASHINGTON, DC	7105	12.35	1.14	11.21	-1.03	12.24	0.11
MON. PEAK, CA	7110	14.41	1.40	13.01	0.92	12.09	2.32
HARTESBESTHOEK, SA	7501	14.45	4.24	10.21	0.43	9.78	4.67
RGO, ENGLAND	7840	9.77	0.78	8.99	0.60	8.39	1.38
SALRO, SAUDI ARABIA	7832	12.59	2.53	10.06	-0.22	10.28	2.31
SIMOSATO, JAPAN	7837	17.13	2.58	14.55	-0.20	14.75	2.38
ZIMMERWALD, CH	7810	8.97	-0.86	9.83	0.51	9.32	-0.35
WETTZELL, DE	8834	11.36	1.75	9.61	0.34	9.27	2.09

Table 3. *LAGEOS 2 POD: Core sites' RMS of fit using ITRF2000,
ITRF2005P and ITRF2005D, and differences. RMS in red (negative) indicates
ITRF2005P performs better than ITRF2005D*

		ITRF2000 (IGN)		ITRF2005P (IGN)		ITRF2005D (DGFI)	
SITE NAME	**SITE ID**	RMS [mm]	ΔRMS [mm] 2000-2005P	RMS [mm]	ΔRMS [mm] 2005P-2005D	RMS [mm]	ΔRMS [mm] 2000-2005D
BEIJING, PRC	7249	19.11	3.60	15.51	0.89	14.62	4.49
GRASSE, FRANCE	7835	10.58	3.47	7.11	0.34	6.77	3.81
GFZ POTSDAM, DE	7836	11.96	1.23	10.73	0.91	9.82	2.14
GRAZ, AUSTRIA	7839	8.63	1.34	7.29	0.30	6.99	1.64
HALEAKALA, HI	7210	16.33	3.61	12.72	1.68	11.04	5.29
MLRO, MATERA, IT	7941	10.60	2.37	8.23	0.62	7.61	2.99
MLRS, TEXAS, USA	7080	13.21	1.93	11.28	1.32	9.96	3.25
YARRAGADEE, AUSTRALIA	7090	10.87	0.09	10.78	2.22	8.56	2.31
GGAO, WASHINGTON, DC	7105	11.80	1.24	10.56	0.10	10.46	1.34
MON. PEAK, CA	7110	12.73	0.53	12.2	1.33	10.87	1.86
HARTESBESTHOEK, SA	7501	16.53	5.19	11.34	1.33	10.01	6.52
RGO, ENGLAND	7840	8.74	-0.08	8.82	1.15	7.67	1.07
SALRO, SAUDI ARABIA	7832	11.22	1.95	9.27	0.25	9.02	2.20
SIMOSATO, JAPAN	7837	17.35	3.10	14.25	-0.60	14.85	2.50
ZIMMERWALD, CH	7810	9.23	-0.09	9.32	0.90	8.42	0.81
WETTZELL, DE	8834	10.92	1.20	9.72	0.83	8.89	2.03

SLR contribution to ITRF2005 had some basic differences from what was submitted to ITRF2000:

- The new submission used the Mendes-Pavlis (2004) refraction model.
- Only the data spanning 1993 to end of 2005 were used instead of the 1976 -2000 that was used in ITRF2000.

The first difference was quickly discarded since the same SLR contributions were used in both ITRF2005 versions, P and D. Additionally, tests that were done to quantify the effect of the new refraction model (~0.4 ppb at most), gave no indication of any such large systematic scale differences between the two solutions with the character of the observed scale differences between the two TRFs. Considering the magnitude of the change in the VLBI-SLR scale difference between the two TRFs, a possibly missing relativistic correction in the formulation of the SLR-modeled time-delay advocated by Ashby (2003), was also investigated. Despite the close agreement in magnitude, this correction was also rejected as the cause of the scale differences, a

conclusion that was also supported by Ashby himself (2006, personal communication). The POD tests were extended to include other SLR targets with orbits markedly different from LAGEOS, such as JASON-1 and Starlette. A corollary benefit from these POD tests was that while LAGEOS data were satisfactorily reduced with the scaled version of ITRF2005P, Starlette data for example showed a slight degradation. This implies either a certain distortion in the ITRF2005P solution, or a significant error in the CoM value used for Starlette. The latter is highly unlikely, but cannot be outright discarded.

A final plausible cause investigated as a possible explanation was the fact that the SLR contribution to ITRF2005 did not contain the historical LAGEOS data from the period 1976-1992. To test this last theory, we reduced all of that data and generated solutions that included that data, which we later compared to the two ITRF2005 solutions. Figure 1 shows the LAGEOS data distribution (weekly resolution) for the ILRS network from 1976 to early 2006. It can be seen that there is no dramatic difference between the two networks that supported the two ITRFs.

The SLR data for the period 1976-1992 is certainly not of the same quality as for the recent years, and the network had undergone several upgrade stages during that period. The initial predominantly NASA-supported network from 1976 to 1980 was more of a research and test-bed outfit than an operational one. The two international MERIT campaigns in the early 80s forced the upgrade of the network, its expansion and strengthening with the addition of several stations outside North America and
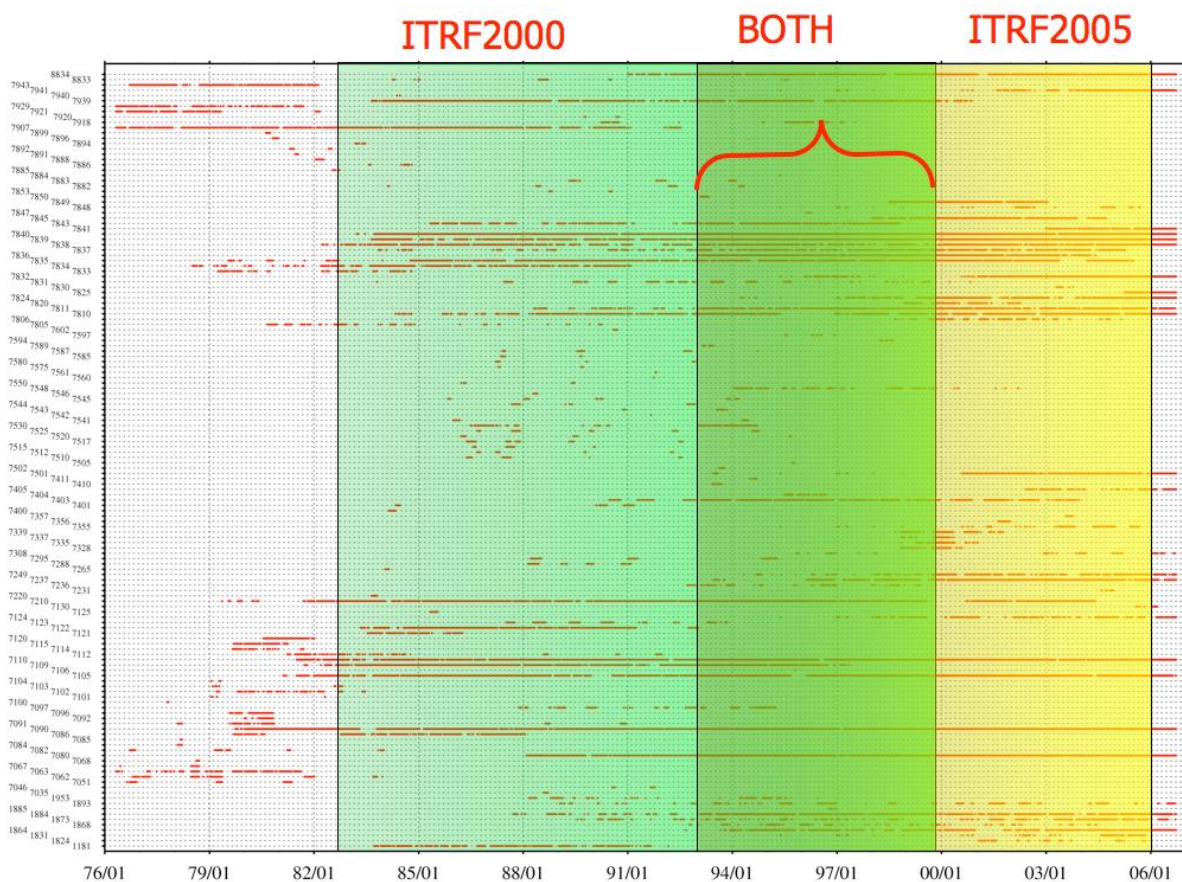
Figure 1. The LAGEOS and LAGEOS 2 data distribution for 1976 – 2006, and the portions used in the SLR submissions for the development of ITRF2000 (green) and ITRF2005 (yellow).
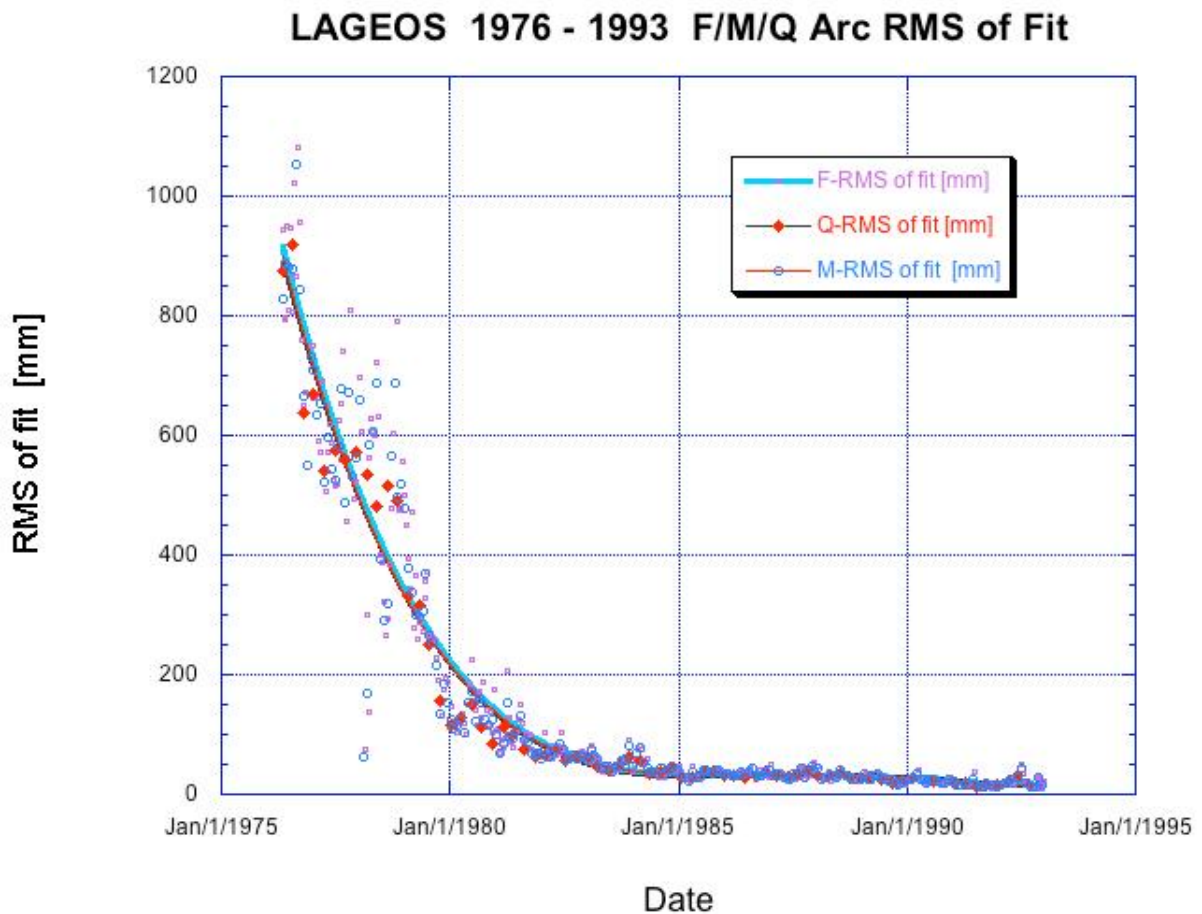
Figure 2. Orbital arc RMS of fit to LAGEOS data, 1976 – 1992.
Results from reductions with three different arc-lengths are shown
here, fortnightly (F), monthly (M) and quarterly (Q).

Europe, and ushered an era of operational mentality across continents, countries and agencies supporting these stations. As a result, the quality of the data improved by an order of magnitude, the quantity increased too, and internationally coordinated scheduling of operations was initiated for improved data yield. The result of these changes is reflected directly in the improved RMS of fit to the collected data, using the same models across all periods of time, as this is illustrated by the graph in Figure 2.

The development of TRFs that included the SLR data from the 1976-1992 period made little difference in their intrinsic scale and scale rate (~10% at most). On the other hand, it does improve the error statistics for sites that span both periods of time and it resulted in capturing in a single consistent frame all SLR sites that ever tracked either or both LAGEOS satellites. This result left the question about the SLR-VLBI scale difference in ITRF2005 open and unanswered, despite the fact that it eliminated a large number of serious candidate explanations.

Recent (spring 2007) developments

During the 2007 General Assembly of the European Geosciences Union (EGU) in Vienna, Austria, MacMillan (2007) brought to the attention of the ITRF community the finding that the official International VLBI Service (IVS) submission to ITRF2005 had an error in the application of the pole tide, which generated a scale bias with respect to the true scale of ITRF.
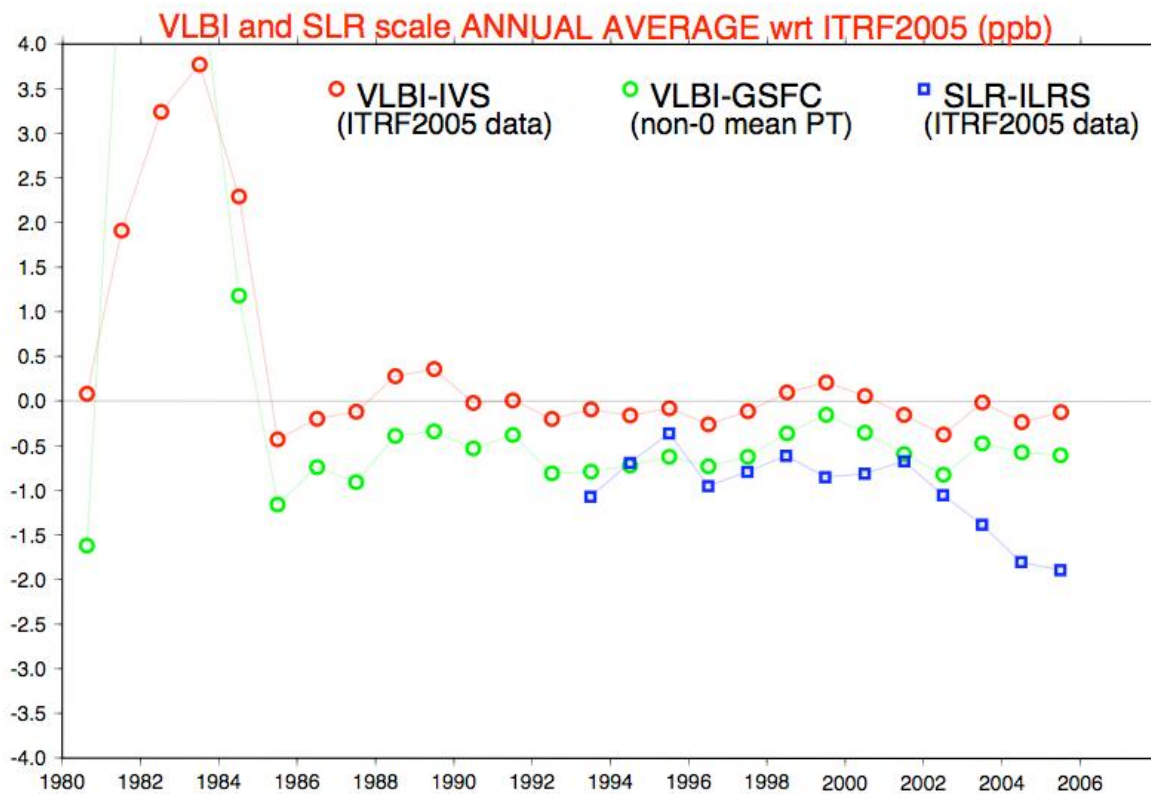
Figure 3. *Time series of annual scale differences between various
VLBI solutions and the SLR submission to ITRF2005,
with respect to the ITRF2005 frame, (Altamimi, 2007).*

After an exchange of corrected submission files, Z. Altamimi generated new test
solutions that indicate that indeed, this error causes about 0.5 ppb scale bias between
the SLR and VLBI frames of reference. This can be seen in the graph that Altamimi
(2007) circulated via email on June 18, 2007, under the subject matter: "Pole tide
effect on VLBI scale". As you can verify from Figure 3, except for the period after 2004
when the SLR network covers only the one hemisphere of the globe, the scale difference
between the two techniques is at the same level of discrepancy as it was during the
development of ITRF2000. This means that there is really no reason for the exclusion
of SLR from the definition of the scale of ITRF2005. The "significant"scale rate is
also a result of the poor network configuration in the latter years and the consideration
of some questionable site tie vectors (as pointed out by the DGFI combination center), and
could have been dampened by appropriate weighting of the weekly contributions for
that period of time, or editing of the ties (as DGFI did for ITRF2005D).

Summary

The release of ITRF2005 in mid-2006 created a great commotion within the geodetic
community with its departure from prior tradition, to adopt the scale implied by VLBI
only, excluding SLR from the usual 50-50 sharing of this privilege. Additionally, the
indication that SLR scale was not only off by more than 1 ppb from the true scale but
also suffered from a significant rate change of -0.15 ppb/y, sent SLR analysts
scrambling for answers. As we have seen here, none of the most plausible causes

could be found responsible for the observed discrepancy. The matter was never closed, and it was always suspected that in addition to the acknowledged effect of the deteriorating SLR network, either an error in another technique's submission were the cause, or the new way of constructing the ITRF, or a combination of all. The April 2007 findings of MacMillan's investigation in the VLBI scale definition explained for the most part the constant scale offset. The remaining scale rate effect seems to be the result of the new way the ITRF is constructed and the deterioration of the SLR network during 2004- 2006. The recent re-establishment of the SLR sites at Haleakala, Hawaii and Arequipa, Peru, and the new and improved re-analysis of the SLR data this year are expected to resolve many of these remaining issues and restore the faith of the ITRF community in SLR's unique ability to define the ITRF scale in the absolute sense.

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An Optimised Global SLR Network For Terrestrial Reference Frame Definition

Ramesh Govind[1]

1. Geoscience Australia, Canberra, Australia

Abstract

It is a continuing debate on the current station distribution and geometry of the global SLR network. In order to design the optimum network for high quality geodetic products, a simulation study was undertaken. Data for previously closed or additional new stations was simulated and augmented into the existing available data set and the relevant geodetic parameters estimated. Weekly estimates of the degree one coefficients of the Earth's gravity field (centre of mass) is used as a measure of the influence of the simulated data with respect to the original solutions -- as determined from the observed data set. The simulated data, observed data, and the computation standards are described. On the basis of these results, an optimised global network of SLR stations is presented.

Performance of Southern Hemisphere Stations

John McK. Luck[1]

1.   EOS Space Systems Pty.Ltd., Canberra, Australia

Abstract

The opening of the San Juan station in Argentina, and upgrades to other stations, has lifted the productivity of Southern Hemisphere stations to perhaps 40% of the global total, with a nice distribution in longitude. Various operational statistics will illustrate the improvements achieved up to the start of October 2006.

Introduction

The new San Juan station came on-line in March 2006, in collaboration with NAOC, Beijing. Its performance is highly impressive, and is significantly helping to satisfy the eternal cry for more SLR observations from the Southern Hemisphere.

At the same time, the BKG station TIGO at Concepcion, Chile has been upgraded to hectoHertz ranging with reliability enhancements, and has improved its output considerably in recent months. MOBLAS 8 at Papeete, Tahiti and MOBLAS 6 at Hartebeesthoek, South Africa are also making significant contributions. Of the Australian stations, MOBLAS 5 at Yarragadee continues to be the benchmark and workhorse station for the entire global SLR network, while the re-built EOS/GA station on Mount Stromlo is again one of the top performers.

Statistics for three 28-week time periods in Fig.1 and Table 1 show that data quantities from Southern Hemisphere stations have sustainably improved this year (2006). Other performance metrics are also displayed in this paper.
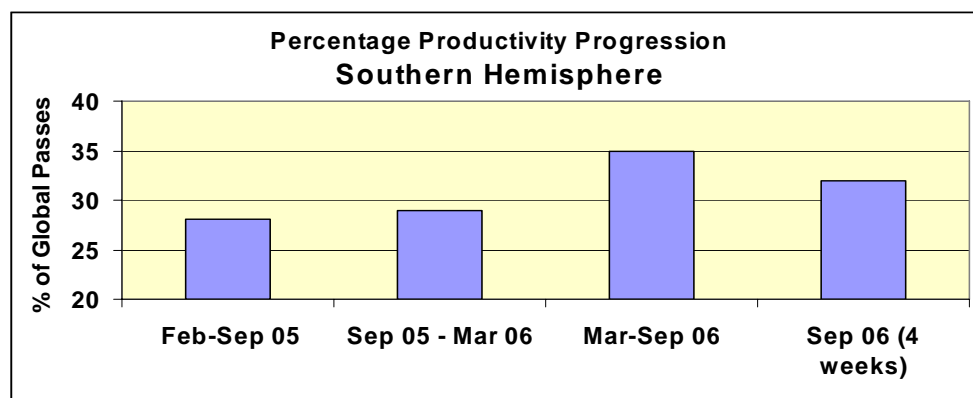
Figure 1: Percentages of passes from Southern Hemisphere stations. Data extracted from CDDIS weekly SLRQL reports

Table 1: Pass percentages from S. Hemisphere stations, and also by ILRS Network

Period	Southern Hemisphere	By Network (see (Luck, 2006)		
		WPLTN	NASA	EUROLAS
2005 Feb-Sept	28	38	15	46
2005 Sept – 2006 Mar	29	44	15	41
2006 Mar-Sept	35	42	16	41
2006 Sept 03-30	32	45	12	43

Numbers of passes by station

In Fig.2, station totals are grouped by hemisphere. Some of the least productive Northern Hemisphere stations are not shown. Each point is a 28-week total.
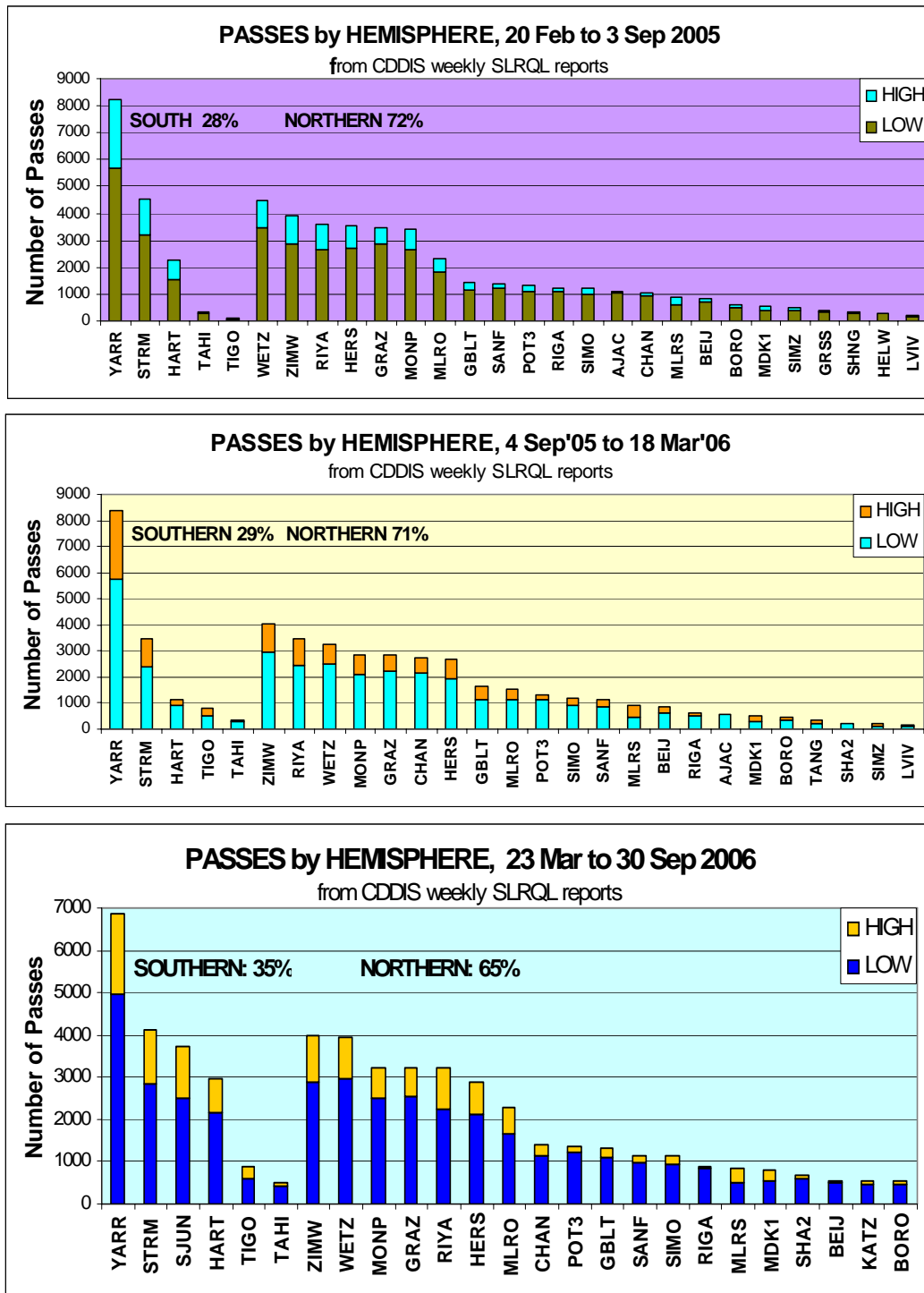
Figure 2: *Station totals for three 28-week periods, grouped by hemisphere.*

Range bias stability

Fig.3 compares Southern and Northern Hemisphere stations for the RMSs since 19 March this year. They are the RMSs of range biases for LAGEOS I and II combined taken from NICT daily analysis reports, after some outlier editing.
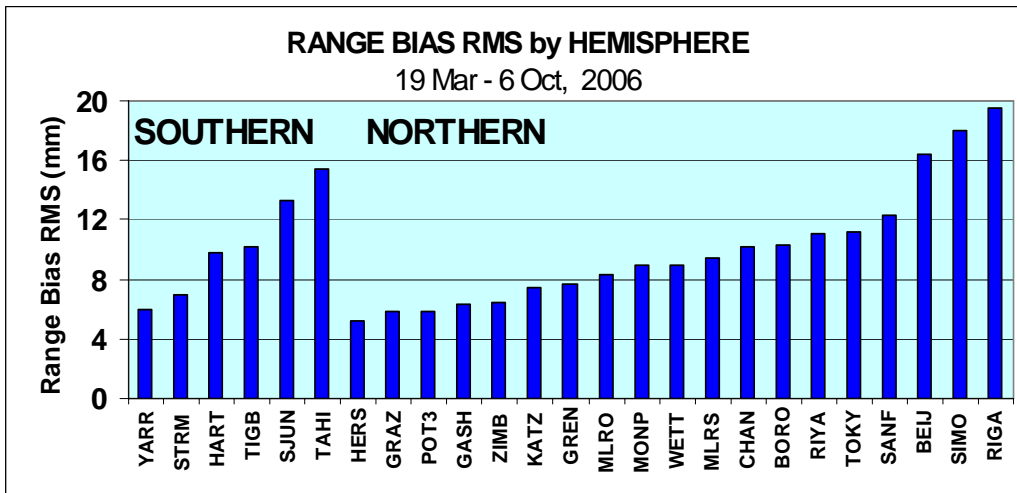
Figure 3: *RMS of Range Bias per station per hemisphere, L1 & L2*
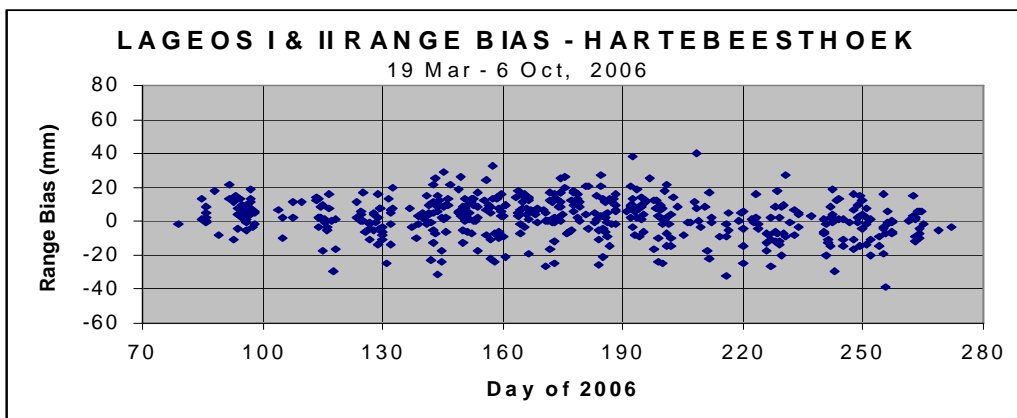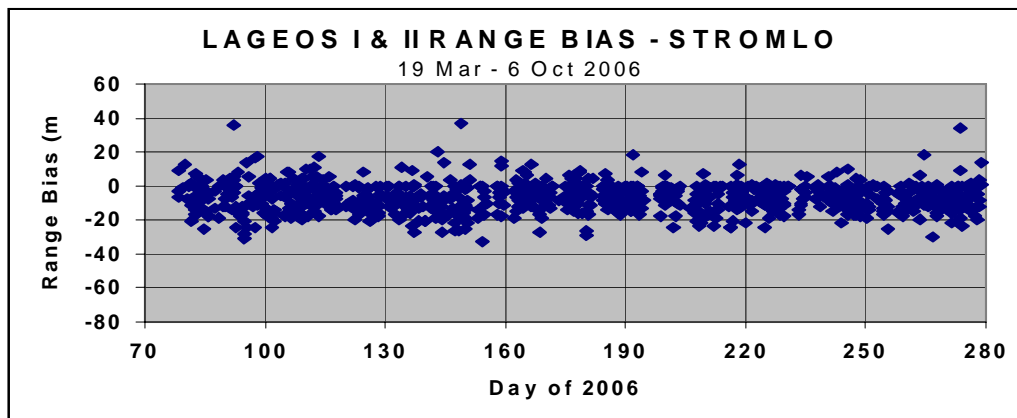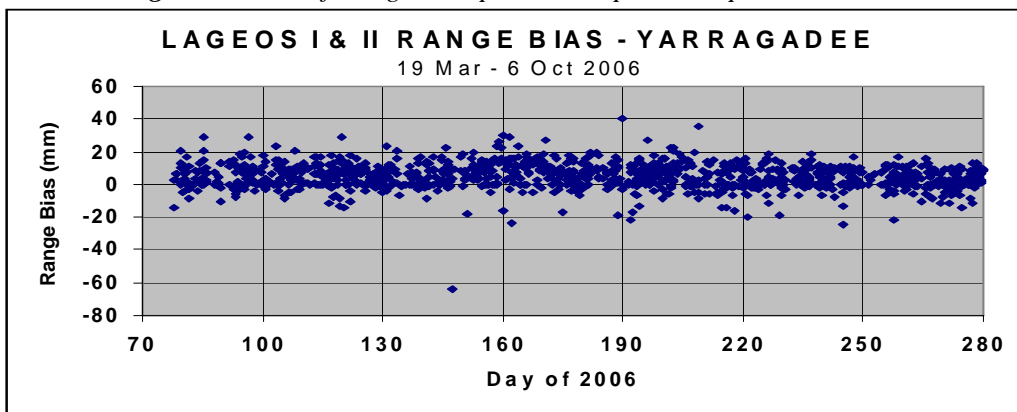
Figure 4a: *Range Biases for LAGEOS I & II for Yarragadee, Stromlo and Hartebeesthoek .*
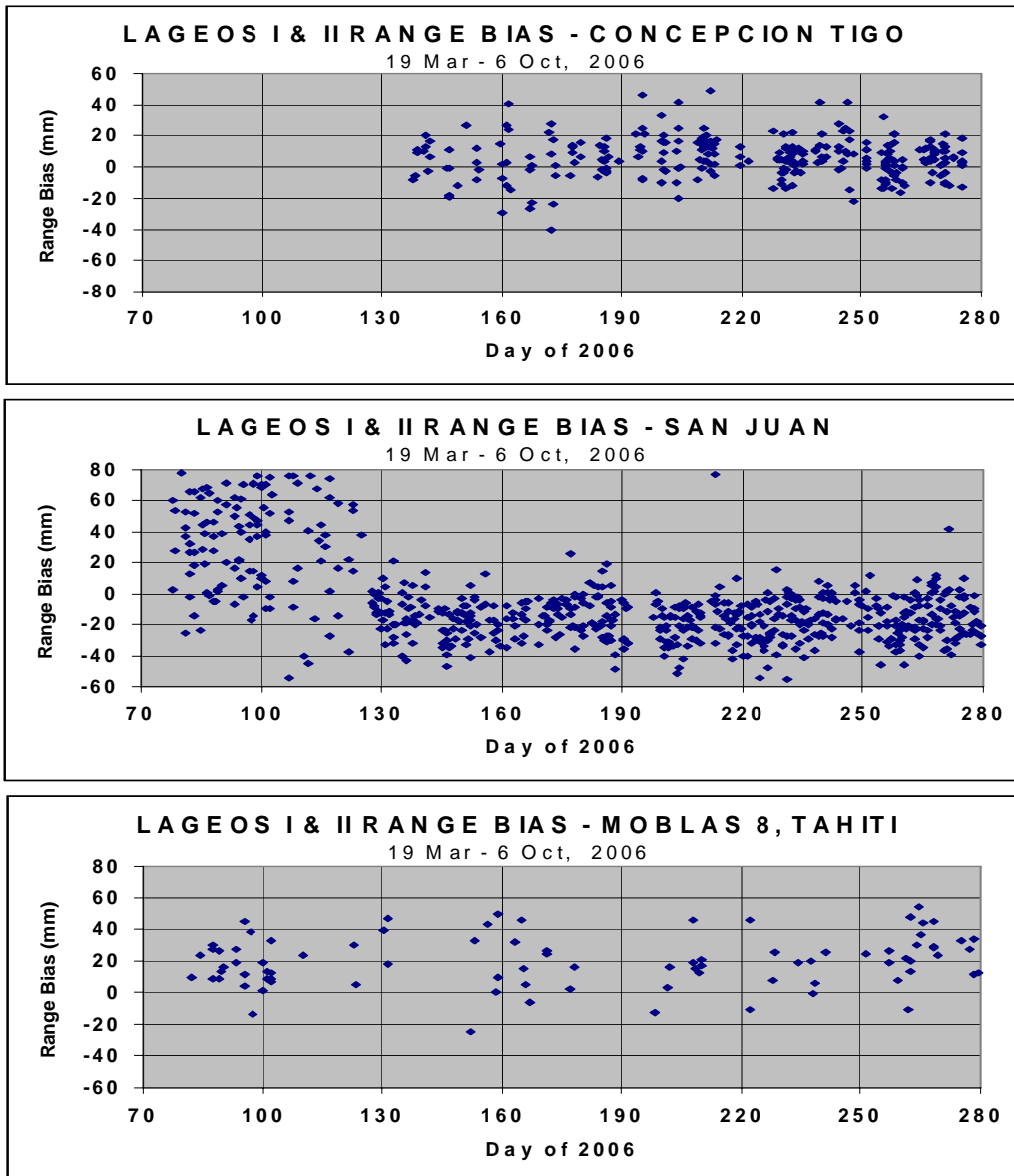
Figure 4b: Range Biases for LAGEOS I & II for Conception, San Juan and Tahiti.

The time series for the 6 stations are shown in Figures 4a and 4b.

Normal points per pass

This category reflects the observing efficiency of the stations, and is affected by skill in acquiring satellites and interleaving passes as well as factors like aperture, laser power, sun avoidance, priorities and bad weather. In general, a low ratio means more uncertainty in determining time bias, unless the few normal points are very well distributed throughout the pass. Fig 5 contrasts northern and southern hemispheres.

Normal point precision

NP precision is calculated as the RMS of normal points about a trend-line fitted through the orbit residuals of the Analysis Centre's global solution. It is thus a measure of a station's internal consistency, and is affected by short-term variations in the station's observations, method of forming normal points, and errors in weather data as well as the Analysis Centre's methods of filtering and fitting. Fig.6 shows the results for the 28-week period Mar-Sep 2006 taken from the NICT daily analysis

reports, but only for passes containing at least four NPs, and Fig.7 shows the time-series for each station over the same period.
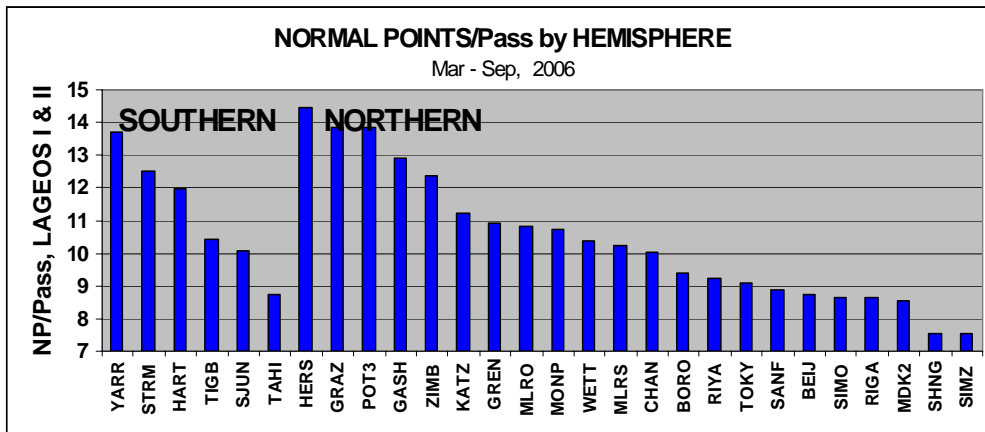
Figure 5: *Normal points per Pass, LAGEOS I & II combined, extracted from NICT daily Analysis Reports. (Note truncated vertical scale - it looks worse than it is!)*
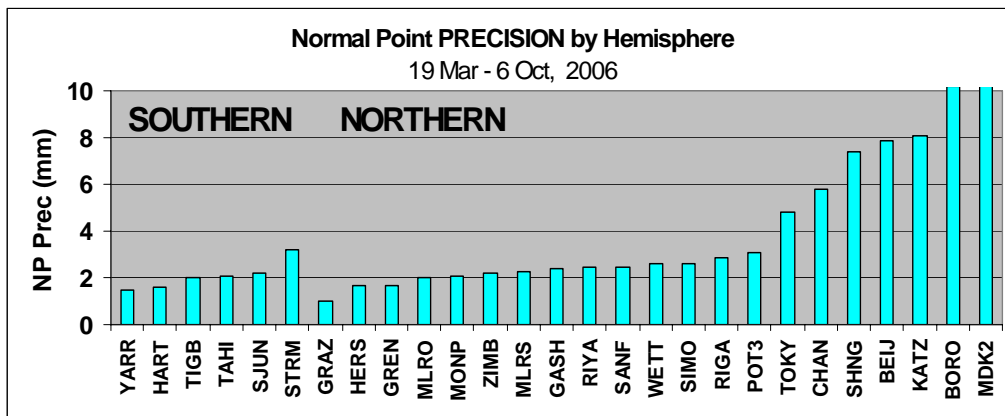
Figure 6: *Normal Point Precisions Summary*
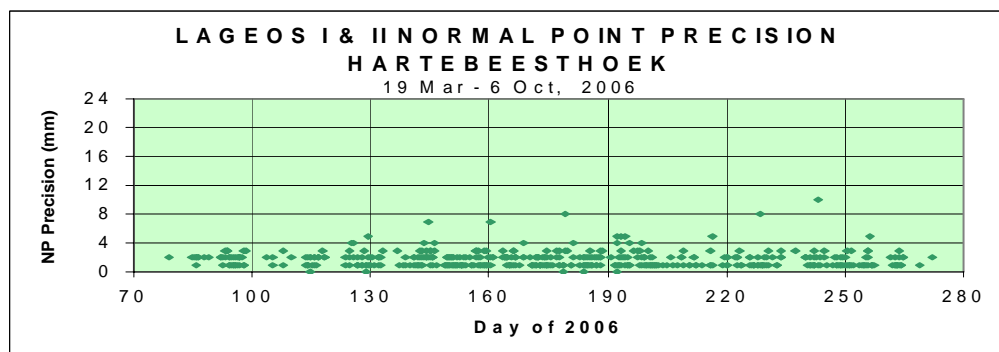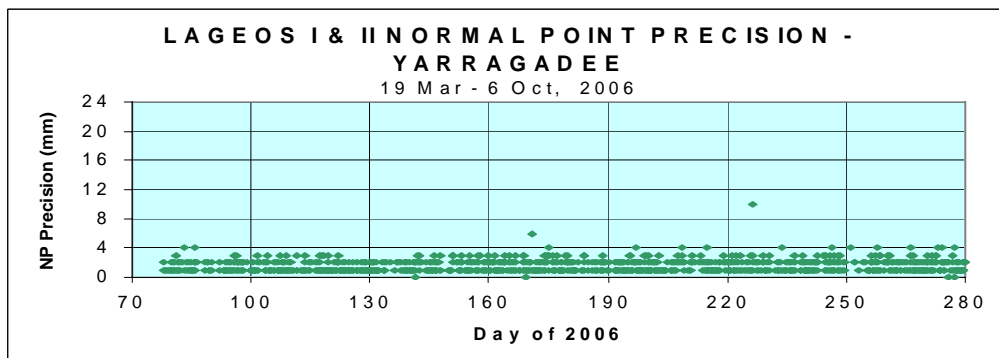
Figure 7a: *Normal Point Precisions for Southern Hemisphere stations*
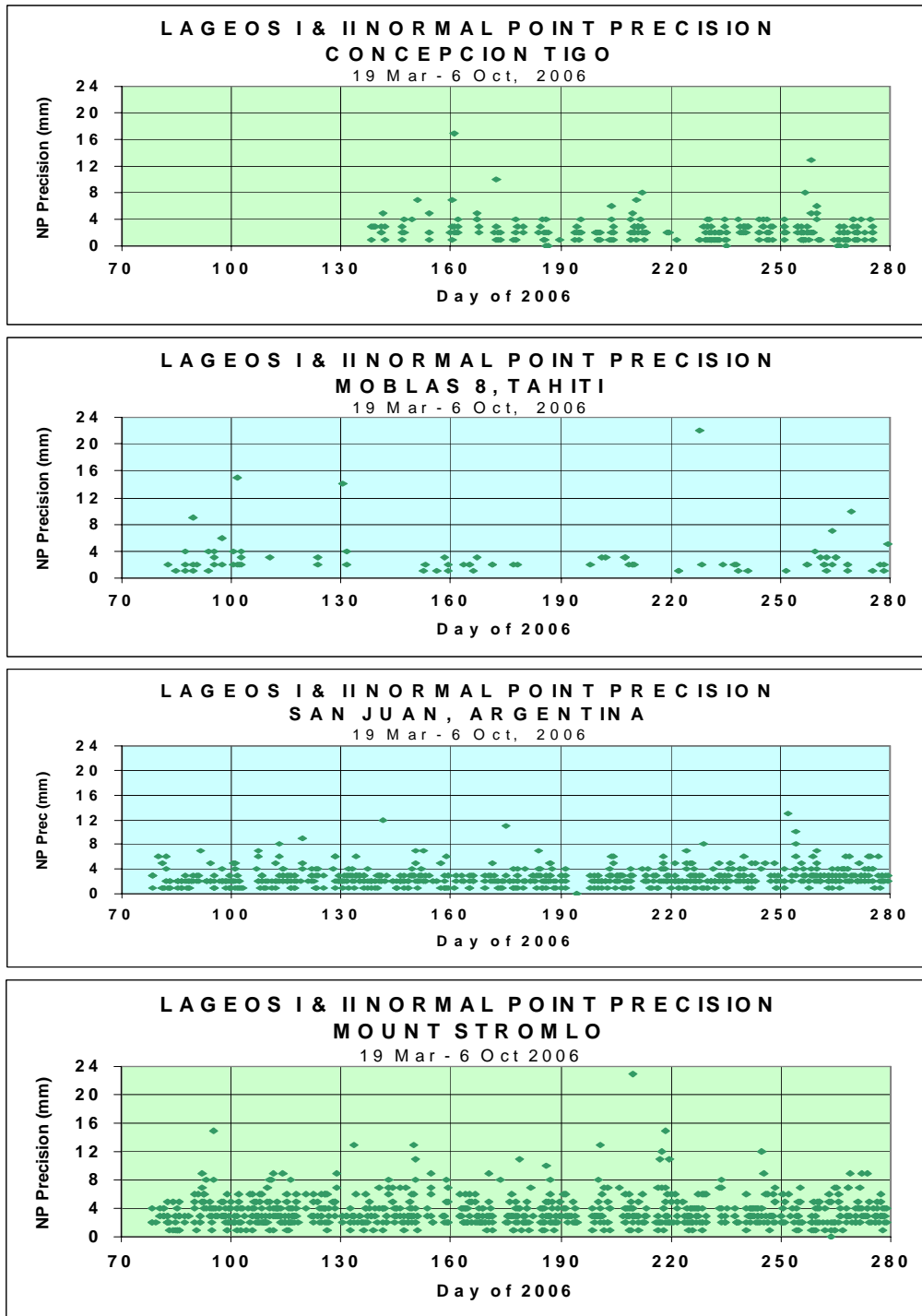
Figure 7b: *Normal Point Precisions for Southern Hemisphere stations*

System delay

The system delays are the results of system calibration by pre- and/or post-pass ground target ranging, or equivalent. They have arbitrary values and are allowed to jump when, for example, cables are changed in the paths to the timing system, components in the optical path are moved, or other repairs and maintenance are performed. Otherwise, however, they should remain constant. In particular, they should not show drifts such as TIGO has been undergoing since about day 225 in Fig.8. The results in Fig.8 are from Ajisai entries in NICT daily analysis reports, with respect to the average system delay over the 28-week period.
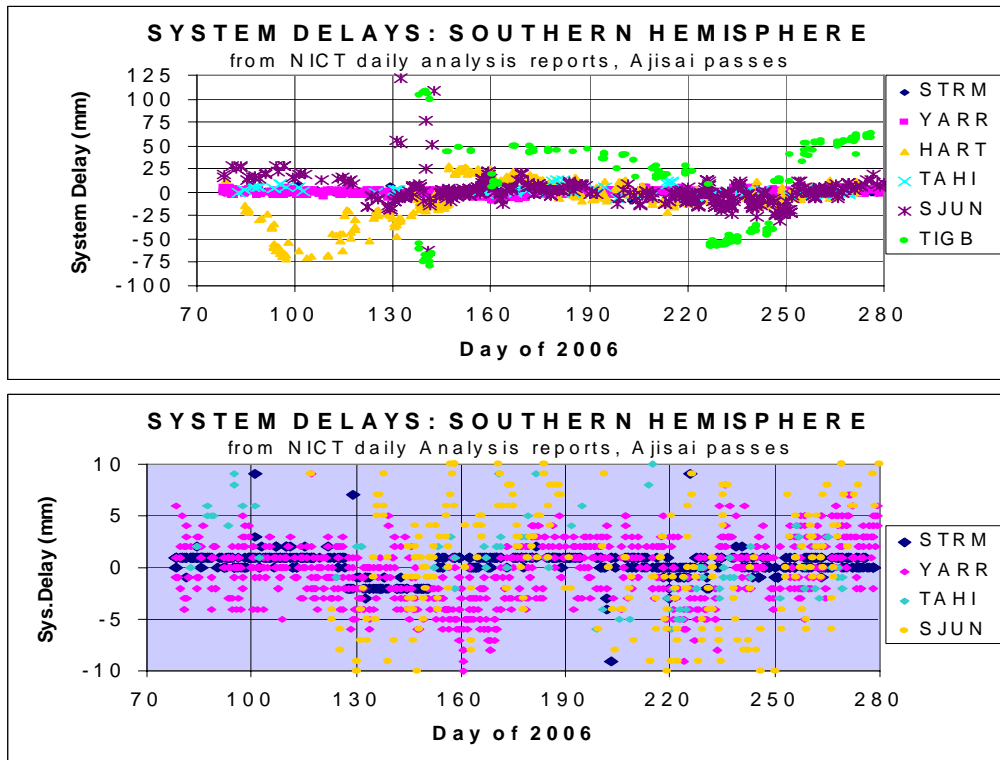
Figure 8: *System Delays per pass (Ajisai). The lower plot is at expanded vertical scale.*

Conclusions

There has been a boom in Southern Hemisphere ranging in 2006, due mainly to the commissioning of the San Juan station, whose productivity is the more remarkable because it only observes at night-time. Tahiti only has limited day-time tracking.

The quality of ranging is comparable with Northern Hemisphere stations, too, although some stations show worrying trends in their system delay stabilities while Stromlo should be doing far better in its normal point precisions. The imminent resurrection of Arequipa, Peru should further enhance the Southern Hemisphere contribution to global SLR performance.

Acknowledgements

The data used here were extracted from the CDDIS SLR Data Reports, courtesy Carey Noll, and from the NICT daily Multi-Satellite Bias Analysis Reports, courtesy Toshi Otsubo. These reports are produced on behalf of the International Laser Ranging Service (ILRS).

Reference

[1] Luck, J.McK.: "*Performance of WPLTN Stations*", these proceedings (2006)

The Evolution of SLR/LLR in Response to Mission Needs

Peter Shelus[1]

1. University of Texas at Austin/CSR

Abstract

The response of the laser ranging network to the needs of the various missions over the past 40 years or so has been an evolving one. The targets have been varied and the science has been exciting. With the establishment of the International Laser Ranging Service (ILRS) and its Missions Working Group, this planning and coordination has been put on a much more formal basis. This presentation reviews some of the history, provides information on where we find ourselves right now, and tries to look a bit into the future as to where we wish to be.

Assessment of SLR Network Performance

Mark Torrence [1] and Peter Dunn [1]

1. SGT Inc, Greenbelt, Maryland, USA

Abstract

The SLR global performance report card is updated quarterly on the ILRS web-site and presents a broad view of the state of the network. The information summarized in that report can be treated in several different ways to clarify particular features. The usual expression of the station characteristics as a function of calendar time provides a method to monitor the evolution of the health of a station by considering the quantity of normal points collected, as well as the volume of full rate observations and the noise level of these data for each satellite. If the same variables are expressed as a function of local time, the distinction between day-time and night-time performance of a station is high-lighted. Satellite signature effects can be demonstrated by again plotting these same variables but as a function of range value, and this will also vary by station. We demonstrate the use of these alternative representations for all the stations in the network to many satellites and solicit ideas which could enhance the definition of the each observatory's contribution to the Global Network and the analyst's understanding of the data.

Introduction

The motivation for constructing graphs of station performance arose from an assessment of potential corner cube array design for HEO satellites. Looking at the SLR data as a function of local time and as a function of the satellite range may reveal station performance characteristics in SLR data such as whether patterns vary from year to year, and whether there are indications of satellite dependencies.
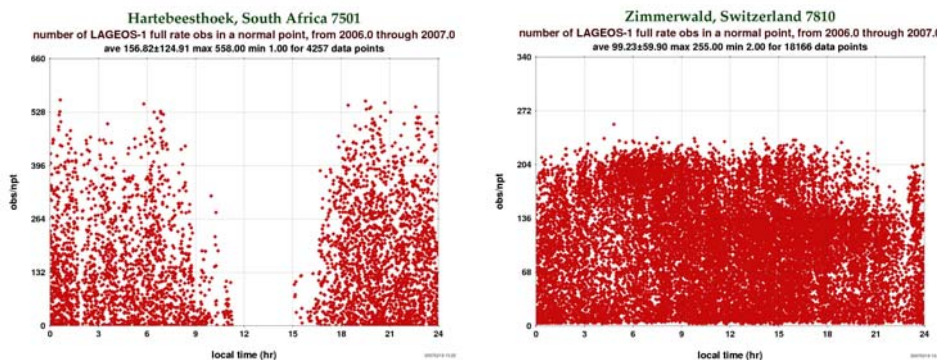
Figure 1 *Number of full rate observations in a normal point for Hartebeesthoek and Zimmerwald.*
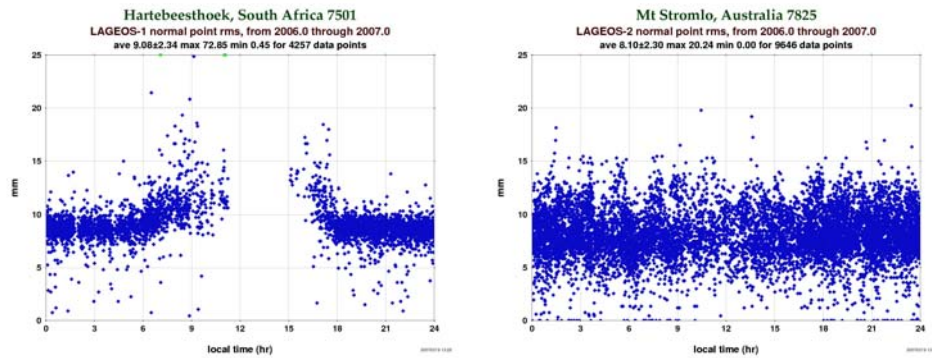
Figure 2: *Normal point rms as function of local time for Hartebeesthoek and Mt Stromlo.*
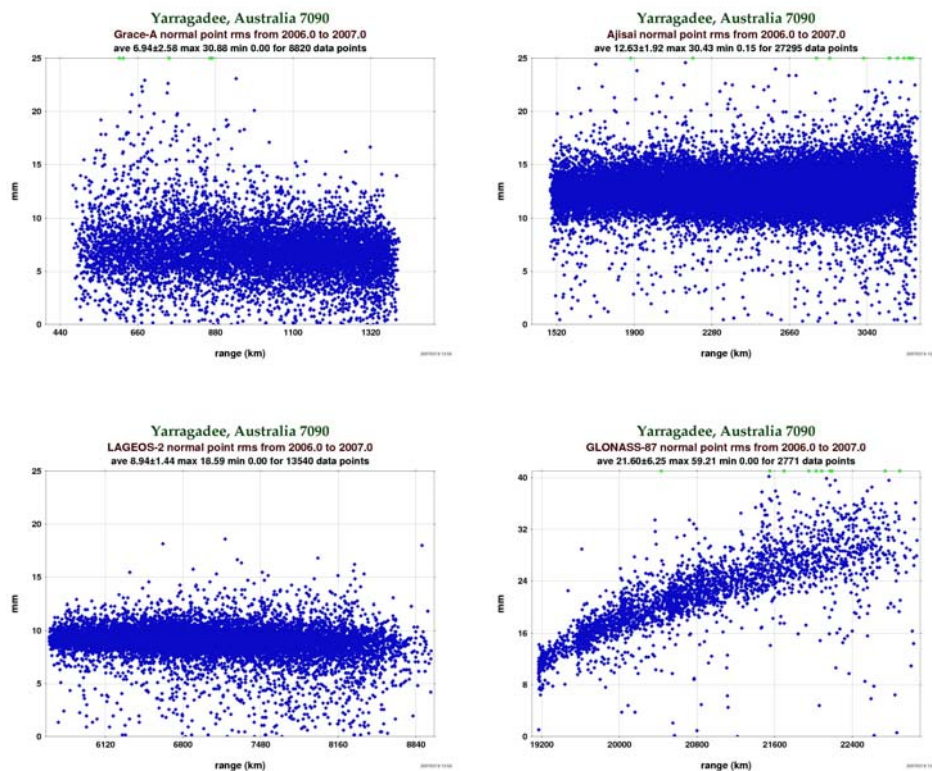
Figure 3: *Normal point rms as function of range for Yarragadee for Grace-A, Ajisai, LAGEOS-2 and GLONASS-87.*

The pattern seen in the normal point rms as a function of range for Yarragadee tracking GLONASS-87 is most probably due to the large array cross section of GLONASS-87 resulting in center-of-mass offset which is a function of viewing geometry.
See
http://ilrs.gsfc.nasa.gov/cgibin/satellite_missions/select.cgi?sat_code=GL88&sat_name=GLONASS-88&tab_id=com

Plots of this type will be available at the ILRS web site.

Performance of WPLTN Stations

John McK. Luck[1]

1. EOS Space Systems Pty.Ltd., Canberra, Australia

Abstract

There have been significant upgrades to WPLTN stations in the last year. Performance statistics for each station will be presented, which may highlight where further improvements could be achieved.

Introduction

The working and developing stations which constitute the Western Pacific Laser Tracking Network (WPLTN) include Tokyo, Simosato and Tanegashima (Japan), Shanghai, Beijing, Changchun, Yunnan, Wuhan and the CTLRS (China), Yarragadee and Mount Stromlo (Australia), Riyadh (Saudi Arabia), Maidanak (Russia), and most recently the new Chinese-supplied station at San Juan, Argentina. In 2006, as well as the commissioning of San Juan, Shanghai moved to a new site and significant upgrades came to fruition at Simosato and Changchun. San Juan has been accepted as a member of WPLTN, and Yarragadee has dual membership with WPLTN and the NASA network.

These developments have produced a noticeable increase in the productivity and quality of the network as a whole. It is therefore timely to review its performance and to compare it with the NASA and Eurolas networks. (This paper was actually presented at the WPLTN General Assembly.)

For the purposes of this paper, Yarragadee is included in WPLTN, TIGO in Concepcion (Chile) and the Ukraine stations in Eurolas, and Hartebeesthoek and Tahiti in NASA. Data are shown in four periods – three 28-week periods spanning 20 Feb 2005 to 2 Sep 2006, and the 4-week period 3-30 Sep 2006 leading up to the Workshop. In many ways the data displays emulate the ILRS Quarterly Global SLR Performance Reports, arranged differently.

Productivity

The numbers of passes summarized by network are shown in Fig.1 as percentages of the global totals. The increase since 2005 seems to be sustained, at the expense of the NASA network. Data were extracted from the weekly CDDIS SLR Data Reports.
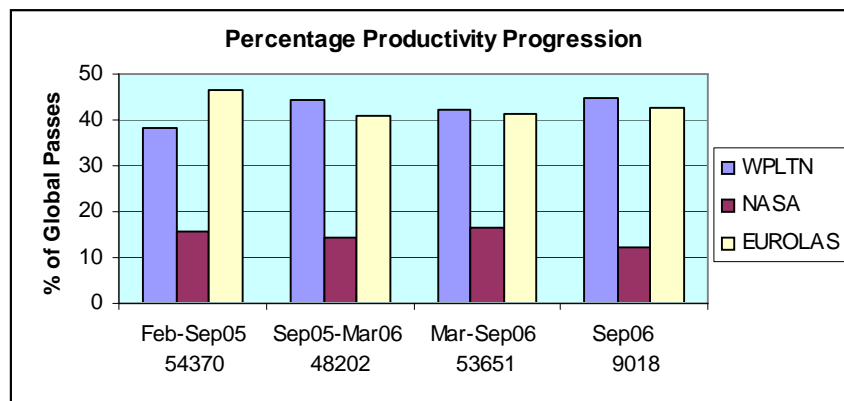
Figure 1: Productivity comparison. The global totals of passes are on the bottom line.

Fig.2 shows the numbers of passes per station per period, grouped by network.
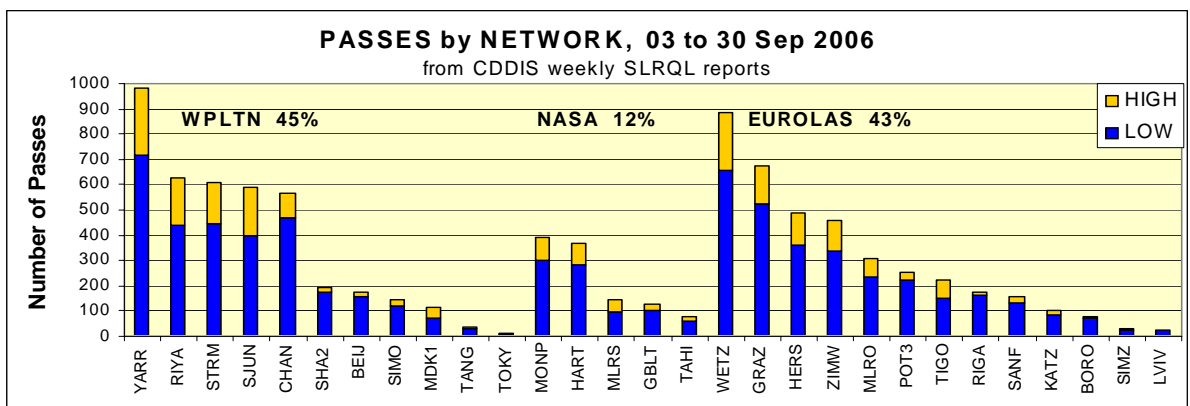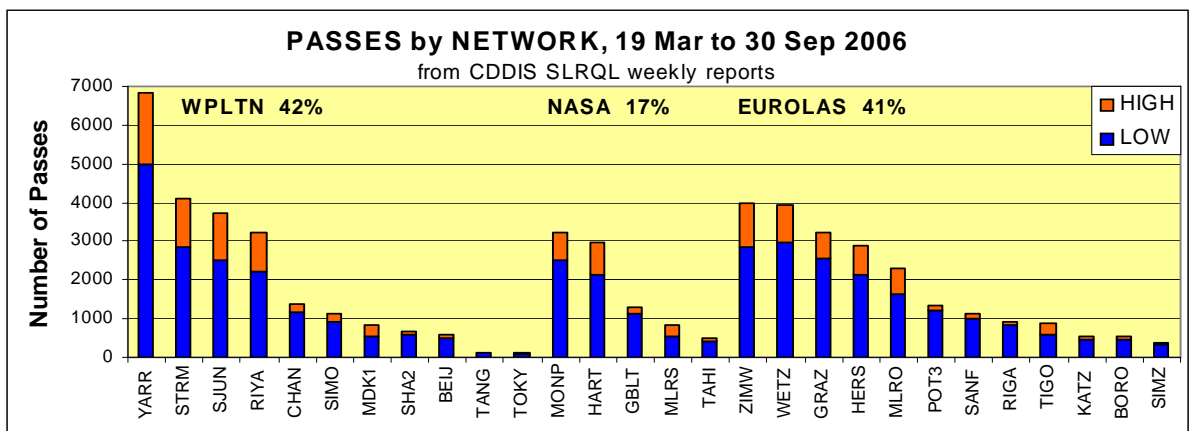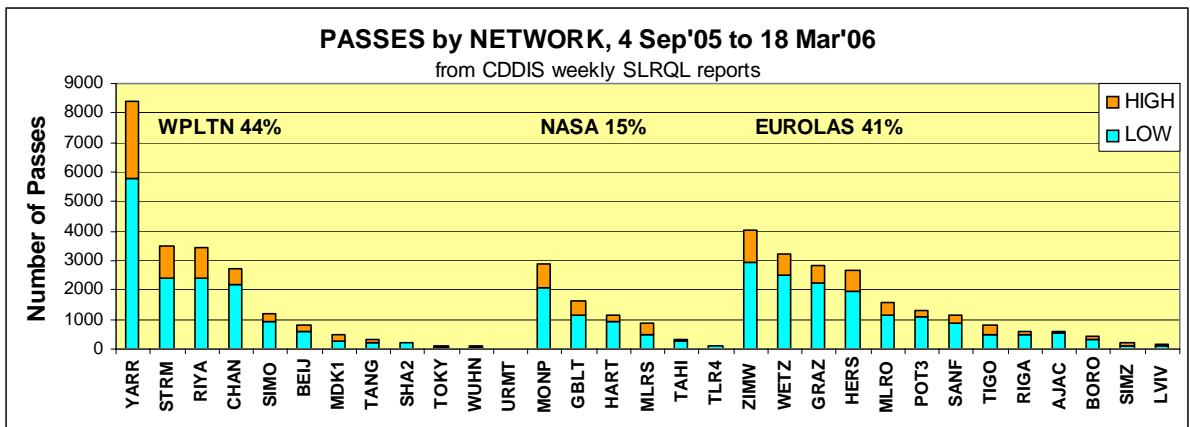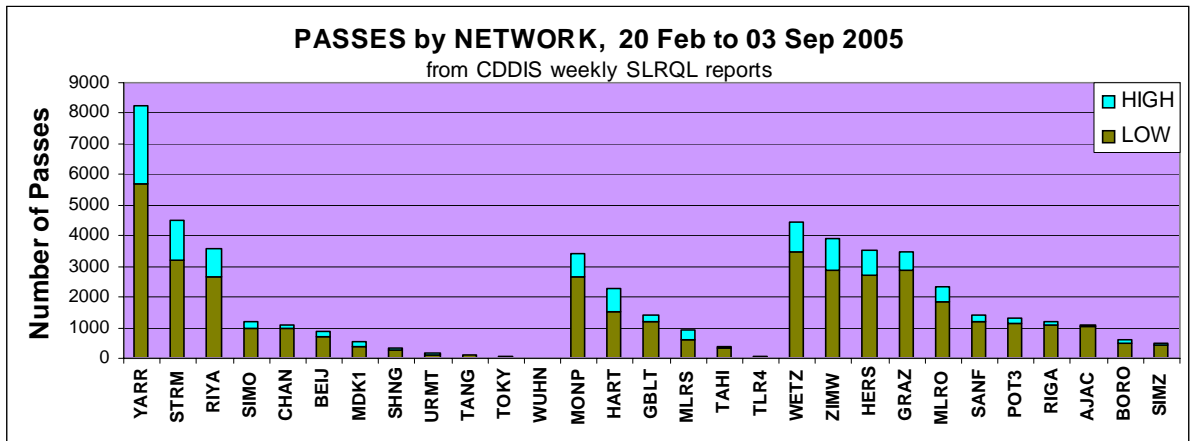
Figure 2*: Numbers of passes per station in each of the four periods.*

Normal Points per Pass

This category reflects the observing efficiency of the stations, and is affected by skill in acquiring satellites and interleaving passes, as well as factors like aperture, laser power, sun avoidance, priorities, and bad weather. In general, low ratios mean more uncertainty in determining time bias, unless the normal points are very well distributed throughout a pass.
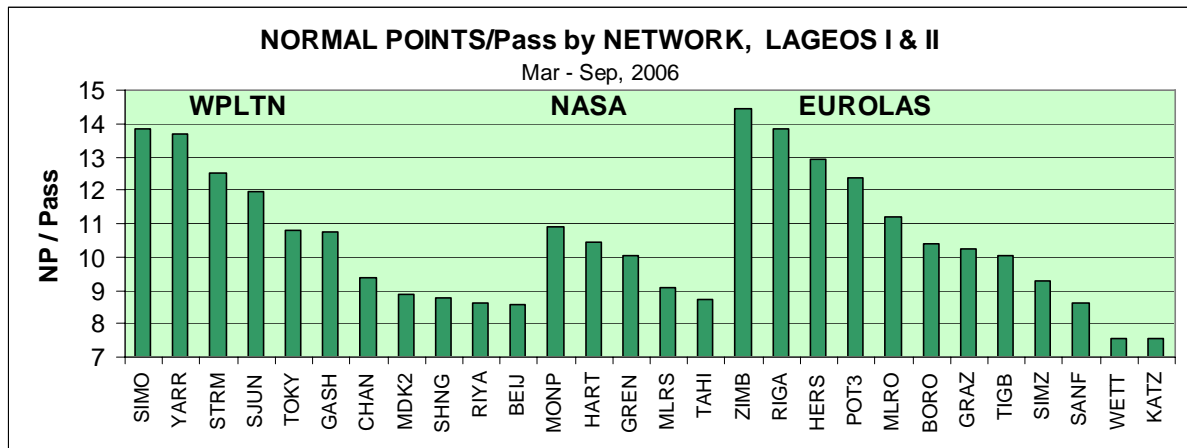
Figure 3: *Normal points per pass in much of 2006.*
Data from daily NICT Multi-Satellite Bias Analysis Reports.

The best of the WPLTN stations are comparable with Eurolas. Stations with low ratios – in all networks! – should aim to improve coverage during passes.

Normal Point Precision

For Fig.4, the average NP Precision values were calculated after removal of obvious outliers. Stations not shown were off-scale. The best stations achieve 2 mm, and 3 mm should be the aim. Clearly, several WPLTN stations and some from eastern Europe need to improve.
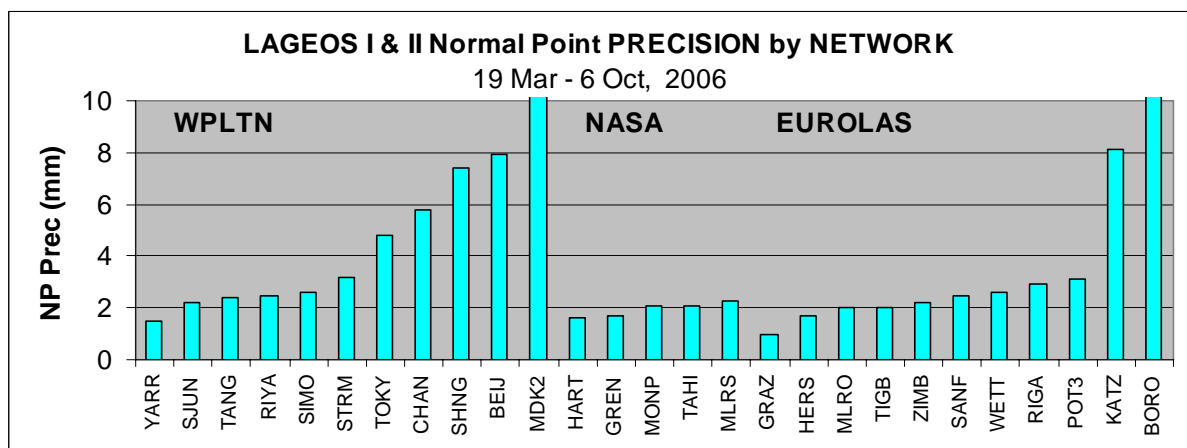
Figure 4: *Average Normal Point Precisions for much of 2006.*
Data from NICT reports.

Time series graphs for some of the stations are shown in Fig.5. Only passes containing at least 4 Normal Points are plotted. Graphs for Yarragadee, Stromlo and San Juan are given in the companion 'Southern Hemisphere' paper (Luck, 2006).
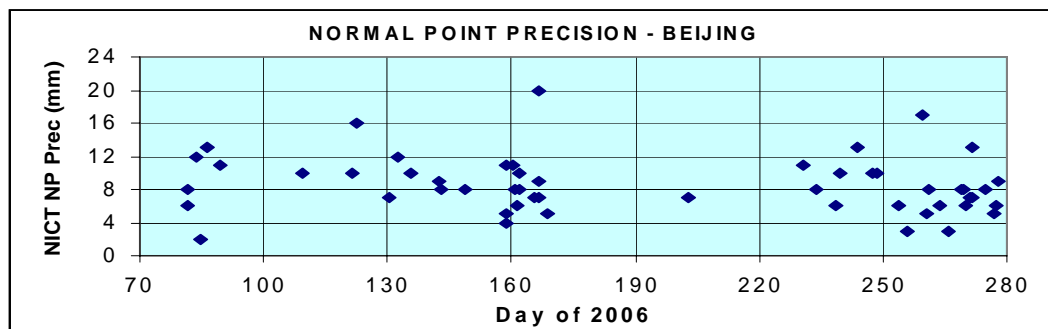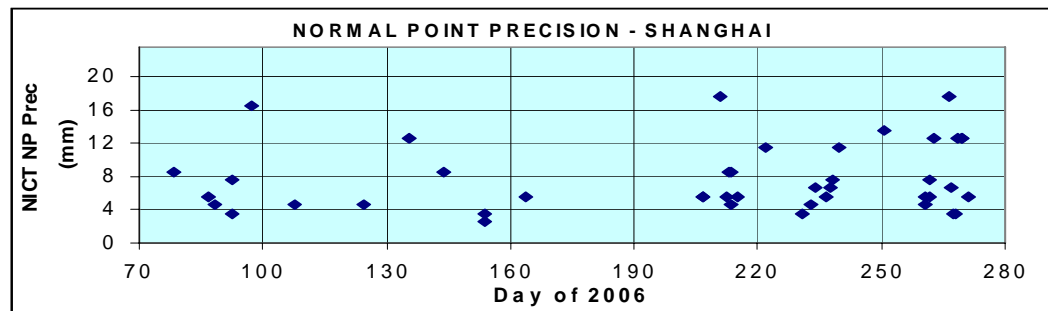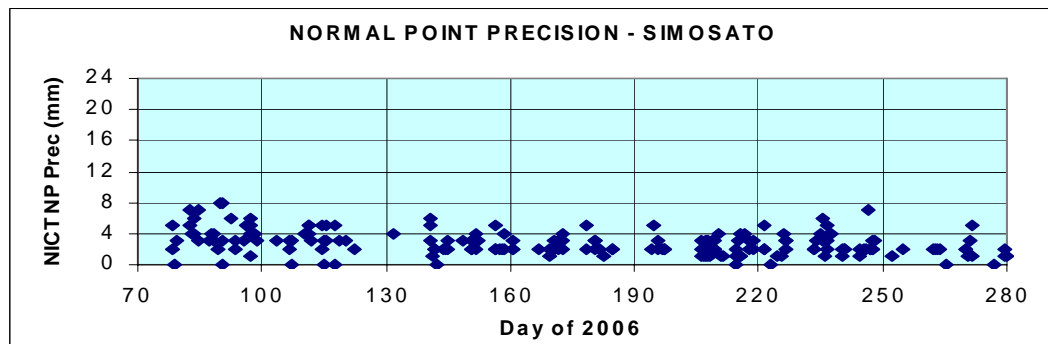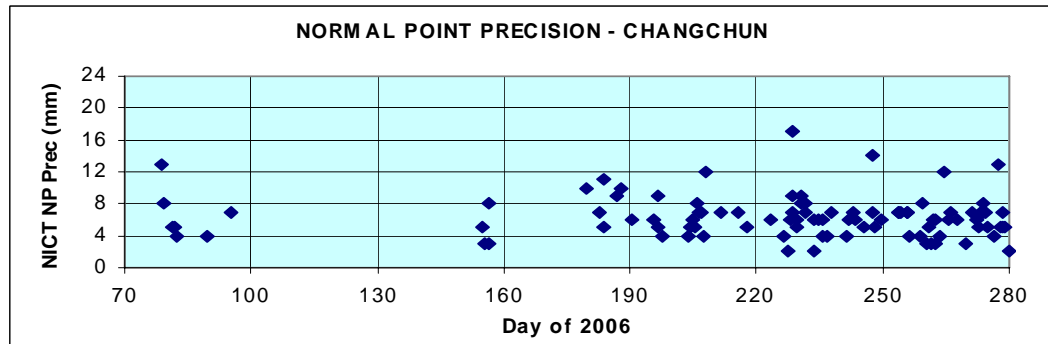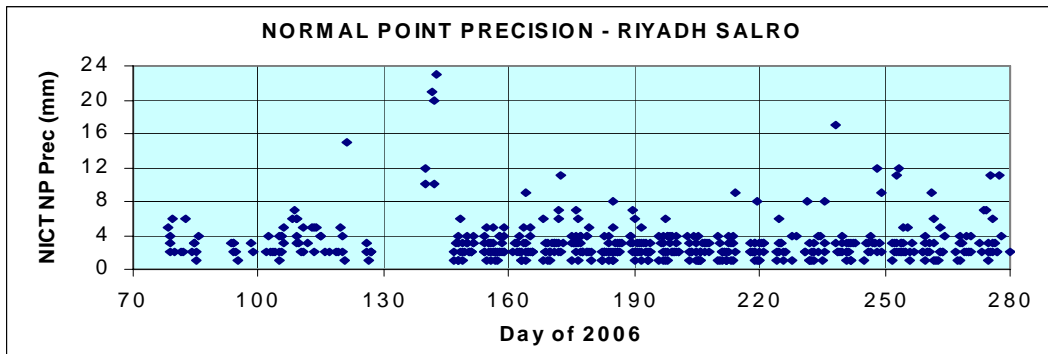
Figure 5*: Normal Point precisions for selected WPLTN stations. Data from NICT reports. See also (Luck, 2006)*

Accuracy – Range Bias and System Calibration

More important than the precision of the measurements is their accuracy, i.e. how closely the numbers obtained reflect the true distances. There is no perfect way to assess accuracy, so we use range biases, which in a sense give a station's range errors against a sophisticated average over all stations using the satellites' orbits as constraints; and we use ground-target ranging to measure the system delays that are applied to the range measurements. Both these methods have drawbacks. Range biases depend upon the set of station coordinates and the processing philosophy adopted by any particular Analysis Centre. For ground-targets, the distance from invariant point to target must be measured with millimeter accuracy, and preferably be checked frequently by a technique such as MINICO (Luck, 2005).
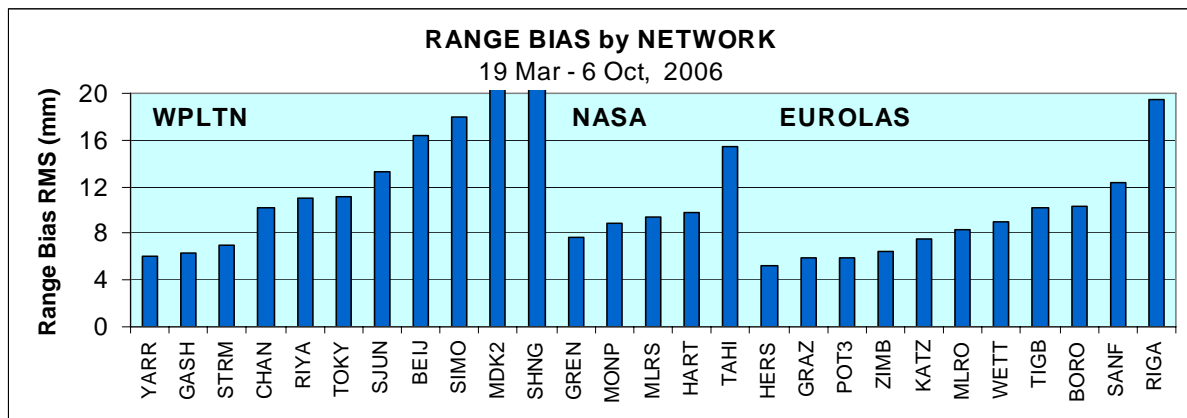
Figure 6: Range bias RMS about mean values by station. Data from NICT reports.
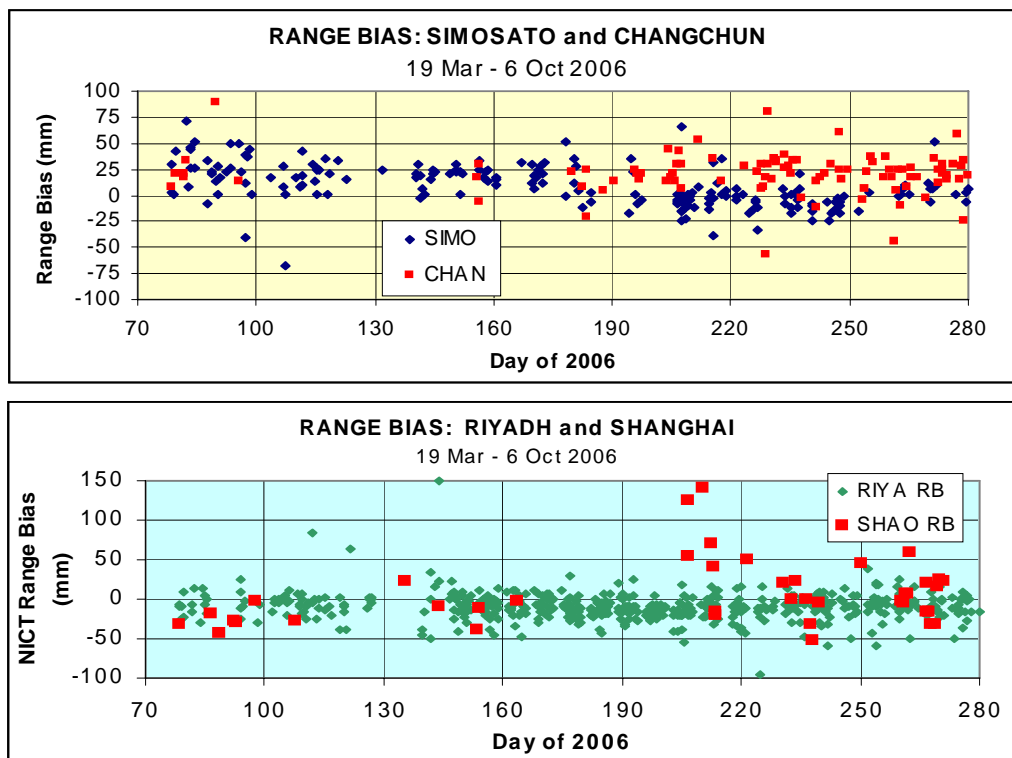
Figure 7: Range bias time series for reasonably productive stations.
Data from NICT reports.

RMS variations of LAGEOS I & II range biases about their station means for a period in 2006 are shown in Fig.6, and time series for some of them in Fig.7. Yarragadee,

Stromlo and San Juan are shown in the companion "Southern Hemisphere" paper (Luck, 2006).

System Delays

In Fig.8, the average system delay for each station has been subtracted from its values to clarify the comparisons. Large jumps, which are perfectly valid, occurred during the period at Simosato and Riyadh, so in Fig.9 they are adjusted to their piecewise averages.
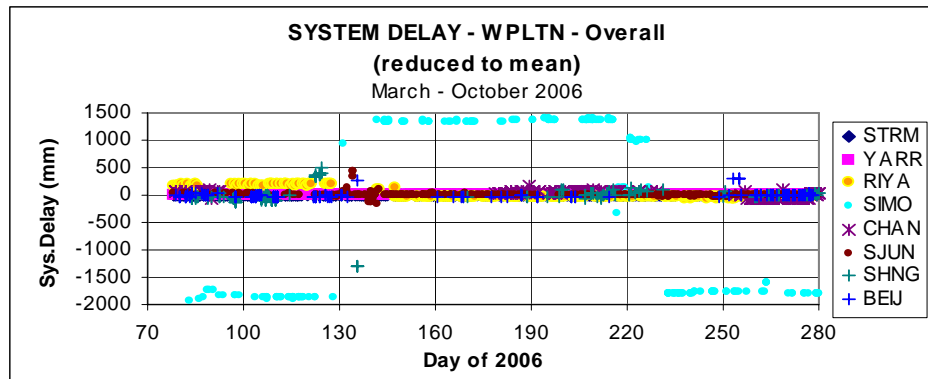
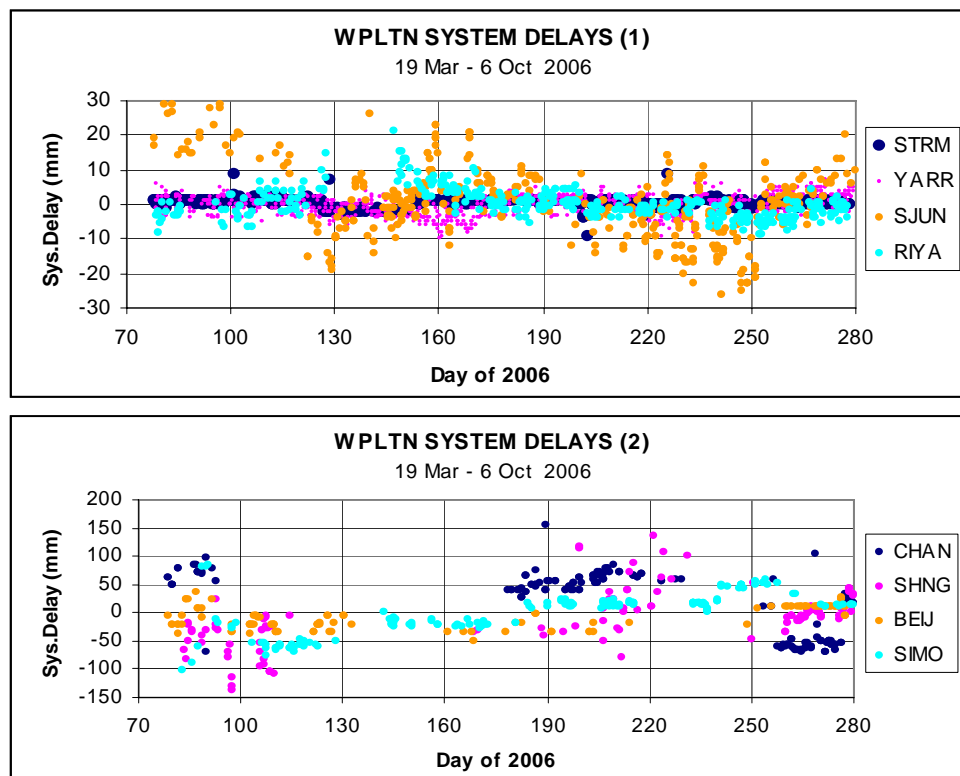*Figure 8: Relative system delays for productive stations. Data from NICT reports.*

Figure 9: Relative system delays at different expanded vertical scales. Data from NICT Reports, AJISAI passes.

There is substantial scatter for most stations except Yarragadee, Stromlo and Riyadh, and drifts in several, most notably Riyadh and Simosato, which are even more worrying. Stations are strongly urged to investigate the causes of the scatters and drifts, because it is then likely that there are also large scatters and drifts within

passes. Fortunately, there is little evidence of correlations between range bias and system delay (although if there were, it should be easily fixed).

Conclusions

The number of passes acquired by WPLTN stations has improved in the 12 months to October 2006, and now exceeds Eurolas. This is largely due to the commissioning of San Juan and upgrades at some other stations. Most stations now track GPS-35 &-36 successfully, at night. When stations like Changchun and San Juan achieve daylight tracking, the productivity ratios should improve even further.

The analysts prefer passes well tracked from observing horizon to observing horizon, or at worst that include segments near both horizons and at maximum elevation. NPs/Pass is a rough measure of how well this is achieved, but inspection of the NICT reports shows that sparse passes invariably fail to produce a Time Bias of decent quality, which indicates poor NP distribution. Fig.3 indicates that many stations (in all networks) need to improve this aspect of operations.

The quality of WPLTN stations, assessed by Normal Point precision and Range Bias RMS for LAGEOS I & II combined, is an area needing improvement, with only 5 stations showing NP precision better than 3 mm and 3 stations with Range Bias RMS below 8 mm. It is suggested that detailed attention to stabilizing system delays is needed at many stations.

And if you think that this paper is just stating the bleeding obvious, then I have found by long and bitter experience that that is exactly what is sometimes needed!

Acknowledgements

References

[1]   Luck, J.McK.: "*Five Target System Calibration*", Proc. 14th International Laser Ranging Workshop, San Fernando, Spain. Boletin ROA No.5/2005, pp.311-321 (2005)

[2]   Luck, J.McK.: "*Performance of Southern Hemisphere Stations*", these proceedings (2006)

Archiving and Infrastructure Support at the ILRS Data Centers

C. Noll[1], M. Torrence[2], W. Seemueller[3]

1. NASA Goddard Space Flight Center, Code 690.5, Greenbelt, MD 20771, USA.

2. SGT, Inc., mark.h.torrence.1@gsfc.nasa.gov

3. Deutsches Geodätisches Forschungsinstitut (DGFI), Marstallplatz 8, D-80539 Muenchen, Germany.

Contact: seemueller@dgfi.badw.de   /Fax: +49 89 23031-1240,

Carey.Noll@nasa.gov /Fax: 301-614-6015

Abstract

Two global data centers have supported the International Laser Ranging Service (ILRS) since its start in 1998. The Crustal Dynamics Data Information System (CDDIS), located at NASA's Goddard Space Flight Center, and the Eurolas Data Center (EDC), located at DGFI, are active archives of laser ranging data and products derived from these data. The laser data sets consist of on-site normal points and full-rate data. The official ILRS products, currently station positions and EOP, are also made available to the user community through these data centers. Infrastructure support for the ILRS include reports of data holdings and quality, satellite predictions, and station configuration information. This presentation will describe this laser ranging archive available at the ILRS data centers and plans for future enhancements.

Data Center Archive Contents

Currently, the ILRS data and product archive consists of normal point and full-rate data, satellite prediction information, and site positions and velocities. Data since mid-1976 are available at the data centers; ILRS products from January 1993 to the present are also available.

Normal point data is the primary ILRS station data product, gradually replacing on-site sampled data and later full-rate data as the primary data product starting in 1991. Normal points are generated on-site very shortly after the satellite pass and transmitted within a few hours to the ILRS operations centers and, from there, to the ILRS data centers.

Full-rate data were the prime SLR product in the 1970's and early to mid 1980's. In the late 1980's, the normal point generation process was refined and normal points were obtained from the full-rate data during post-processing. In the 1990's, on-site normal point production became the accepted process. In the mid 1990's, the SLR/LLR CSTG subcommission agreed that there was no formal requirement for full-rate due to the transition and acceptance of on-site generated normal points as the prime and only station data product. Many stations, however, continue to provide full-rate data to the ILRS data centers since they are sometimes required for specific needs (e.g., center-of-mass analysis, retroreflector experiments, co-location analysis, etc.). Figure 1 summarizes the data holdings (full-rate or on-site normal point) of the CDDIS archive by year versus satellites tracked and network size.

The ILRS currently provides satellite predictions for the network in two formats: Tuned Inter-Range Vectors (TIRVs) and the newer Consolidated Prediction Format (CPF). The CPF is now considered the operational format for prediction providers and

network stations. However, TIRVs continue to be generated by the prediction providers and made available through email and at the data centers to accommodate stations that are continuing efforts to transition to the CPF.

The CPF information accurately predicts positions and ranges for a much wider variety of laser ranging targets than had been previously possible. Rather than using the tuned IRV's with an integrator, the new predictions provide daily tables of X, Y, and Z positions for each target which can then be interpolated for very accurate predictions. CPF provides an expanded format capability and greatly improves tracking on low satellites because the full modeling potential of the orbit computation at the prediction center will be passed on to the stations. Drag files and special maneuver files are no longer necessary. These predictions are available via email or via anonymous ftp from the data centers.
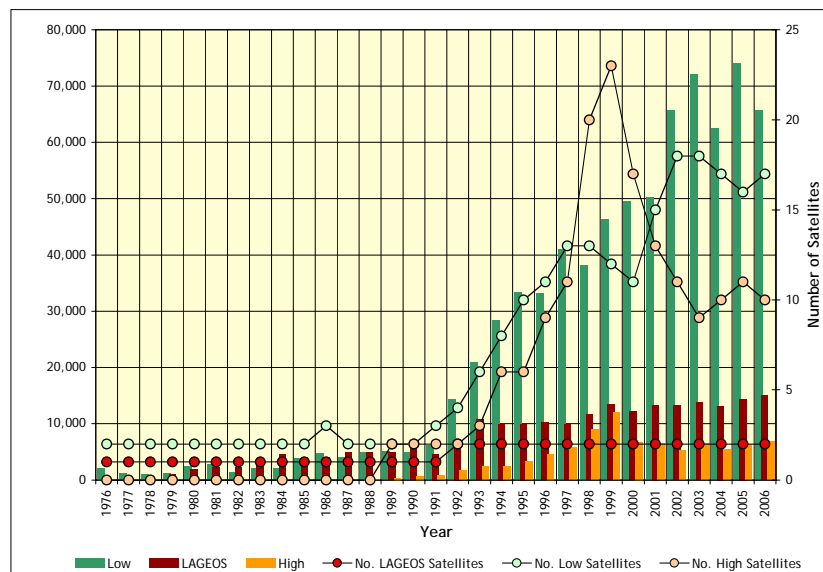
Figure 1. *Laser ranging data volume by year*

Six ILRS analysis centers (AC), ASI/Italy, BKG/Germany, DGFI/Germany, GFZ/Germany, JCET/USA, and NSGF/UK produce weekly solutions on LAGEOS-1 and -2 for global station coordinates and Earth orientation parameters (EOP). Each week, ASI (primary ILRS Combination Center) and DGFI (backup ILRS Combination Center) merge the individual AC solutions into the official ILRS Combination Product. This combination product is available every Wednesday via anonymous ftp from the data centers. The IERS uses this product for the multi-technique Combination Pilot Project and the Bulletin A EOP.

Performance

The ILRS Central Bureau staff has developed various reports and plots to monitor network performance. This information is updated on a frequent basis dependent upon the type of report. Station operators, analysts, and other ILRS groups can view these reports and plots to quickly ascertain how individual stations are performing as well as how the overall network is supporting the various missions. All plots and reports can be accessed through the station pages on the ILRS Web site at URL http://ilrs.gsfc.nasa.gov/stations.

The ILRS performance "report cards" are generated on a quarterly basis and show data volume, data quality, and ILRS operational compliance information. The

statistics are presented in tabular form by station and sorted by total passes in descending order. Plots of data volume (passes, normal points, minutes of data) and RMS (LAGEOS, Starlette, calibration) are created from this information and available on the report card Web site:

http://ilrs.gsfc.nasa.gov/stations/site_info/global_report_cards/index.html

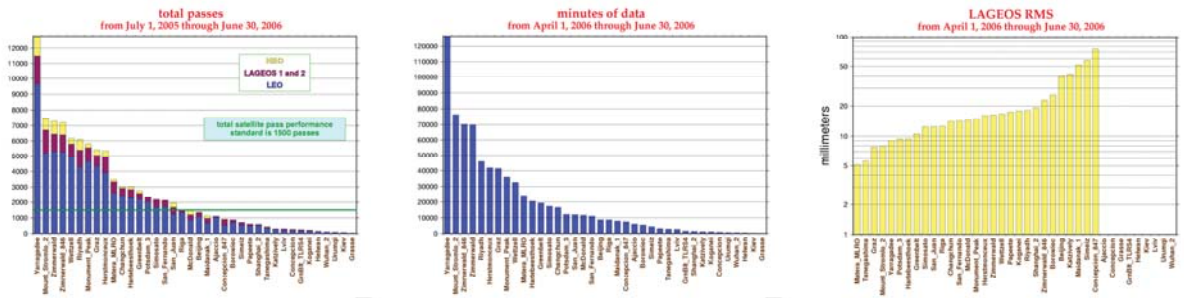Example plots from the latest report card are shown in Figure 2.

Figure 2a. *Total passes for 2006q3 report card.*

Figure 2b. *Minutes of data for 2006q3 report card.*

Figure 2c. *LAGEOS RMS for 2006q3 report card.*

A plot of the satellite ground tracks of the last seven days of geodetic satellite data is updated daily and available through the ILRS Web site at:

http://ilrs.gsfc.nasa.gov/stations/recent_groundtrack.html.

The plot, shown in Figure 3 for a week in November 2006, graphs the actual network ground tracks of Etalon, LAGEOS, Ajisai, Starlette, and Stella over the previous seven days based upon the archived normal point data.
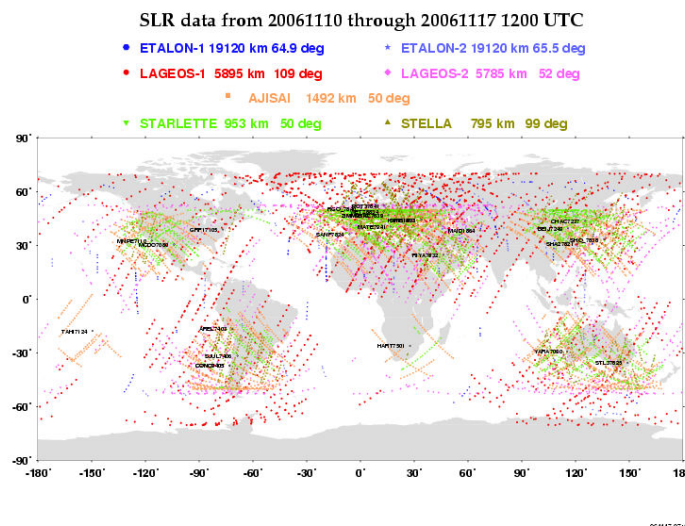
Figure 3. *Plot of the satellite ground tracks of the last seven days of geodetic satellite data.*

Plots of station performance and meteorological data are regularly generated. The plots are sorted by station and come in two forms: for data from the past year and for data since the year 2000. The information presented in these plots for each station in the ILRS network are: total number of normal points, total number of full-rate points, average number of data points per LAGEOS normal point, LAGEOS normal point rms, calibration rms, and system delay, and station temperature, pressure, and

humidity (as recorded in the normal point data). Examples of these plots for the Yarragadee station are shown in Figure 4. The plots are available through the individual station pages on the ILRS Web site (http://ilrs.gsfc.nasa.gov/stations).
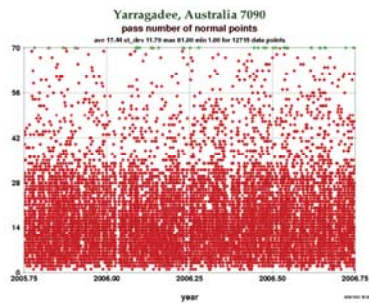

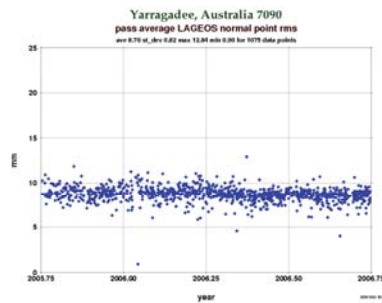**Figure 4a.** *Total number of normal points from Yarragadee for the past year.*

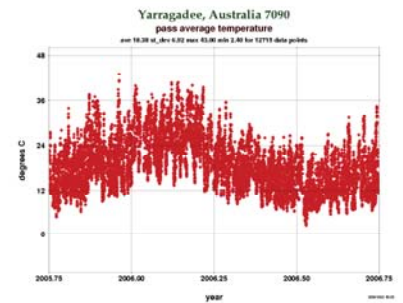**Figure 4b.** *Pass average LAGEOS normal point RMS from Yarragadee for the past year.*

Figure 4c. *Average temperature Yarragadee for the past year.*

Future Plans

Additional plots of station performance are under development for the ILRS Web site. These plots include statistics for all currently tracked satellites and all operational stations as a function of time; full-rate observations per normal point and normal point rms are also computed as a function of range and time. Examples of the new charts for the Yarragadee station are shown in Figure 5 below.
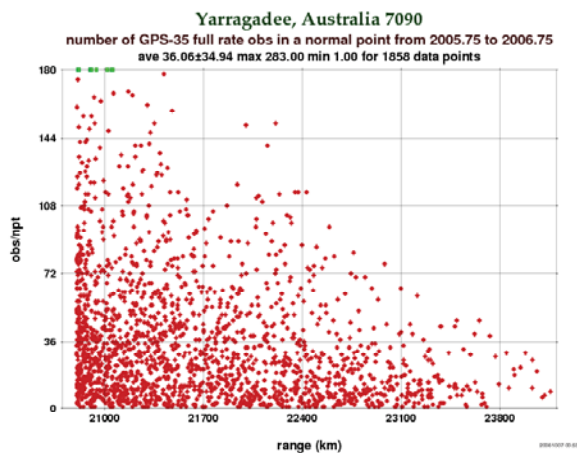
Figure 5a. *Number of GPS-35 full-rate observations per normal point from Yarragadee for the past year.*
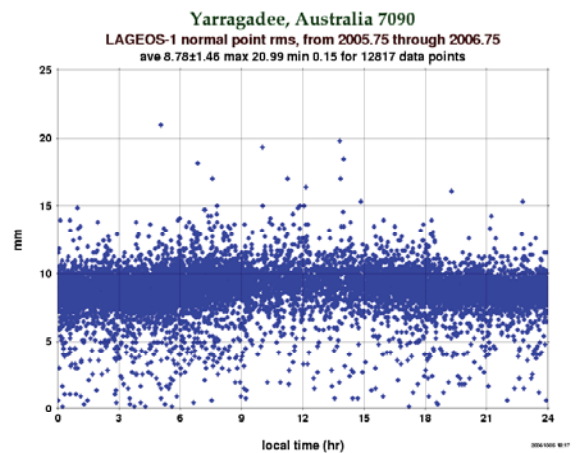
Figure 5b. *LAGEOS-1 normal point rms from Yarragadee for the past year.*

Minico Calibration of System Delay Calibration at Mount Stromlo SLR

John McK. Luck[1]

1. EOS Space Systems Pty.Ltd., Canberra, Australia

Abstract

The MINICO method of ranging to four ground targets in rapid succession has been adopted as a nearly daily routine at Stromlo. In essence, it calibrates the range used for regular pre- and post-pass system delay calibrations. It also provides interesting information on the stability of the calibration pillars and of the telescope pier. There is a clear annual cycle of amplitude 1 mm in the results. The routine biennial precision ground survey was performed in August 2006. Its agreement, or otherwise, with the MINICO determinations of pier ranges will be presented.

A Summary of Observations of GioveA, taken from Mt Stromlo SLR Station

C.J. Moore[1]

1.   EOS Space Systems Pty. Limited, 111 Canberra Ave., Griffith, A.C.T. Australia.

Contact: cmoore@eos-aus.com

Abstract

A summary of satellite Giove A SLR data taken at Mt Stromlo over the period from May to August 2006 is presented, and some factors affecting tracking productivity are discussed. Although in a high earth orbit, Giove A has a large optical back scattering cross-section, and this has provided data for an empirical analysis of link budget factors which has allowed potential productivity gains to be assessed.

Introduction

The new Mt Stromlo SLR station has been in operation since December 2004 and data production has been reasonable and overall performance has been very good. Mt Stromlo productivity levels often exceed many other SLR stations. Nevertheless, improvements can be always be made, and this paper describes an analysis of the potential increases to productivity levels that may result from increased laser output energy, particularly as it applies to tracking Giove A and other high earth orbit satellites.

Total number of passes	77	100%
Number low elevation	11	14%
Number weather affected	33	43%
Number available	33	43%
Number attempted	21	27%
Number tracked	12	15%
Tracked/Possible	12/33	36%

***Table 1** Productivity Metrics*

SLR productivity (i.e. detection of returns) of high satellites is particularly sensitive to environmental factors such as cloud, air mass water vapour content and photon noise during daylight hours. These high satellites include the Glonass and GPS satellites, Etalon 1 and 2 and the first Galileo test satellite, Giove A. Satellites such as Lageos 1 and 2 are also affected although to a lesser extent. To illustrate the relationships between laser energy and productivity from high satellites, an analysis of Giove A tracking at Mt Stromlo is presented, particularly taking into account actual availability of passes and their distribution with elevation.
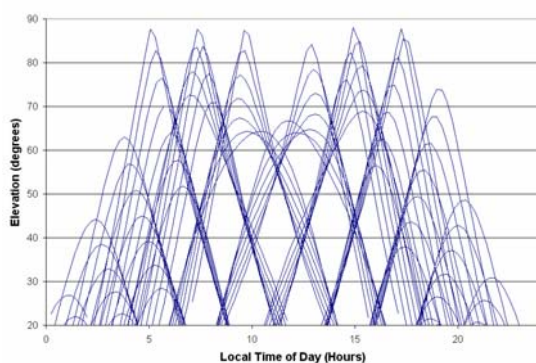
Tracking Giove A

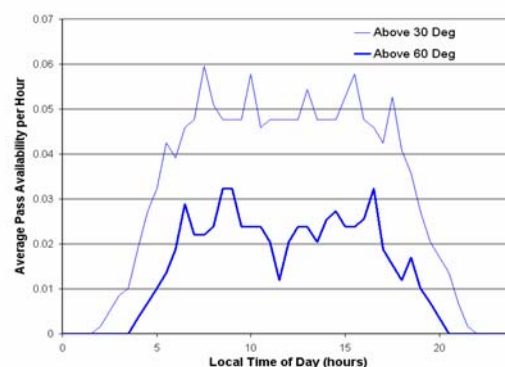***Figure 1:***Giove A passes, June 1 to August 9, 2006*

Figure 2: *Giove A Pass Availability*

Although Giove A was launched in December 2005, the ILRS was not requested to commence SLR tracking until late May 2006. The data from Mt Stromlo presented here are from observations taken from June 1st until August 9th (i.e. day 152 to 221). Table 1 summarizes the productivity statistics for this period and Figure 1 shows all of the available passes above the site's 20 degree horizon for this period.

By plotting pass elevations over 24 hour intervals, it was found that Giove A availability during the data period was on average not evenly distributed throughout the day. Figure 2 shows a frequency distribution plot (using time intervals of 0.1 hours) which indicated that there was a gap in passes during the period from approximately 18:00 to 04:00 local time (8:00 to 18:00 UTC) where passes were very sparse. There was also a significant reduction of very high passes in the middle of the day.

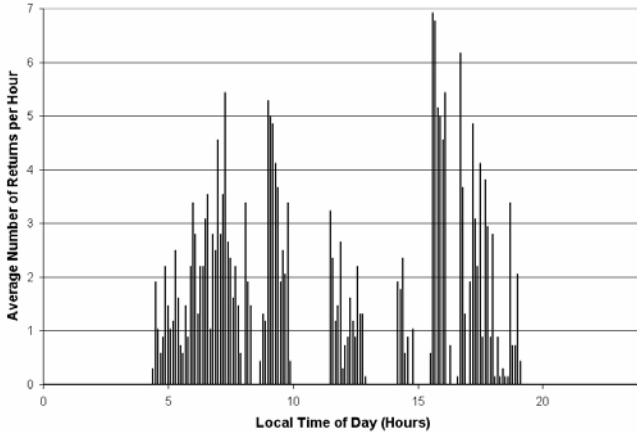### *Actual Productivity of Giove A at Mt Stromlo*

Figure 3: *Giove A Productivity*

While there are many factors affecting successful SLR tracking, it does appear that the distribution of available passes had influenced actual productivity of Giove A. Figure 3 shows the average distribution of number of successful (single-shot) returns over the course of a day, and as expected there were no passes tracked during the middle of the night. The impact of a reduced number of very high passes in the middle of the day is also apparent. However other factors such as sun avoidance and increased daylight noise would have also contributed to reduced productivity.

Figure 2 illustrates that SLR returns were being obtained from a wide range of target elevations (and thus ranges). To assess how productivity was dependent on target elevation a link budget analysis was performed. The following sections describe this analysis and results obtained.

Link Budget Analysis

Estimation of the SLR link budget was made using the standard link budget formulae which determines the average number of detected photons (returns) per laser pulse, N_{pe}, as [1],

$$N_{pe} = \eta_q E_T \frac{\lambda}{hc} \eta_T G_T \sigma_{sat} (4\pi R^2)^{-2} A_T \eta_R \tau_A^2 \tau_C^2 \tag{1}$$

The transmit gain, G_T is given by $\quad G_T = \dfrac{8}{\theta_K^2} \exp\left[-2\left(\dfrac{\theta_P}{\theta_K}\right)^2\right]$

For Giove-A and Mt Stromlo SLR laser we set the detector quantum efficiency, η_q, to 20%, the transmit and receive path efficiencies, η_R, η_T, to 90%, the laser pulse energy, E_T, to 13.5 mJ, the receive aperture area, A_T, to 0.7 m^2, the beam spread,

θ_P, to 1 arcsec, the pointing accuracy, θ_K, to 2 arcsec and the usual values to wavelength, λ, Planck's constant, h, and speed of light, c. The atmospheric transmittance, τ_A, was determined from an elevation dependent model [2] which gives transmittance at zenith of approximately 81% reducing to 72% at 20 degrees.

Figure 4: Link Budget versus Elevation

Clear skies were assumed, so that cloud transmittance, τ_C, was set to 100%.

The Satellite back scattering cross section, σ_{sat}, for Giove A has been estimated to be in the order of $46 \times 10^6 \, m^2$ (Dave Arnold, private communication). R is the distance from station to satellite (in meters) and is determined from orbit predictions.

The absolute value of estimated link budget is not critical and errors due to these assumptions do not affect this analysis. However, using these values, the average link budget estimates for Giove A against satellite elevation was calculated as shown in Figure 4. The polynomial regression line fitted to the average link budget estimates allows conversion or mapping between elevation, link budget estimates and hence laser energy. This equation is

$$N_{pe} = 0.0243 + 0.0092 \times Elev - 4 \times 10^{-5} Elev^2 \qquad (2)$$

where the elevation, *Elev*, is valid over the range 15 to 85 degrees.

Elevation Analysis

The mapping between link budget estimates and elevation allowed elevation to be used to provide a relationship between link budget estimates (i.e. laser power) and productivity. This analysis presents statistical analysis based on 5 degree elevation intervals from 20 degrees (the site horizon) to 90 degrees. For each elevation interval, the actual number of returns achieved (productivity) was normalized by the number of available passes in each interval to give the number of returns per pass.

The number of available passes per elevation interval is shown in Figure 5 and the productivity data for each elevation interval is shown in Figure 6. The second plot clearly illustrates that productivity falls with lower elevations (due to a decreasing link budget from an increasing range) and higher elevations (due to a lower number of available passes).

Figure 5: Available Giove A Passes versus Elevation

Hence a normalized productivity can be determined by dividing actual productivity data by the data availability. The results for Giove A are shown in Figure 7.
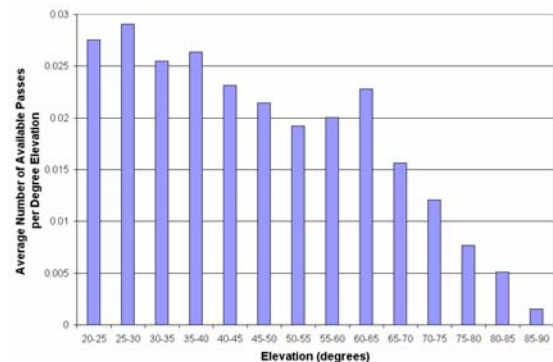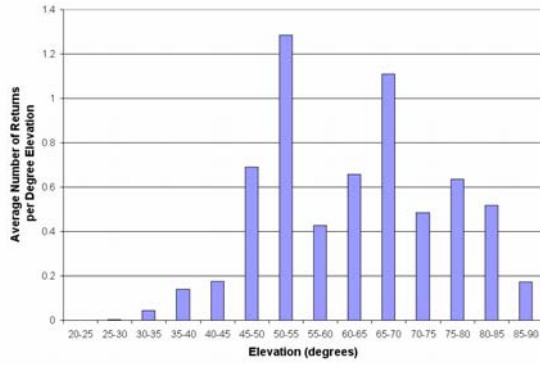
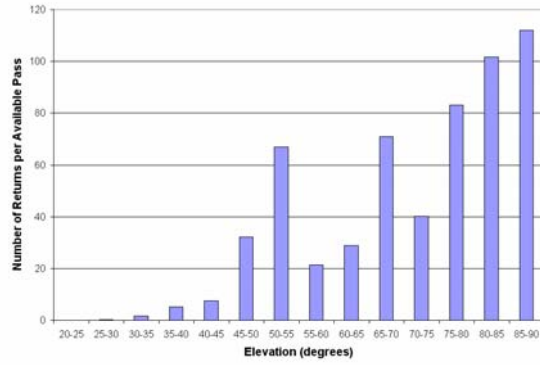**Figure 6:** *Giove A Productivity versus Elevation*

Figure 7: *Giove A Normalized Productivity versus Elevation*

Normalized Productivity

Figure 7 illustrates that, all else being equal, more returns are expected when the satellite is at a higher elevation. Scatter in this data indicates that in practice other factors such as weather are influencing productivity. It also appears that below approximately 40 to 45 degrees elevation, few returns were being detected with the given laser power levels.

When returns were detected at the lower elevations, observation logs indicated that the atmosphere was particularly clear and clean of particles, and that a strong signal had already been detected, and the satellite was being tracked as it descended in elevation.
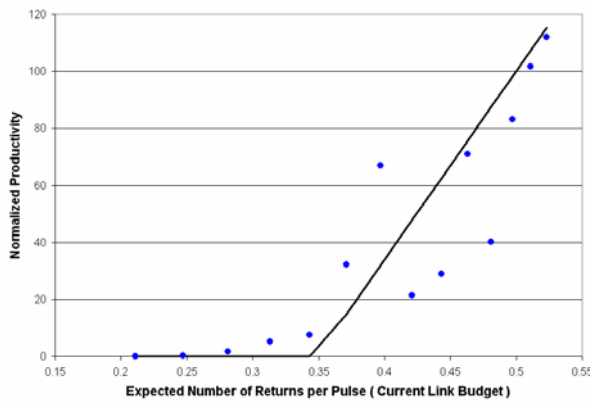

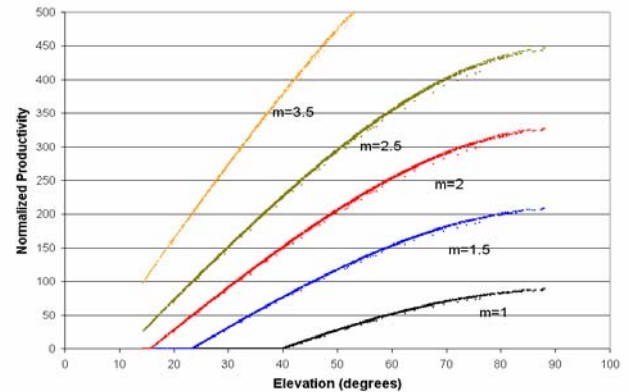**Figure 8:** *Normalized Productivity versus Link Budget*

Figure 9: *Normalized Productivity Gains*

Using the conversion equation (2), normalized productivity can be compared to estimated link budget for each elevation interval. The results are shown in the Figure 8.

It appears that for link budget levels below 0.35 there is little or no productivity. For levels above 0.35, normalized productivity (η) appears to increase linearly with estimated link budget. A regression equation gives

$$\eta = 660 \times N_{pe} - 230 \quad N_{pe} > 0.35$$
$$\eta = 0 \quad\quad\quad\quad\quad\quad N_{pe} < 0.35$$

(3)

Of course ideally, it should be expected that actual return rate is proportional to expected return rate. In practice, it appears that this may be the case once the link budget reaches some "threshold" value.

Potential Productivity Gains

Equation (3) suggests that increasing the link budget (say by increasing laser power) to values less than 0.35 will give little or no improvement to productivity levels. However there should be significant gains by increasing link budget levels that are currently below 0.35 to values in excess of the 0.35.

Consider an increased link budget $N'_{pe} = mN_{pe}$ which is a result of multiplying current levels by a factor of m. From equation (3) the actual normalized productivity rate is expected to be now η', where

$$\eta' = 660 \times mN_{pe} - 230 \quad mN_{pe} > 0.35$$
$$\eta' = 0 \qquad\qquad\qquad mN_{pe} < 0.35$$

(4)

Figure 9 shows plots of increased normalized productivity depending on the link budget multiplier, m.

Using the data gathered on Giove A pass availability, as shown in figure 5, the effect of link budget increases on actual productivity can be determined. Figure 10 shows such productivity plots for various values of m. The heavy line with m =1 is a smoothed curve using current data and is effectively equivalent to the plot shown in Figure 6.
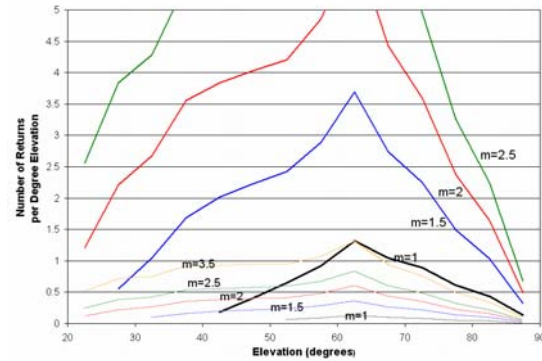

Figure 10: Productivity Gains

There are two sets of plots shown in Figure 10. The darker lines represent productivity increases based on current data while the lighter lines represent productivities assuming a factor of 10 (or 1 ND) loss in the number of returned photons. This factor is chosen to represent the loss when the enclosure glass window is installed and to account to some degree the effect of less than ideal sky conditions. The next section describes an analysis on the effect of the enclosure window, and for weak signals, it appears that a factor of 4 in link budget is required to compensate for the glass window.

It is clear that based on current data, increasing the link budget by 50% or 100% should make a substantial improvement to productivity including the possibility of obtaining reasonable number of returns from Giove A at elevations below 30 degrees. However, it is important that improved productivity levels can be maintained when the enclosure window is in place or when sky conditions deteriorate. Assuming a 1 ND loss, the second figure shows that an increase in link budget by a factor of 2 or more will be sufficient to maintain productivity at levels at least as good as current levels, and probably better at elevations below 40 degrees.

Effect of Enclosure Window

The Mt Stromlo SLR station is designed to allow continuous and unmanned operations in all weather conditions. This is in part achieved by having a weather-proof telescope enclosure incorporating a glass window. Such a window has many advantages for operations, but will also attenuate the transmit and receive beams. An assessment of the net impact from operating through the glass window is presented from comparisons made with data obtained when there was no glass window in place, i.e. the glass window is exchanged with an "air window".

Near Field Target

A comparison of measurements to calibration pier (at a range of approximately 92m) with and without the glass window in place are shown in the Figure 11. The mean difference between the signals is approximately 0.061 ns (in two way time of flight) consistent with having a window with glass thickness of 18.3mm.

For a given configuration (i.e. fixed laser power, ND filters etc.) and equal time periods the return rate with a glass window in place is 6.8% while in air the rate is 10.3%. Thus the difference in average return rate gives a loss of approximately 30%.
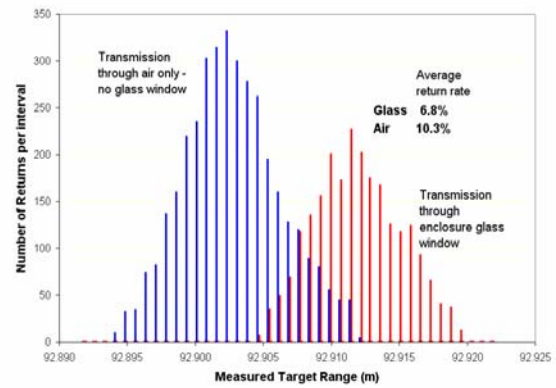

Figure 11: *Near Field Target Histogram*

Far Field Targets

Data from far field targets at ranges of 6,100 to 10,000 km allows a comparison of results for relatively good signals (Lageos 1) and weaker signals (Lageos 2). These satellites are used since comparisons are difficult using much higher satellites when fewer returns are available when the glass window is in place. The second and third plots show average return rates and return rate (suitably normalized by tracking periods) distributions for the two signal levels.
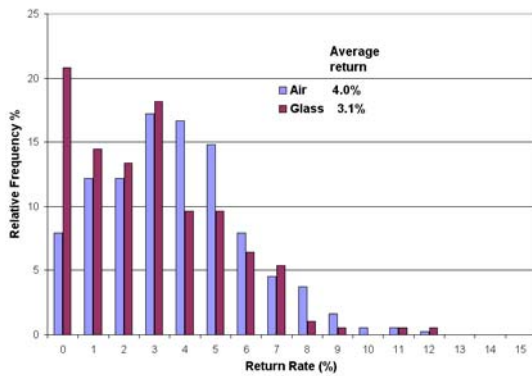

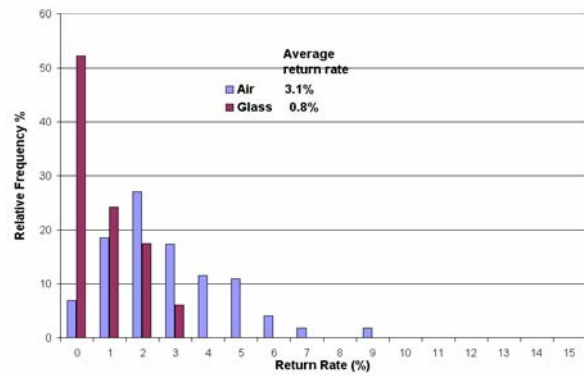**Figure 12:** *Lageos 1 Return Rate Distribution*

Figure 13: *Lageos 2 Return Rate Distribution*

Good Return Signal

When average return rate is relatively good, above 4% in air, the average return rate decreased to about 3% when the glass window was in place - indicating a 25-30% loss, similar to that for a near field target. The plot clearly demonstrates the relative decline in return rates above 3% when the window is in place and also the greater fraction of time there are no returns.

Weak Return Signal

When the return signal is weaker, in the case around 3% in air, the effect of the glass window is proportionally greater as illustrated in the third plot. In this case, the average return dropped to less than 1% when the glass was in place giving a loss of

over 75%. Return rates with the glass in place do not exceed 4% and there are no returns for at least 50% of the time.

Conclusions

Mt Stromlo SLR station has successfully tracked Giove A for a number of months commencing in June 2006. A link budget analysis of the distribution of productivity data for this satellite with elevation has allowed an assessment of factors that may improve SLR productivity for Giove A (and other high earth orbit satellites).

Threshold effects associated with decreasing link budgets have been identified both during tracking of Giove A (e.g. with decreasing elevation) and also with Lageos 1 and 2 with transmission though air versus a glass enclosure window. Such threshold effects result in a rapid deterioration in detectable signal when return rates fall below approximately 3 or 4% for the current configuration at Mt Stromlo. Because of this threshold effect, it is possible that an increase in the link budget by a factor of two or better may lead to a substantial improvement in productivity. It is hoped that such an improvement can be demonstrated once the planned upgrade of the SLR laser power at Mt Stromlo has been implemented.

References:

[1] Degnan, J., Millimeter Accuracy Satellite Laser Ranging: A Review. Geodynamics Series 25.
[2] Degnan, J., 1993. AGU Geodynamics Monograph Vol.25, p.139-140