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.

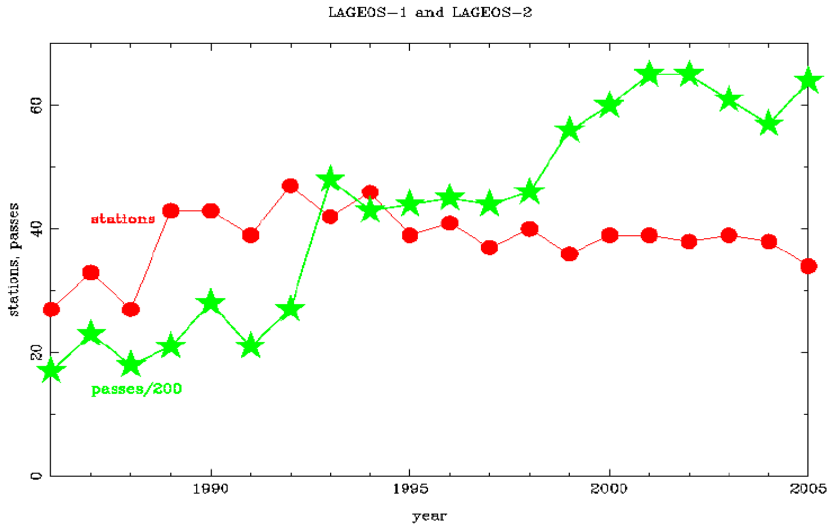

Figure 1. *The yearly number of stations that tracked LAGEOS-1 and/or LAGEOS-2, and their production in terms of number of passes.*

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.

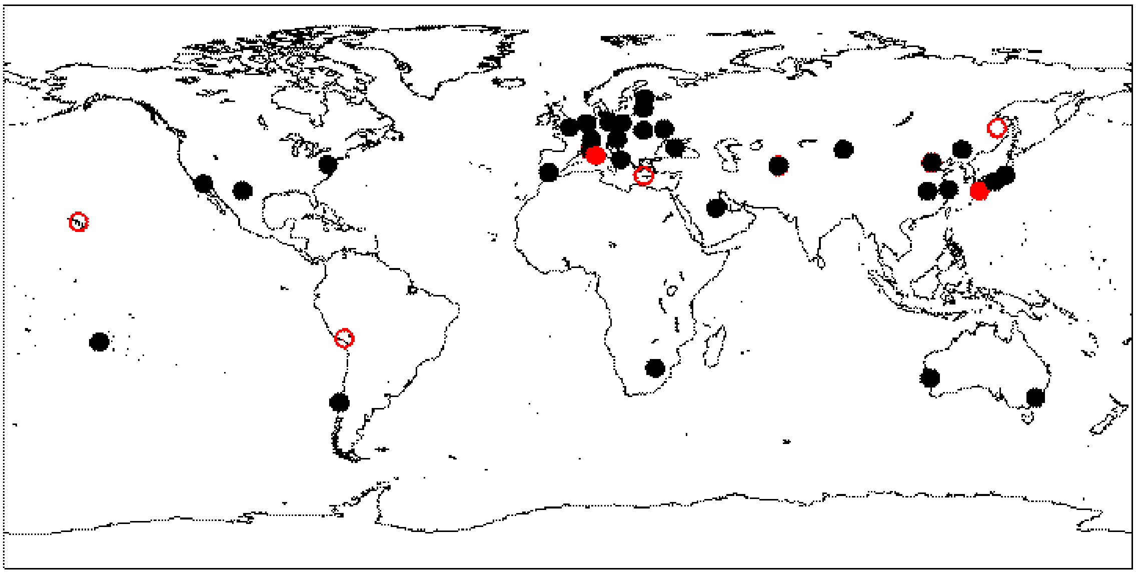

__Figure 2.__ The global network of SLR stations, Black circles indicate stations that have been active in both 2003 and 2005. Open red circles represent stations that were active in 2003, but not in 2005. Solid red circles represent stations that were active in 2005, but not in 2003.

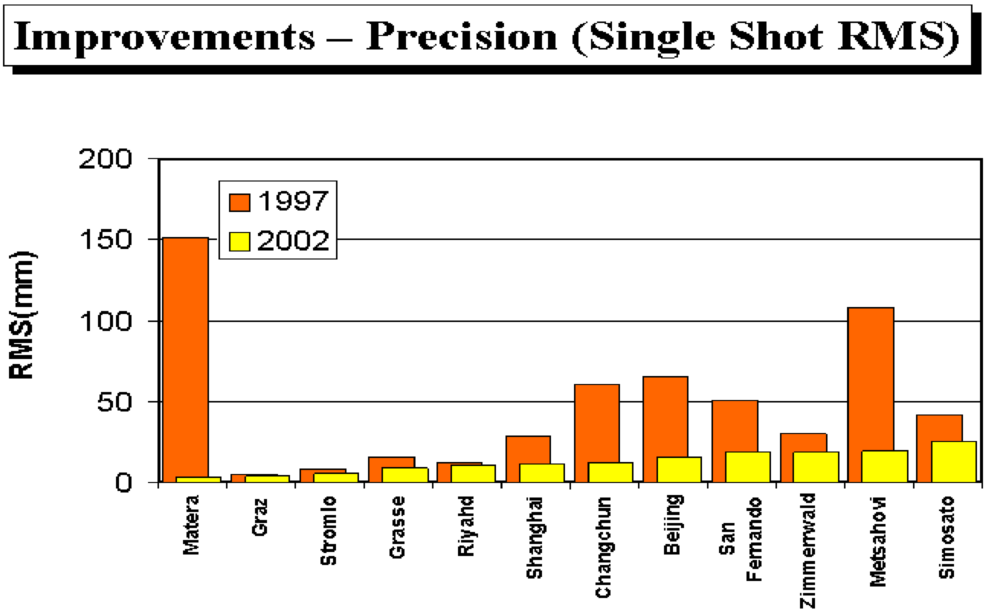

__Figure 3.__ A comparison of the single-shot precision of a number of representative SLR stations, in 2002 as compared to 1997 (courtesy Van Husson).

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.

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

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

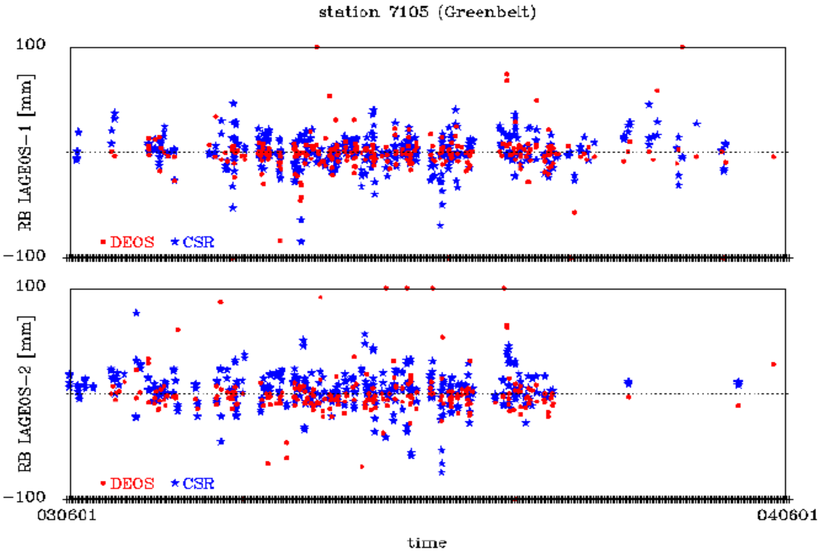

Figure 4. *A comparison of bias values reported for common LAGEOS-1 passes over station Greenbelt by QC centers CSR and Delft, as an illustration of the scatter and uncertainties in these values (direct comparison).*

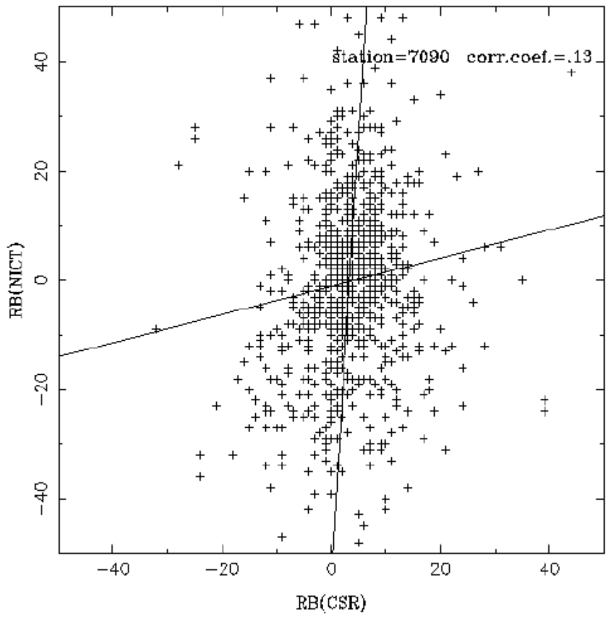

Figure 5. *A comparison of bias values reported for common LAGEOS-1 passes over station Yarragadee by QC centers CSR and NICT, as an illustration of the scatter and uncertainties in these values (covariance-style comparison).*

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.

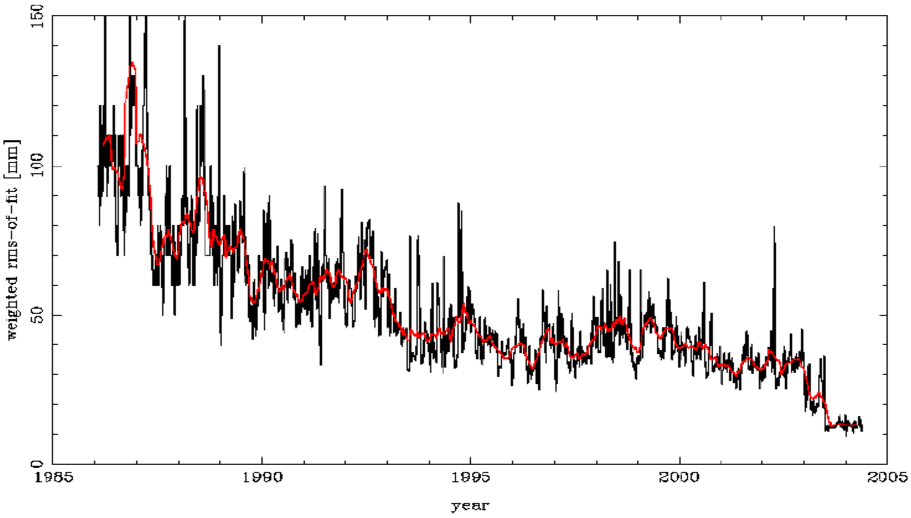

Figure 6. *Overview of the LAGEOS-1 rms-of-fit of the weekly orbital computations as done by Delft University of Technology.*

	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).

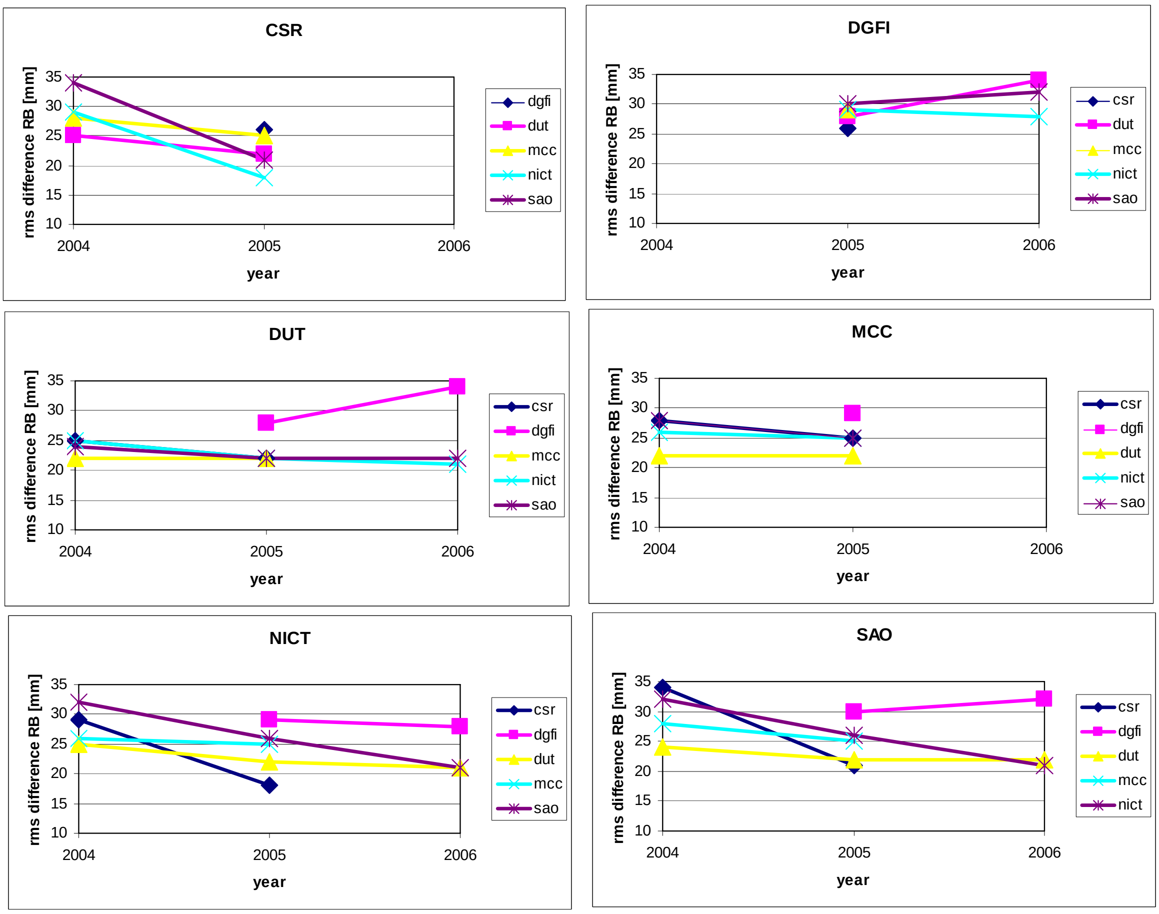

Figure 7. *Statistics of the differences between bias values for common LAGEOS-1 and LAGEOS-2 passes observed by the global network of SLR stations, as reported by various pairs of QC centers. Entries are for 2004, 2005 and 2006, respectively. All values are in mm*

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.*

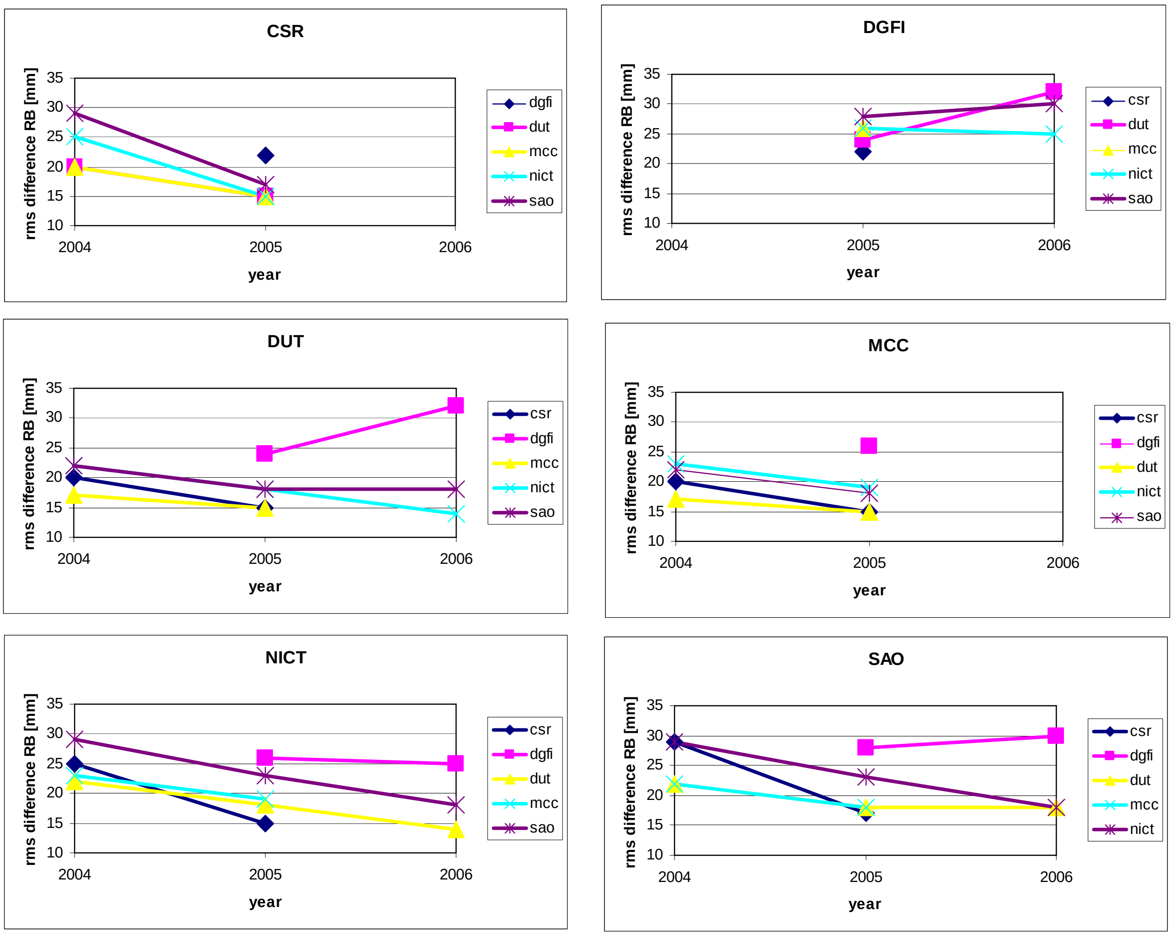

Figure 8. *Statistics of the differences between bias values for common LAGEOS-1 and LAGEOS-2 passes observed by the so-called AWG core stations, as reported by various pairs of QC centers. Entries are for 2004, 2005 and 2006, respectively. All values are in mm.*

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

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