

18 YEARS OF QC ANALYSIS AT DELFT UNIVERSITY OF TECHNOLOGY

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Abstract

In this paper the development and performance of the Quick-Look Data Analysis Center of Delft University of Technology over almost two complete decades is evaluated. Based on orbit computation of the LAGEOS satellites, this analysis has been used for a variety of purposes: (i) support of the WEGENER/MEDLAS project, (ii) rapid-turnaround EOP determination, and (iii) quality control of the global network of SLR stations. The threshold for reliably assessing possible data problems has been reduced by a factor of about 10 over this time-frame, to a level of a few cm at this moment. In addition to illustrating this development and highlighting current performance, recent developments are also addressed.

Introduction

The Quick-Look Data Analysis Center (QLDAC) of Delft University of Technology was initiated in the mid-1980s, as one of the Delft contributions to the WEGENER/MEDLAS project [Reinhart 1985]. This project was aimed at the determination of crustal deformations in the central and eastern Mediterranean area, by deploying transportable SLR systems on specific locations for relatively short periods of time, and doing repeat observations in successive years. QLDAC started its operations officially in January 1986. With the exception of the first few months of 1987, the analysis system has operated continuously, and still does so to this very day. In essence, three different (partly overlapping) time-periods can be distinguished, which are more-or-less governed by the specific targets of the weekly analyses.

Initially, the analysis activities were fully devoted to support the observational campaigns. Here, the specific goal of the analysis was twofold: (i) perform a semi real-time quality assessment of the observations taken by the mobile SLR systems, and (ii) keep track of the number of high-quality passes taken on LAGEOS-1 (LAGEOS-2 was launched in October 1992). As for the first requirement, it was crucial to spend as little time as possible at any location. Possible data problems needed to be identified as soon as possible, which prompted this QC service. At the time, a turnaround period of between 3 days and 10 days was considered acceptable: the analyses were performed every Tuesday, and basically covered the full week from Sunday to Saturday prior to that. As for the second requirement, it was deemed necessary to acquire 50 good passes on LAGEOS-1 to fulfil the science objective, and once that was achieved, to move to the next location. QLDAC operated in this campaign-oriented style in the years in which WEGENER/MEDLAS organized campaigns in the Mediterranean area: 1986, 1987, 1989 and 1992.

A second characteristic element was initiated in the middle of 1987. Initially considered as a by-product, QLDAC was "forced" to solve for Earth Orientation Parameters (EOPs) on a regular basis to maximize the quality of the geometric component of the weekly analyses. Since the semi real-time monitoring of polar motion was an activity done by few analysis centers only at the time, QLDAC was approached by the BIH to submit these parameters for inclusion in their weekly reports. This started in the middle of 1987, and continues to this very day (as contributions to the IERS Bulletin A reports).

Finally, the QC service was expanded to the entire network of SLR stations: it was soon realized that the QC activities were equally well applicable to the other SLR stations, and could be used for their benefit as well. This more global target came to fruition in the years after 1992 for obvious reasons.

Measurement statistics

It is worthwhile to take a look at the input material first. A direct issue here is statistics on the number of stations and passes that have been processed by QLDAC. Figure 1 shows the yearly number of stations that have been active, as well as the yearly number of passes obtained on each of the satellites LAGEOS-1 and -2 (table complete until May 2004).

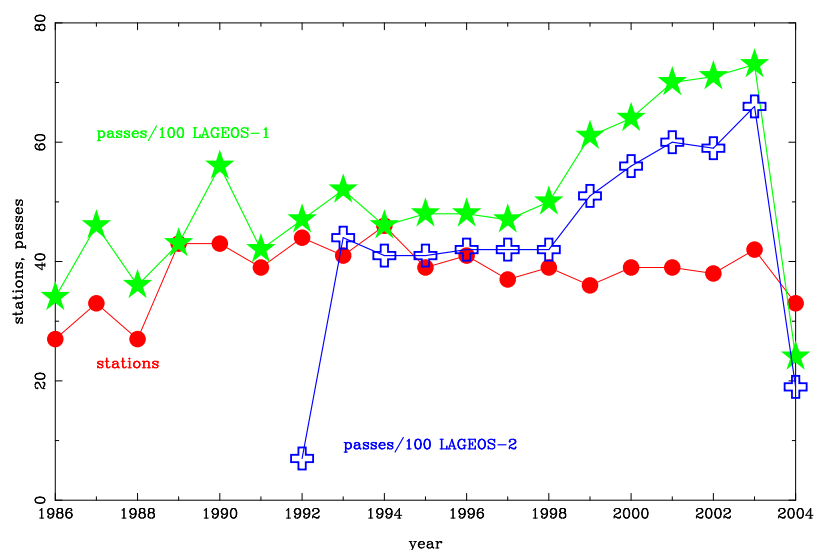


Figure 1: Overview of the yearly number of stations that have tracked LAGEOS-1 and/or LAGEOS-2, plus the yearly number of passes on each of those satellites.

It is clearly visible that the number of stations was modest in the late 1980s, but rapidly increased to about 40 since then. The yearly number of satellite passes shows a steady value in the years until 1998, and a linear rise in the years after that, to about 7500 for LAGEOS-1 and about 6500 for LAGEOS-2. Since the number of stations remains stable, this increased productivity must be ascribed to better efficiencies: more shifts, interleaving, automation, less hardware failures, etc. The data yield on LAGEOS-1 exceeds that of LAGEOS-2 because of more favorable orbital characteristics of the former.

Quality

A crucial element of the QLDAC analyses is of course the overall quality of the computation results; this holds in particular for the QC aspect. This is basically driven by three issues: (i) the quality of the SLR observations themselves, (ii) the quality of the computation model and (iii) the analysis strategy, including the parameters that are solved for and related issues.

Observations

Clearly, the first issue is beyond the control of any analysis center. However, the claimed precision or consistency is known to have improved considerably with time. To illustrate this, Figure 2 shows the single-shot RMS values for a number of stations in their configuration of 1997 and of 2002. It is obvious that these stations (representative for the entire network) have shown considerable progress on this aspect. Clearly, they (and effectively the far majority of the global network) are below the 20 mm

level for single-shot precision, with obvious consequences for the precision of their normal points. The absolute accuracy can be expected to have made similar progress, and this will be the subject of the next section.

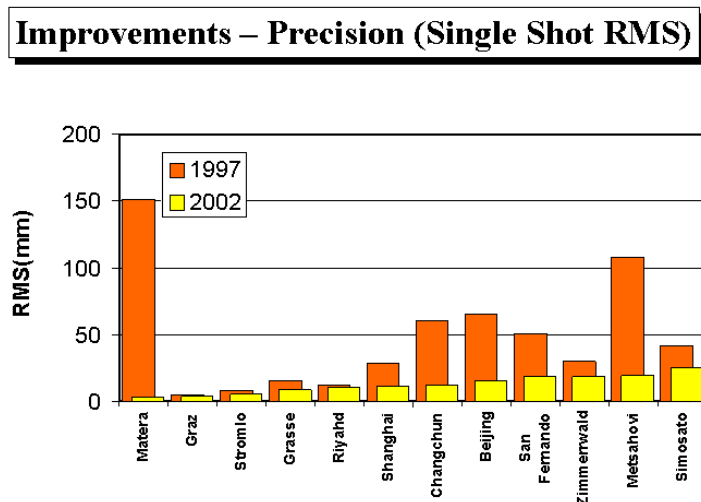


Figure 2: The single-shot precision of a number of SLR stations, for their technical configurations of 1997 and 2002 (courtesy Van Husson).

Models

The quality of the computation model and the analysis strategy are crucial for the level of significance of the QC service. The most important developments are summarized in Table 1. This table clearly shows that the improvements have taken place continuously throughout this 18-year period, albeit that new elements have been introduced "block-wise" at specific dates. Because of the high altitude of the satellites, the LAGEOS pair is relatively insensitive to the (details of the) dynamic forces acting on it; it is reasonable to expect that the changes in the geometric component of the problem (earth reference system, measurement modeling) have played a dominant role here.

Although not of direct influence on the overall technical performance of the analysis system, it is worthwhile to mention here that QLDAC has gone through various stages of practical implementation of the QC activities. Initially, in the WEGENER/MEDLAS years, the analysis system relied on human interference: manual starting of the various conversion and analysis steps, a detailed checking of results, etc. In the 1990s, the system was basically operated in a menu-driven configuration, with interactive means to perform a large variety of QC activities, but always in need of a human operator. Reflecting the decrease of human capacity, the absence of dedicated observational campaigns and benefitting from the improved quality and reliability of the SLR observations and the means of communication, the QLDAC analysis options were trimmed down to the basic elements and the overall system was converted into a fully automatic mode of operation around the turn of the year 2002/2003; in essence, checking of the results is not done until several hours after they have been distributed to the community (or, in case of holidays or meetings abroad, weeks after the event).

Results

The core of the analysis activities is the fitting of a mathematical model of the satellite orbit(s) through the observations taken by the global SLR network, currently in data arcs of 8 days length. This is done with the NASA program for data reduction and geodetic parameter estimation GEODYN-II [Eddy 1990]. Here, the root-mean-square of the weighted residuals (the difference between the actual

date	model element	strategy
January 1986	<i>initial settings</i>	<i>initial settings</i>
May 1987	DUT/SOM 87.1 station coordinates Wahr solid earth tides Schwiderski ocean tides	
April 1989	GEM-T1 gravity and tides DUT/SOM 89.3 station coordinates	
July 1991	GEM-T2 gravity and tides DUT/SOM ERS90 station coordinates	data weight rss 50 mm + station noise
October 1992	LAGEOS-2 251 mm c.o.m. offset	1-cpr radial accelerations estimated
January 1994	JGM-2 gravity and tides DUT/SOM 93L05 station coordinates	3-day EOPs estimated data weight rss 30 mm + station noise
January 2003	EGM96 gravity and tides ITRF2000 station coordinates zero degree elevation cut-off	1-cpr cross-track accelerations estimated data weight rss 15 mm + station noise
July 2003	ocean loading atmospheric pressure loading	1-day EOPs estimated degree-1 gravity field terms estimated estimation of 1-cpr terms twice per arc

Table 1: Overview of the major developments in the QLDAC processing.

observations and the model equivalents) is minimized. Therefore, this rms-of-fit is a good first indicator of the quality of the solution. The time-history of this rms-of-fit is depicted in Figure 3, which covers the full period from 1986 to May 1, 2004. The thin line shows the values for the individual analyses, whereas the red line indicates the running average taken over 15 weekly computations.

It is clearly visible that this fit, and thus the quality of the orbital solutions and that of other parameters, has made significant progress through time: from about 10-12 cm in the WEGENER/MEDLAS days to a consistent 10-15 mm in 2004. As expected, this trend shows a large correlation with the development of the analysis model and the modifications in the analysis strategy, as reported in Table 1.

It will be obvious that the capabilities for the monitoring of the performance of the individual SLR stations, including the detection of possible data anomalies, are proportional to this overall rms-of-fit. In essence, it means that the current threshold for detecting potential data problems (in particular possible range biases) can be put at about 2-3 cm, or equivalent to two times the level of significance as represented by the weighted rms-of-fit.

As an illustration of the current capabilities, Figure 4 shows just one example of the estimated values for the apparent range biases of the station Yarragadee (Australia, site id 7090). This example is representative for the results obtained weekly for the entire network of SLR stations. These biases are not necessarily to be considered as real (systematic) errors in the SLR observations; as long as they remain below the $2\text{-}\sigma$ level (*i.e.* about 2-3 cm), they may equally well reflect the radial uncertainty of the (satellite orbit) solution and/or the model (station coordinates). Only when these range bias values exceed this value, the result is to be interpreted as an actual systematic error of the observations, albeit with an inherent uncertainty of a few centimeter again.

Figure 4 also shows the values derived by the Center for Space Research (CSR) in Austin, Texas. It is clearly visible that the CSR solutions, too, show a similar inherent bias uncertainty of 1-2 cm for this station. It can be shown that real range biases are picked up by QLDAC and CSR with a consistency of a single cm or better. Equivalently, the analysis system provides estimates for the so-called timing

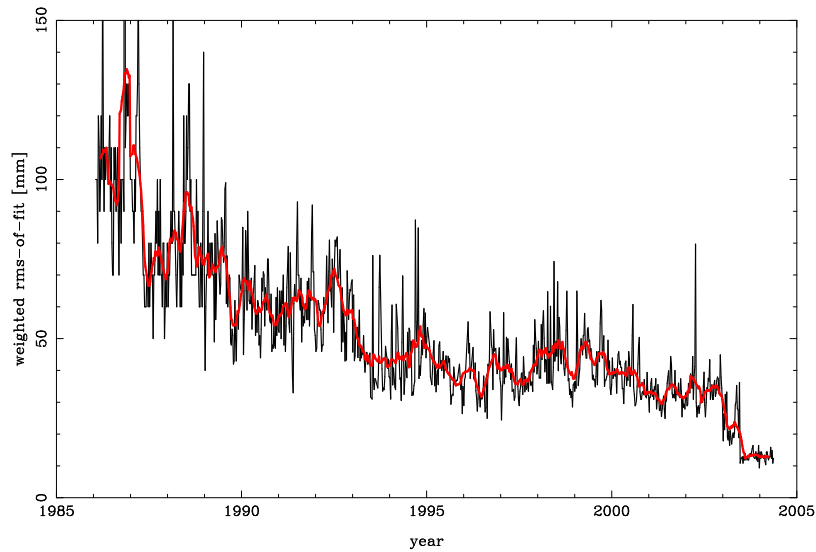


Figure 3: The weighted rms-of-fit of the weekly data analysis, covering the 18-year period over which QLDAC has been operational.

biases. However, since the SLR stations are synchronized at the level of a single nanosecond by virtue of GPS timing techniques, it is unrealistic to interpret these timing biases as real errors of the (time-tagging of the) SLR observations, unless they are very large. Instead, they represent either uncertainties of the orbital solutions, or errors in the model for this particular station position. These timing biases typically have an rms value of about $12 \mu\text{sec}$, which corresponds with an uncertainty in the along-track component of the orbital solutions of about 5 cm [Bock 2004].

As mentioned before, one of the spin-offs of the weekly QC analyses is the solution of EOPs. Because of the 100% correlation with the ascending node of the satellite(s), estimation of the UT1-UTC component cannot be considered as a realistic contribution, and is to be ignored by definition. The time-interval for which EOPs have been estimated has changed throughout the years from 5 days to 3 days to 1 day (cf. Table 1). The rms scatter of the daily pole position solutions is about 0.4-0.5 marcsec. A similar rms value was representative for the quality of the EOP solutions in the late 1980s and 1990s, albeit for 5-day and 3-day estimation intervals, so progress is visible here too.

Recent developments

At this moment (June 2004), the QLDAC analyses are performed on a weekly basis: the QC assessments are performed every Tuesday, and relate to the observations taken in the previous week running from Sunday to Saturday. It is recognized that this analysis frequency and delay w.r.t. the actual epoch of data-taking is far from ideal according to modern standards. Therefore, QLDAC has been testing a daily analysis of the observations. This analysis is performed around noon every day, and covers the 8 full days directly prior to the day on which the analysis is done. In technical details and procedures, this daily analysis is identical to the current standard product. Clearly, the major benefit from this high-frequency evaluation is the rapid QC feedback to the stations. These can be expected to benefit from the rapid turn-around of these new high-frequency analyses (which, on average, reduces the time-delay from $0.5 \times 8 + 2 = 6$ days to $0.5 + 0.5 = 1$ day). This new daily service will replace the current weekly service in the Summer of 2004.

Conclusions

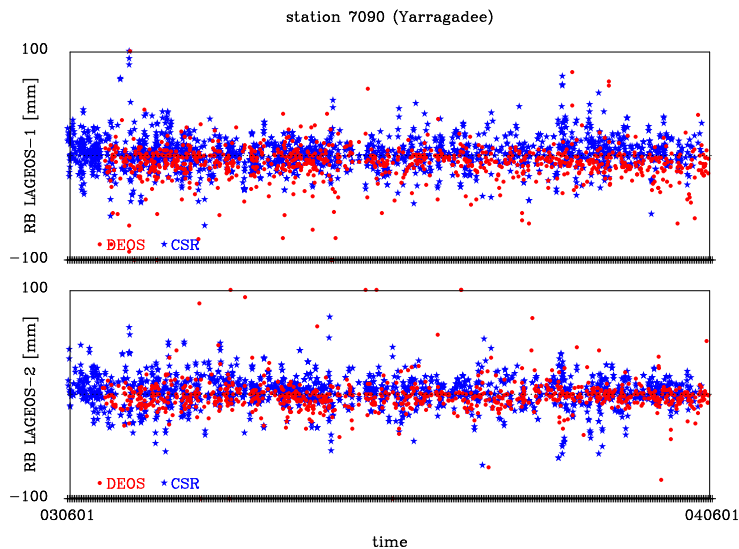


Figure 4: Time-history of the apparent range biases of station Yarragadee (Australia, 7090), as determined by QLDAC (red circles) and CSR (blue stars), during the period June 2003 - June 2004, for LAGEOS-1 (top) and LAGEOS-2 (bottom), respectively.

In conclusion, the performance of QLDAC has shown a considerable development over the course of almost two decades as described here, and with it the capability to detect possible data problems: initially this was at the level of several dm, whereas nowadays this has been reduced by a factor of about 10. QLDAC is expected to shift from a weekly, fully automated operational scheme to a daily scheme, in order to better satisfy modern turn-around requirements for data quality evaluations.

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