

# Time Bias of Laser Ranging Observations

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## Abstract

The Time Transfer by Laser Link (T2L2) experiment on-board Jason-2 allowed the comparison of remote clocks located at the Satellite Laser Ranging (SLR) stations of the International Laser Ranging Service (ILRS) to a level of a few nanoseconds (ns). The ILRS has a standard requirement that all sites maintain their local time within  $\pm 100$  ns of Coordinated Universal Time UTC(GPS). To accomplish this comparison, we computed a dynamical on-board time scale using the many ground-to-space time transfers that were observed by the Grasse SLR station, together with a frequency model of the reference oscillator (clock) of the Jason-2 satellite. Calibrated ground links at the Grasse station achieved an accuracy of 3 ns relative to the "GPS time" scale. From many calculations of the time transfer in non-common view from Grasse to the other SLR stations, we established a history of time biases per station over 8 years (2008-2016). We observe time biases of up to several microseconds for some stations. Following the recommendation of the ILRS-Analysis Working Group, we converted these series into a common file of time bias and phase drift values using the Solution INdependent EXchange (SINEX) format in order to be considered for inclusion in the Precise Orbit Determination (POD) and analyses for estimation of geophysical products using SLR observations.

**Keywords:** time transfer, satellite laser ranging, systematic errors, time bias

## 1 Introduction

Many space geodesy applications currently demand better accuracy and better long-term stability, including the terrestrial reference frame and the precise orbit determination of Earth observation satellites (e.g. Zelensky et al. [2010, 2014]). In addition to other space geodesy techniques, the Satellite Laser Ranging (SLR) is affected by range biases; caused by a combination of interaction of the laser pulses with a target retro-reflector, as well as unaccounted for electronic delays at the station [Appleby et al., 2016]. In addition recent experiments involving time transfer by laser ranging using the Jason-2 Time Transfer by Laser Link (T2L2) experiment showed that the reference clocks used by some laser ranging stations are not always well synchronized to UTC ( $> \pm 100$  ns).

The resulting "time bias" of the ranging measurements, however, is not easily detected by Precise Orbit Determination (POD) beyond the level of a few  $\mu$ s. Whereas the range bias is correlated with the radial component of the orbit and with the altitude of the station, the time bias is correlated with the along-track component of the orbit. For a time shift of 1  $\mu$ s, the along-track error depends on the satellite velocity with an effect

of 6-7 mm for Low Earth Orbit (LEO) observation missions and up to 4 mm for LAGEOS. The Time Transfer by Laser Link (T2L2) experiment on-board Jason-2 provides many opportunities to independently validate and/or calibrate the local time scale of the SLR stations.

The first metrological results were obtained using time transfer where SLR stations in Europe viewed the Jason-2 satellite at nearly the same time (known as the common-view mode). Observations in common-view mode bypass the phase & frequency changes of the oscillator and allow ground-to-ground time transfer of tens of picoseconds stability over 100 seconds with an accuracy better than 1 ns [Exertier et al., 2014]. On the other hand, taking into account the altitude of Jason-2 (of 1336 km), the comparison of remote ground clocks located on different continents can only be achieved through the calculation of a dynamical on-orbit time scale to account for the time-of-flight of the satellite between the ground stations. We demonstrated that this time scale can be realized from the many ground-to-space time transfers that were observed by a sub-network of SLR stations equipped with an H<sub>2</sub>-maser clock together with a frequency model of the on-board oscillator [Belli et al., 2016]. By integrating this model over more than 10,000 seconds from a primary SLR ground station which local time scale was referenced to the *Global Positioning System (GPS) time* (near UTC) at 1 ns, we calculated all possible non-common view time transfers resulting in the synchronization of the International Laser Ranging Service (ILRS) network of stations to UTC from 2008 to 2016 [Exertier et al., 2017].

The result of this synchronization, under the form of a history of time shifts per station relative to UTC, however, showed a great inhomogeneity of the current laser ranging network from the point of view of Time and Frequency (T/F). A few stations have been calibrated enabling a long-term stability of their reference clock to a few nanoseconds accuracy relative to UTC. But many T/F systems (clocks) used in SLR stations actually have a time shift (a systematic error in the

epoch of observations) greater than 100 ns, which is the limit for space geodesy purposes that has been recommended by the ILRS [Pearlman et al., 2002].

The purpose of this paper, after summarizing the principle, method and results, is to demonstrate that the time biases determined by T2L2 have the right properties of accuracy, stability and availability for the space geodesy community considering satellite POD, the estimation of geophysical products, and the improvement of the terrestrial reference frame. Section 2 presents the T2L2 experiment and the method used to determine the time biases. Section 3 briefly gives some ideas about the potential sources of time bias in T/F technology that is used at laser ranging stations. Section 4 presents an example of history of time bias, followed by a conclusion.

## 2 Time Transfer

### 2.1 The T2L2 experiment

The T2L2 experiment is a payload on the oceanographic mission Jason-2, launched at an altitude of 1336 km on 20 June 2008. T2L2 consists of two components; (*i*) an active optics unit located near the Laser Reflector Array (LRA) that is used to detect the laser pulses coming from the ground laser ranging stations; and (*ii*) a picosecond resolution and precision event timer linked to the Ultra-Stable Oscillator (USO) of the Doppler Orbitography and Radiopositioning Integrated on Satellite (DORIS) receiver that is used to time these pulses.

Regarding the operation of the mission, T2L2 is operated in two configurations: the common view or the non-common view time transfers. The common view time transfer occurs when, at least, two different stations see the satellite at the same time, while the non-common view occurs when the involved stations are distant, typically at distances of more than 4000 km. During the common view configuration, the on-board instabilities coming from the USO can be neglected. The stability of the time transfer is thus achieved at a

level of a few ps at 75 s (ground-to-space<sup>1</sup> time transfer) in addition to an accuracy of 150 ps (ground-to-ground<sup>2</sup> time transfer) [Exertier et al., 2010, 2014]. In case of the non-common view time transfer configuration however, the period of time over which the satellite is not tracked can reach 5000 to 10,000 s. Over that period, it is necessary to take into account the instabilities of the USO which are of a few parts in  $10^{-12}$ , thus introducing potential errors of tens of ns when calculating the synchronization. The accuracy for the non-common view time transfer and the time biases estimation is  $\pm 5$  ns [Exertier et al., 2017].

## 2.2 On-orbit time realization

The on-board time&frequency reference system of Jason-2 is based on the DORIS USO; its frequency stability is of  $3 \times 10^{-13}$  between 10 to 100 s and evolves according to  $\tau^{3/2}$  [Auriol and Tourain, 2010]. Over periods longer than 1000 seconds, the USO instabilities are due to several effects such as the frequency drift (of  $10^{-11}$  per day), slight variations of the temperature and, above all, the short but regular exposures to radiation encountered in the region of the South Atlantic Anomaly (SAA). In order to study the oscillator and to fulfill the requirement of the time transfer between remote ground clocks at a level of a few ns, we developed a frequency model [Belli et al., 2016].

The frequency model, actually, is based on physical processes that describe the environmentally-induced changes of the USO frequency. Concerning the radiation effects, the model takes into account the high energy proton flux that is measured by the ICARE-NG instrument [Bezerra et al., 2011] carried on Jason-2. The thermo-electric effect comes from the temperature changes that are precisely measured inside the DORIS receiver; additionally at the orbital period (of 110 min), the relativistic effects (velocity and gravitational redshift) are also calculated. Finally, the aging effect is also modeled as a drift whose amplitude is decreasing

over the long term. The integration of the model over 10,000 s becomes an on-orbit time realization, where stations can rely on it for time synchronization.

## 2.3 Synchronization of the ILRS network

The time transfer in non-common view consists of comparing two remote clocks without any *a priori* reference. What is under consideration, here, is the determination of clock shifts relative to UTC. It is thus necessary to establish each time transfer from a primary station which serves as a reference, being time-calibrated (ground links and/or cables) on the one hand and monitored by UTC or GPS time via, e.g. a dedicated microwave system (Global Navigation Satellite System (GNSS) or Two-Way Satellite Time and Frequency Transfer (TWSTFT)) on the other (see Figure 1). In our calculation, we use the Grasse SLR stations (7845) which has both a GPS time geodetic receiver and a TWSTFT antenna on site. From the T/F reference point of the laboratory, the receiver/antenna has been calibrated, thus making it possible to connect the epoch of laser ranging measurements to both the local and to the global GPS time scale very accurately (at 1 ns).

In this way, the local time scale of other laser ranging stations can be compared to the GPS time scale (i.e. UTC) from available non-common view time transfers calculated from the primary Grasse station. The on-orbit time realization (see Section 2.2) that is computed at least between these two stations plays a major role but introduces by itself some uncertainty. In order to control this uncertainty, it is possible to transfer time by this method from Grasse to Grasse when it is possible to use successive passes (from around 7200 to 14400 seconds). The result is based on the assumption of the high stability of the Grasse T/F system during that period of time ( $< 10^{-14}$ ) that is much less than 1 ns. That is achievable thanks to a hydrogen maser clock.

<sup>1</sup>Synchronization between ground and space clocks

<sup>2</sup>Synchronization between two ground clocks

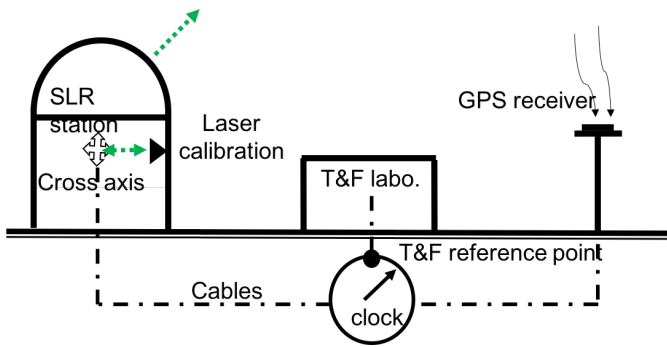


Figure 1: Schematic representation of a SLR station. The reference point for both ranging and timing is the cross-axis of the telescope. The time&frequency laboratory is often distant from the telescope, such as the geodetic receiver used to monitor the clock by using another time transfer technique such as GPS or TWSTFT.

### 3 Time biases origin in SLR stations

From the considerations described above about the necessary time calibration of at least one laser ranging station of the network (the primary station), we deduced several sources of problems that may arise. Time biases are intrinsic to several aspects of the currently used T/F technologies in laser ranging stations such as:

- delay in cables,
- clock stability (avoid free running oscillator),
- resolution of the event timer (for a ns synchronization, ps resolution event timer should be used),
- calibration of the antenna in the case of GPS Disciplined Oscillator (GPSDO) [Lombardi, 2008],
- calibration of the time distribution,
- time reference location,
- manual operation (cables changes...), should be monitored and referenced.

Looking back on the clock stability, even if some stations use highly stable clocks (such as H<sub>2</sub>-maser or Cesium), the reference point of the T/F laboratory should be continuously monitored (and never left free running), by using a Pulse Per Second (PPS) signal coming from another time or frequency transfer technique, such as the GPS or TWSTFT. This implies that the station benefits from an on-site geodetic receiver whose ground link(s) to the T/F reference point is(are) time calibrated. In addition, the distance of the event timer of the laser ranging system to the T/F reference point must also be time calibrated. We highly recommend that the stations carry out a full time calibration regularly, in order to evaluate the delays due to the cables and electronic devices used to distribute the PPS signals. When this is not done, the delays end up simply not being included in the T/F scheme of the station, and are transformed into Time Biases.

### 4 Time Series of Time Bias per Station

We present some time series of time bias obtained for three different laser stations (Figure 2: Grasse 7845, Figure 3: Wettzell 8834 and Figure 4: Yarragadee 7090) from 2008 to 2016. For these figures, the X-axis is given in years and the Y-axis is in s. We also plot the ILRS recommendation in blue (i.e.  $\pm 100$ ns). The main observation is that some of the SLR stations are still subject to time biases which can reach several  $\mu$ s. Their free running oscillator is thus not correctly tied to UTC for several reasons, as described in Section 3. Lower but more or less stable values of time bias (of several hundreds of ns) are due to delay(s) in the ground cables (a missing time calibration). Jumps and rapid changes of the phase clock system may occur in case of human operations, such as a switch of the phase to suddenly reduce the time bias, or a change of cable(s).

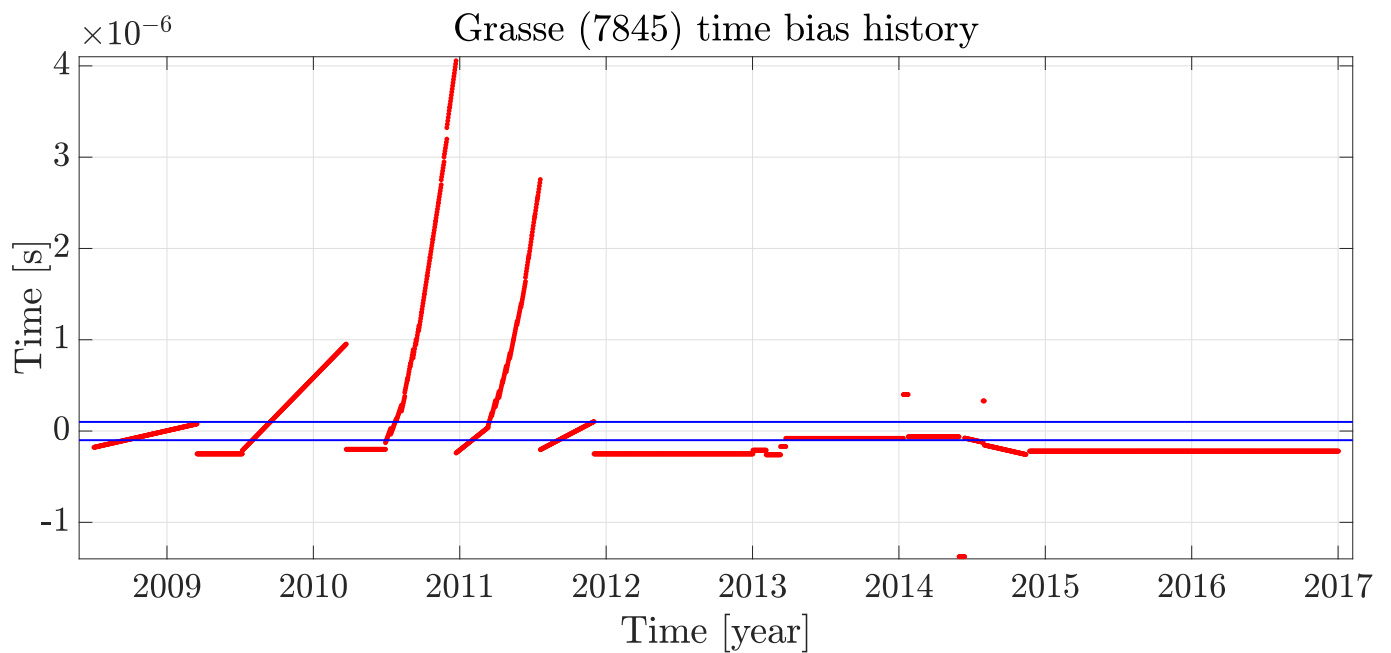


Figure 2: Time bias evolution (in red) for the Grasse (7845) station from the beginning of T2L2 mission (June 2008) to 2017. X-axis is in year and the Y-axis is time bias in seconds. The blue lines are the ILRS recommendations ( $\pm 100$  ns from UTC). Until 2012, the H<sub>2</sub>-maser (local clock) remained in free running mode, which explained the high variation of the time bias which reached several  $\mu$ s. In the beginning of 2013, some cable changes affected the Time Bias, whose value then returned to being within the ILRS recommendations.

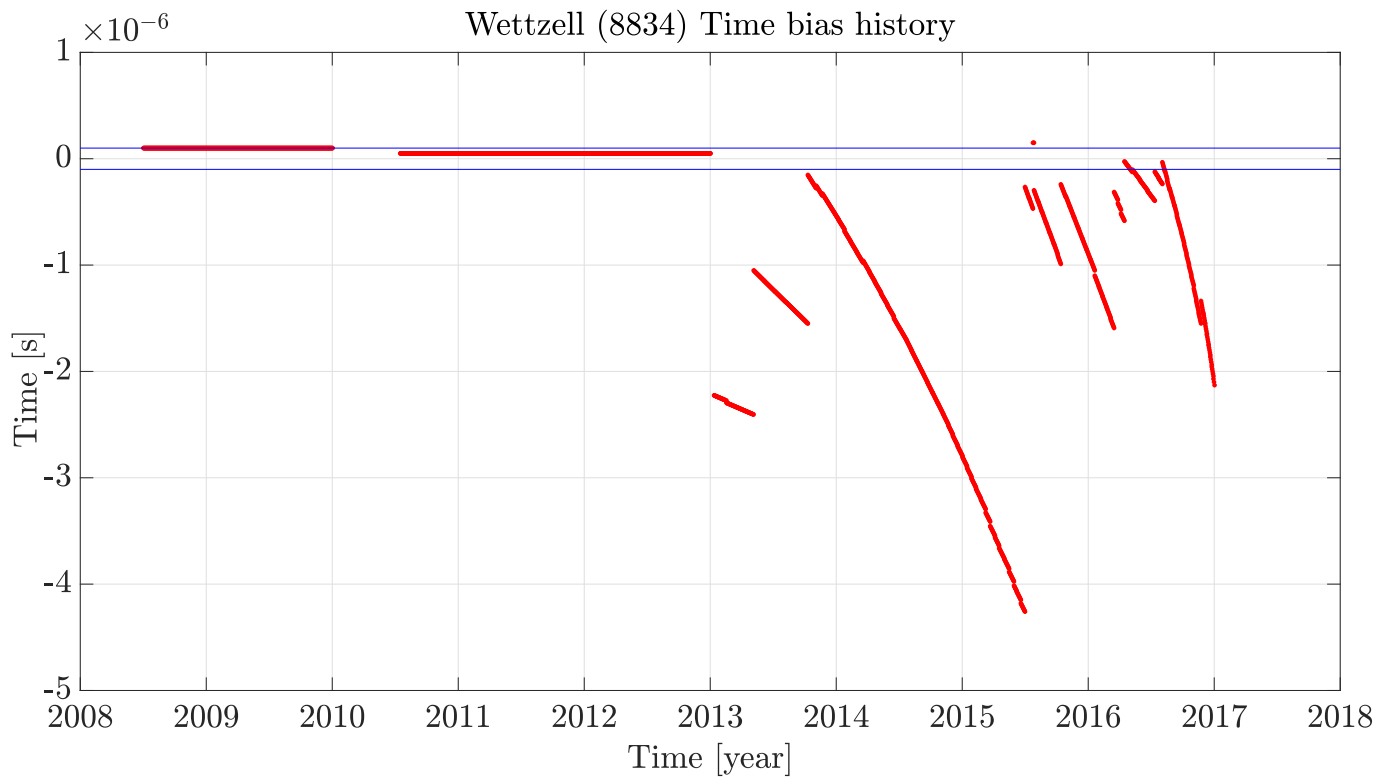


Figure 3: Time bias evolution (in red) for the Wetzell (8834) station from the beginning of T2L2 mission (June 2008) to 2017. X-axis is in year and the Y-axis is time bias in seconds. The blue lines are the ILRS recommendations ( $\pm 100$  ns from UTC).

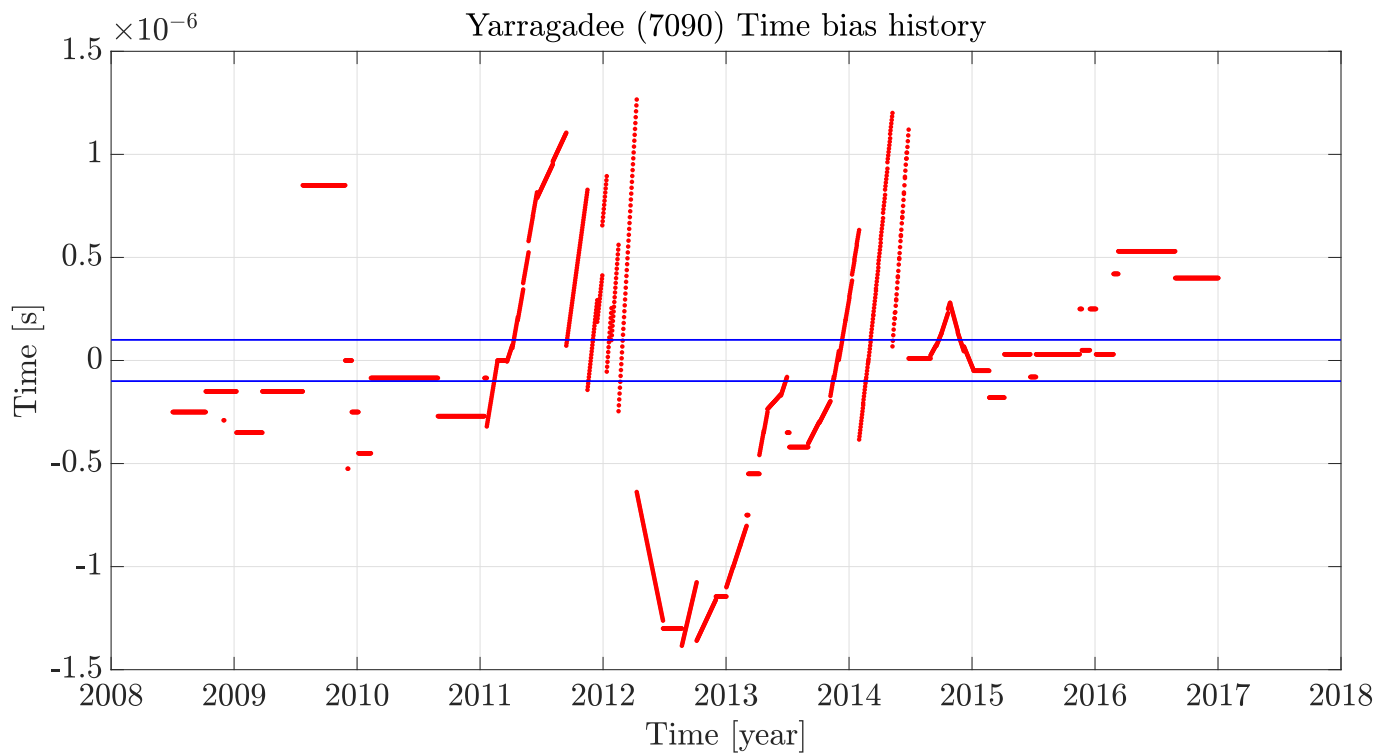


Figure 4: Time bias evolution (in red) for the Yarragadee (7090) station from the beginning of T2L2 mission (June 2008) to 2017. X-axis is in year and the Y-axis is time bias in seconds. The blue lines are the ILRS recommendations ( $\pm 100$  ns from UTC).

## 5 Conclusion

We developed a new, independent, and direct method to determine the time bias to UTC at the laser ranging stations of the ILRS network, with an accuracy of  $\pm 5$  ns. The T2L2 experiment on-board Jason-2, which provides ground-to-space time transfers on the one hand, and the frequency modeling of the on-board USO on the other hand, plays a major role in comparing ground clocks over continental distances. This method that is based on the integration of the frequency model provides to users (SLR stations) a new on-orbit time realization as a tool of time calibration.

We computed time biases from a reference station (Grasse, 7845) linked to the UTC timescale at 1 ns, for more than 30 SLR stations of the network. The results show that almost all the stations are subject to time biases of several hundreds of nanoseconds at some point in time; some of them reach an extremely high level of several  $\mu$ s to UTC, well above the ILRS-recommended a maximum of  $\pm 100$  ns.

Time biases are intrinsic to the different T/F technologies. Thus, we highly recommend to stations to regularly perform a full time calibration (delay in cables, stability of the clock, free-running oscillator, change of event timer, manual changes, etc.). But considering the SLR time-bias results provided by T2L2 for the past nine years, we also recommend that stations should track Jason-2 and should provide their Full Rate data to the ILRS data centers in order to be time calibrated by our method.

Several research efforts are currently underway at NASA Goddard and at the CNES in order to determine the impact of such time biases on different geodetic products (e.g. orbit determination and station coordinate estimation). Microsecond time biases will lead to millimeter effects, making it impossible for most of the SLR stations of the current ILRS network to reach the Global Geodetic Observing System (GGOS) requirements in term of positioning: a 1 mm accuracy and a stability of 0.1 mm per year [Plag and Pearlman, 2009].

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