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Time Calibration of JAXA's Pinpoint Moon Lander SLIM

Miriam Sawczuck[a]*, Yukio Yamamoto[a], Kyoko Mimura[a]

[a] *Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Japan*
* Corresponding Author, sawczuck.miriam@jaxa.jp

Abstract

Accurate and precise time calibration is crucial for all space missions to handle the timing of command execution and telemetry data generation. For space probes that leave the Earth's orbit and cannot use a GPS-based time reference, JAXA employs a time calibration system to correlate the probe's on-board time counter, driven by oscillator frequency signals, with Coordinated Universal Time (UTC). The rate at which the counter increments can vary due to factors such as temperature; therefore, regular calibration is necessary. This calibration process involves aligning the spacecraft's time counter at the time of transmission with the ground station's UTC at the time of reception and correcting for various delays. This correction process, as well as the decoding methods used by ground stations for the encoded data, can result in inaccuracies. JAXA's small lunar lander SLIM (Smart Lander for Investigating Moon), landed with high precision within 55 meters of its target landing site on the Moon in January 2024. For this high-precision landing, the timing of the command execution and, consequently, the lander's time correlation with the ground stations was critical. To prepare for the landing, we conducted two accuracy evaluations of the time calibration: one before SLIM's launch using data from a thermal vacuum test, and one after its launch using actual telemetry data. In the post-launch evaluation one ground station showed unexpectedly low precision, which required further investigation. However, in both evaluations, the stability of the final calculated time rate, which measures the time required for the spacecraft counter to increment by one count, was within the target accuracy of 3 parts per million (ppm) for the required temperature and time range.

Keywords: Time Calibration, Spacecraft Clock, Time Indicator, Ground System, Moon Landing

1. Introduction

The Institute of Space and Astronautical Science (ISAS) of Japan's Aerospace Exploration Agency (JAXA) uses a time calibration system [1] for satellites and spacecrafts that are not equipped with GPS. The system calibrates a time indicator (TI), a counter-value generated on-board the spacecraft, with a standard time system on the Earth, the Coordinated Universal Time (UTC). Since the rate at which the TI increases is not constant, but depends on factors such as temperature, this calibration must occur regularly.

For JAXA's small lunar lander SLIM (Smart Lander for Investigating Moon), of which one objective was a landing accuracy within 100 meters [2], it was necessary to predict a TI ten hours in the future, to ensure the right timing of the landing command. When predicting a TI in the future, errors in the calibration will accumulate over this time, making it crucial to be aware of clock frequency instabilities such as temperature dependency, and evaluate the possible accuracy. Therefore, we evaluated these instabilities as well as the overall time calibration accuracy of SLIM's on-board clock, using data from a thermal-vacuum test conducted on SLIM before its launch, as well as actual telemetry data during its operation.

In Section 2 of this paper, we will introduce JAXA's time calibration system and discuss inaccuracies of the time calibration process. In Section 3, we will describe the methods used to evaluate the accuracy of the calibrated time based on the example of the moon lander SLIM. The results will be presented in Section 4 and discussed in Section 5.

2. Background

2.1 Time Calibration System

Some ground stations have their own time calibration process, but they are developed independently, so ISAS uses its own calibration system to unify the calibration method and be able to evaluate its precision. It is similar to SPICE SCLK, a spacecraft time calibration framework developed by Navigation and Ancillary Information Facility (NAIF), National Aeronautics and Space Administration (NASA), commonly used in planetary exploration missions.

Compared to SPICE, ISAS's system is more suitable to JAXA's spacecrafts and ground systems, and more flexible with TI discontinuities.

The system consists of two processes, creating a time calibration table, and utilizing it for time calibration. The table creation starts with the TI being generated by a crystal oscillator at the System Management Unit (SMU) on-board the spacecraft and sent as telemetry data to the Earth. The composition of this telemetry data complies with the international standard of the Consultative Committee for Space Data Systems (CCSDS) [3]. The TI, together with the telemetry reception time at the ground station/ Earth-Received Time (t_{ERT}), is added to the time calibration table. The UTC corresponding to the TI, i.e., the time of satellite transmission, can be calculated by correcting for the distance between the spacecraft and the ground station, as well as the circuit delay of each. This correction is shown in Eq. (1), where C_1 is a constant to correct for bitrate dependent time delay (the time gap between TI and ERT measurement timing), and C_2 is a constant to correct for a fixed time delay due to data encoding on-board and decoding at the ground station.

$$t_{cal} = t_{ERT} - \frac{distance}{c} - \frac{C_1}{bitrate} - C_2 \qquad (1)$$

The values needed for this correction, i.e., the distance and bitrate, together with the resulting UTC, are added to the time calibration table. Since the number of bits assigned to the TI value is finite, a period is specified after which the TI will roll over, i.e., return to 0. Therefore, a counter for the number of times this rollover has occurred is added to the time calibration table as well. Furthermore, the table includes the time rate (r), which is defined in Eq. (2). The initial value of the time rate, the constants C_1 and C_2, and the period for the rollover, are defined in the spacecraft settings.

$$r = \frac{UTC(t_2) - UTC(t_1)}{TI(t_2) - TI(t_1)} \qquad (2)$$

The distance value needed for the correction in Eq. (1) is the length of the radio path, i.e., the downlink range. However, this value is not always measured, and the measured values are not available in real-time. Therefore, in our system we cannot use the actual measured downlink range values. Instead, we use the antenna prediction file, which is created in advance for the operation of the antenna/ ground station and includes the predicted downlink range at regular intervals. The downlink range for each ERT is then calculated via quadratic interpolation of three values in the file. Furthermore, the bitrate values used in Eq. (1) are not the measured values, either, but one of three values (low, normal and high bitrate) prepared in the bitrate settings, since the sending bitrate is almost constant. When creating the time calibration table, the above-mentioned spacecraft settings, antenna prediction file and bitrate settings are input to the system. Additionally, a leap second file is input, to adjust for irregularities in the Earth's rotation at the specific ERT by adding the appropriate number of leap seconds to the UTC.

This table with UTC-TI pairs then allows to convert between TI and UTC at any time via linear inter- and extrapolation. This is performed in two directions, to convert the spacecraft time (TI) to the Earth's standard time (UTC) for data being sent by the spacecraft, as well as to convert the Earth's standard time to the spacecraft's time for sending commands to the spacecraft. The time calibration table is created independently for each ground station and frequency band. However, the main time calibration is performed with the master time calibration table. The input for both tables is visualized in Fig. 1.

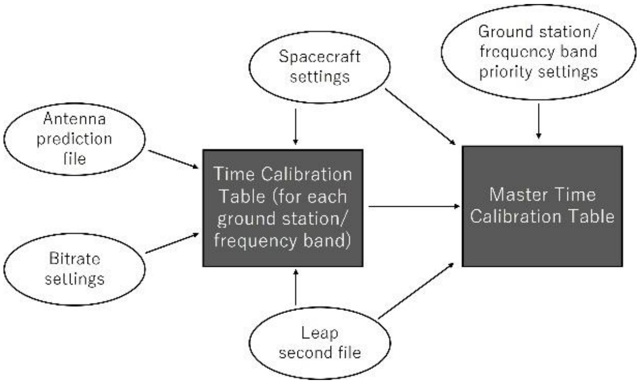

Fig. 1. Input to create the time calibration tables.

2.2 Master Time Calibration Table

To achieve a higher precision, our system creates a master time calibration table, produced by merging the time calibration tables created for each station and frequency band, but thinning its values to keep an appropriate time interval between them. The default of this interval is one hour. Furthermore, we define a discontinuity inequality to discard TI values if they show a sudden drastic change out of the possible error range. For this definition, we need the rate variation, determined by the oscillator stability. With the rate of change σ and a reference rate $\overline{r}$, the correct rate can be calculated via Eq. (3).

$$r = (1+\sigma)\overline{r} \qquad (3)$$

Apart from this oscillator stability, the error of the discrete TI value can be assumed to be zero. Therefore, with the error of the UTC value ϵ, composed of the ERT resolution, the error of the downlink range, and other transmission delays, the actual measured rate $\hat{r}$ can be calculated via Eq. (4).

$$\hat{r} = \frac{\Delta\widehat{UTC}}{\Delta\widehat{TI}} = \frac{\Delta UTC+2\epsilon}{\Delta TI} = \left(1+\frac{2\epsilon}{\Delta t}\right) r \qquad (4)$$

Putting these two equations together, we can calculate the variation of the actual rate from the reference rate.

$$\hat{r} = \left(1+\frac{2\epsilon}{\Delta t}\right)(1+\sigma)\overline{r} \approx \left(1+\frac{2\epsilon}{\Delta t}+\sigma\right)\overline{r} \qquad (5)$$

Therefore, we define discontinuity to occur if the difference of the ratio of the measured rate $\hat{r}$ and the reference rate $\overline{r}$ and one is larger than the specified threshold as in Eq. (6).

$$\left|1-\frac{\hat{r}}{\overline{r}}\right| > \frac{2\epsilon}{\Delta t}+\sigma \qquad (6)$$

The threshold values of ϵ and σ used for this discontinuity judgement are specified in the spacecraft settings.

We can also use Eq. (6) to calculate the threshold for the time interval Δt, used to thin out the master time calibration table values. To keep the error of the time rate low, $\frac{2\epsilon}{\Delta t}$ should be of the same order as σ. We therefore set them equal to calculate Δt, which gives us a time interval of approximately 667 seconds. Any interval larger than this will ensure a lower time rate error, so we keep the default of one hour. If there are multiple values after the appropriate time interval, one is selected via the ground station/ frequency band priority settings.

2.3 Inaccuracies

SLIM's on-board clock is made of a quartz crystal oscillator, whose frequency stability, and therefore the time rate dispersion, is dependent on the surrounding temperature. In many spacecrafts, this temperature dependency is the main factor of time calibration inaccuracy. However, in the case of SLIM, the temperature is measured, and temperature compensation is automatically performed [4]. Therefore, this inaccuracy is assured to be lower than 3 ppm. A larger inaccuracy originates from the reception time resolution. This resolution depends on the ground station where the ERT is measured and can therefore vary. In the case of SLIM, the resolution is assured to be lower than 1 ms. Processing delay, mostly due to en- and decoding of the data, can be a large inaccuracy in the case of a low transmission bitrate and/or bad weather conditions. In SLIM's case, the bitrate is set to 32 kbit/s, 16 kbit/s or 512 bit/s, and therefore, in the worst case, the inaccuracy due to processing delay can be around 3 ms. Another inaccuracy is the radio propagation delay. This delay is corrected for, however, for this correction we need the length of the radio path (downlink range), i.e., the distance between the ground station and the satellite. The actual downlink range is difficult to use in our system, because it is not always measured. Another option is using observations during the transmission time to determine the downlink range, but such data only becomes available several days after the data transmission from the spacecraft. Since our system requires the calibration table to be available as fast as possible, we use the predicted downlink range, which is calculated in advance for ground station operation. This difference between predicted and real value introduces uncertainty. However, this uncertainty depends on the distance of the spacecraft, in SLIM's case this is a small value of approximately 1 ppm. All of these factors affecting the precision of the time calibration and their order of inaccuracy in SLIM's case are summarized in Table 1.

Table 1. Inaccuracy factors and their order of precision for time calibration.

Factor	Order of precision [ms]
Oscillator stability (σ)	3e-3
Reception/ Earth Received Time (ERT) resolution (ϵ)	1
Time between the measurements of TI and reception time	0 (corrected via C_1in Eq. (1))
Processing delay between the TI measurement and the ground station (ϵ)	1~3 (in case of low bitrate)
Radio propagation delay (SLIM) (ϵ)	1e-3
Processing delay between the ground station and the ERT measurement	0 (corrected via C_2 in Eq. (1))

3. Methods

With the inaccuracies explained above summarized in the values ϵ and σ, we can calculate the expected time error for a prediction of 10 hours in the future with Eq. (6). We use an approximate UTC error of ϵ=1 ms, the default time interval of the master time calibration table (Δt=3600s), and the frequency stability of SLIM's on-board clock of 3 ppm, resulting in a time rate error of 3.6 ppm, and therefore an expected time error of about 128 ms for a TI prediction of 10 hours in the future. We will evaluate the measured time rate dispersion, and calculate the future TI ($TI(t_2)$ with Eq. 2) with the time rate shifted by its standard deviation, to show if the maximum time calibration error is below this threshold.

Apart from the standard deviation, we can use several values for the time rate to predict the future TI. First, we can use the TI and time rate at a specific, e.g., the current, time. However, this causes the error of the current TI to be multiplied with time and, in case of the current TI being an outlier, can therefore lead to a large deviation from the real TI. Therefore, it is better to either use the mean value of the time rate for the above calculation, or to use a least square fit of the TI over time to determine the time rate. We will use these methods to calculate the predicted TI at 10 and 24 hours before the start of SLIM's landing sequence, and compare it to the TI measured at this time.

Since each ground station has its own circuit delays etc., we evaluate the accuracy of each station used for SLIM's data reception separately, i.e. the ground stations of the Usuda Deep Space Center (UDSC), the Kagoshima Uchinoura Space Center (KSC), and the Ground Network (GN) owned by JAXA, as well as the ground stations of the Deep Space Network (DSN) owned by NASA. The ground stations are summarized in Table 2 (see end of the text). Furthermore, we evaluate the accuracy of the master time calibration table.

Additionally, we will evaluate the dispersion of the time rate not over time, but temperature, to investigate a possible temperature dependency of the time rate and ensure that the rate stability is within the expected 3 ppm.

In the figures created for this evaluation, we mark the time of important events, which are summarized in Table 3.

Table 3. Important events and their timeline

Date	Time	Event
2023-09-07	14:01:37	Transmission of first time calibration data
2023-10-04	06:47:22	Moon swing-by
2023-12-25	07:51:00	Lunar orbit insertion
2024-01-18	14:32:47	Last time calibration setting for landing
2024-01-19	15:00:00	Start of landing sequence
2024-01-19	15:20:00	Moon landing
2024-04-28	19:20:34	Transmission of last time calibration data

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4. Results

4.1 Temperature Dependency

Before SLIM’s launch, we evaluated the temperature dependency of its on-board clock with thermal-vacuum test data. We plotted the rapidly changing temperature and the corresponding time rate over the time of the measurement (see Fig. 2) and found that the change of the rate over 42.0 °C is 10.921 $\mu s/tick$. If this change of temperature were to occur over a 10-hour time period, the time error would be 393.164 ms.

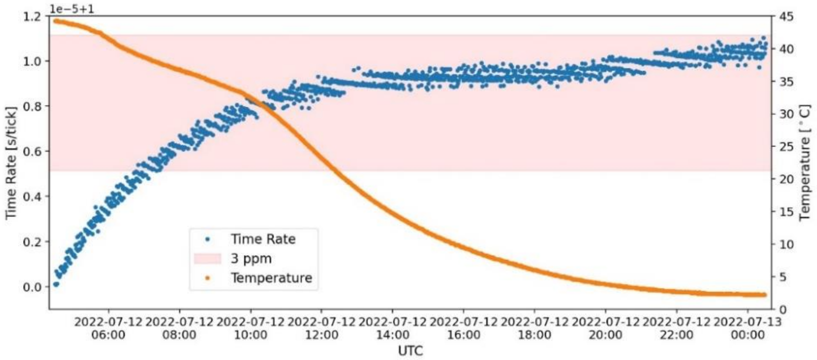

Fig. 2. Temperature dependency of the time rate

We investigate the measured temperature close to SLIM’s landing, to find out the actual temperature change. We find that, in the last 36 hours before SLIM’s landing sequence, the temperature is between 19.5 °C and 23.2 °C, corresponding to a change of 3.7 °C (see Fig. 3). We show the corresponding time rate in Fig. 3, as well. However, since the TI in this case is received by ground stations and the time rate error includes not only the temperature change but all uncertainties listed in Table 1, we cannot evaluate the temperature dependence of the time rate, but only the accuracy of the time rate in total, which will be done in the next subsection.

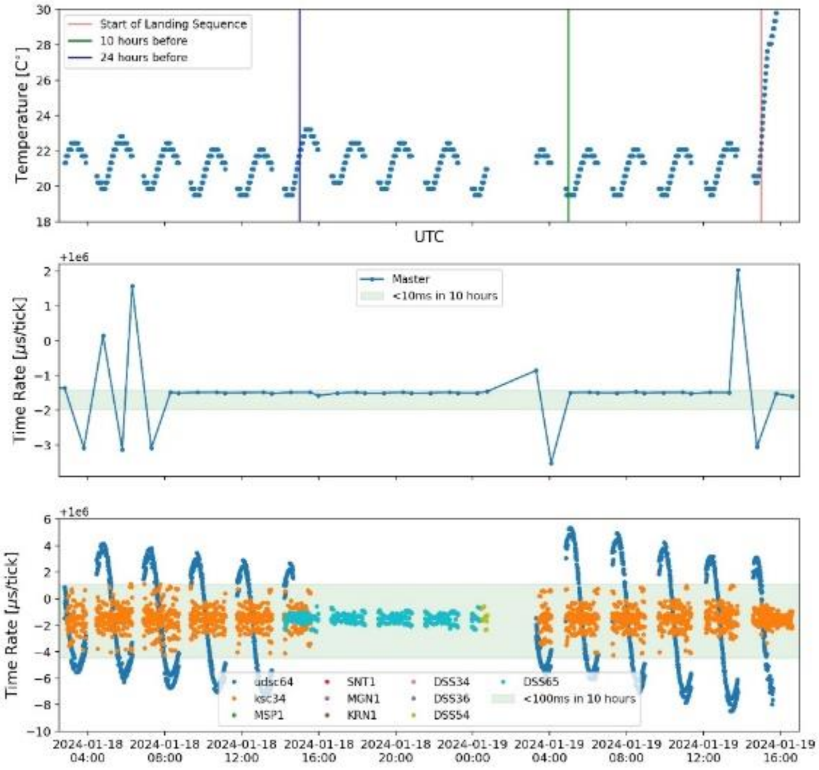

Fig. 3. Temperature and time rate of all ground stations and the master time calibration table close to SLIM’s landing

4.2 Time Rate Stability and Time Error

First, we evaluate the time rate stability of all ground stations and the master time calibration table (see Figs. 4-5). Excluding outliers, there seem to be four levels of dispersion, with udsc64 having the largest dispersion, then ksc34, then GN and DSN stations, and the lowest are the values from the master time calibration table, as can be seen in Fig. 5. We can also see that around certain events, e.g., shortly after the launch or the moon swing-by, the dispersion becomes larger. Therefore, for a low time error, the ground station as well as the time range need to be evaluated and chosen carefully for the best result.

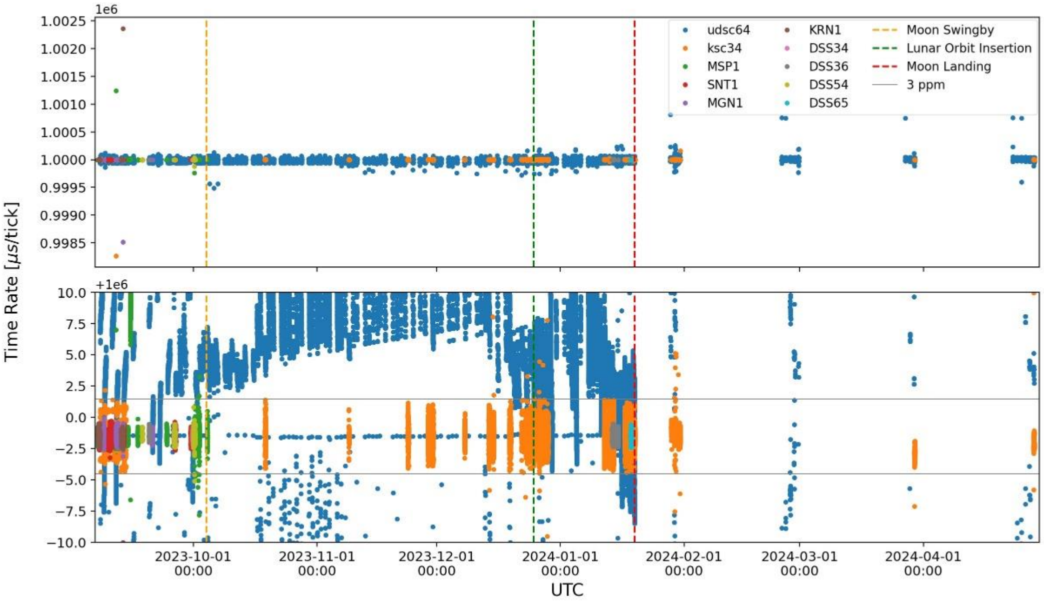

Fig. 4. Time rate of all ground stations during SLIM's active phase

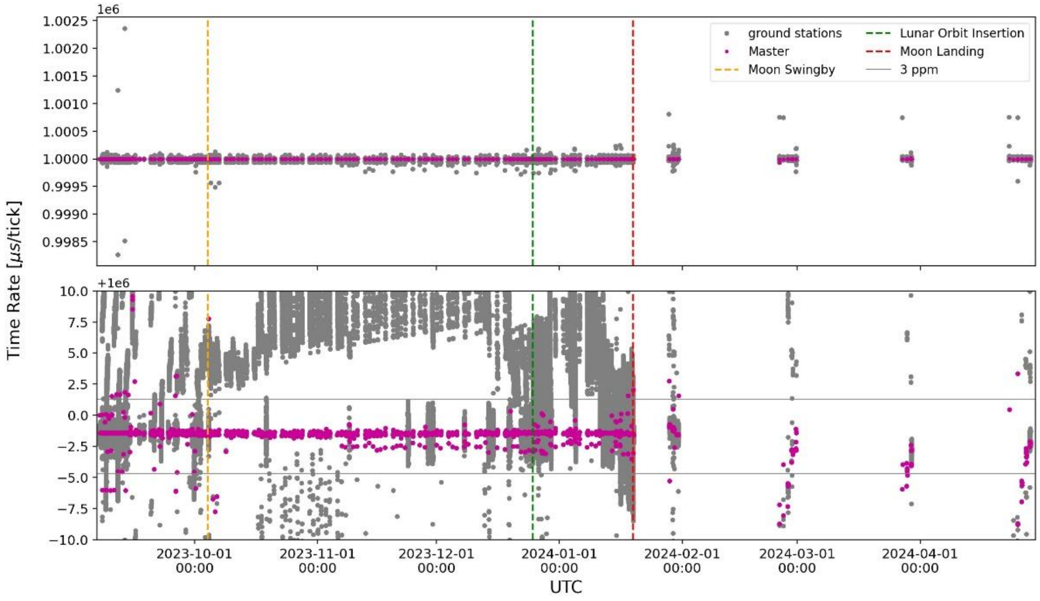

Fig. 5. Time rate of the master time calibration table compared to all ground stations during SLIM's active phase

Since we measure the time rate over a long period of time, we can use its dispersion to estimate the maximum uncertainty of the measured time rate. Since more than 80 percent of the time rate values fall within one standard deviation for all ground stations, we define it as maximum Δr and use it to calculate the maximum error of the calibrated time for a prediction of 10 hours in the future. This calculation is done for two time ranges, one starting with

SLIM’s lunar orbit insertion and ending with the start of its landing sequence (see Table 4), and one using all data, starting with SLIM’s launch and ending with its last data transmission (see Table 5). For the first, smaller time range, some ground stations did not receive data, which is why they are excluded. Coloured in green in the tables are the values within the required error range, i.e., lower than 128 ms.

Table 4. Accuracy and precision of each ground station for a time range between SLIM’s LOI and landing sequence. The values within the required error range of 128 ms for a 10-hour prediction are highlighted in green.

Ground station	Mean [$\mu s/tick$]	Δr [$\mu s/tick$]	10-hour prediction error [ms]	Number of points	Within Δr [%]
udsc64	999998.554	± 17.172	618.198	33270	99.02
ksc34	999998.555	± 0.949	34.170	17180	90.42
DSS36	999998.563	± 0.375	13.503	2245	82.27
DSS54	999998.515	± 0.302	10.877	1136	85.04
DSS65	999998.511	± 0.300	10.810	1040	84.04
Master	999998.490	± 0.603	21.717	255	92.55

Table 5. Accuracy and precision of each ground station for the whole time range of available data. The values within the required error range of 128 ms for a 10-hour prediction are highlighted in green.

Ground station	Mean [$\mu s/tick$]	Δr [$\mu s/tick$]	10-hour prediction error [ms]	Number of points	Within Δr [%]
udsc64	999998.415	± 20.767	747.630	158570	96.50
ksc34	999998.516	± 7.424	267.268	55431	99.95
MSP1	999998.895	± 10.787	388.340	14078	99.09
SNT1	999998.564	± 0.352	12.688	10095	88.43
MGN1	999998.091	± 26.021	936.769	3248	99.97
KRN1	999999.362	± 43.386	1561.883	2959	99.97
DSS34	999998.530	± 0.205	7.381	137	81.02
DSS36	999998.564	± 0.359	12.907	2622	80.63
DSS54	999998.523	± 1.929	69.432	4569	99.96
DSS65	999998.511	± 0.300	10.810	1040	84.04
Master	999998.300	± 2.301	82.839	1330	96.84

To predict the future TI, we can simply use the current TI and Eq. (2). However, this causes the error of the current TI to be multiplied with time. For example, since our goal is to predict a TI 10 hours in the future, we use the TI value 10 hours before the start of SLIM’s landing sequence for the calculation. As we can see in Fig. 6, the rate deviates from its average at this time. Therefore, the difference between the measured and predicted TI is 0.078 ticks (approximately 78 ms). Since for the master time calibration table approximately 97% of the time rate values are within the standard deviation, and the standard deviation achieves the required precision for the master table, whatever value we choose, the goal precision will likely be achieved. However, using either the average value of the rate, or fitting the TI over time and using the fit parameter of the slope as the rate, and calculate the TI with Eq. (2), we get a more reliable result. The results for the different methods, including using only one point, but at a better position than described above (i.e., 24 hours before the start of the landing sequence, s. Fig. 6) can be seen in Fig. 7.

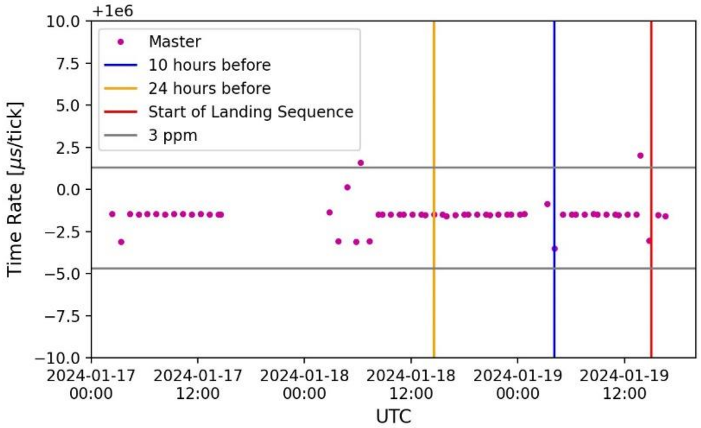

Fig. 6. Time rate of master time calibration table close to SLIM's landing

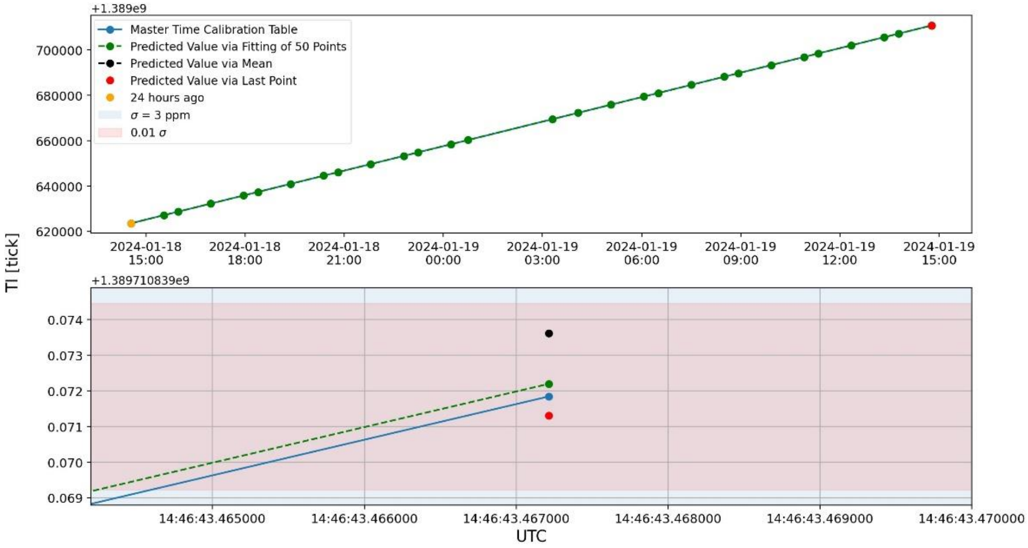

Fig. 7. Differences between the measured TI (master time calibration table) and the predicted TIs using the mean value of the time rate, a least squares polynomial fit, and the value 24 hours in the past

The least square fit is done with 50 data points, which equals approximately 3.5 days. As mentioned above, certain events cause a larger dispersion of the time rate, and therefore using a larger time range for the fit can lead to a larger uncertainty. The 50 points used here are only an example. The mean value we use is the one calculated with the smaller time range in Table 4. All resulting values are within 0.01 of the required rate error of 3 ppm, with a time error of approximately 0.35 ms for the least square fit, 1.77 ms for the average value of the time rate, and 0.54 ms when using one point 24 hours before the landing sequence.

5. Discussion

We evaluated the temperature dependency of SLIM's on-board clock with experimental data before launch, and found that, while we can clearly see the dependency of the time rate on the temperature, even for large temperature changes the time rate does not change drastically, and is within the expected 3 ppm for a temperature change of more than 20 °C. In reality, in the 24 hours before SLIM's landing sequency, the temperature only changed by approximately 3.7 °C, in which case the change of the time rate due to the temperature is negligible compared to transmission and decoding uncertainties. In Fig. 3, the pattern of udsc64 matches the pattern of the temperature, however, this is an indirect dependency caused by SLIM orbiting the moon. The change of the distance between SLIM and the moon's surface influences the temperature, and the distance between SLIM and the ground station udsc64 influences its ERT due to its decimals being fixed below 1 ms, causing an overcorrection of the radio propagation delay.

Furthermore, we evaluated the overall time calibration accuracy with all uncertainties considered and found that, if we use a smaller time range of the data, i.e., exclude the data close to the spacecraft launch where the operation is not yet stable, four out of five ground stations achieve the accuracy objective of 128 ms for a prediction of 10 hours in the future. Especially the master time calibration table results in a high accuracy with a maximum error of 22 ms and a mostly stable time rate over a long period of time. Moreover, our example of the TI prediction showed that the real error of the master time calibration table is likely to be on the order of 0.5 to 2 ms.

The time rate of the ground station udsc64 seems unstable compared to the other ground stations (see Fig. 4). As mentioned above, this is due to the decimals of its reception time being fixed, and the potential resolution therefore not fulfilled. Most of the GN ground stations do not achieve the objective, however, this is because they only received data close to SLIM's launch, in which case outliers are included.

In conclusion, using the master time calibration table and choosing the time range of the used data so that outliers are not included in the calculation, the accuracy objective of 128 ms for a 10-hour prediction is easily achievable with JAXA's time calibration system and SLIM's hardware. Therefore, we ensured that the accuracy of the time calibration system does not impede SLIM's moon landing accuracy.

Table 2. Ground stations used for SLIM's data transmission

Acronym	Location	Space Center	Organization
udsc64	Usuda, Japan	Usuda Space Center	JAXA
ksc34	Kagoshima, Japan	Kagoshima Uchinoura Space Center	
MSP1	Maspalomas, Canary Islands	Ground Network	
SNT1	Santiago, Chile		
MGN1	Mingenew, Australia		
KRN1	Kiruna, Sweden		
DSS34	Canberra, Australia	Deep Space Network	NASA
DSS36			
DSS54	Goldstone, Spain		
DSS65			

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