New Application for Khz Laser Ranging: Time Transfer Via Ajisai

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Introduction

It was 14 years ago when the use of laser ranging technique was proposed for time transfer application for the first time (Kunimori, et al., 1992). The concept is to exchange laser pulses between two laser ranging stations via the curved mirrors carried on the AJISAI satellite (Sasaki and Hashimoto, 1987) shown in Fig. 1. The AJISAI satellite, launched in August 1996, carries 314 mirror panels as well as 1436 retroreflectors. Laser ranging stations usually detect retroreflected signals from the retroreflectors. However, the optical reflection by the mirrors were expected to be useful as if they were a two-way 'zero-delay' optical transponder, although they were originally designed to be used for photographical observations. It should be also emphasised that the optical components on the AJISAI satellite has almost no limit of lifetime, and therefore it can be used for many decades with no risk factors for long-term variation of transponder delay, etc.

This concept has not been realised yet. In this paper, the difficulties we have encountered for the realisation of this concept are briefly reviewed. Then, some new possible approaches, especially the use of the kHz laser ranging technology, are proposed. A possible scenario is lastly given based on the assumption of multiple kHz laser ranging station in Europe region (Kirchner and Koidl, 2004; Gibbs, et al., 2006).

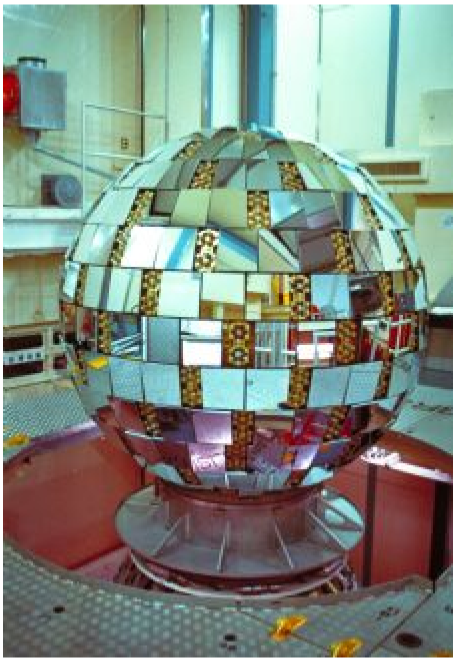

Figure. 1. *Japanese geodetic satellite AJISAI (photo: courtesy of JAXA).*

Time Transfer via AJISAI: Concept and Difficulties

As seen in Fig. 1, the surface of the AJISAI satellite is mostly covered by the mirrors whose curvature is 8.5 to 9 metres. The size of each mirror panel is approximately 400 cm2 (~ 20 cm by 20 cm) at maximum. The laser retroreflectors (12 retroreflectors in one holder) are placed in the gap of the mirror panels.

This satellite flashes three or six times per its rotation period when it is illuminated by the sun. This is because three mirror panels located in the same row point toward the same latitudal angle. The placement of mirror panels was arranged so that the flashed mirror panels can be identified by the time intervals between flashes.

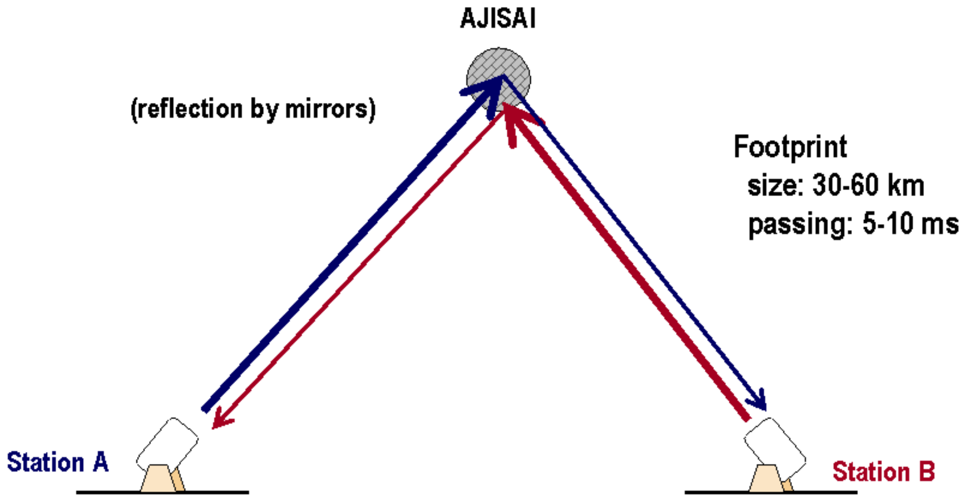

Figure 2. *AJISAI time transfer experiment: basic concept.*

A schematic view of the time transfer experiment via AJISAI proposed by Kunimori et al. (1992) is shown in Fig. 2. Like the radio-based two-way time transfer, the signal transmitted from one station goes to the other and vice versa. The curved mirrors make the reflection beam much wider to about 30 to 60 km size. Such a large footprint passes the receiving station just in 5 or 10 milliseconds.

The time diagram of signal passage between station A and B is illustrated in Fig. 3 where the 'ordinary' ranging of the station A and the signal transfer from the station A to the station B are shown. The signal transfer from the station B to the station A is simply given just by swapping the subscripts A and B. The case [1] is the prediction where the distance (in a time unit) $R_{A1}*$ is the predicted one-way distance from the station A to the satellite and the time duration $D_{A1}*$ is the predicted one-way internal system delay. The laser pulse is intended to hit the satellite at epoch t_0 of an imaginary 'true' clock. Assuming the clock of the station A is fast by ΔT_A compared to the 'true' clock, the station-transmission and the satellite-hit events come earlier by ΔT_A (case [2]). In reality, the laser does not exactly fire at the commanded epoch, and the delay is hereby set to L_A (case [3]). Now the start event $t_T(A)$ is given as:

$$t_T(A) = t_0 - \Delta T_A - R_{A1}^{\ *} - D_{A1}^{\ *} + L_A \quad (\text{'true' clock})$$
$$= t_0 - R_{A1}^{\ *} - D_{A1}^{\ *} + L_A \quad (\text{station A's clock})$$

Then, neglecting the centre-of-mass correction of the satellite, the reflected signal by retroreflectors comes back to the station A at:

$$t_R(A \to A) = t_0 - \Delta T_A + R_{A2} + (R_{A1} - R_{A1}^{\ *}) + D_{A2} + (D_{A1} - D_{A1}^{\ *}) + L_A \quad (\text{'true' clock})$$
$$= t_0 + R_{A2} + (R_{A1} - R_{A1}^{\ *}) + D_{A2} + (D_{A1} - D_{A1}^{\ *}) + L_A \quad (\text{station A's clock})$$

where R_{A1} and R_{A2} are the true outgoing and incoming one-way distance and D_{A1} and D_{A2} are the true outgoing and incoming one-way internal system delay.

What we usually use for the laser ranging is the difference (time interval) of the above two:

$$t_R(A \to A) - t_T(A) = R_{A1} + R_{A2} + D_{A1} + D_{A2}$$

from which we subtract the internal system delay $D_{A1} + D_{A2}$ to obtain the two-way distance $R_{A1} + R_{A2}$. The clock offset ΔT_A and the laser firing delay L_A does not appear here, and therefore they are hardly observable from the ordinary laser ranging measurement.

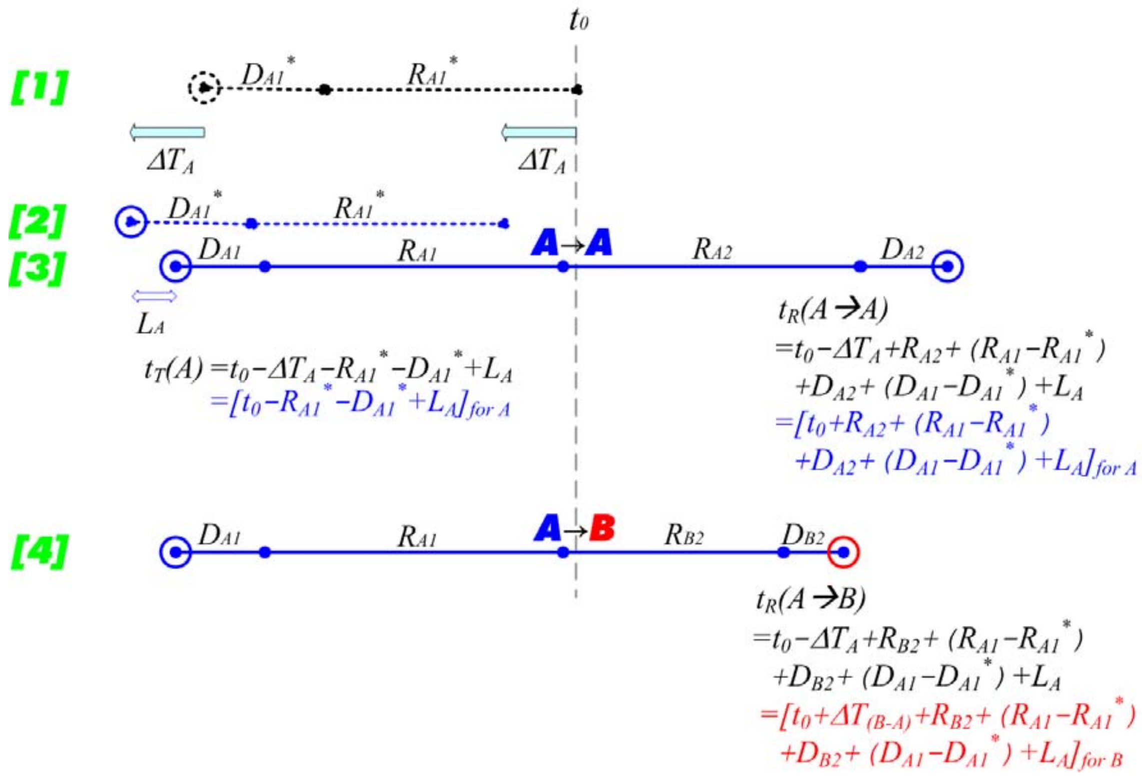

Figure 3. *Time diagram of ordinary laser ranging (A→A) and time transfer (A→B).*

Coming back to Fig. 3, the case [4] shows the signal transfer from the station A to the station B. The stop event at the station B comes at:

$$t_R(A \to B) = t_0 - \Delta T_A + R_{B2} + (R_{A1} - R_{A1}^*) + D_{B2} + (D_{A1} - D_{A1}^*) + L_A \quad (\text{'true' clock})$$

$$= t_0 + \Delta T_{B-A} + R_{B2} + (R_{A1} - R_{A1}^*) + D_{B2} + (D_{A1} - D_{A1}^*) + L_A$$

(station B's clock)

where the subscript B corresponds to variables for the station B. The opposite direction from the station B to the station A is given by an equation of swapping A and B in the above formulae. Using them, the two-way time transfer to obtain the difference of the clock offset, $\Delta T_{B\text{-}A} = \Delta T_B - \Delta T_A$ is given as the difference of two range observations $\rho_{A\text{->}B}$ and $\rho_{B\text{->}A}$, as below:

$$\begin{aligned} &\rho_{A\to B} - \rho_{B\to A} \\ &= t_R(A \to B) - t_T(A) - t_R(B \to A) + t_T(B) \\ &\quad \vdots \\ &= 2\Delta T_{B-A} + [(R_{B2} - R_{B1}) - (R_{A2} - R_{A1})] + D_{B2} - D_{B1} - D_{A2} + D_{A1} \end{aligned}$$

Now the double-difference $[(R_{B2} - R_{B1}) - (R_{A2} - R_{A1})]$ can be precisely calculated from the orbital motion of the satellite. On the other hand, the double-difference of the incoming/outgoing one-way internal system delay should be given to obtain the absolute value of $\Delta T_{B\text{-}A}$. That is, either (1) incoming minus outgoing (D_{A1} - D_{A2}) and (D_{B1} – D_{B2}) should be given, or (2) inter-station difference of one-way internal system delay (D_{B1} - D_{A1}) and (D_{B2} – D_{A2}) should be given. These values cannot be easily measured from the ordinary laser ranging systems. Note that, in spite of the difficulties in deriving the absolute accurate $\Delta T_{B\text{-}A}$, the variation of clock offsets would be relatively easily observed, leaving the constant offset of the '*D*' values and assuming them to be constant.

Beside this issue, the experiment itself has seemed unrealistic due to the following problems:

(a) The footprint passage time duration is just 5 to 10 ms. Compared to the laser firing interval of 100 to 200 ms (5 to 10 Hz lasers), it is much shorter. The footprint passage happens usually only three times per the rotation period of AJISAI, currently ~ 2s. Hence, the probability of hitting the laser at the right time was just 2.5 to 10 %. The chance was very limited.

(b) The mirror-reflection signal should reach the other station. If one wants to use a single range gate (common to laser ranging observation), the signals from the station A and the station B should hit the satellite almost at the same time. The multiple stop events should also be recorded, which is not possible by the ordinary time interval counters.

(c) The expected number of photons was just 1 to a few photons for the mirror-reflection signals, assuming a 100mJ/pulse laser. Very high sensitivity (or very strong laser) was required.

Expected breakthrough using kHz laser ranging technology

The problems (a) and (b) in the previous section are likely to be solved by the newly emerging kHz laser ranging networks. Firstly, as for the problem (a), the kHz laser (2 kHz in this case) fires 10 to 20 times per the footprint passage duration. The observation opportunity will not be missed. The kHz laser ranging systems almost automatically requires an event timer, instead of a time interval counter, due to the longer satellite ranges compared to the laser firing interval. The problem (b) will also be solved.

Especially in the European laser ranging network, multiple stations are moving toward the kHz laser ranging, following a very successful achievement at Graz, Austria. This region might be useful to exchange time signals via AJISAI between ~1000 km distant stations.

On the other hand, the link budget issue (the problem (c) in the previous section) gets more serious with kHz lasers. For instance the laser energy transmitted from the Graz system is 400 μJ/pulse, which is only 0.4 % of a traditional 100 mJ/pulse laser. The expected number of photons becomes a few hundredths of photons/pulse, and 1/10 to 1 photons/footprint passage. This would probably be the key issue for the realization of this experiment. We need to increase the laser energy and/or enhance the optical efficiency.

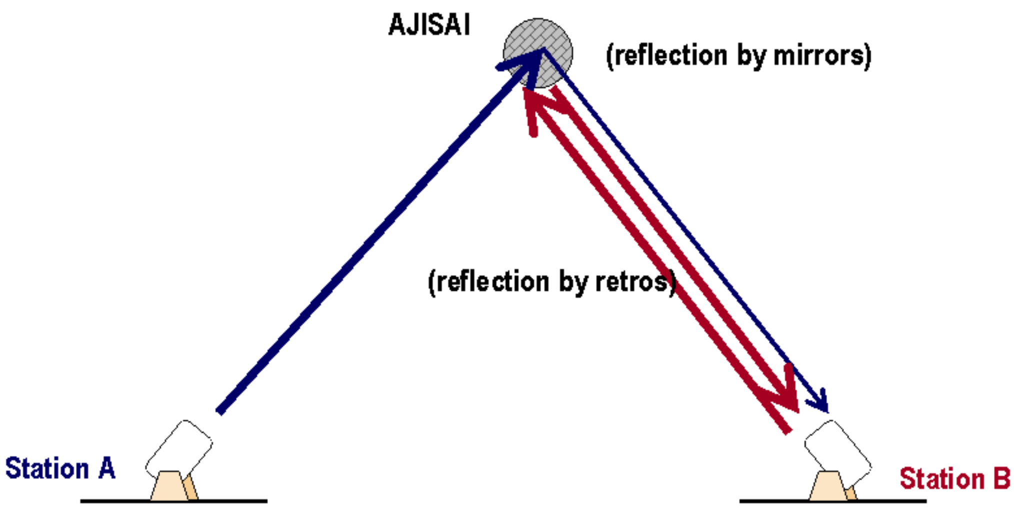

Figure 4. *AJISAI time transfer experiment: new concept.*

New experiment algorithms

As the single (A→B or B→A) signal transfer itself seems an uneasy task due to the weak link, we cannot expect the two-way (A→B and B→A) signal transfer at least at the initial stage. We re-examined the time diagram (Fig. 3) and conceived a novel way to achieve the time comparison experiment, as follows.

Let us assume the situation illustrated in Fig. 4, that is, one gets the single (A→B) signal transfer and the laser ranging (B→B). Subtracting the former range observation $\rho_{A->B}$ by the latter range observation $\rho_{B->B}$:

$$\begin{aligned} &\rho_{A\to B} - \rho_{B\to B} \\ &= t_R(A\to B) - t_T(A) - t_R(B\to B) + t_T(B) \\ &\quad \vdots \\ &= \Delta T_{B-A} + [R_{A1} - R_{B1}] + [D_{A1} - D_{B1}] \end{aligned}$$

where the clock offset difference ΔT_{B-A} appears. The second term, one-way range difference $[R_{A1} - R_{B1}]$, can be given at a few cm precision from an orbit determination procedure. The centre-of-mass corrections for R_{A1} and R_{B1} are different in this case due to the different reflection point: a mirror and retroreflectors, which should be taken into account for sub-nanosecond time comparison. The third term, difference of one-way outgoing system delay $[D_{A1} - D_{B1}]$, is still a problem to be solved, like the case of the two-way signal transfer. It is, nevertheless, now a difference of outgoing system delay, not the double difference of outgoing and incoming system delay.

Likewise, for example, by subtracting $\rho_{A->B}$ by $\rho_{A->A}$, the outgoing path will be cancelled and the incoming differences should be considered.

In this way, the clock offset information can be obtained by the single signal transfer and the ordinary laser ranging observation. This will ease the difficulties, especially on the weak link budget.

Conclusions

The time transfer via AJISAI is a long-lasting technology potentially with a very high precision/accuracy of 100 ps or even better. This will be one of new fields for a newly emerging kHz laser ranging 'network', especially in Europe. We have also derived a new algorithm which requires only single signal transfer, which will ease the weak link problem.

References

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