A possible use of Ajisai mirrors for two-way laser synchronisation

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Abstract

Remote clock comparisons using pulsed laser signals are under investigation since some years. Presently a Japanese group is analysing a complete passive two-way synchronisation technique using the mirrors onboard the geodetic satellite Ajisai. Also in Europe some research projects are devoted to determine advantages and disadvantages of a possible optical time transfer via Ajisai.
The geographical disposition of numerous European Satellite Laser Ranging (SLR) stations located relatively near to one another, as well as their regularly use of other high accuracy synchronisation systems, could be very advantageous for future laser links. In this contest, some geometrical configurations of an hypothetical European optical link are investigated. Fictitious time comparisons between some SLR laboratories using Ajisai are taken into account pointing out the common visibility durations and the available synchronisation windows. For a system quality characterisation, the statistical problems due to the fact that measurements are not always feasible with such a link (satellite not in view, bad weather) are also highlighted. Finally, a possible connection between a mobile station and a fix one is considered.
Topics such as Ajisai mirror disposition effects, energy dependence with distances, precession and nutation phenomena will be taken into account in future studies.

1. Introduction

Time and frequency community is investigating new remote clock synchronisation systems in the microwave and also in the optical domain, in order to improve nowadays time and frequency comparison accuracy. The most popular remote clock synchronisation method is currently based on the Global Positioning System constellation (GPS). Its "*common view*" configuration guarantees accuracy of a few nanoseconds. With two-way microwave time transfer systems, which are under test since some years, better values of accuracy can be reached. Synchronisation techniques in the visible range, however, seem to be the best candidate to guarantee measurement accuracy of hundreds of picoseconds with the smallest theoretical implications.
Drawbacks and disadvantages connected to optical clock comparisons are numerous and of different nature. Some of them can highly limit the correct working of this technique especially if clock synchronisations are frequently and periodically needed. These problems can be of technological nature but some others are strictly connected to the chosen geometrical link configuration. Furthermore, in case of optical applications performed inside the atmosphere, the dependence with weather conditions should be also taken into account.
These, however, are not the aims of this study. The hereafter considerations refer to the possibility of performing a quantitative characterisation of a two-way laser synchronisation technique between remote ground clocks using a specific satellite (Section 2). The possibility of performing the optical remote time transfers using the mirrors onboard the geodetic satellite Ajisai is considered. The choice of Ajisai is due to the fact that this satellite is currently the only one equipped both with retroreflectors and mirrors. These mirrors can be used to re-direct the signals towards a desired direction in order to realise (at least in theory) a complete passive two-way synchronisation. Clock comparisons, therefore, must be thought as performed periodically in time, when Ajisai mirrors are correctly oriented, in such a way to collect several measurements that can then be statistically analysed to infer stability and uncertainty of the synchronisation link. Keeping this aim in mind, some geometrical configurations in a possible European link contest via Ajisai are here investigated. By examining the various passages of this particular satellite over Europe, the *common visibility windows* (i.e. the useful time intervals during which two or more remote stations can connect one another viewing the same satellite) are determined to illustrate the synchronisation possibilities of the chosen technique (Section 2.1).
The common visibility values reported in the following sections refer to a particular Ajisai passage after having chosen some specific ground sites. Obviously these results are valid also for future passages since the considered link configuration repeats after a known *periodicity*, which is related to the satellite specifics.

In this contest, therefore, the satellite *periodicity* represents the time necessary to a chosen passage to repeat identically, i.e. the time interval necessary to the satellite ground tracks projected on the Earth surface, to return and to pass exactly over the previous tracks. An evaluation of the Ajisai repetition rate is reported in Section 2.2.
A lot of other passages besides the chosen one, can be used to determine the visibility windows. However the aim here is not to calculate all the common visibility sessions and their durations. The intent is to give an order of magnitude of how long can last a two-way optical link between some chosen stations using Ajisai. With this satellite, however, the optical link can be interrupted also when a geometrical view between two stations exists. In fact connections can fail because Ajisai is spin stabilised and as a consequence its mirrors are not fixedly oriented in the sky. Therefore, during a single common visibility window, also the *synchronisation windows* (i.e. the time intervals during which mirrors are correctly oriented to establish the link) must be considered to understand when a time comparison can be performed (Section 2.3).
Finally, the possibility to realise an optical fiber connection between two stations, besides the one via Ajisai, is considered in order to overpass the high pre-synchronisation needed between transmitters and receivers (Section 3).

2. Statistical analysis with unevenly time comparison sequences

The characterisation of a synchronisation system, such as its stability, is often based on the statistical analysis of regularly spaced data and performed by means of particular statistical tools such as the Allan or related variances that requires samples evenly spaced in time. The amount and the type of the noises affecting the considered data series can therefore be determined. Furthermore, evenly spaced time transfer sequences can also be easily manipulated with statistical filtering operations to improve particular features such as long-term stability in the time scale realisation.
Unfortunately, these tools or data modification techniques cannot be immediately applied to unevenly spaced time series. Clock comparisons, moreover, are often requested on a particular date, such as in the computation of a time scale or in dating an event. The International Atomic Time scale (TAI), for example, is currently realised using time differences on particular days of the week (referring to the Modified Julian Date, the measures considered are those obtained in the days with a Modified Julian Date ending in four or nine). These comparisons are elaborated with suitable techniques to guarantee the best long-term stability of the time scale. With a-periodically clock synchronisations the desired time transfer might be absent, therefore, the problem of performing remote comparisons discontinuously in time must be carefully considered.
When performing noise characterisations, irregular sequences can be handled in several ways. Three different approaches have been analysed in [1], [2] and [3]. One possibility evaluates a fictitious average constant time interval between the unevenly spaced data and all the comparisons are treated as equispaced. This approach is the easiest one but does not solve the problem of irregularly sequences, however the analysis performed using this simple solution gives some useful results when the data a-periodicity is not too high.
A second solution reconstructs the missing values in such a way to regenerate an evenly sequence using some interpolation techniques. The straight line law and a 5th order polynomial rule were examined in [1].
The third approach, analysed in [2] and [3], is probably the most elegant of these three techniques. In fact it tries to individuate between the unevenly data, those particular regularities that might be present in the sequence. The noise estimations performed using these particularly time intervals have the advantage that they are not biased as instead the previous two methods.
In all the three approaches, however, the results are strictly correlated to the type of a-periodicity affecting the clock comparison sequence. This is why it is necessary to determine the synchronisation repetition rate also when measurements are performed discontinuously in time.
The second problem of when a particular time comparison is needed on a specific date (see [1], [2] or [3]), implies the missing value reconstruction if the necessary datum does not exist. Also in this case, the knowledge of the time transfer repetition is important because it affects the reconstructed data accuracy.
As a consequence, when the time transfer system is not regularly and the characterisation of the synchronisation technique is needed or the measures must be used in a time scale realisation, one of the first informations to determine is the comparison a-periodicity. Technological or other nature problems that might degrade the measures or other effect can be considered in successive steps.

2.1 Common visibility: case of some European stations

The use of Ajisai in a two-way remote clock comparison via laser link implies that time transfers are performed in a desultory way. The satellite, in fact, might be not in view or its mirrors might not be oriented towards the desired direction. This new situation, which cannot be found in the microwave synchronisation systems counterpart, needs some investigation if the optical technique is to be used regularly to compare remote clocks.
In this section, the determined values represent only an order of magnitude of how long can be a comparison performed between two ground laboratories using the Japanese satellite. Different values of the common visibility duration, in fact, can be obtained changing the geometrical link configurations, therefore, the hereafter analysis refers

to a particular Ajisai passage on August 11th 1998 from 15:31 UTC to 16:06 UTC over Europe. This passage has been chosen because the satellite can be seen contemporaneously with high elevation angles from the stations considered representing one of the best situations for the common visibility. The results, although obtained for one particular satellite passage, are nevertheless of general character (Section 2.2).
Ajisai orbits the Earth in a nearly circular orbit with a revolution period of 115.717 minutes. The inclination angle of the satellite orbital plane is approximately 50°.
Besides from the satellite orbit specifications, the visibility window durations depend also on the ground station locations. The farther the sites are respect to one another, the shorter the visibility window. This is why, in the present study, the stations were chosen near one another. The considered laboratories are listed in table 1.

Table 1. *Considered SLR stations.*

SLR Stations	Latitude	Longitude	Elevation
Grasse (F)	43° 45' N	06° 55' E	1320 m
Graz (A)	47° 04' N	15° 30' E	495 m
Wettzell (D)	49° 09' N	12° 53' E	660 m
San Fernando (S)	36° 27' N	06° 12' W	53 m
Cagliari (I)	39° 08' N	08° 58' E	184 m
Matera (I)	40° 39' N	16° 42' E	530 m

Once the stations and the satellite passage have been selected it is possible to determine the common visibility durations. Figure 1 reports the elevation angles for each single SLR station tracking Ajisai. A threshold of 30° as minimum elevation angle to acquire the weak signals reflected by the Ajisai mirrors is considered. It can be seen that the common visibility between Wettzell and Graz, for instance, lasts about ten minutes. For other pairs of stations the common visibility value decreases. The chosen passage, in effect, optimises the common visibility between the two stations of Graz and Wettzell. Of course, if the visibility between other two stations must be optimised it is sufficient to consider other Ajisai passages. The chosen one however has the particularity of optimising also a multiple co-visibility between more than two stations at the same time as showed in Figure 2. In this figure, the same data plotted in Figure 1 are reported in a way to highlight the length of the common visibility for each couple of considered stations. Larger dots represent elevation angles greater than the limit value of 30°. Small dots instead represent elevation angles smaller than 30°. Also in this case, other Ajisai passages exist that can guarantee a better multiple co-visibility, however the value displacement from those here obtained is minimal.

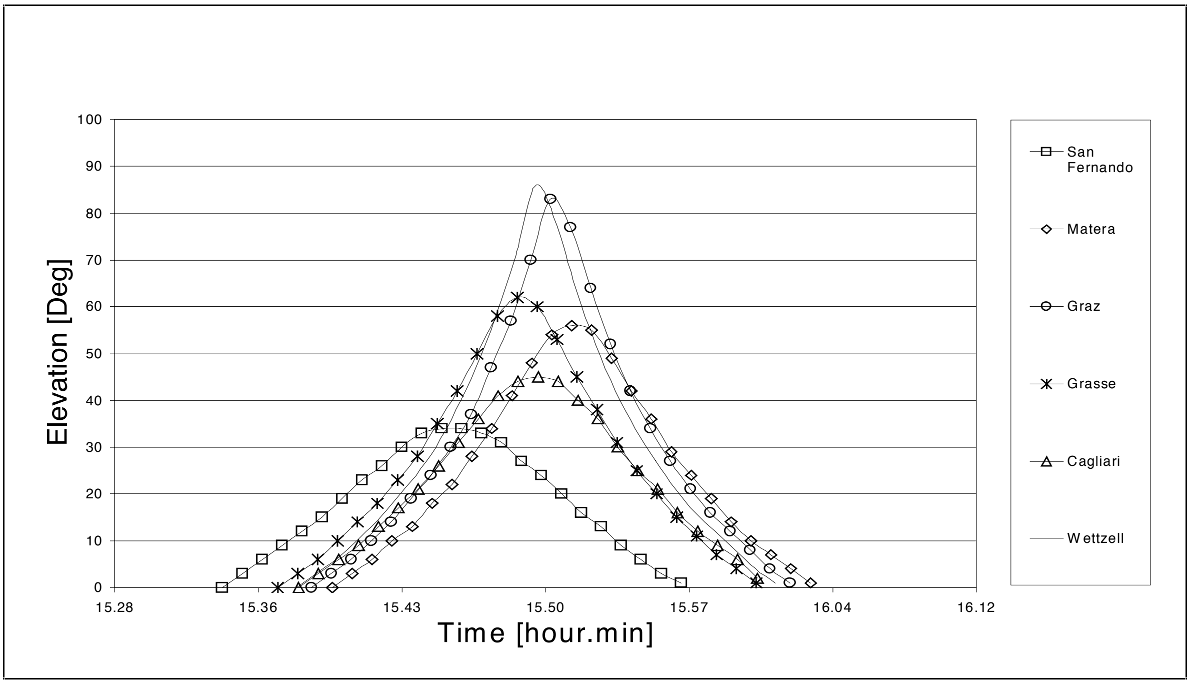


Figure 1. *Elevation angles for the selected SLR stations when tracking Ajisai on August 11th 1998 from 15:31 UTC to 16:06 UTC.*

From the Figure 2, without considering San Fernando centre, it can also be seen that in the case of the chosen Ajisai passage the multiple common time visibility lasts about six minutes for the remaining five selected stations.
The time intervals that can be determined considering each possible couple of stations are long enough to guarantee a remote clock synchronisation. Furthermore, the imposed condition, i.e. elevation angle greeter than 30°, is restrictive.

The Grasse station, for example, guarantees a minimum elevation angle of 5° to acquire a satellite. Therefore, the determined common time visibilities can be considered a little longer. However drawbacks and problems must be taken into account, in fact the obtained visibility values were determined in a nearly optimal configuration. As the consequence, they must be considered as the highest values (although not the maximal) that occur only when Ajisai repeats passages similar to the chosen one. With other kind of passages, instead, these durations always decrease. As a consequence visibilities as the illustrated one are not usual. Generally they are shorter in time. Furthermore common visibility does not imply a continuous laser connection (Section 2.3).

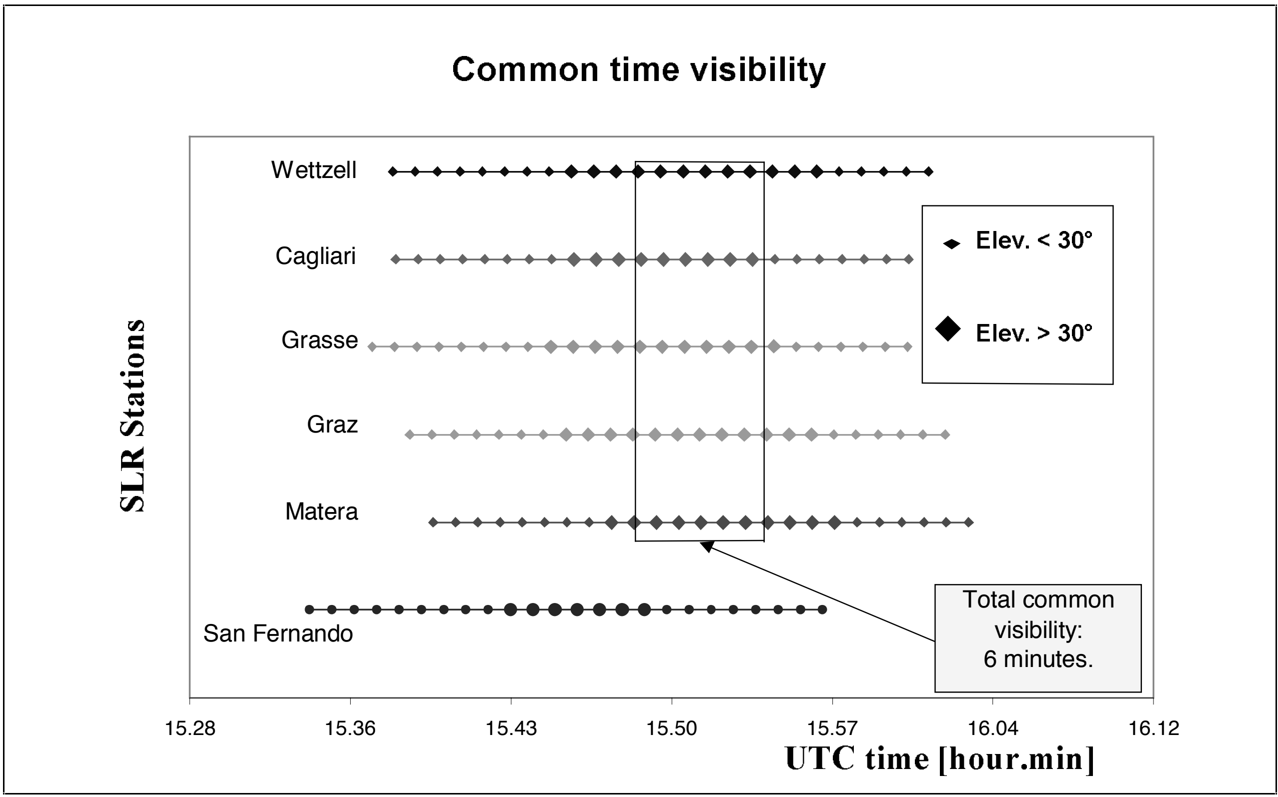
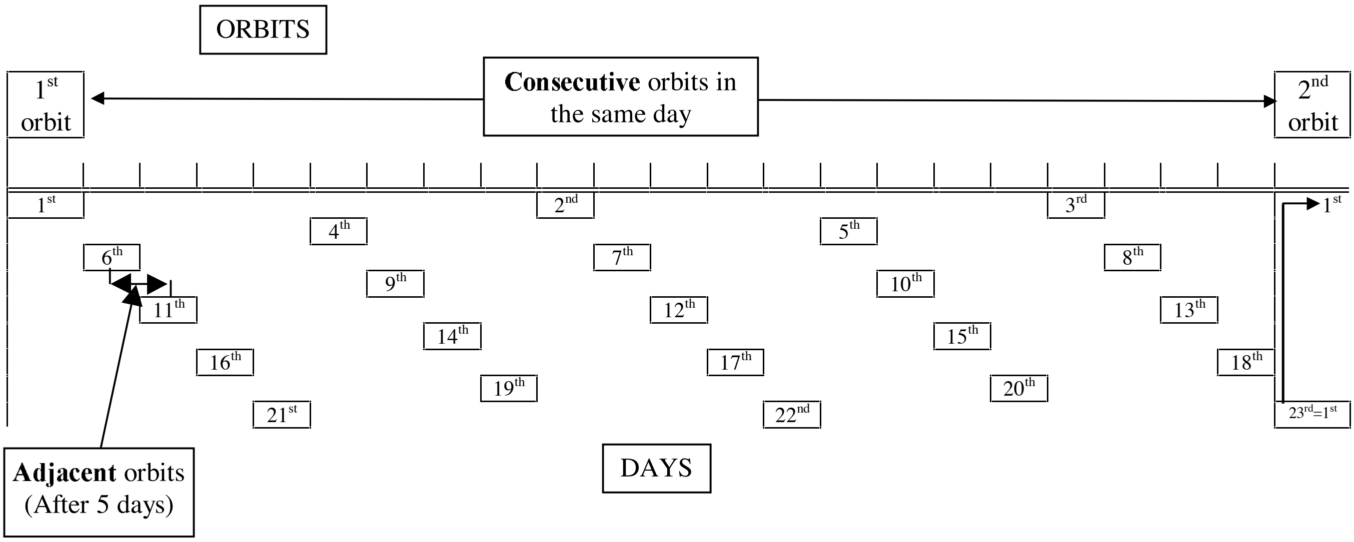


Figure 2. *Common Ajisai visibility windows for the selected SLR stations on August 11th 1998 from 15:31 UTC to 16:06 UTC.*

2.2 Time comparisons repetition

The knowledge of the repetition period of the link configuration is necessary in metrological applications such as noise recognition, accuracy determination or time scale realisation. Besides from weather condition effects, comparisons performed via Ajisai are strictly related to the satellite orbit modification, as a consequence, also satellite precession, its nutation and drug effects should be taken into account. However, as a first step value, the comparison repetition rate can be approximated disregarding bad weather, and considering only the main perturbative phenomena.

The time interval after which a link configuration repeats identically can be determined observing when an Ajisai ground track exactly cover the previous tracks "projected" by the satellite during its previous passages. Since during each sideral day (one sideral day = $23^h\ 56^m\ 05^s$) Ajisai covers about 12.4103513 ≈ (12+9/22) revolutions around the Earth, in 22 sideral days an integer number of orbits are covered around our planet, i.e. 273 orbits (the residual is Δrev/day=0.0012). The 274th ground track, therefore, passes "*exactly*" over the first one projected 22 days before (both the Earth and the satellite rounded for an integer number of revolutions after this time of 22 days has passed). Moreover, when the Earth equator is considered, two consecutive Ajisai ground tracks are displaced by about 3230 km, whilst two adjacent ground tracks (the two nearest ground tracks not necessary consecutive) are separated by about 145 km only. Each adjacent ground track is covered after 5 days since the previous one. The following scheme represents how the Ajisai ground tracks cover the soil at the equator day after day (between two consecutive orbits of the same day), until they completely overlap after the repetition period of 22 days.



However, if the rotation of the satellite orbital plane is also considered, it results that the *right ascension* of the *ascending node* changes with a rate of -3.074° each solar day. Therefore in 22 sideral days the orbital plane rotates of other -67.444° and the condition of an integer number of orbits covered in an integer number of days is no more verified after 22 days. Also the *argument of perigee* changes in time. For Ajisai it has a rate of +2.547° each solar day. Considering these two perturbative effects it can be determined that, Ajisai repeats its ground tracks after approximately *{15 solar days + 19^h 43^m 14^s}* ± 6^s or analogously after *{15 sideral days + 20^h 41^m 59^s}* ± 6^s.
The obtained *{15 solar days + 19^h 43^m 14^s}* value is to be considered as a *global* repetition time interval. During this repetition time Ajisai covers 196.888 orbits (the reason because the number of orbits is not an integer value is mainly connected to the variation of the *argument of perigee*), therefore the satellite can be seen from one single site more frequently also during the same day. Because the consecutive ground track separation is about 3230 km and because the satellite geometrical footprint (i.e. the ground sites that can view the satellite with a 0° elevation angle) has a diameter of about 7480 km, a geographical point chosen on the equator can see the satellite for at least three consecutive passages. Of course considering different passages (but the same site) the time intervals between *satellite rises* and *satellite sets* have different length. Furthermore, during the same day there are at least other three consecutive passages useful to establish a link. Because the number of Ajisai revolutions per day is not exactly an integer number, the time separation between the two series of three passages is not exactly equispaced by twelve hours. Only after *{15 solar days + 19^h 43^m 14^s}* the two blocks (each one composed by at least three passages) have completed an entire loop of one day, in such a way to repeat identically as when they occurred for the first time.
If higher latitudes than the equator are considered, the two blocks close in time until they merge in a single one. This occurs when latitudes comparable to the value of the orbital inclination angle are considered. Therefore, in such a situation, there are at least six consecutive passages for each day potentially useful for the SLR stations listed previously in table 1. Also in this case the repetition of this single block from one day to the following one is not exactly 24 hours. Once again only after *{15 solar days + 19^h 43^m 14^s}* the block repeats exactly.
For instance in the case of the Grasse station, during the repetition time of *{15 solar days + 19^h 43^m 14^s}*, 110 Ajisai passages can be tracked, with a mean value of 6.9 passages per day. Similar values can be obtained for the other considered stations. As a consequence, during a day, even 7 or 8 potentially consecutive Ajisai passages (each one separated by about 2^h ± 7^m) can be considered to perform time comparisons for each station. However, some of these are characterised by very low elevation angles and cannot be considered because the common view is very poor. It depends as already stated by the chosen couple of stations and by the elevation of the satellite during its passage.
Once chosen a pair of stations it is possible to determine when during the global repetition interval it is feasible to compare clocks. The determination of this *sample time* is the basic datum to be used in the theory introduced in [1], [2] or [3] to deduce a stability characterisation and an uncertainty estimation for the considered synchronisation technique. In the Ajisai case, whichever couple of laboratories is considered, at least one or two passages for each day show high elevation angles for both the stations in order to perform an accurate time transfer. However, measurements are not exactly equispaced between one another by the same separation time and they are not performed at the same hours of the day.

2.3 Synchronisation windows

In the previous sections the common visibility windows and their repetition rates were introduced and determined. However a geometrical visibility between two stations via Ajisai does not imply that the optical link is always possible.

During each common visibility session there are only a discrete sequence of synchronisation windows in which the link is feasible.
This is a specific drawback of Ajisai, due to the fact that its mirrors continuously change their orientations because of the satellite spin stabilisation. The laser beam transmitted by a SLR station, therefore, is not always reflected to the desired direction. Even a continuous source is seemed on the Earth as a pulsed source once the Ajisai mirrors have reflected its light. Sunlight reflections over the Japanese satellite mirrors [4], for example, are seen as three flashes for a single Ajisai rotation each long about 5 to 10 ms. This implies that in the case of an optical two-station link, three reflections can be seen for each 1.7 s (Ajisai rotation period around its axes) and each synchronisation window has a maximum duration of 5 – 10 ms. As a consequence, during the common visibility of 10 minutes previously obtained between Graz and Wettzell during the chosen Ajisai passage, there are a maximum of 1058 useful windows to perform a time transfer each one long about 5 - 10 ms. Considering the current repetition fire rate of the selected European SLR stations (from 4 pps to 10 pps except for Matera) only one single pulse can be sent during one synchronisation window. Therefore during this particular common visibility, a maximum of 1058 useful pulses can be sent and received. Consequently, a maximum of 1058 time comparisons can be realised in the chosen time window.
These results are simply the starting values from which a complete characterisation of the chosen comparison technique can be performed.

3. Two-way link using a mobile laser station

A two-way optical link via Ajisai using pulsed sources is affected by other drawbacks such as the fact that the satellite must be reached by the two laser beams nearly at the same time. Furthermore the chosen mirrors must be hit exactly when their orientations are in the right direction to reflect the signals towards the receiving stations. This implies highly accurate predictions of the Ajisai attitude and spin motion and also a high pre-synchronisation level between the two ground stations before the new comparison is performed.
Actually these two specifics can highly limit a two-way time transfer between remote clocks using this Japanese satellite. However, in a preliminary connection test, where only the system feasibility need to be investigated, it is possible to simplify these conditions considering in the same location two adjacent stations controlled by a single clock. In this simplified scenario the common visibility windows are equal to the time intervals between the satellite rise and the satellite set for the considered site. Furthermore, two closed stations have the advantage that the signal paths towards the satellite are practically identical and it is not necessary to delay the fire instants between the two transmitters. The high pre-synchronisation needed between stations, moreover, can be supplied by an optical fiber connection. This physical link, in fact, gives the possibility to “inform” the receiving section of the two stations on when the transmitting sections have really sent the beam (the detectors can be switched on only when necessary).
The two station displacement, however, must not be too small in order to avoid the detection of the retroreflector reflection. In fact, if the two stations are too close one another, when one of them sends the pulse, the receiving station will be covered by the retroreflector flash. Because only the mirror reflections carry the information, these signals are weaker that those reflected by the retroreflectors. Therefore the second station must be out of the coming back footprint generated by the retroreflectors facing the first station.

4. Conclusions

Two different optical link configurations using the Japanese satellite Ajisai have been theoretically considered and the possibility of performing a laser time comparison with such connections has been analysed. Having the aim of describing this new synchronisation technique with a time domain characterisation, some geometrical features have been highlighted showing the drawbacks of obtaining discontinuously in time comparisons. Unevenly time transfers, in fact, need to be handled with care: time scale determinations might be biased and noise recognition can be distorted.
A multiple co-visibility of Ajisai between some European stations, has been determined selecting a particular satellite passage. *Common time windows* have been taken into account and a determination of the *repetition rate* of this connection has been also performed. During the co-visibility period the maximum number of *synchronisation windows* allowed using Ajisai has been calculated.
The second considered link configuration of two stations nearly collocated is only a preliminary solution to test the feasibility of the considered connection avoiding the highly clock pre-synchronisation needed between the ground stations.
To evaluate if the two-way link via Ajisai is feasible, however, other important topics need consideration. For example the energy budget of the receiving signals as a function of ground stations and type of satellite passages and the Ajisai mirror disposition effects are under investigation.

5.Bibliography

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