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NOVEL TIME SYNCHRONISATION TECHNIQUES FOR DEEP SPACE PROBES

Executive Summary

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ACRONYMS

DIAA	Dipartimento di Ingegneria Aerospaziale e Astronautica
ESTRACK	European Space Tracking
GEO	Geostationary Earth Orbit
GS	Ground Station
GUI	Graphical User Interface
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
MoM	Minute of Meeting
PMX	Progress Meeting N.X
RTT	Round Trip Time
SC	Spacecraft
SE	Space Engineering SpA
SNR	Signal to Noise Ratio
STD	Standard Deviation
TEC	Total Electron Content
TECU	TEC Units
TN	Technical Note
TWSTF	Two-Way Satellite Time and Frequency Transfer
WP	Work Package
ZTD	Zenith Total Delay

REFERENCES

Ref. 1   ESA Invitation to Tender: AO/1-5209/07/NL/HE, Novel Time Synchronisation Techniques for Deep Space Probes

Ref. 2   Space Engineering Proposal No.2007/05/30.39 "Novel Time Synchronisation Techniques for Deep Space Probes"

Ref. 3   Novel Time Synchronisation Techniques for Deep Space Probes TN WP1.1 – Science Mission Requirements V.2.00 – Università di Roma "La Sapienza"

Ref. 4   Novel Time Synchronisation Techniques for Deep Space Probes TN WP1.2 – Time Synchronisation Techniques V.1.00 – Università di Roma "La Sapienza"

Ref. 5   Novel Time Synchronisation Techniques for Deep Space Probes TN WP2 – Preliminary Assessment V.2.00 – Space Engineering

Ref. 6   Novel Time Synchronisation Techniques for Deep Space Probes TN WP3 – Assessment within Selected Scenario – V.1.00 – Space Engineering / Università di Roma "La Sapienza"

Ref. 7   Novel Time Synchronisation Techniques for Deep Space Probes TN WP4 – Overall Simulations – V.1.00 – Space Engineering / Università di Roma "La Sapienza"

Ref. 8   Novel Time Synchronisation Techniques for Deep Space Probes TN WP5 – Results Assessment and Conclusions (Global Report Phase 1) – V.2.00 – Space Engineering / Università di Roma "La Sapienza"

Ref. 9   Novel Time Synchronisation Techniques for Deep Space Probes TN WP67 – Field Trials High Level Specs – V.2.00 – Space Engineering

Ref. 10   Novel Time Synchronisation Techniques for Deep Space Probes TN WP8 – Detailed Specifications – V.1.00 – Space Engineering

Ref. 11   Novel Time Synchronisation Techniques for Deep Space Probes TN WP9 – Global Report Phase 2 – V.1.00 – Space Engineering

Ref. 12   Novel Time Synchronisation Techniques for Deep Space Probes – Final Report – V.1.00 – Space Engineering

1. Synchronisation Techniques Review

Availability of a precise time scale reference is a key issue for several space missions. In particular while it is clear that atomic clocks have already a good flight experience, unfortunately they also have heavy requirements in terms of volume, mass, power and cost, which do not fit all applications. A possible alternative to this solution is the use of a good, but not extremely accurate, precise oscillators, which can be synchronized from time to time with respect to a ground station master clock: this is the aim of the current study promoted by ESA on synchronisation techniques suitable for deep space applications.
Among the investigated methods reported in Table 1, the selected approach is based on the classical crosslink technique modified in order to support, in three different steps, (i) the GS-SC Doppler tracking, (ii) the Frequency Transfer and (iii) the Time Transfer.

Synchronisation Technique	Pros	Cons
Cross-Link with Asynchronous Two-Ways Doppler Tracking	It allows both the time and the frequency transferring. Similar approach has already been applied in a deep space mission.	The accuracy depends on the up and down link asymmetries and the error sources are several (atmosphere, motion geometry, etc.). Nevertheless no particular reason is against its application to deep space missions.
Two-Ways Laser Link	It is simple being based on well known algorithms (interpolation, least square fitting).	For deep space applications it needs complicated beaming operations to point the receiver.
Feed-forward and Feedback Synchronisation	It is based on well known algorithms (feed-forward and feedback standard approach).	The approach based on feedback allows this technique to be applied between G/S and S/C whose relative distance is below a given limit (not suitable for deep space applications).
Pulsar Based Synchronisation	It uses a very stable reference (Pulsar).	Very low level of the received signal (from the Pulsar). At the moment state-of-the-art receivers are not yet available.

Table 1 – Techniques Summary

Actual differences in the link path will clearly involve errors on the frequency and time obtained on board. Specifically, performance depends on a number of error sources, namely geometry differences between uplink and downlink, troposphere and ionosphere propagation effects and solar plasma. Also, a host of relativistic effects (namely Sagnac, red-shift, second order Doppler and Shapiro) affect the solution. Finally, some operational-related issues, as the ageing of the components, the occurrence of frequency dips, the retrace after on-off operations and the long lasting out-of-service effects also must be taken into account to have a global evaluation of the technique.

Some of these error sources can be analytically investigated, while for others a simulation is the best way to provide an estimate of their effect. In order to obtain a figure for the performance of the crosslink technique a purposely developed code has been implemented.

By including the specific mission profile, it is possible to estimate the accuracy of the time and frequency transfer depending on the selected trajectory.

2. Missions Review

At the beginning of the project a review of scientific missions, dealing with the time and frequency transfer, has been carried out (see Ref. 3). A classification of such missions is reported in Table 2.

| Scope	Mission Scenario		
	Terrestrial	Inner Planets	Deep Space
Timing Devoted	ACES EGE		SAGAS
Precise Tracking	GRACE	MESSENGER Bepi-Colombo	Cassini
Standard	SMART-1 GAIA	MRO	

Table 2 – Classification of the reviewed missions

A first group is composed by missions expressly devoted to timing goals, which will carry on board atomic clocks.

Then there is a second class of missions where the tracking, and not the time-tagging of the events, should be really precise to achieve mission goals. Since tracking and timing issues are equivalent (accuracy in time can be roughly considered as equal to ratio between the accuracy obtained in position and the speed of light), even if atomic clocks are not accommodated on board but only at the ground station, these missions require special provision in order to improve the tracking performances. Typical solution includes a coherent transponder and specific design selection as multiple frequency link or high performance cryogenic receivers at the ground in order to counteract noises.

A third group of considered missions is not aimed at time or frequency experiment and it doesn't require a state-of-the-art accuracy in tracking, but in a certain meaning represents the large majority of the possible missions. This group is important because offers a sketch of how timing is considered, and which are the level of relevant performances required in a common mission design.

It is interesting to note that there is a difference between the accuracy achievable by considering real-time and post-processed observables. Such a difference is about two orders of magnitude as far as it concerns tracking (ranging and range-rate) observables, and can be larger as far as it concerns the time scale alone.

The following plot could be useful to have a resuming sketch of the performances level already achieved or foreseen for the future missions.
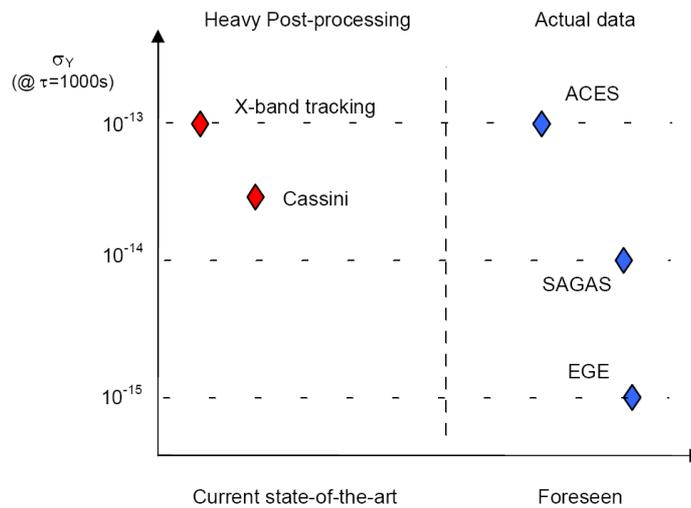
Figure 1 – Performances attained/foreseen in terms of Allan variance

Note the partition between post-processed and actual data: tracking data (typical X-band, Cassini) allow computing the Allan deviation of the residuals, after a large amount of work has been performed, while actual data would be referred to the statistics of the ticks actually generated by the on-board clock. Ground based standards today available can be represented by Cs clock ($\sigma_y=10^{-15}$ @ 1000s integration time) or Sr clock ($\sigma_y=10^{-16}$ @ 1000s).

Moreover, among the several missions analysed the following two classes of accuracy can be identified:

Clock	Time Stability @ 1000 sec	Frequency Accuracy $\Delta f/f$	Mission
Atomic	$10^{-16} \dots 10^{-14}$	$10^{-17} \dots 10^{-16}$	ACES, EGE, SAGAS
Not Atomic	$10^{-13} \dots 10^{-10}$	10^{-14}	Bepi Colombo, Cassini

Table 3 – Time Stability and Frequency Accuracy

3. Analysis and Simulations Results

According to the SoW three different missions have been simulated: Lunar, Mercurian and Jovian. Table 4 reports a summary of the analysed missions and the conclusions achieved for each of them.

Mission	Relevant Effects	Conclusions
Lunar	Geometric	All the analysed effects, but the geometric one, are negligible. Only the geometric asymmetry needs to be compensated to achieve the ESTRACK network accuracy.
Mercurian	All	While all the analyzed effects provide not negligible contributions to the delay asymmetries with respect to the ESTRACK accuracy using the S-band (see Ref. 7), the contribution of the effects depending on the signal frequency (e.g. ionosphere and solar plasma) are attenuated using the X-band. A compensation of these effects should be however foreseen to maintain the accuracy close to that available from the ESTRACK network.
Jovian	All	The same conclusions achieved for the Mercurian Misson are valid also for the Jovian Mission. However some of the analysed effects imply greater contributions to the links asymmetries than the corresponding effects evaluated on the Mercurian Mission. This is mainly due to the bigger distance from GS and SC. A compensation of these effects is necessary to achieve the accuracy of the ESTRACK network.

Table 4 – Relevant Effects Summary

A spacecraft orbiting around Jupiter, inside its sphere of influence, has been taken as reference for a typical deep space mission. The results achieved by simulation and analysis are shown in Table 5.

Row	Error Source	Delay STD	Doppler STD
1	Geometric Asymmetry	6.67ns (2m)	$0.33 \cdot 10^{-12}$ (0.1mm/sec)
2	Time Estimation Algorithms & Phase Noise	1.25ps (0.375mm)	$1.25 \cdot 10^{-12}$ (0.375mm/sec)
3	Others Asymmetries (Atmosphere, Relativistic, …)	0.80ns (0.24m)	$0.03 \cdot 10^{-12}$ (0.009mm/sec)
4	**Total** (separate Delay & Doppler)	6.72ns (2.01m)	$1.29 \cdot 10^{-12}$ (0.387mm/sec)
5	Impact of Doppler on Delay	3.87ns (1.16m)	←
6	**Total** (including impact of Doppler on Delay)	7.75ns (2.33m)	

Table 5 – Accuracies Budget

The geometrical asymmetry (row 1 of Table 5) is by far the bigger contribution to the accuracy. It has been limited by considering a single geometric reflection point at the SC of the signal sent by the GS. This constraint allows creating the triangle GS-SC-GS whose

edges are the up and down signal propagation paths and the straight line connecting the two GS positions corresponding to the transmitting and receiving times. An error less than 10Km in estimating the SC position (triangle vertex) it is enough to keep the geometric error, carried out in computing the geometric asymmetry, below 2m.

The measures of time and frequency are based on timing estimation algorithms exploiting the carrier phase. The accuracy achievable by this algorithms in the X-band (i.e. 8 GHz) is $1.25 \cdot 10^{-12}$ sec (i.e. 1/100 of the carrier period) corresponding to a Doppler factor $\delta = 1.25 \cdot 10^{-12}$ (through the approximation $dT \approx \delta$).
The contribution to the accuracy due to the phase noise has been also computed for the mission under exam and it is close to $1.25 \cdot 10^{-12}$ therefore, using a standard precision oscillator, it can be considered absorbed by the error due to the estimation algorithms.
These data are reported in row 2 of Table 5.

The total contribution to the accuracy due to both the atmosphere and relativistic asymmetries is reported in Row 3 of Table 5. The relativistic asymmetries are bigger than the atmospheric ones for this type of missions being however the overall error below 1ns in time and $0.03 \cdot 10^{-12}$ in Doppler frequency.

Summing the standard deviations of these contributions separately, the technique provides two different error budgets for the time and the frequency transfers respectively as shown in row 4 of Table 5. Since the accuracy obtained for the frequency transfer affects that achieved for the time transfer, it is necessary to estimate which is its impact. This can be done through using the formula:

$$\varepsilon_{\Delta t} = \frac{RTT}{2} \cdot \varepsilon_{\delta}$$

being RTT the round trip time. The corresponding numerical value, for the mission under exam, is reported in row 5 of Table 5.
It is worth noting that adopting the Ka-band (e.g. 30 GHz) and considering the case of nearer missions (e.g. missions to Mars) the impact of the frequency transfer accuracy on the time transfer precision reduces by a factor:

$$\frac{Ka}{X} \frac{5.2\,AU}{1.5\,AU} = 13$$

4. Conclusions

As final conclusion it is possible to state that the study carried out in this project provided a positive evaluation of the Cross-Link Technique employed for deep space missions. An accuracy better than 10nsec seems achievable for the time transfer under the constraints of having neither on-board atomic oscillator nor on-board synchronous processing, which are the main responsible of the payload cost (as far as the time transfer techniques are concerned).