Carlo Gavazzi Space SpA

SynDee

Novel Time Synchronization Techniques for Deep Space Probes

Executive Summary

Objectives

Space exploration is entering the next generation with a new initiative both for manned as unmanned exploration of the Moon and Mars. Alternative architectures for communication, navigation, and time dissemination are being investigated.

Among the many technical considerations is the need for time synchronization and dissemination. Time is central to communication and navigation. It is also fundamental for Deep Space Tracking or scientific applications such as Very Long Baseline Interferometry (VLBI) that involve the assimilation of data from widely separated sources.

The main purposes of the SynDee project are thus:

- To study a **novel time transfer method** between ground and deep space probes, making suitable to determine the synchronization error of a low-cost on-board oscillator and, where feasible, to lock it to a high accuracy ground clock.
- To assess the performances of such novel method by means of **simulations** in three possible mission scenarios: Moon, Mars and Deep Space.
- To assess the improvement of this method both for **synchronization** as for **ranging** purposes by comparison with traditional techniques.
- To define a top-level architecture for a **field trial** experiment, to test the proposed techniques in a real environment, and to assess possible use of available ESA assets.

Project Activities

The SynDee project can be divided into two following main phases.

Phase 1 is devoted to the definition of new synchronization algorithms for space missions. The main tasks carried out in this framework are:

- **System Consolidation**, covering the analysis of science mission requirements, and the selection of the mission profile that will be used as reference for the simulations. The novel synchronization techniques and algorithms were studied and specified, providing inputs to the next modeling task. Main effects of these algorithms on ESA ground stations and space segment were assessed.
- **Mission and Synchronization Modeling**: detailed models for the generation of mission data were set-up and run. Dedicated MATLAB® models for each synchronization technique were developed and tested separately.
- **Overall Simulations**: mission data were provided as input to the synchronization models, and overall simulations were carried out. Different types of instabilities were generated both on mission data and synchronization models. Simulations were repeated with instability data, to assess the real performances of each technique. Finally, results have been used to evaluate the impact of the novel time synchronization techniques on orbit determination performances.
- **Navigation Performance Assessment**: results of overall simulations with instability have been used to evaluate the impact of the novel time synchronization techniques on orbit determination performances.

Phase 2 addresses the preliminary definition of a field trial allowing to verify the synchronization techniques in a real environment. The main tasks carried out in this framework are:

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- **Field Trial System Architecture**: the overall architecture of the field trial has been studied, including some preliminary requirements to the trial subsystems and a representativeness analysis to assess the actual capability to reproduce the desired Space Mission environment.
- **Ground and Space Segment Definition and ESA Assets Identification**, to investigate some possible assets (including both ground and space segment) to be used for the field trial.
- **Ground and Space Segment HW and SW Definition**: to preliminary assess the hardware and software elements necessary to implement the field trial.
- **Test Plan Definition**: the test activities to be carried out in the field trial have been specified, with the aim to assess the synchronization algorithms performance in the emulated environment.

Moreover, at the end of Phase 1, additional tasks were agreed, to improve the performance of the prediction algorithms, and to evaluate the **impact of a possible S-Clock payload implementation on a Transponder** already selected for a real mission. In particular, the impacts of implementing an S-clock payload on the Transponder embarked on the Bepi-Colombo Mission have been evaluated in terms of required HW/SW and additional mass, volume and power budgets.

Proposed Synchronization Techniques

A set of novel synchronization techniques were specified in detail. As a prerequisite, all the proposed techniques are applicable only to a spacecraft equipped with a **regenerative transponder**.

Two of the proposed techniques have been selected for simulation: Technique 2, based on frequency lock of the S-Clock to the G-Clock with periodic time lock, and Technique 3, based on high-rate time lock of the S-Clock with the estimated deviation from the G-Clock. These techniques provide different performances when applied to different mission profiles.

Technique 2 is thought for synchronization of remote clocks at great distances. The key idea is that the onboard S-Clock is locked in frequency to the incoming signal generated on ground. Theoretically the lock can be done either on the RF carrier or directly on the pseudo noise signal modulation, as they are generated coherently on ground. Indeed, this procedure allows locking the S-clock to the Doppler-shifted frequency, and introduces a phase error between the G-Clock and the S-Clock due to the propagation delay. To correct these two impairments, the Ground Station has to predict the uplink Doppler experienced by the signal. This prediction is needed due to the very long propagation delays characterizing deep space missions. In the first project phase, the Uplink Doppler estimation was based on typical Orbit Determination campaigns and therefore on two-way Doppler and delay measurements and Delta-DOR in some missions.

The Estimated Doppler experienced in the Uplink (EDOUP) is sent from the ground station to the S-Clock payload via the telecommand link. The time error of the S-Clock is corrected on the base of Pseudo Delay Measurements carried out both onboard and on ground. This requires the transmission of time stamps indicating the time of transmission measured by the local clock referring to a specific transmission of the PN code. These time stamps are sent via telecommands for the ground-to-space link and via telemetry for the space-to-ground link. This operation is called “time lock”, and is performed with a period comparable to the two-way propagation delay.

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Early it came out the inadequacy of such a simple process which impacted the synchronization performance making the S-Clock working even worse than in free running conditions. As a consequence, even if not foreseen in the initial contract, a prediction method has been defined combining orbit determination data with rough real time two-way Doppler measurements.

Technique 3 is based on a "time-lock" of the S-Clock to the G-Clock. The S-Clock is in free-running conditions, meaning that it is not frequency-locked to any external source. In this technique, the "time lock" is carried out with a much higher frequency (in the order of 1 Hz). It has to be highlighted that the time corrections are computed every two-way delay periods, since this technique can be considered as a closed-loop technique with a loop delay equal to the 2-way delay. Furthermore, the S-Clock frequency drift is compensated dynamically through the measurements performed on ground. This procedure has been defined because of two reasons: on one side, typically the frequency drift is modeled as a perfect linear behavior. Therefore, in the simulation of the S-Clock impairment, the drift is actually perfectly linear. In real applications, this drift is pre-compensated applying a tuning that takes into account this drift. Since no model was found on the residuals of such a compensation, this dynamic compensation allows introducing some kind of mismatching, in this case due to the measurements noise. The second reason is to try to really improve frequency drift corrections, allowing a dynamic response to the actual S-Clock behavior over time.

This technique 3 is thought for near-Earth missions (i.e. Moon), since the limiting factor is the clock behavior over the 2-way delay. Therefore, the longer the propagation delay, the higher the clock instability affecting the synchronization.

Main Simulation Results

For **Technique 2**, the performances reported in the table below are obtained using a TCXO, and are equivalent to those of a Master Oscillator. This because the S-clock is frequency-locked to the uplink signal, and thus the TCXO frequency drift is not considered.

S-Clock Synchronization Performance for Technique 2 with TCXO			
MISSION SCENARIO	**TCXO ΔT (absolute)**	**TCXO ΔT (r.m.s.)**	**TCXO Δf/f (r.m.s.)**
Moon	~10^{-9} s	$5.9991 \cdot 10^{-10}$ s	$2.3331 \cdot 10^{-12}$
Mars	~10^{-6} s	$4.9873 \cdot 10^{-7}$ s	$3.5561 \cdot 10^{-10}$
Asteroid	~10^{-9} s	$3.2891 \cdot 10^{-9}$ s	$1.0061 \cdot 10^{-11}$

Clearly this technique is applicable only in the case in which it is possible to have a good prediction of the Doppler and delay. Excellent results are obtained with the Deep Space mission.

The accuracy of the prediction of the Doppler and delay depends heavily on the characteristics of the mission itself and on the particular orbit prediction technique associated with the tracking infrastructure available. Prediction errors of the Doppler and delay increase with the prediction interval. An advanced "hybrid algorithm" for the prediction technique using estimated data for predicting changes of the real data over the 2-way delay has been implemented. The advanced "hybrid algorithm" is therefore reducing the prediction interval to the minimum duration possible.

The impact of Technique 2 for orbit determination improvements is expected to be negligible. In fact, the synchronized S-Clock would allow to enhance range measurements only, while two-way Doppler measurements could not benefit from the proposed technique.

For **Technique 3**, instead, the Master Oscillator (a space-qualified OCXO) shall be used as S-Clock, being it not frequency-locked and deriving the synchronization performance from a clock bias/drift compensation procedure. The dominant error in this case is due to the S-clock noise behavior over the two-way propagation delay.

S-Clock Synchronization Performance for Technique 3 with MO			
MISSION SCENARIO	**MO ΔT (absolute)**	**MO ΔT (r.m.s.)**	**MO Δf/f (r.m.s.)**
Moon	~10^{-11} s	$2.5186*10^{-11}$ s	$1.0831*10^{-11}$
Mars	~10^{-8} s	$2.4932*10^{-8}$ s	$7.1157*10^{-12}$
Asteroid	~10^{-8} s	$1.2820*10^{-8}$ s	$7.5547*10^{-11}$

For the Moon mission the time keeping performances of the locked MO are very good being comparable to that of the Ground H maser.

For long 2-way delay Technique 3 requires computing and correcting the MO frequency drift and frequency offset. This is realized in a transient period after which the performances are depending both upon the time error accumulated by the MO over the 2-way delay and the accuracy of the delay asymmetry prediction.

Technique 3 is not competitive with Technique 2 for accurate Doppler prediction as the ones realized in the Deep Space mission. In the case of inaccurate Doppler prediction Technique 3 is however superior to Technique 2 as demonstrated by the Mars mission.

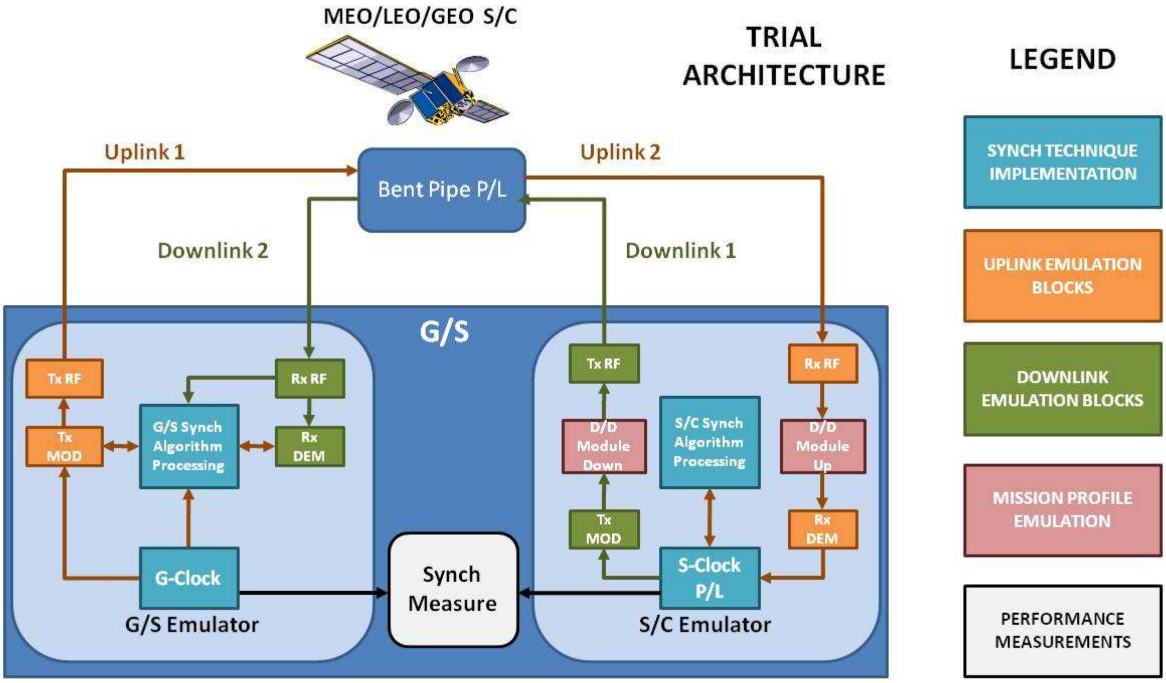
Field Trial Definition

The first step towards the Field Trial Definition was the identification of a suitable **architecture** to validate the synchronization algorithms performance in an environment as close to a real space mission environment as possible. Dealing with this, a set of evaluation criteria have been defined and analyzed; these criteria have been used to assess the suitability of a large set of proposed configurations.

Thanks to this assessment, three candidate trial configurations have been selected and ranked, all based on a **double-hop** approach: MEO double hop + Channel emulator; GEO double hop + Channel emulator; LEO double hop + Channel emulator. In these configuration, the real channel hop through a LEO, MEO or GEO satellite allows introducing real impairments due to atmospheric effects, antenna tracking effects on the electronic group delay, and the asymmetries due to the fluctuations of both the spacecraft emulator and the ground station.

On the other hand, the extreme conditions of deep space channel impose the need to introduce an emulator block, able to introduce effects characterizing deep space missions, such as Doppler Profiles, Delay Profiles and relativistic effects.

The following figure shows the architecture defined, with a general view of all the subsystems and their physical location.

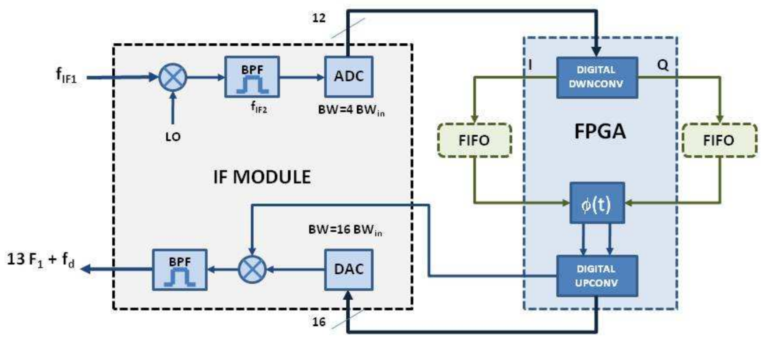


One of the key components of the proposed architecture is the **D/D module**. It adds digitally on the received signal the delay, Doppler, relativistic effects and noise impairments reproducing the specific mission profiles.

Two D/D modules are in charge of emulating the Uplink and Downlink mission profiles respectively. The D/D uplink module is also in charge of performing a second non-coherent down-conversion to the second IF frequency.

The signal is digitalized and stored in a FIFO to emulate the desired delay. At the FIFO output, the signal is processed to introduce digitally Doppler and noise.

Several configurations can be implemented to interface the D/D Module with the IF Module of the regenerative transponder. In the selected configuration (see figure) the signal is split in two paths, one of whom perform the subcarrier lock. The locked oscillator is used to produce a suitable coherent frequency that will up-convert the ranging signal at ($13\ F_1 + f_d$) where the latter is the Doppler shift. In this way, the IF signal is coherent.



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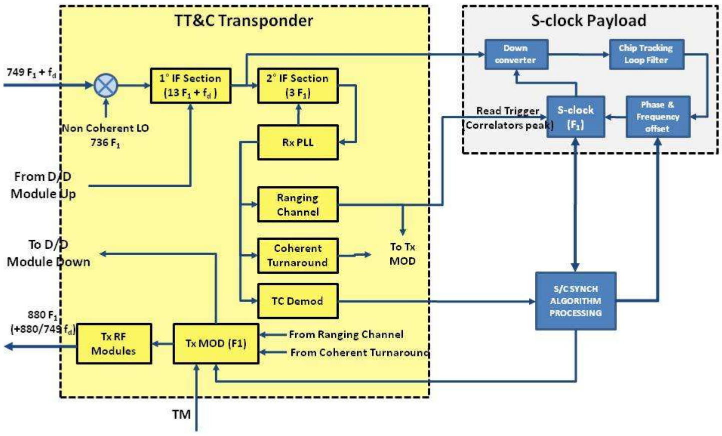
The other two main blocks of the field trial architecture are the S-Clock Payload, integrated with the TT&R regenerative transponder, and the Ground Segment Emulator, including the G/S Synchronization Algorithms Processing.

The **S-Clock Payload** includes the S-Clock itself (a TCXO or a Master Oscillator, depending on the mission profile), a tracking loop to lock the incoming IF signal, a non-coherent down converter (if a non-coherent transponder is used in the field trial), an additional block introducing phase and frequency control offsets generated by the S/C synchronization algorithm processing.



The synchronization algorithm processing onboard the spacecraft will: (1) process the algorithm information coming from the Ground Station synchronization processing and sent through the Telemetry (i.e. Predicted Uplink Doppler, Predicted Uplink Delay etc.); (2) generate the S-Clock Control Signals; (3) receive the S-Clock Time stamps, triggered by the TT&C correlators; (4) send the algorithm result information to the Telecommand modulator.

The **Ground Segment Emulator** includes two major components: the G-Clock itself, and the control electronics implementing the corresponding outputs of the G/S Synchronization Algorithm Processing. In order to not degrade the performance of both techniques, the G-clock shall have an accuracy characterized by stability negligible with respect to the synchronization accuracies expected. To achieve that order of stability, the G-clock used in the Ground Segment emulator is the G-clock of the selected Ground Station for the field trial.

Using DSP techniques the tasks associated to the signal processing and operations required by the algorithm shall be implemented. This implementation on DSP allows to have a flexible breadboard which can be tuned during the trial operations in order to verify different payload configurations (i.e. loop bandwidth).

The G/S Synchronization Algorithms Processing implements these main functions: (1) computation of PDG; (2) store Orbit Prediction Data; (3) EDOUP Prediction Algorithm; (4) EDUP Prediction Algorithm; (5) S-Clock ΔT estimation.

From the Field Trail architecture proposed, three level of tests have been defined in the **Test Plan**:

- **Sub-system Tests**, aimed to calibrate G/S and S/C Emulators in order to minimize systematic errors via calibration, such as the time-varying group delays;
- **First Level System Tests**, aimed to calibrate the residuals expected to affect the overall synchronization accuracy, and to determine the errors of the double hop +G/S and S/C emulator.
- **Second Level System Tests**, aimed to verify the overall synchronization algorithm performance in the field trial, for each selected mission to be emulated.

Conclusions

The main results achieved in the SynDee project can be summarized as follows:

- A comprehensive characterization of **science mission scenarios** of interest for the current study (near Earth, medium and long distances) has been provided. Mission characteristics were then used as starting point to identify the critical phases of the mission in terms of time synchronization and navigation accuracy and to derive a set of common mission requirements of almost general application to any science mission.
- **Novel techniques for time transfer** between ground and space clocks were identified and specified. All the proposed techniques are applicable only to a spacecraft equipped with a regenerative transponder.
- **Dedicated simulators** were developed, to properly model the different mission scenarios under study, and the implementation of the novel synchronization techniques.
- Overall simulations merging mission and synchronization modeling were carried out, and simulations results have been used to evaluate the impact of the novel time synchronization techniques on orbit determination performances. Results show a **good performance of the proposed algorithms for the different mission profiles**. A key performance advantage of these techniques is the virtual absence of the ageing effect on the S-Clock, being it continuously synchronized to an ultra-stable G-Clock during each visibility period. This characteristic is extremely useful for very long duration missions, typical of deep space exploration programs.
- A dedicated study has been carried out to identify the modifications required to add the **S-Clock Payload** to a standard regenerative transponder implementing the space segment functions needed for the tracking, and to specify the additional equipment (both HW and SW) needed to implement the proposed synchronization algorithms.
- The system architecture for a potential **Field Trial** has been studied, and the main building blocks have been specified in terms of HW/SW components and ESA assets. The major issue to be faced is the correct representation of the dynamics of the deep space channel, mainly in terms of Doppler and propagation delay profiles. The proposed approach foresees a **double-hop** scheme, thus introducing real ground-to-satellite issues to be properly handled, coupled with an **hardware-based emulator**, which would reproduce the channel impairments of a deep space mission introducing a certain noise, delay and Doppler on the IF signal. A representativeness analysis demonstrated that this approach allows implementing both the synchronization techniques subject of the study, and emulating the correct Doppler and Delay profiles as introduced in the system simulations.

The synchronization techniques proposed and characterized in the SynDee study are a valuable alternative to the use of high-quality space qualified clocks on board deep space probes, being able to lock, with a very good level of accuracy, a less expensive clock on-bard the spacecraft to an ultra-stable ground-based clock. The performances are guaranteed during the visibility periods, when ground-to-space link is established, and do not suffer from ageing effects, apart from those of the ground-based clock.

SynDee Team

Carlo Gavazzi Space is a leading aerospace company with large experience in system and technology development, starting from design and manufacturing of Small Satellites and of Telecommunications and Earth Observation Payloads, up to space-based technology exploitation, through an experienced Business Unit dedicated to Applications. Moreover, CGS has a relevant expertise in Earth Observation, Navigation and Telecommunication, specially devoted to Governmental Authorities.

In the SynDee project, Carlo Gavazzi Space covered the following tasks: project management and reporting, system engineering and activities coordination, modeling of synchronization techniques, integration of synchronization models and mission models, overall simulation with integrated models, field trial overall architecture study and space segment definition.

Deimos Space is a Spanish aerospace company active in the fields of Mission Analysis and Flight Dynamics tools, GNC Algorithms and Simulation SW, Software systems following ESA standards, Operational facilities, Ground Segment facilities, Database systems, Object-Oriented systems, On-board real-time software, Networked systems, with the aim to develop high-tech state-of-the-art solutions, mainly for the aerospace sector, with total commitment to the customer and to quality as top priorities. Regardless its short history (founded in 2001), DEIMOS has already been awarded with a high number of ESA contracts at ESTEC, ESOC, ESRIN and VILSPA and is cooperating with most outstanding space company in Europe, namely with System Integrators and with several non-prime companies and SME. Furthermore DEIMOS has established fruitful cooperation with national and international research institutes and universities.

Main DEIMOS responsibilities in the SynDee project cover mission requirements analysis, mission models, analysis of the navigation improvement with the proposed synchronization techniques, all aspects related to Ground Stations, including field trial ground segment definition.

Kytime is a private consulting company, founded by Prof. Giovanni Busca in August 2001 after his retirement from the direction of the Observatoire of Neuchatel (ON).

Kytime involvement in the SynDee project includes novel synchronization techniques and algorithms definition, inputs and support to synchronization algorithms modeling, support to models integration, support to overall simulations, test plan definition for the field trial.