Novel Time Synchronization Techniques for Deep Space Probes

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***Abstract*—New initiatives both for manned and unmanned exploration of the Moon and Mars have stimulated investigations on time synchronization due to its central role in communication, navigation and time stamping of scientific experiments. In the framework of the European Space Agency (ESA) project Novel Time Synchronization Techniques for Deep Space Probes (Syndee) two novel algorithms are proposed for locking a low-cost on-board oscillator (Space Clock) to the Ground Station reference clock. Performances of these Novel techniques are assessed via simulations in three mission scenarios: Moon Mission, Mars Mission and Deep Space Mission.**

I. Introduction

Space exploration is entering the next generation with a new initiative both for manned as unmanned exploration of the Moon and Mars.

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.

Most space missions, also require some kind of clock synchronization. There is usually the need to synchronize the space clock (S-clock) with a ground clock (G-clock) reference. Moving from the requirement for Deep Space Missions time synchronization, two novel Time and Frequency synchronization techniques have been proposed in the framework of the Syndee Project [1]. This paper is organized as follow. Section II introduces the two novel synchronization techniques, and provides an overview of functionalities and equipments needed for the ground segment and for the payload onboard the probes. Section III introduces the system simulator developed and provides an overview of the system modeling approach. Section IV shows the synchronization performance achievable in three space missions profile, and provides a critical analysis of the results. Finally, Section V draws the conclusions.

II. Novel Time and Frequency Synchronization Techniques for Deep Space Missions

A. Basic Introduction

The very basic idea of synchronization techniques is to minimize the absolute time error Δt between a high precision reference Ground Clock (G-clock) and the clock onboard the probe (S-clock) resulting from bias in the synchronization process.

One of the key concepts is the pseudo delay measurement. The use of pseudo-delay is a common technique in the "IEEE Standard for Precision Clock Synchronization Protocol for Networked Measurement and Control System" [2] and is proposed in this context for S-clock measurements.

The G-clock sends a synchronization signal to the S-clock together with the time of transmission as read by the ground clock. The S-clock receives the signal, measures the arrival time as read by the S-clock, and compute the pseudo delay affected by the clock time offset. Finally, the spacecraft send back the downlink synchronization signal and the pseudo delay measured. On ground, the Ground station can measure the pseudo delay for the downlink. In a straightforward way it is possible to show that with these measures the ground station can estimate the S-clock time offset as:

$$\Delta t = [(PDS - PDG) - DAS]/2 \quad (1)$$

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Where PDS is the Pseudo-Delay measured by the S-Clock, PDG is the Pseudo-Delay measured by the G-Clock and DAS is the Delay Asymmetry., which has contributions from the Geometry, Ionosphere-troposphere and Electronic Delays.

The geometrical delay AS is the difference of the uplink and the down link ranges. It can be estimated from the time evolution of the 2-way delay or from the integrated Doppler measured in the conventional tracking techniques.

Other AS can be estimated or calibrated. In particular the ionosphere or plasma delays asymmetry of the up and down links can be estimated from multi-frequencies measurements and models. Techniques exist, as for example the ones scheduled for Bepi-Colombo [3], which can model the medium delay with a very high accuracy. The asymmetry due to troposphere can be modeled from atmospheric parameters monitoring.

An important asymmetry contribution, for which no model is possible, is the Electronics Delay ASymmetry (EDAS) which is produced by the Ground station and possibly also by the space transponder. Uncontrolled delay variations can reach nanoseconds level for ground station antenna front end as shown in [4]. The delays have to be calibrated in order to correct these variations by measurements prior and after a tracking session.

The second point concerns the S-clock stability. Since the S-Clock is changing over the 2-way delay, if the Δt value computed on ground is used to correct the S-clock, the synchronization accuracy is affected by the time error accumulated by the free running clock over the 2-way delay.

The Pseudo-Delay technique is used in both the synchronization techniques. The measurement of pseudo delays is assumed to be possible thanks to the availability onboard of a regenerative Tracking, Telemetry and Commands (TT&C) payload implementing the Pseudo Noise (PN) regenerative ranging. This ranging technique has a noticeable advantage with respect to the current ranging and tracking techniques based on turnaround transparent payloads. Thanks to the reduction of the Noise Bandwidth of the payload,, regenerative ranging can lead to a potential gain up to 30 dB [5].

B. *Novel Synchronization Techniques*

The first synchronization algorithm is based on the key idea to lock the frequency of the onboard Space-Clock to the frequency of the Ground Clock with a frequency offset loop in which the Doppler shift of the uplink carrier frequency is compensated. The prediction of the Doppler-shift is performed by the Ground Station by measuring the actual value of ½(2-way Doppler) and correcting this value with the Doppler asymmetry estimated via the Orbit Determination. The predicted Doppler shift of the uplink carrier is sent to the spacecraft via the Telemetry link.

For locking in time the Space clock Pseudo Delay Measurements are performed both onboard and on ground. This allows to evaluate the Time error of the S-clock, and to compensate it. The time lock is performed for the initial synchronization of the Space Clock and successively with a period comparable to the two-way propagation delay for limiting the residual time errors eventually produced by Doppler prediction errors.

The second synchronization algorithm is a closed loop algorithm applicable to near-Earth missions (i.e. Moon.) where the loop delay is shorter. In the absence of the frequency lock, the performance is limited by the free running clock stability over the 2-way delay. The time lock is carried out with a frequency in the order of 1 Hz. Furthermore, the Space Clock frequency drift is compensated dynamically through the Pseudo Delay measurements performed on ground.

III. System Simulator

A system simulator was developed in Matlab to assess synchronization performances of the two techniques. The following sections describes the simulator building blocks.

A. *Mission Scenarios*

In order to assess synchronization techniques performance, three type of missions characterized by different distances from the Earth are selected: Moon, Mars and Asteroid missions.

As the synchronization techniques performance depend also on the accuracy of the Estimated Uplink Delay (EDUP) and Estimated Uplink Doppler (EDOUP), also the orbit determination process have been simulated. Therefore, for each mission three different profiles are considered.

Nominal: it is the reference trajectory of the spacecraft, which is generated by propagating an initial state vector.

Real: the real trajectory consists of a realization of the actual set of errors sources considered in the simulation. They essentially comprise errors in the initial state vector, solar radiation pressure and station location.

Estimated: the predicted trajectory is obtained by propagating a realization of the best knowledge of the real orbit obtained from a previous Orbit Determination campaign. The generation of the Estimated mission data is based on radiometric measurements which are therefore required to be fed into the overall simulation environment.

The prediction accuracy depends on the type of measurements assumed for the initial state vector determination. In the three mission scenarios, different measurements have been hypothesized on the base of the typical measures as done today. In particular for the *Moon* scenario, the initial covariance matrix is derived from an orbit determination campaign based on range and Doppler measurements from a single station. On the contrary, for the *Mars and Asteroid* scenarios the initial covariance matrix is derived from an orbit determination campaign based on range, Doppler and delta DOR from two stations.

Each simulated time span falls within a single GS-to-SC visibility window.

B. *Channel Model*

The Uplink and Downlink channels are modeled in a very simple way. In particular, the main effects introduced on the signal by the communication channel are:

1. *Doppler shift*;
2. *Propagation delay;*
3. *Ionosphere effects*
4. *Thermal noise.*

C. *Payload Model*

The payload models implemented in the simulator can be grouped in two categories: the synchronization algorithm processing and the payload-induced effects. In particular, they have been modeled introducing the effect of the onboard clocks phase noise and frequency drift for the free-running clock and phase locked clock for the first and second technique respectively. The phase noise actually affects both the accuracy of the locked S-clock and of the pseudo delay measurements onboard.

TABLE I. TCXO SPECIFICATIONS

PARAMETER	Value	Units
Short-term stability (Allan Variance)	1 x 10^{-9}	/second
Long term stability	1	ppm / year
SSB Phase Noise	-75 @ 10 Hz -105 @ 100 Hz -130 @ 1 kHz -140 @ 10 kHz -140 @ 50 kHz	dBc

For the generation of S-clock time jitter realization over the whole simulation time the Barnes model has been used [6] Two different clocks have been considered for the two techniques.

For the first technique, thanks to the frequency lock a low precision oscillator can be used. The deriving benefit is a reduced power consumption onboard needed to meet the required timing accuracy with respect to the use a free running clock. In particular, a Temperature Controlled Crystal Oscillators (TCXO) is selected as the S-clock. The following TABLE I. shows the TCXO specifications considered.

The regenerative payload is modeled simulating the effect of the Phase Locked Loop (PLL) onboard. In particular, a second order PLL with active filter with dumping factor $1/\sqrt{2}$ is considered. The PLL loop bandwidth was optimized in the three scenarios (characterized by three different C/N_0 values) in order to minimize the output phase instability. For the second technique, as the clock is in free running conditions over the two way delay, a space qualified example of Space qualified Oven Controlled crystal Oscillator (OCXO) is considered. Its characteristics are summarizes below in TABLE II.

D. *Ground Stations Model and ground synchronization processing*

The ground station model basically includes the ground reference clock (G-Clock) and the synchronization processing.

The G-clock is modeled as a perfect clock. This assumption does not impact the simulation results, since for such clocks the stability over the two-way propagation delay can be neglected with respect to the instability introduced by the S-clock.

TABLE II. OCXO SPECIFICATIONS

PARAMETER	Value	Units
Frequency	5 - 200	MHz
Short-term stability (Allan Deviation)	3*10^{-12} (0.1s<τ<100s)	/second
Time error	10 ps @ 1s 0.1 ns @ 100 s 1 ns @ 1000 s	-

Concerning the synchronization processing, the main functionalities are the computation of the EDOUP and EDUP to be sent to the S-clock payload to correct it. The estimation of these two values is based on Orbit Determination data updated in real time comparing them with real-time two-way Doppler and Delay measurements. An extrapolation allows to predict the expected error after the one-way delay, and this value is used to correct the OD prediction. Figure 1. shows a comparison of the Uplink Doppler estimation errors in the Asteroid scenario coming from OD data and this new prediction processing method.

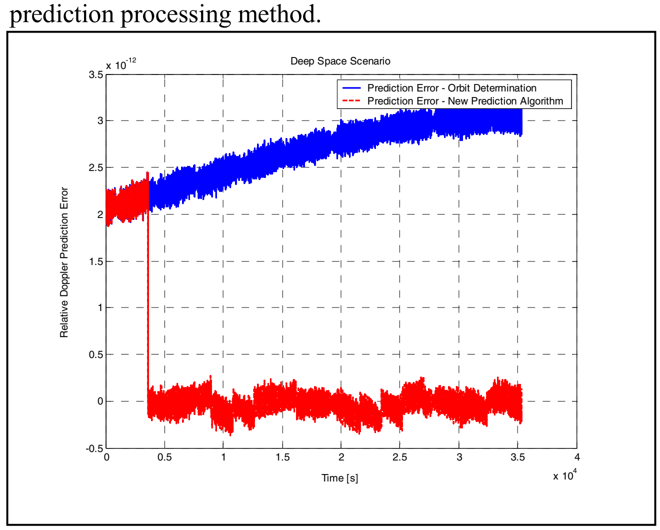

Figure 1. Example of Doppler Prediction Errors

IV. SIMULATION RESULTS

This section shows the synchronization accuracy achieved thanks to the novel synchronization techniques proposed. This assessment is performed by means of the system simulator. The two techniques are verified in the three mission scenarios. The main results and a critical analysis is shown in the rest of the section.

A. *Technique 1- Frequency lock*

<u>MOON SCENARIO</u>

Figure 2. shows the S-clock error in terms of absolute time error ΔT and the relative frequency offset. Analyzing the results and the different components which contributes to the total error, from this simulation it comes out that in the Moon scenario for the second synchronization technique the

frequency error is dominated by the prediction error of the Doppler. Figure 3. shows the Allan Deviation of the S-clock versus the integration time $\tilde{\tau}$

MARS SCENARIO

Figure 4. shows the S-clock error in terms of time error ΔT (top figure) and relative frequency offset (bottom figure). Figure 5. shows the Allan Deviation of the S-clock versus the integration time $\tilde{\tau}$.

ASTEROID SCENARIO

Figure 6. shows the S-clock error in terms of time error ΔT (top figure) and relative frequency offset (bottom figure). Figure 7. shows the Allan Deviation of the S-clock versus the integration time $\tilde{\tau}$.

B. Technique 2- Time lock

MOON SCENARIO

This technique results extremely effective in the Moon scenario. Figure 8. shows the S-clock errors in terms of time offset and relative frequency offset. Figure 9. shows the Allan variance as a function of the integration time τ.

MARS SCENARIO

Figure 10. shows the S-clock errors in terms of time offset and relative frequency offset. It has to be noted that the frequency offset plot shows a series of negative spikes which are not really errors, but are the frequency correction applied to compensate the clock ΔT measured on ground.

In the same figure, it is possible to see how the drift compensation procedure works: in the first iterations, the parabolic behaviour of the ΔT due to the linear drift is compensated; after that, the frequency bias is reduced. It has to be noted that the compensation procedure is affected by the S-clock flicker noise. This effect is expected to be lowered in real operations, since the linear frequency drift is an effect with very low variations. As a consequence, the a-priori knowledge of the drift can be successfully used for compensation. In these simulations has been decided anyway to do not consider this concern. Figure 11. shows the Allan variance as a function of the integration time τ

ASTEROID SCENARIO

Figure 12. shows the S-clock errors in terms of time offset and relative frequency offset. It has to be noted that the frequency offset plot shows a series of negative spikes which are not really errors, but are the frequency correction applied to compensate the clock ΔT measured on ground. As for the Mars scenario, it is possible to see the positive effect of the drift compensation procedure. Finally, Figure 13. shows the Allan variance as a function of the integration time $\tilde{\tau}$

V. CONCLUSIONS

A. Novel Synchronization techniques Performance Analysis

TECHNIQUE 1 – Frequency Lock

This technique is applicable only in the case in which is possible to have a good prediction of the Doppler and delay. Excellent results are obtained with the Asteroid 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. For example the Doppler and delay prediction is inadequate even with the use of ΔDOR in the case of the Mars mission, while for the Moon mission prediction errors are determined also by the limited tracking resources.

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. However the accuracy gain is only a factor of 2 to 3 in the case of important estimation errors and is negligible when estimation errors are relatively small as is the case for the Deep Space mission.

The major result of this technique is that using a very simple TCXO onboard it is possible to achieve a good accuracy, which can be maintained in the long term. As a consequence, this technique is very suitable to small-size missions with limited power and mass capabilities and requiring moderate onboard synchronization performance in the long term.

TECHNIQUE 2 – Time Lock

For the Moon mission the time keeping performances of the OCXO are very good being comparable to that of the Ground Hydrogen maser. For long 2-way delay Technique 2 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 2 is not competitive with Technique 1 for accurate Doppler prediction as the ones realized in the Deep Space mission. In the case of inaccurate Doppler prediction Technique 2 is however superior to Technique 1 as demonstrated by the Mars mission.

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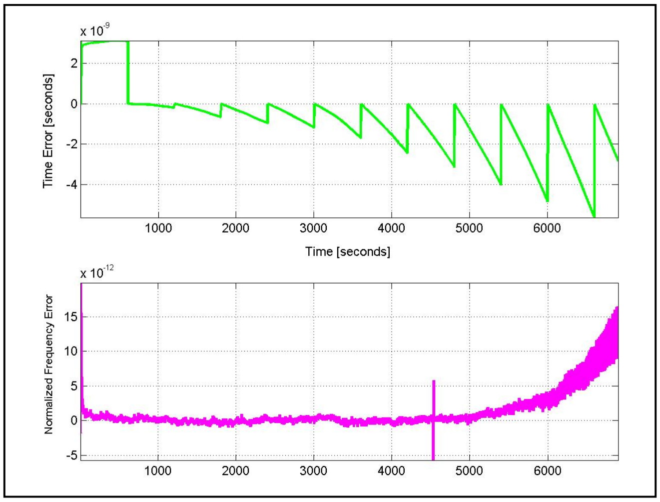

Figure 2. Technique 1 Moon Scenario results – S-Clock (TCXO) Time and Relative Frequency error over time.

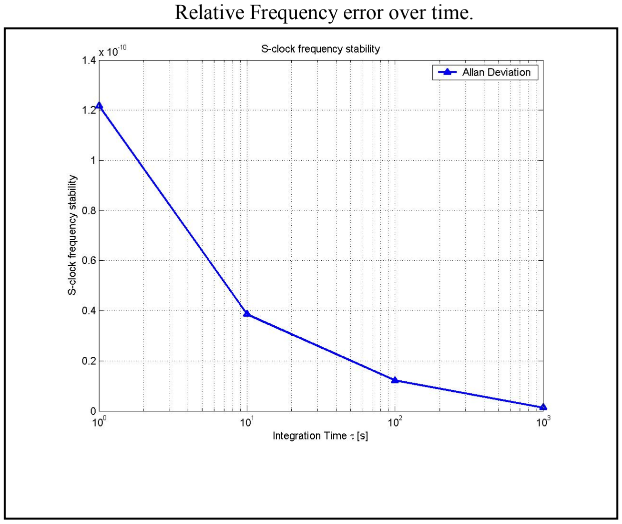

Figure 3. Technique 1 Moon Scenario results – S-clock (TCXO) Allan Deviation vs integration time.

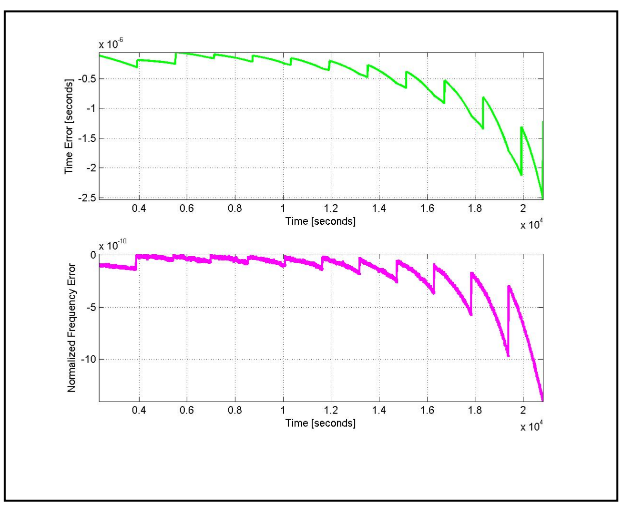

Figure 4. Technique 1 Mars Scenario results – S-Clock (TCXO) Time and Relative Frequency error over time.

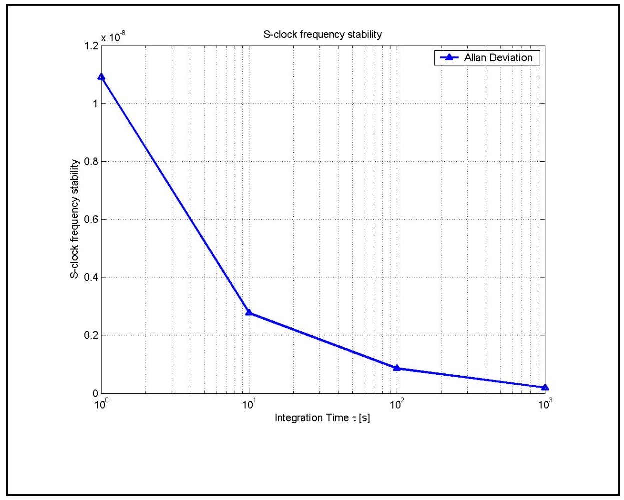

Figure 5. Technique 1 Mars Scenario results – S-clock (TCXO) Allan Deviation vs integration time.

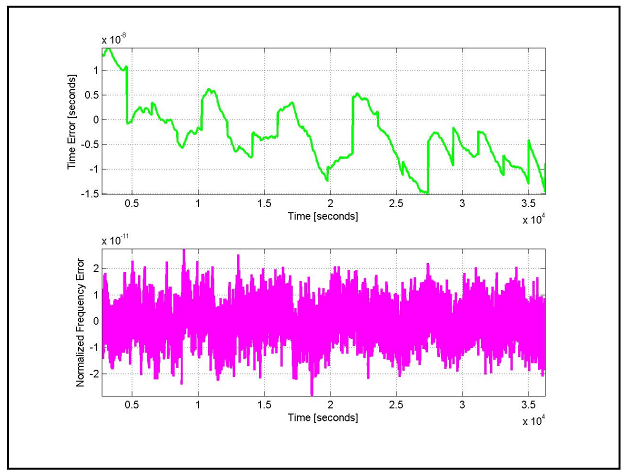

Figure 6. Technique 1 Asteroid Scenario results – S-Clock (TCXO) Time and relative Frequency error over time.

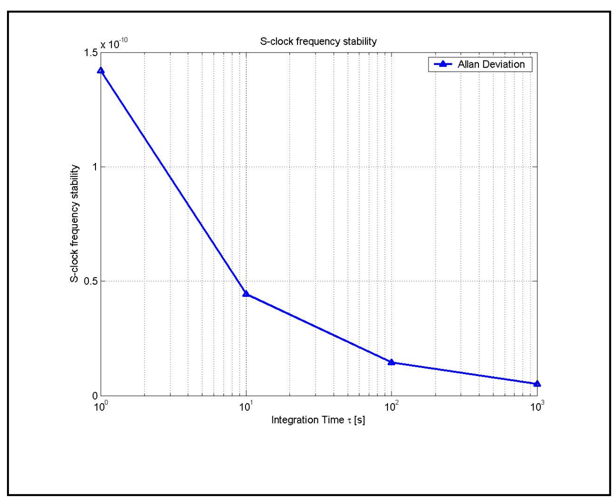

Figure 7. Technique 1 Asteroid Scenario results – S-clock (TCXO) Allan Deviation vs integration time.

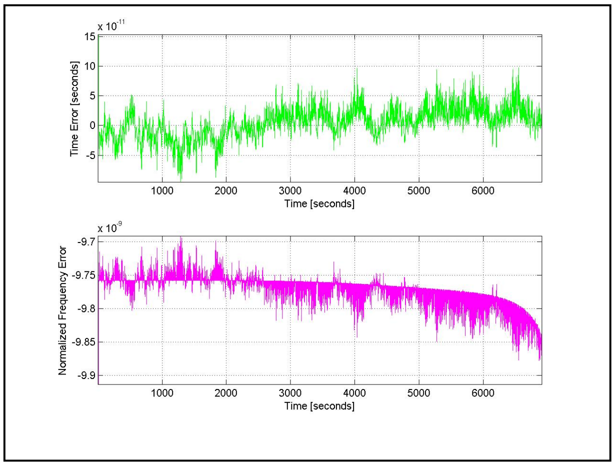

Figure 8. Technique 2 Moon Scenario results – S-Clock (OCXO) Time and Frequency error over time - Zoom.

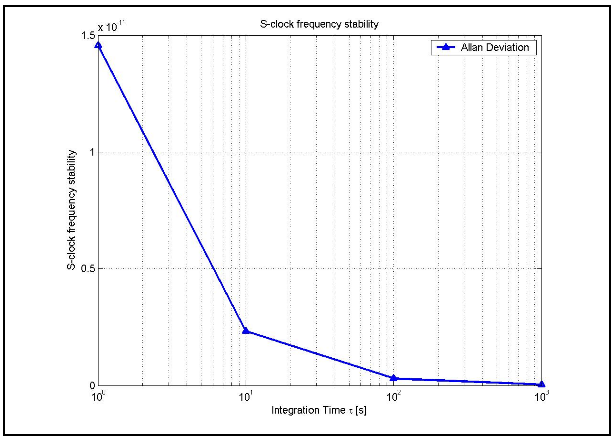

Figure 9. Technique 2 Moon Scenario results – S-Clock (OCXO) Allan Variance vs Integration time.

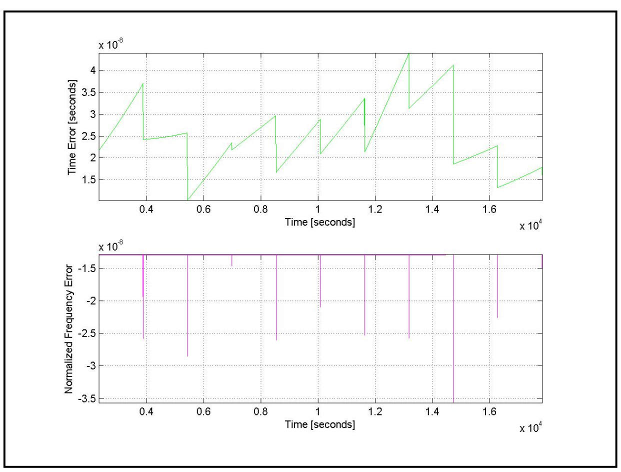

Figure 10. Technique 2 Mars Scenario results – S-Clock (OCXO) Time and Frequency error over time.

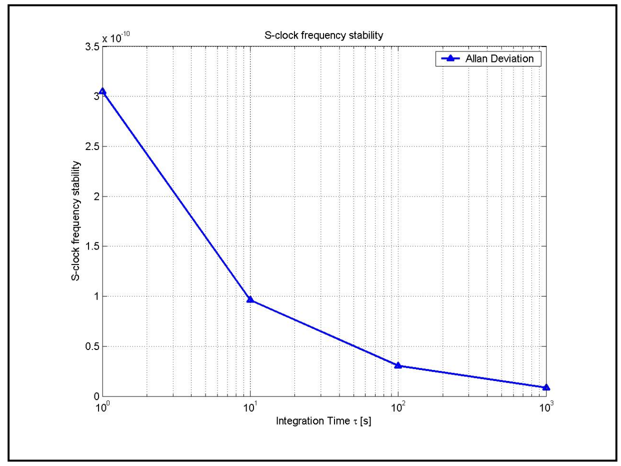

Figure 11. Technique 2 Mars Scenario results – S-clock (OCXO) Allan Variance vs integration time.

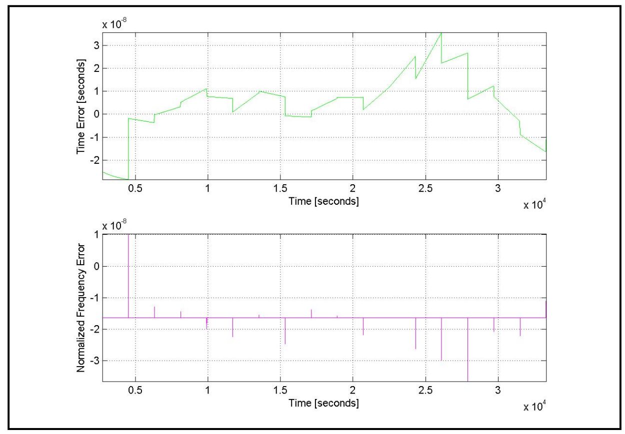

Figure 12. Technique 2 Asteroid Scenario results – S-Clock (OCXO) Time and Frequency error over time.

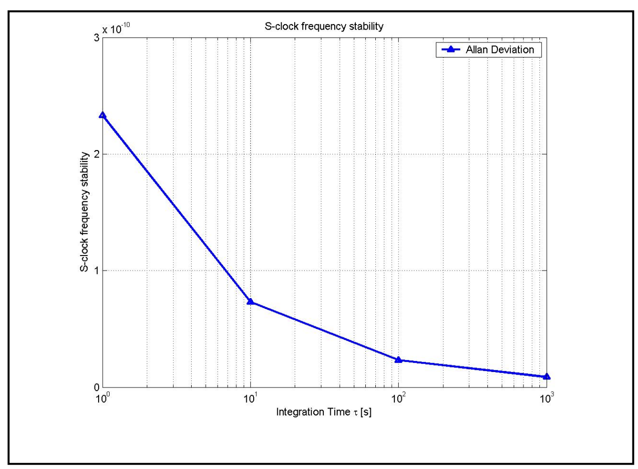

Figure 13. Technique 2 Asteroid Scenario results – S-clock (OCXO) Allan Variance vs integration time.