SCIENCE-QUALITY OSCILLATORS FOR DEEP SPACE PROBES

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Abstract

Planetary missions carry oscillators as clocks for purposes of telecommunications, navigation, and mission timekeeping. In many cases, radio science experiments also utilize oscillators and typically push the limits of their stability in order to optimize science return, especially atmospheric physics. The number of design options for oscillators has increased, offering lower cost and mass and sufficient stability performance for non-scientific applications. Since the designation label Ultra-Stable Oscillator was coined, new labels such as Sufficiently Stable Oscillators have entered into usage and applied to models that vary by one or more orders of magnitude in frequency stability, causing possible misunderstandings for experiment planners. Additionally, the usage of crystal oscillators (e.g., Galileo probe) is compared with atomic frequency standards using rubidium gas cells (e.g., Huygens), where characteristics vary in relevant parameters such as the Allan Deviation at integration times between 1 and 100 seconds, phase noise at various frequency offsets, long-term drift, and several environmental parameters. For purposes of comparison of classes of oscillators, however, the Allan Deviation at 100 s can act as a summary indicator of the quality. The Voyager-era dual-oven USO has 100-second Allan Deviation of ~E-12 (where the approximation sign indicates 1 to 3 parts). It was also flown on Galileo and later on the Mars Reconnaissance Orbiter. Since then, a single-oven USO was introduced by another vendor with an order of magnitude improvement in stability. The ~E-13 USO was flown on Mars Global Surveyor (MGS), Cassini, GRACE, New Horizons, and several other near and deep space missions with Radio Science investigations; the most recent delivery was for the GRAIL project. A near complete list of missions, the type and provider of their USOs and the complete set of characterization parameters is available in Asmar et al., (2003).

1. Introduction

Spacecraft carry various types of oscillators acting as timekeeping clocks or communication signal sources. Radio Scientists and navigators also utilize high stability oscillators. The Voyager Radio Science Team custom-developed with an industrial partner the first deep space quartz crystal Ultra Stable Oscillator (USO), introducing the “ultra-stable” class; specifications were derived from radio occultation investigations of the atmosphere of the outer planets. Since then, the number of options for users has increased significantly.

USOs are characterized by several relevant parameters such as the Allan Deviation at integration times between 1 and 100 seconds, phase noise at various frequency offsets, long-term drift, and several environmental parameters. For purposes of comparison of classes of oscillators, however, the Allan Deviation at 100 s can act as a summary indicator of the quality. The Voyager-era dual-oven USO has 100-second Allan Deviation of ~E-12 (where the approximation sign indicates 1 to 3 parts). It was also flown on Galileo and later on the Mars Reconnaissance Orbiter. Since then, a single-oven USO was introduced by another vendor with an order of magnitude improvement in stability. The ~E-13 USO was flown on Mars Global Surveyor (MGS), Cassini, GRACE, New Horizons, and several other near and deep space missions with Radio Science investigations; the most recent delivery was for the GRAIL project. A near complete list of missions, the type and provider of their USOs and the complete set of characterization parameters is available in Asmar et al., (2003).

Shortly after the E-13 USO development, another design was introduced, with lower cost, characterized by 100-s Allan Deviation of ~E-11 and flown on the Mars Odyssey missions for UHF proximity communications purposes. In the same time period, the Titan Doppler Wind Experiment on the Huygens probe required an oscillator with stability requirements of ~E-10
(at time scales from a few to 30 minutes) and a rubidium-based USO was selected.

Despite the range in stability performance from E-10 to E-13, these oscillators were called ultra-stable in many project documents. The designation of the Odyssey-era E-11 oscillator was later labeled a Sufficiently Stable Oscillator (SSO). When mission planners are considering a stable oscillator, there is a danger of selecting a device that turns out not meet science requirements but is still designated ultra-stable. The Allan Deviation at 100 s summary indicator of the quality is recommended for usage.

2. Precision versus Accuracy

A recurring question is the criterion for a choice between quartz crystal oscillators and rubidium atomic oscillators for planetary probes. The Galileo probe into Jupiter utilized a quartz oscillator for a Doppler wind experiment while the Huygens probe to Titan utilized a rubidium oscillator for the same type of experiment. The criterion was the requirement for precision versus accuracy. A quartz crystal USO is very precise in that it can reach high stability after the required warm up period but the absolute value of its output frequency is not accurate and will experience normal drift. Most Radio Science observations emphasize the relative changes in the output frequency over the duration of the experiment and do not require a strict specification on the accuracy as long as the phase is highly stable. A rubidium oscillator is tied to the frequency of the rubidium atomic transition and outputs an absolute and accurate measurement of the frequency after a warm up period (typically significantly shorter than the quartz warm-up period) but the output is statistically noisier. So, while a rubidium oscillator is nosier but more accurate over short time periods, a quartz oscillator is less accurate but more precise over a longer time period. Figure 1 graphically illustrates the conceptual contrast between precision and accuracy.

3. Future Trends

Research facilities such as the JHU-Applied Physics Laboratory, in some cases with funding through technology programs at the NASA-Jet Propulsion Laboratory, have continued further developments of the next generation USOs. A prototype has been developed for a quartz crystal USO with a synthesizer to tune the output frequency in flight. USOs are currently tuned once to the specific mission channel assignment and are not altered in flight. There are mission scenarios where a modification of the USO output frequency can help operations. A synthesizer-equipped USO provides in situ frequency control. Taking this concept a step further, a “disciplined” quartz USO can overcome the poorer accuracy in comparison with a rubidium USO. A synthesizer can be used to modify the output frequency via on-board firmware that monitors the output signal and either decide on the modification or receive commands from a mission operations team for the modified output frequency. This type of USO is now technologically feasible but flight models have not been developed for specific missions yet.

The second trend for future instrumentation is the reduction in the phase noise of the USO. Breaking the 5E-14 theoretical limit of quartz crystal oscillator stability can only be accomplished with alternate material and method called “piezoelectric artificials.” Research has been advanced in identifying the appropriate material that can enable an order of magnitude improvement in oscillator stability. Such device could begin to rival the use of the ground-based hydrogen masers currently providing the stability and timing reference for two-way Doppler links for most US-developed telecommunications systems. Note that the future “space clock” has already been demonstrated in the laboratory to achieve E-14 stability (100-second Allan deviation); this atomic clock technology is also at a stage of readiness for a flight demonstration.

The third trend is miniaturization. Spacecraft mass and power resources for small and low-cost missions require a significant reduction of these parameters without sacrificing the stability for science applications. The E-13 quartz USO which typically weights ~2 kg and requires ~3 W of power in the steady state can now be available with a mass reduced to 0.5 kg and power reduced to ~1 W. This is achieved by significant simplification in the electronics and number of available output ports as has been demonstrated with the USO for the Solar Probe mission.

4. Conclusion

Stable oscillator for planetary probes are available in several levels of quality, primarily
Phase stability, spanning three orders of magnitude. The number of design options for oscillators has increased, offering lower cost and mass and sufficient stability performance for non-scientific applications. New trends potentially offer exciting devices capable of benefiting from superior accuracy and stability with electronic disciplining of the output signal of quartz crystal oscillators.

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Figure 1: Graphical illustration of precision versus accuracy for oscillators (Vig 2001)

References
