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Characteristic Trends of Ultrastable Oscillators for Radio Science Experiments

S. W. Asmar
Communications Systems and Research Section

Telecommunication systems of spacecraft on deep-space missions also function as instruments for radio science experiments. Several missions augmented the radio communication system with an ultrastable oscillator (USO) in order to provide a highly stable reference signal for one-way downlink. Since the first quartz USO was flown on Voyager, the technology has advanced significantly, affording future missions higher sensitivity in reconstructing the temperature–pressure profiles of the atmospheres under study as well as the ability to study other physical phenomena of interest to radio science. The ultrastable class of oscillators has been flown on Voyagers I and II, the Galileo Orbiter, the Galileo Probe, Mars Observer, and Mars Global Surveyor. These have been quartz crystal resonators. The Cassini spacecraft will carry another quartz USO and two rubidium USOs for the Huygens Probe in support of the Doppler Wind Experiment. There are plans to fly USOs on several other future missions. This article surveys the trends in stability and spectral purity performance; design characteristics, including size and mass; and the history of these clocks in space.

I. Introduction

Telecommunication systems of spacecraft on deep-space missions also function as instruments for radio science experiments. Radio scientists utilize the telecommunication links between spacecraft and Earth to examine very small changes in the phase/frequency, amplitude, and/or polarization of radio signals to investigate a host of physical phenomena in the solar system. Several missions augmented the radio communication system with an ultrastable oscillator (USO) in order to provide a highly stable reference signal for one-way downlink. This configuration is used in order to enable better investigations of the atmospheres of the planets occulting the line of sight to the spacecraft; one-way communication was required, and the transponders' built-in auxiliary oscillators were neither sufficiently stable nor sufficiently spectrally pure for the occultation experiments. Since radio science instrumentation is distributed between the spacecraft and the ground stations, the Deep Space Network (DSN) also is equipped to function as a world-class instrument for radio science research. For a detailed account of radio science experiments, methodology, key discoveries, and the DSN's historical contribution to the field, see [1]. Also, the tools of radio science can and have been utilized in addressing several mission engineering challenges, e.g., characterization of spacecraft nutation and anomalous motion, antenna calibrations, and communications during surface landing phases.

Since the first quartz USO was flown on Voyager (VGR), the technology has advanced significantly, affording future missions higher sensitivity in reconstructing the temperature–pressure profiles of the atmospheres under study as well as the ability to study other physical phenomena of interest to radio science. This article surveys the trends in stability and spectral purity performance; design characteristics, including size and mass; and the history of these clocks in space.

II. Science Overview

Almost every deep-space mission conducted successful radio science experiments, which typically are divided in two classes: propagation, and celestial mechanics and gravitation. These have resulted in hundreds of journal articles. Examples of these experiments include planetary atmospheric temperature–pressure profiles and ionospheric composition; the structure of planetary rings; planetary gravitational fields, shapes, and masses; planetary surface characteristics; wind profiles; magnetic fields; electron content and scintillation in solar corona and solar wind; mass flux and particle distribution of comets; the search for gravitational radiation; gravitational redshift; and relativistic time-delay experiments. Stable one-way downlink is essential to propagation experiments, although several aspects can be accomplished via two-way coherent links, as well as to redshift and wind-profile experiments. In addition to the completed experiments to date (e.g., Mariner(s), Pioneer(s), Voyager(s), Galileo, Ulysses, Magellan, etc.) [3], there are important planned experiments on upcoming missions (e.g., the Cassini–Huygens mission to Saturn and Titan) and possible future experiments with missions in the planning stages (e.g., Pluto Express, Rosetta, Discovery missions, etc.).[1]

III. Instrumentation

The elements of the instrumentation required for engineering implementation on board a spacecraft with radio science experiments as part of its mission objectives vary in complexity depending on the sophistication of the experiments. They include transponders (which are available on every deep-space mission, although some missions have considered transceivers), an attitude control system that provides for a "quiet" spacecraft, an ultrastable oscillator, translators that are needed for coherent transmission of signals not used by the primary transponder (e.g., Ka-band [32 GHz] for the Cassini mission), and uplink signal-processing equipment for proposed uplink radio occultation experiments.

With this instrumentation, the fundamental limits on sensitivity of the end-to-end system are the frequency stability, amplitude stability, signal-to-noise ratio, accuracy in reconstructing navigation trajectories, and media propagation effects. The frequency stability of the one-way link typically is limited by the performance of the USO.

IV. Ultrastable Oscillators

The ultrastable class of oscillators has been flown on Voyagers I and II, the Galileo (GLL) Orbiter, the Galileo Probe, Mars Observer, and Mars Global Surveyor (MGS). These have been quartz crystal resonators. The Cassini spacecraft will carry another quartz USO and two rubidium USOs for the Huygens Probe in support of the Doppler Wind Experiment. There are plans to fly USOs on several other future missions.

Needed to eliminate the time required by the transponder to lock up on the uplink during an occultation egress as well as the media effect on the uplink, USOs become the heart of the radio science instrumentation on board the spacecraft. Quartz crystal resonators, relatively small in mass, volume,

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[1] For a list, see S. W. Asmar and R. G. Herrera, *Radio Science Handbook*, JPL D-7938 (internal document), Jet Propulsion Laboratory, Pasadena, California, 1995.

and power, have been easier to space qualify than atomic clocks. The latter also are being considered for space flight.

The USO technology can be divided in these design classes:

(1) Voyager Class: includes Voyagers I and II and the Galileo Orbiter.
(2) Mars Class: includes Mars Observer, Mars Global Surveyor, and Cassini.
(3) Pluto Class.
(4) Huygens Class.
(5) Galileo Probe Class.

In the first class, five identical units were procured at the same time; two flew on the Voyagers, one on Galileo [2], and two were spares. In the second class, a flight unit and a spare were procured; one flew on Mars Observer and the refurbished spare flew on Mars Global Surveyor. A flight unit and a spare of a similar design were later procured for the Cassini mission. In the third class, a new tactical BVA design is proposed for flight on the Pluto Express mission; it shows significant reduction in mass and size without compromising the performance demonstrated by the Mars class [4].

The Huygens rubidium USOs were chosen over quartz due to the need for a very short warm-up time and less stringent long-term stability. The Galileo Probe USOs had similar requirements, but quartz oscillators were chosen; insufficient documentation is available on them. In the case of both probes (Huygens and the Galileo Probe), one USO was on the probe as part of its transmitter chain (e.g., the Huygens transmit ultrastable oscillator [TUSO]) and a second identical unit was on the orbiter (Cassini and Galileo) as part of the receiving chain of the orbiter signal (e.g., the Huygens receive ultrastable oscillator [RUSO]).

Table 1 lists seven oscillators and several key parameters characterizing them, such as mass, size, power, performance measured by Allan deviation (AD), phase noise (PN), drift rates, environmental performance, etc.[2] Cost estimates are not included in the table, but in some cases may be obtained from the author or the providers.

In addition to serving as an historical summary for interested managers, scientists, and engineers, the table has two key areas of note. The first is the major improvement in stability between the Voyager-class and Mars-class oscillators—an order of magnitude in Allan deviation. The second area is the significant miniaturization proposed for the Pluto class of oscillator.

V. Conclusion

Almost every deep-space mission conducted successful radio science experiments. With the available instrumentation, the fundamental limits on sensitivity of the end-to-end system are the frequency stability, amplitude stability, signal-to-noise ratio, accuracy in reconstructing navigation trajectories, and media propagation effects. The frequency stability of the one-way link typically is limited by the performance of the USO. Since the first quartz USO was flown on Voyager, the technology has advanced significantly, affording future missions higher sensitivity in reconstructing the temperature–pressure profiles of the atmospheres under study as well as the ability to study other physical phenomena of interest to radio science.

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[2] In Table 1, the following acronyms are used: Applied Physics Laboratory (APL); 2.29 GHz, S-band (S); 8.4 GHz, X-band (X); radio frequency subsystem (RFS); and radio frequency instrument subsystem (RFIS).

Table 1. USO technology information summary.

Parameter	Voyager	Galileo	Mars Observer	Cassini	Pluto	Huygens	Galileo Probe
Maker	Frequency Elect. Inc.	Frequency Elect. Inc.	APL	APL	APL	DASA, Germany	Hughes contract
Year	1975	1975	1987	1993	1994	1993	~1975
Type of quartz crystal cut	AT	AT	SC	SC	SC	Rubidium	SC
Number of ovens	2	2	1	1	1	2	2
Mass, kg	1.1	1.1	1.3	2.0	0.32	2.1	?
Steady-state power consumption, W	2.2	2.2	2.2	2.8	0.8	10.4	~1
Dimensions (L × W × H or D × L), cm	10.2 × 19.5	10.2 × 19.5	10.2 × 10.2 × 16.8	10.2 × 12.8 × 19.4	5.3 × 6.9 × 9.7	17 × 14.9 × 11.8	4.6 × 14
Resonator frequency, MHz	6.38	6.38	4.79	4.79	~10	6835	4.6
Nominal output frequency, MHz	19.137	19.125	19.144	114.917	38.262	10.00	23.117
Assigned deep-space channel	18 (VGR II)	14	20	23	16	23	n/a
USO-reference downlink bands	S, X	S, X	X	S, X, Ka	X, (Ka)	S	1.387 GHz
Drift rate, Hz/s	-1.3×10^{-7}	-1.5×10^{-7}	2.3×10^{-6}	Not available	Not available	2×10^{-7}	2×10^{-7}
Aging, 24 h	5×10^{-11}	5×10^{-11}	2×10^{-11}	7×10^{-11}	2×10^{-11}	2×10^{-9}	?
Long-term aging, 5 yr	2×10^{-7}	2×10^{-7}	10^{-7}	10^{-6}	Not available	4×10^{-6}	?
Temperature, deg C	5×10^{-12}	5×10^{-12}	3×10^{-12}	2×10^{-12}	10^{-12}	4×10^{-12}	3×10^{-12}
Radiation, rad	2×10^{-12}	2×10^{-12}	10^{-10}	10^{-10}	10^{-10}	2×10^{-14}	2×10^{-13}
Magnetic susceptibility, G	5×10^{-12}	5×10^{-12}	8×10^{-13}	5×10^{-13}	2×10^{-12}	5×10^{-11}	4×10^{-12}
Static acceleration, g	10^{-9}	10^{-9}	3×10^{-9}	10^{-9}	1.5×10^{-9}	10^{-11}	10^{-9}
Harmonic spur, dBc	−40	−40	−60	−60	−50	−60	?
PN 1 Hz, dBc	−100	−100	−110	−85	(−112)	−80	?
PN 10 Hz, dBc	−108	−108	−125	−110	(−117)	−90	?
PN 100 Hz, dBc	−118	−118	−131	−120	(−127)	−110	?
PN 1 kHz, dBc	−138	−138	−131	−125	(−132)	−120	?
AD 0.1 s	(2×10^{-11})	(2×10^{-11})	2×10^{-12}	10^{-12}	10^{-12}	6×10^{-11}	?
AD 1 s	3×10^{-11}	3×10^{-11}	3×10^{-13}	2×10^{-13}	3×10^{-13}	10^{-11}	5×10^{-12}
AD 10 s	4×10^{-12}	4×10^{-12}	10^{-13}	10^{-13}	10^{-13}	5×10^{-12}	?
AD 100 s	10^{-12}	10^{-12}	10^{-13}	10^{-13}	10^{-13}	10^{-12}	?
AD 1000 s	10^{-12}	7×10^{-13}	2×10^{-13}	10^{-13}	2×10^{-13}	10^{-12}	(10^{-10})/ 30 min
Source of AD values	In-flight tests	In-flight tests	In-flight tests	Contract specs	Proposal	Contract specs	(Probe document)
Notes	VGR I & II identical	Different from GLL Probe	MGS USO identical	RFS & RFIS	Tactical BVA	2×10^{-10}/ 15 min	Rad hard/ shield

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