

GRAIL and the Lunar Reconnaissance Orbiter (LRO) missions. On MGS, the Mars Orbiter Laser Altimeter (MOLA) described in Zuber et al. (1992), produced a high-resolution topography field that was correlated with the gravity field measured by the same mission (sometimes, also combined with historical data) leading to important discoveries (Zuber et al. 2000; McGovern et al. 2002). GRAIL did not carry an altimeter, but LRO was in operation in the same time period and carried the Lunar Orbiter Laser Altimeter (LOLA). Science teams used the GRAIL gravity data and LRO altimetry data to produce high-resolution correlations between the two data sets (Zuber et al. 2013b).

5.3.1 Spacecraft Ultrastable Oscillator

5.3.1.1 Purpose and Historical Development

The USO was developed for the purpose of carrying out planetary RO experiments in the one-way mode where there is a stable reference on each end of the link, spacecraft and ground station, or between two spacecraft. Reasons for carrying out the experiment in the one-way mode with a USO include:

- It eliminates the double propagation of the uplink and downlink signals in the same planetary medium under study. The double propagation requires more complex processing (Schinder et al. 2012; Hinson et al. 2008; Hinson et al. 2014; Tellmann et al. 2013), which is further complicated in cases of multi-path signal conditions in the planetary atmosphere (Fjeldbo et al. 1975; Lipa and Tyler 1979). The preferred one-way signal travels from the spacecraft through the medium once. This is typically a downlink configuration but, for the Pluto one-way uplink experiment, the direction was reversed and data were stored on the spacecraft then played back as telemetry files (Tyler et al. 2009).
- It eliminates the time needed by the transponder to lock-up on the uplink signal when the spacecraft is emerging from behind the occulting planetary body. Although the lock-up time can be short (a few seconds to a few minutes, depending on the atmospheric density, uplink SNR, sweep rate, etc.), this delay can be comparable to the length of the observation and cause the loss of the egress experiment in the lower atmospheric region. With a USO, the spacecraft can already be transmitting prior to the beginning of the occultation egress without loss of data.

Without a USO, the transponder's built-in auxiliary oscillator is not sufficiently stable to extract scientifically meaningful data (unless the aux osc stability improves significantly in the future). However, without a USO, an occultation experiment can be carried out in the two-way mode for ingress only (immersion). To clarify these issues, in a highly instructive 1975 paper on the Pioneer 10 RO of Jupiter's ionosphere at S-band (~2.1 GHz), Gunnar Fjeldbo (also known as Gunnar Lindal) and his team of RS pioneers discuss the use of an onboard auxiliary oscillator (referred to as the crystal oscillator, not thermally controlled) and summarize the state of the art at that time as well as the evolving thinking on the instrumentation due to the dilemma they faced prior to the invention of the USO for the Voyager program. The comment "considering to conduct the Pioneer 11 immersion measurements at Jupiter in the two-way mode" was addressed in Section 5.2.2.1. Fjeldbo et al. (1975) stated:

In view of the unexpectedly large topside scale height and temperature revealed by the Pioneer 10 data, we are now considering to conduct the Pioneer 11 immersion measurements at Jupiter in the two-way mode. In this tracking mode, a stable Earth-based oscillator (either a hydrogen maser or a rubidium vapor oscillator) is used to generate a 2.1-GHz uplink carrier. The spacecraft's radio transponder coherently translates the frequency of the uplink signal to approximately 2.3 GHz and retransmits the new RF carrier back to the tracking station where the difference between the uplink and downlink frequencies can be measured. Since the stability of any one of the available ground-based frequency standards is at least an order of magnitude higher than the stability of the spacecraft crystal oscillator, the two-way measurements can be expected to help substantially reduce the current uncertainty in the topside plasma scale height and temperature. Of course, two-way tracking will not yield reliable data in the lower ionosphere where multipath on the uplink may cause the spacecraft's phase-locked loop receiver to change lock from one signal mode to another in an unpredictable manner. However, this disadvantage is not a serious problem since one-way immersion measurements can provide more data on the lower ionosphere.

Due to these challenges on Solar System missions, the first flight instrument developed specifically for RS enhancement was the USO, called the "single most dramatic improvement in radiometric performance" by G. L. Tyler (1987). The USO was developed for the Voyager atmospheric and ring RO experiments to provide a stable reference for the transponder as it transmits a one-way downlink signal to Earth.

The Voyager RS team leader at Stanford University charged a JPL team member, the late Gordon Wood, to partner with industry to develop a very stable clock small enough to fly on the Voyager spacecraft. Frequency Electronics Inc. (FEI) of Long Island, NY, was selected (its founder Martin Bloch and Gordon Wood coined the "ultra-stable" classification). Specifications were derived from the objectives of the Voyager investigations at the outer planets as well as the available technology.

After a prototype unit met the requirements, NASA procured five flight-qualified USOs. Voyager 1 and Voyager 2 carried one each, and the Galileo orbiter later carried USO serial 4 from that batch, later called the 10^{-12} class of stability. The Voyager USOs have since left our Solar System, although the Voyager 1 USO stopped functioning circa 1992 after successfully completing all its required scientific functions at planetary flybys. The Voyager 2 USO is still used for one-way communications at record distances and record longevity. USOs have been single-string science instruments while the transponders they are connected to (cross-strapped) are redundant.

After Voyager and Galileo, Cassini as well as orbiters at Mars, Venus, the Moon, and other planetary and Earth missions (listed in Asmar 2012b and updated in Table 5.1) have carried USOs from various manufacturers including FEI and the Johns Hopkins University Applied Physics Laboratory (APL); see example in Asmar et al. (2019). The post-Voyager USO models were as much as an order of magnitude better in their stability, the 10^{-13} class of stability. This was needed for Mars RO experiments where the atmosphere is significantly less dense than the outer planets. The first of these was flown on MGS, which, for a decade, carried thousands of atmospheric occultations with extremely valuable scientific results.