GRAIL – A Microwave Ranging Instrument To Map Out The Lunar Gravity Field

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***Abstract*— Gravity Recovery and Interior Laboratory, or GRAIL, is a NASA mission to map out the gravity field of the moon to an unprecedented level of detail. The instrument for this mission is based on GRACE (Gravity Recovery and Climate Experiment), an earth-orbiting mission currently mapping out the gravity field of the earth. This paper will describe the similarities and differences between these two instruments with a focus on the microwave ranging measurements used to determine the gravity parameters and the testbed built at Jet Propulsion Laboratory to demonstrate micron level ranging capability. The onboard ultrastable oscillator and RF instruments will be described and noise contributions discussed.**

I. INTRODUCTION

Gravity Recovery and Interior Laboratory (GRAIL) [1] is a NASA mission to map out the gravity field of the moon. It is a Discovery class mission awarded in 2006 and scheduled for launch in September 2011 for a 90-day science mission. The instrument is being/has been built and tested at Jet Propulsion Laboratory (JPL), and will be delivered in the summer of 2010 to Lockheed Martin in Colorado for integration onto the spacecraft.

GRAIL is based on GRACE (Gravity Recovery and Climate Experiment) [2], a pair of satellites currently orbiting the earth and mapping out its gravity field. This paper will describe the GRAIL mission and science goals, the differences between GRAIL and GRACE, an overview of the GRAIL instrument/ranging measurement, and testing performed at JPL.

II. GRAIL MISSION AND SCIENCE GOALS

The GRAIL mission concept is based on Newton's Law F=ma: local mass variations on the moon result in orbital acceleration (and therefore velocity) changes for an orbiting spacecraft. However, resolving a single satellite's minute orbital variations would be extremely difficult. Instead, we launch a pair of orbiting satellites separated by 50 to 250 km over the course of the science mission. These spacecrafts experience lunar gravity variations at different locations/times and thus continually change their distance from one another. This inter-satellite distance can then be measured and used as a signature or footprint to detect mass variations on the moon below.

The mission requirements are set to resolve 30km mass variations at the 0.5mgal level (1 gal = 1 cm/s^2) [3]. The four minimum science goals are to investigate: the structure of the lunar crust and lithosphere, asymmetric thermal evolution of the moon, subsurface structure of impact basins and origin of mascons (mass concentrations), and brecciation and magmatism. The full science goals include obtaining information about the deep interior structure of the moon, and detection of the inner core. [3]

III. GRAIL VERSUS GRACE

GRACE was launched in 2002 and is still returning valuable gravity-map data of the earth. The main differences between the GRAIL and GRACE instruments arise because GRAIL does not have to contend with the earth's atmosphere nor does it have access to the Global Positioning System (GPS). GRACE compensates for atmospheric disturbance primarily by having an accelerometer to measure nongravitational acceleration but also by having two separate microwave ranging frequencies (24GHz and 32GHz) rather than just a single frequency. GRAIL is simplified by omitting the K-Band frequency (24 GHz) as well as the accelerometer (nongravitational forces are small enough to be modeled instead of measured). However, for GRACE, GPS is used to measure relative time between the two satellites, calibrate onboard USO frequencies, and track the two spacecrafts' orbits. With no GPS available at the moon, GRAIL has added an additional S-Band (2GHz) Time Transfer System (TTS) to replace the GPS timing functionality, and an additional X-Band (8GHz) Radio Science Beacon (RSB) which allows for Doppler tracking of the spacecraft and for USO frequency calibrations via the Deep Space Network (DSN).

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

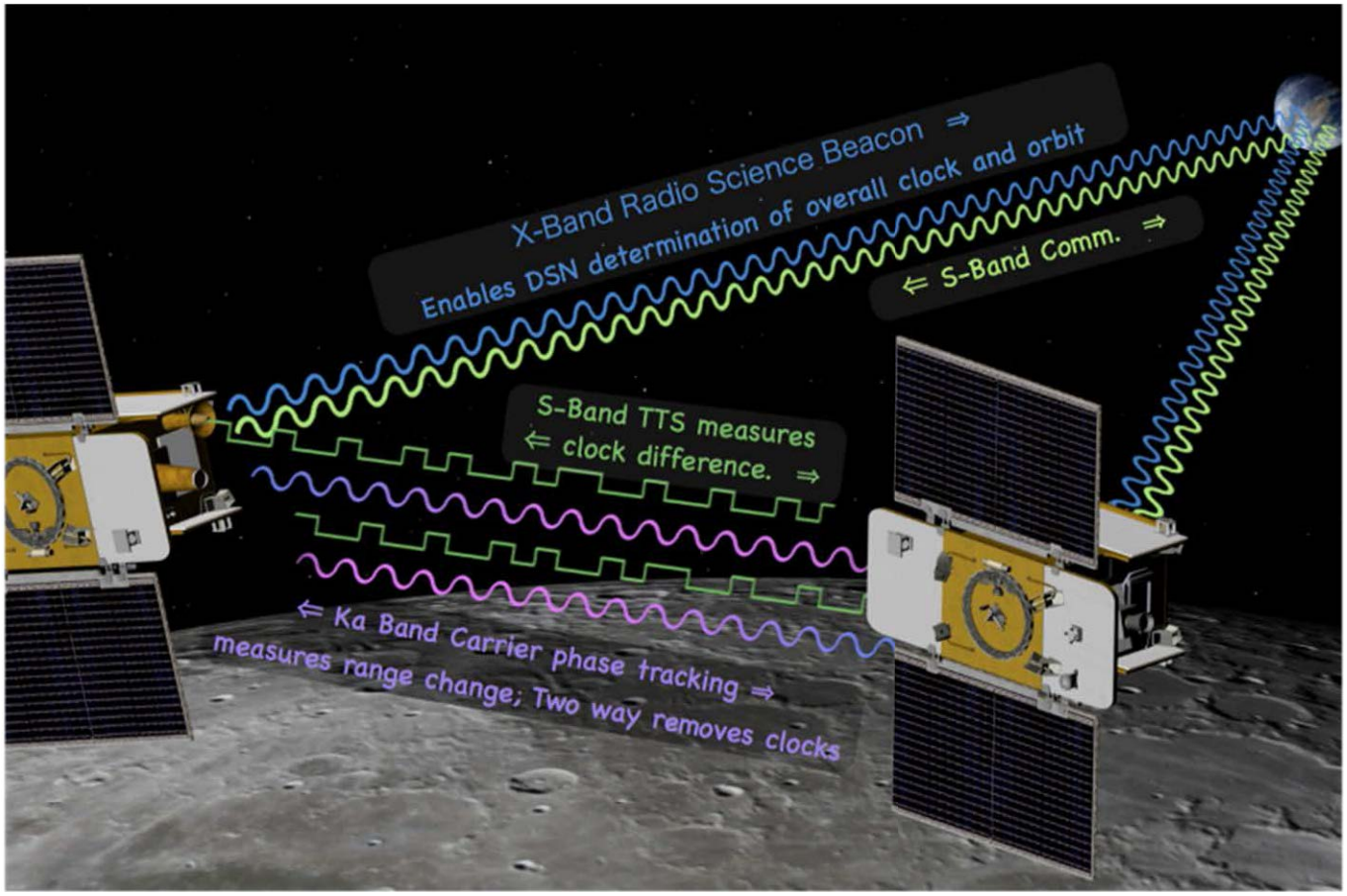

Figure 1. A pictoral representation of the RF signals for GRAIL showing the Ka-Band carrier phase tracking signal, the S-Band time transfer signal and the signals transmitted back to earth.

IV. GRAIL Instrument Overview

Fig. 1 is a pictorial representation of the RF signals for GRAIL and Fig. 2 shows the components on each of the two satellites that create and receive these signals. The Ka-Band (32GHz) ranging signal is sent from one satellite to the other and vice versa at slightly different frequencies so that incoming and outgoing signals on each spacecraft can be mixed down to ~670 kHz, sampled, and tracked to detect phase changes on the order of 10^{-4} cycles. A phase change of 10^{-4} cycles at this frequency corresponds to ~1 µm of relative movement between the two satellites and can be resolved in one second. Onboard oscillator noise is largely canceled by adding the individual phase measurements from each spacecraft (and dividing by two), thus forming a dual-one-way-range (DOWR) [4, 5]. This effectively cancels slow clock noise because phase-noise on this mixed-down 670kHz enters from the LO side of the mixer for one spacecraft and from the other side of the mixer (with the opposite sign) for the other spacecraft. (When considering faster clock noise, the DOWR method can be modeled as a high-pass filter with a time constant equal to the light travel-time between the spacecraft.) The S-Band Time Transfer System enables this phase-addition to be done, in postprocessing, at simultaneous times (to within 100ns) even though the on-board clocks are running at different and potentially varying frequencies (due to USO noise for example). And finally, the RSB enables determination of the overall length/clock scale by comparing the onboard USOs to ground-based masers in the DSN. The RSB (and/or a separate S-Band Telecommunication system) also allows for Doppler tracking via the DSN, so that orbital information and these GRAIL DOWRs (i.e. inter-satellite distances) can all be entered into a JPL navigation program adapted to infer the lunar gravity map.

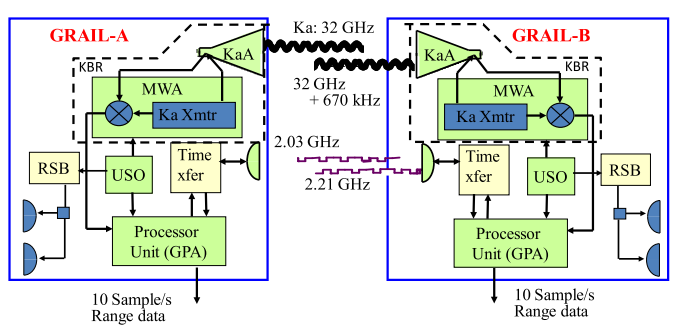

Figure 2. Each GRAIL spacecraft has a USO that feeds three onboard components: the Radio Science Beacon (RSB) which communicates to the DSN for Doppler Tracking and for USO calibration, the Microwave Assembly (MWA) which creates, sends, receives, and mixes down the

32GHz microwave ranging signal, and the Gravity Processor Assembly (GPA) which samples and tracks the mixed-down 670kHz as well as houses much of the S-Band Time Transfer System. Also shown are the Ka horn (KaA) and the S-band antenna (unmarked green vertical semi-circle)

V. GRAIL TESTING AT JPL

Early testing at JPL used JPL's 60-foot anechoic chamber to radiate Ka-Band and S-Band signals from one spacecraft mockup to another positioned fourteen meters away, using a mixture of GRAIL engineering models (EMs), off-the-shelf equipment, and original GRACE prototypes and flight-spare hardware. One spacecraft mockup was moved relative to the other (via a linear stage) in 20-micron steps (Fig. 3) to confirm the microwave ranging functionality. In addition, for a fixed distance between the mockups, the DOWR was monitored for 10,000 seconds to confirm the noise requirements on the measurement system. Even with non-flight-like fluctuations in air temperature and humidity between the Ka-horns, we were able to observe a relatively stable DOWR (Fig. 4) and Fourier transform it to show that noise requirements were being met (Fig. 5). Note this radiated test used two synthesizers locked together rather than two independent USOs, so the raw DOWR in Fig. 4 appears more stable than it would normally appear before using the S-Band clock offset measurements to align the times from the two satellites. Note also that a slight drift of ~2000 microns/day was removed from the data in Fig. 4. This drift is most likely due to non-flight environmental effects (temperature, humidity, mechanical breathing motion).

There are two important ways that this simulation differs from flight-like measurements. First, the time of flight is shorter than it will be in flight, so the DOWR transfer function is shifted up in frequency and the DOWR is much more effective at canceling high frequency clock noise than it will be in flight. Second, we don't have the orbital dynamics that will exist in flight and instead measure in a static reference frame. These effects are accounted for by modeling.

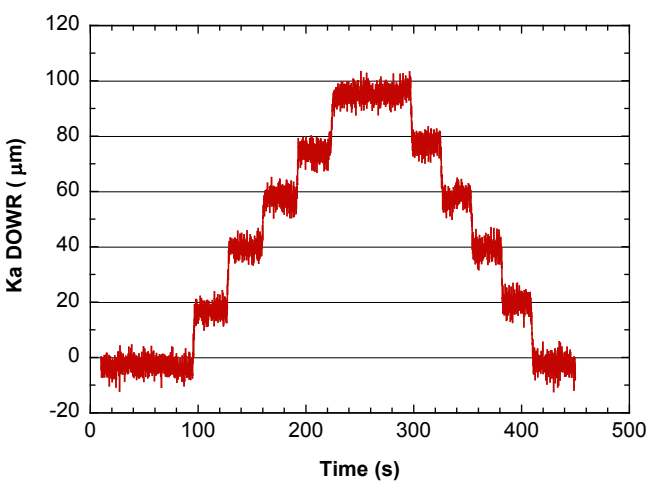

Figure 3. One spacecraft mockup is moved relative to another in 20 micron steps while a GRAIL EM/prototype radiated testbed tracks the motion. The GRAIL Time Transfer System is used to synchronize the two receivers upon booting. Locked synthesizers stand in for USOs to maintain time synchronization throughout the measurement.

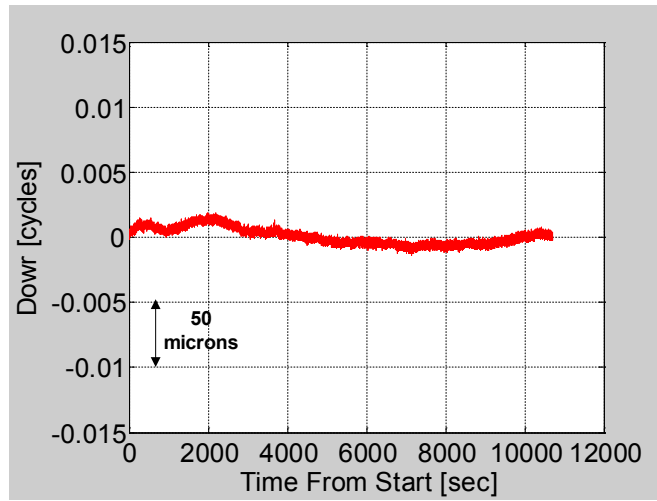

Figure 4. Two spacecraft mockups are held at fixed positions fourteen meters apart for 10,000 seconds while a GRAIL EM/prototype radiated testbed measures their separation. The GRAIL Time Transfer System is used to synchronize the two receivers upon booting. Locked synthesizers stand in for USOs to maintain time synchronization throughout the measurement.

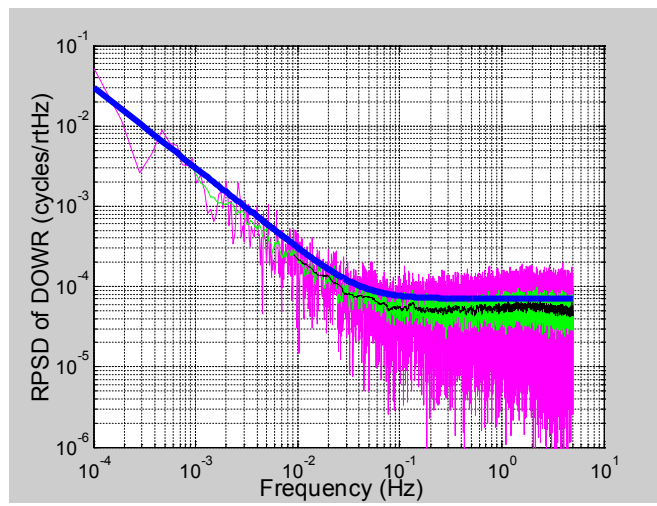

Figure 5. Fourier transform of the data in Fig. 4. Magenta shows the raw Fourier data, green shows 10-point running averages and black shows 100-point running averages. Thick blue line shows the requirements.

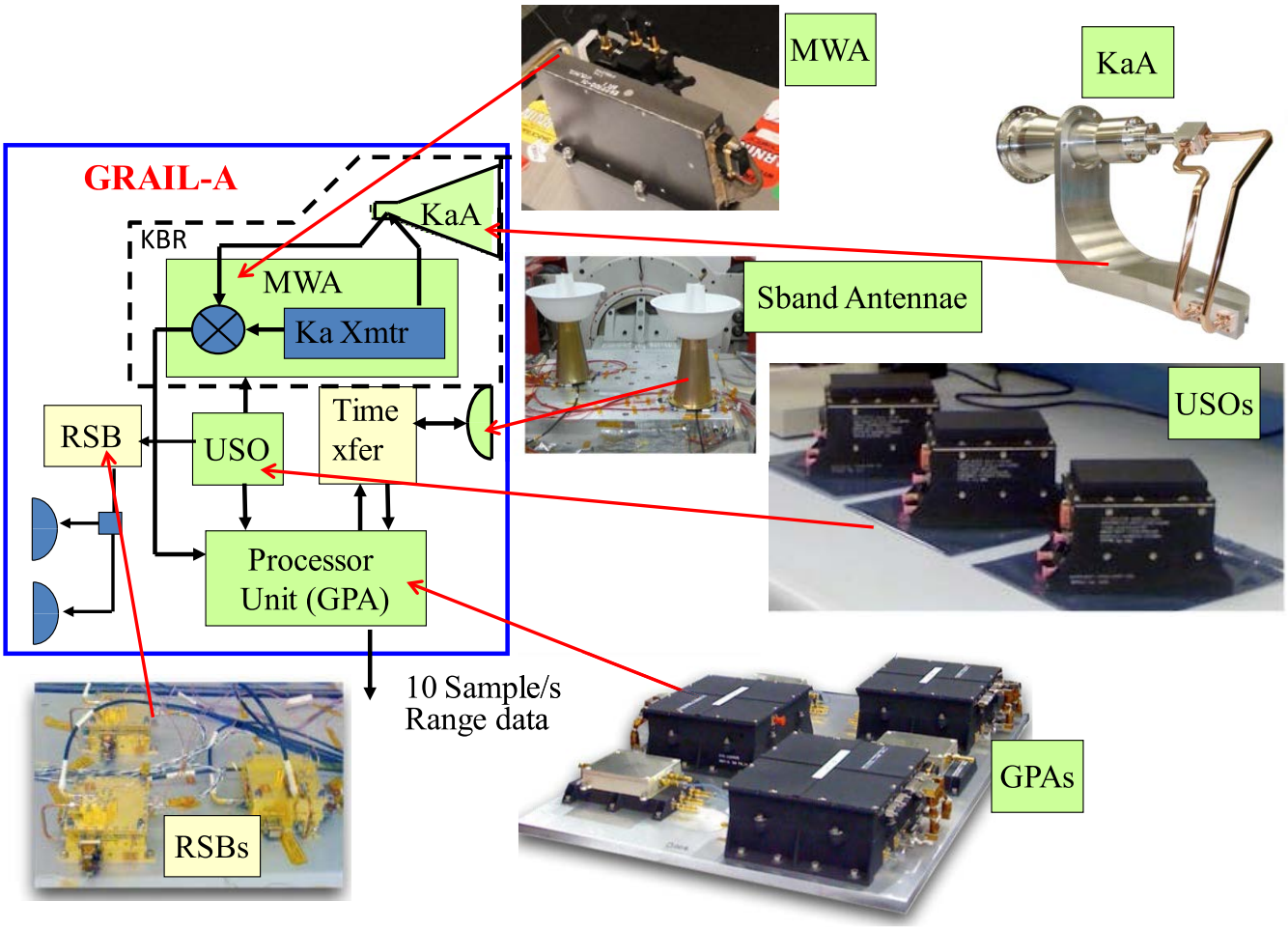

Figure 6. Photographs of GRAIL flight hardware and flight spares.

We performed a system-level test using flight hardware (Fig. 6) for the USOs, MWAs, and GPAs. This was a bench-top test, therefore we used coaxial-cables between the two MWAs and between the two GPAs rather than radiating/receiving through the Ka-horns and S-Band antennae. Note that individual requirements were already confirmed for each component of the system, and this was merely a risk reduction activity after integrating all the subsystems together. Despite the high thermal sensitivity of the non-flight Ka-band cables (and waveguide-to-coax converters), we were still able to show that the end-to-end microwave ranging met requirements at all frequencies except possibly at the air-conditioning cycling frequency.

Fig. 7 shows the raw DOWR in this end-to-end test drifting rapidly as a function of time (millions of microns over the 100,000-second run) because the USOs are not at the exact frequencies programmed into and expected by the GPA receivers. Fig. 8 shows the same data with the linear drift removed to reveal a more stable DOWR, however, with a residual few hundred micron slow variation still caused by USO drift and with shorter-term ~20-micron spikes/oscillations due to environmental effects on the non-flight cables. Still, without yet applying the S-Band clock offset correction, Fourier transforming the linear-drift-removed data of Fig. 8 already results in a root power spectral density (RPSD) that meets requirements at all frequencies other than the air-conditioning cycling frequency (Fig. 9). Fig. 10 shows a much more stable DOWR (steady within 50 microns over the 100,000-second run) after being corrected by the measured clock offsets between the two spacecrafts. Fig. 11 shows the final noise spectrum after the S-Band clock offset correction is applied. Again, it meets requirements at all frequencies except possibly at the air-conditioning cycling frequency, which was expected for this test due to the environmental sensitivity of the non-flight cables. Note again, once again, these tests do not reproduce the flight-like qualities of long time of flight or orbital dynamics.

Finally, Fig. 12 shows typical Allan deviation measurements for GRAIL flight USOs whose state-of-the-art phase-noise and stability properties make these measurements possible. Relative to a hydrogen maser, Allan deviations are 10^{-13} at 1 second and 1000 seconds with even better performance in between. The white-noise level in Fig. 11, and therefore in future GRAIL DOWR measurements, is/will be dominated by the USOs' noise.

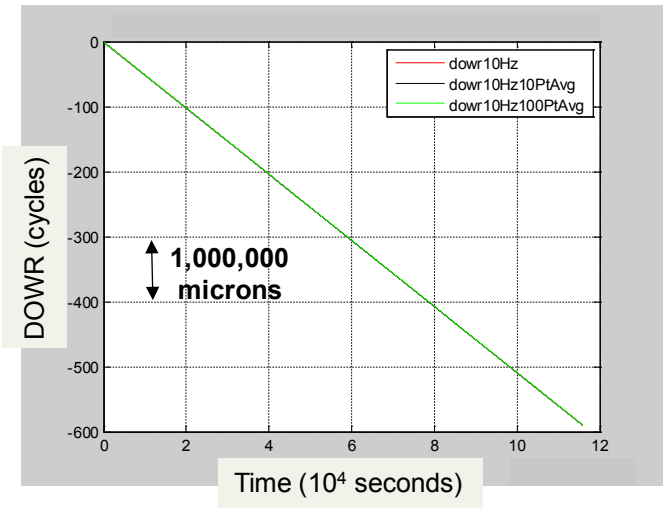

Figure 7. End-to-end benchtop 100,000-second test with non-flight Ka-Band coaxial-cables shows DOWR drifting rapidly because the USOs are not at the exact frequencies programmed into and expected by the GPA receivers.

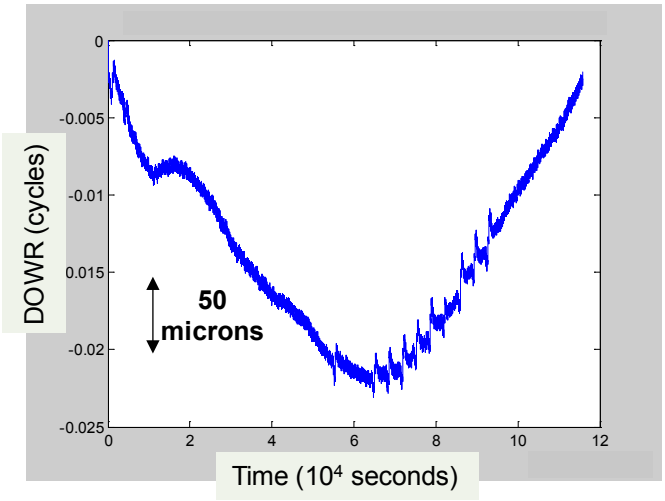

Figure 8. Fig. 7 data with linear drift removed. The sharp spikes in the data correspond to spikes in the room temperature.

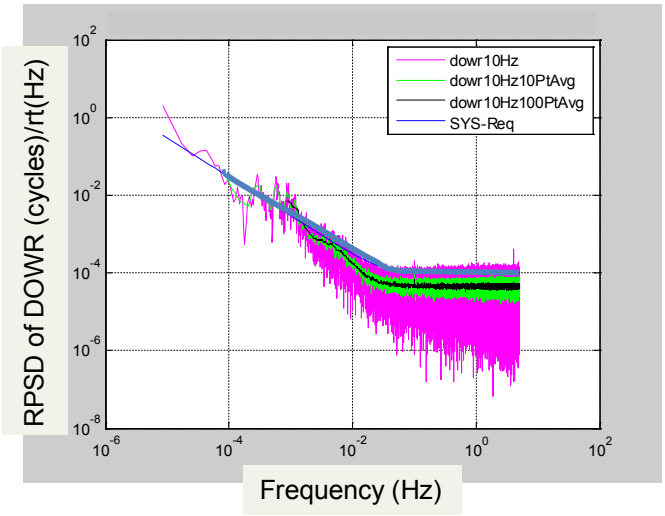

Figure 9. Fourier transform of Fig. 8 data. Magenta shows the raw Fourier data, green shows 10-point running averages and black shows 100-point running averages. Thick blue line shows the requirements.

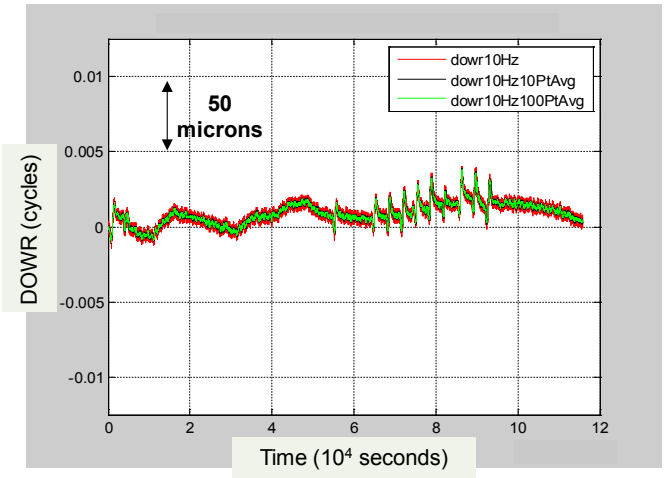

Figure 10. Fig. 7 data with S-Band clock offset correction applied. The sharp spikes in the data correspond to spikes in the room temperature.

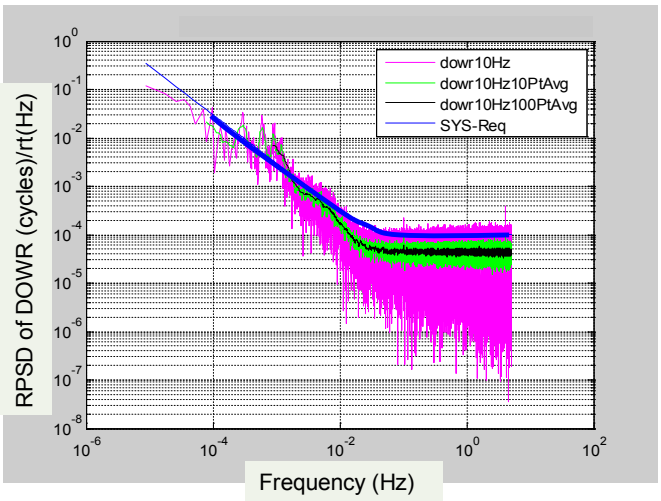

Figure 11. Fourier transform of Fig. 10 data. Magenta shows the raw Fourier data, green shows 10-point running averages and black shows 100-point running averages. Thick blue line shows the requirements.

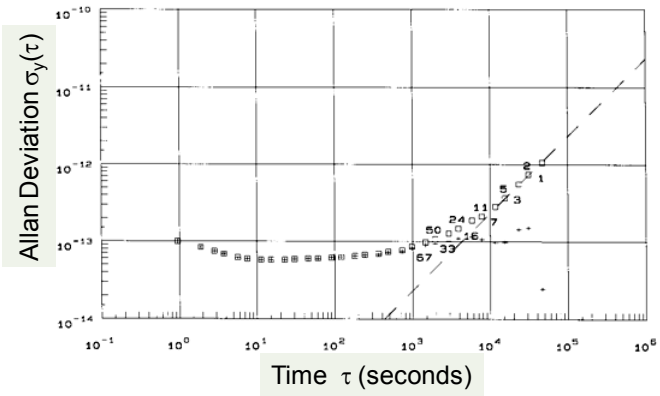

Figure 12. Allan deviation measurements of flight USOs.

VI. Conclusion

We believe the GRAIL mission demonstrates the type of space science that can be done with ultrastable oscillators and low-noise microwave ranging. Following in GRACE's footsteps of providing crucial gravity-field information to the climate, ocean, water, and ice-sheet scientific communities, we anticipate that GRAIL will provide similarly crucial information to the various lunar science communities.

Acknowledgment

The authors gratefully acknowledge the contributions of the many team members for their work in designing, building and testing the various hardware and software components of the system we describe in this paper. We particularly acknowledge Jim Kohel, Jim Kellogg, Garth Franklin, Randy Bartos, William Picket, Christopher Woodruff, and Jacob Gorelick for their contributions to the radiated testbed. William Diener led all the Allan Deviation and Phase Noise measurements at JPL's Frequency Standards Test Lab. The GRAIL instrument team was led by Payload manager Charles Dunn at JPL. The GRAIL USOs were built by the Johns Hopkins Applied Physics Laboratory; the MWAs were built by Space Systems Loral; the Ka horn and waveguide assemblies were built by Custom Microwave; the GPA, Time Transfer System, RSB, and Ka-Band assembly were built at JPL. The Principal Investigator for the mission is Maria Zuber from the Massachusetts Institute of Technology.

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