Moon-to-Earth: Eavesdropping on the GRAIL Inter-Spacecraft Time-Transfer Link using a Large Antenna and a Software Receiver.

Stephan Esterhuizen *California Institute of Technology / JPL Pasadena, California, USA*

ABSTRACT

NASA's twin GRAIL [1] spacecraft (Ebb and Flow) arrived at Earth's Moon on New Year's Day, 2012. GRAIL's primary mission is to create a high-resolution map of the Moon's gravitational field by measuring very precisely the change in distance between the two spacecraft [2]. Each spacecraft transmits two signals to the other spacecraft, a PRN code modulated on a 2 GHz carrier (S-band), as well as an unmodulated carrier at roughly 33 GHz (Ka-band). Since it's not feasible to synchronize the two GRAIL spacecraft's clocks via GPS (as was done with GRACE), the S-band signals are used as a time-transfer link to synchronize either Ebb's clock to Flow or vice versa.

As an independent measure to determine the clock offset of the GRAIL ultra-stable oscillators to UTC(NIST), an experiment was conducted where our JPL team used a large antenna on Earth to eavesdrop on the inter-spacecraft time-transfer link.

BIOGRAPHY

Stephan Esterhuizen completed his Masters degree in Electrical Engineering at the University of Colorado, Boulder in 2006. He received his B.S. in Electrical and Computer Engineering from the University of Colorado, Boulder in 2004. He joined JPL in 2006 where his primary task has been software and hardware development for precision ranging instruments.

I. INTRODUCTION

A. GRAIL Mission

GRAIL-A (Ebb) and GRAIL-B (Flow) were launched 10 September 2011, and after a journey of nearly 4 months, arrived at the Moon on New Year of 2012. The primary science mission was from March to May 2012, with the GRAIL extended mission starting late August 2012 until early December 2012. The primary task of GRAIL is to create high resolution maps of the intensity of the Moon's gravitational field by measuring slight changes in the distance between the two spacecraft. This map will tell scientist about the distribution of mass on the Moon and in turn help them understand the geological processes involved during the formation of the Moon.

B. Objective

Each GRAIL spacecraft has an ultra stable oscillator (USO), these USOs are synchronized to each other using a custom-built time-transfer crosslink signal at S-band. Each spacecraft's Time-Transfer Subsystem (TTS) transmits a pseudo-random ranging (PRN) code to the other spacecraft, where it is consequently tracked, data bits decoded, and clocks synchronized. The TTS provides accurate time synchronization as well as absolute range between the two spacecraft, this absolute range is augmented with the transmission of a pure carrier at Ka-band (33 GHz), allowing each spacecraft to track the carrier phase of the other's transmitted signal and extract very accurate relative changes in range.

It is the purpose of this experiment to intercept the S-band TTS link on Earth in order to provide a very accurate estimate of the absolute timing offset between Lunar Gravity Ranging Subsystem (LGRS) time and Barycentric Dynamical Time (TDB). In this paper this experiment is referred to the GRAIL TTS Direct-To-Earth (DTE) experiment.

C. Signal Structure

The GRAIL spacecraft each transmit 4 different signals as depicted in Figure 1 and summarized in Table I, these signals are all at slightly different frequencies.

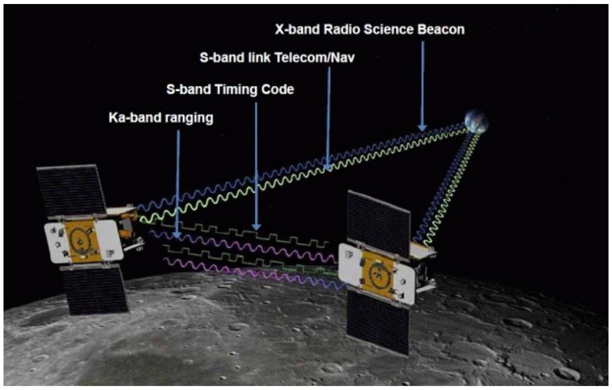

Fig. 1. GRAIL Signals. The S-band inter-spacecraft link transmits a PRN code used for time transfer. The Ka-band link transmits pure tones for relative phase tracking. The X-band Direct-To-Earth link is used to solve for clocks and orbits. The S-band telecom link to Earth transmits and receives spacecraft data

Since the S-band TTS signal is the only signal that provides absolute timing information, we shall focus on the structure of this signal. A description of the signal can be seen in Table II.

Frequency Band	Purpose
S-band (TTS)	Inter-spacecraft time transfer and absolute ranging
Ka-band	Inter-spacecraft relative ranging
X-band	Earth tracks this signal for orbit determination
S-band (Telemetry)	Telemetry to Earth

TABLE I

A TABLE OF SIGNALS TRANSMITTED BY EACH GRAIL SPACECRAFT

Notice the spacecraft transmits ranging codes with an identical pseudo noise code as the GPS C/A code as well as chipping rates in the order of 1 million chips per second.

The data message is, of course, quite different than GPS. The spacecraft transmits an integer epoch counter (eg. how many code epocs have passed) as well as other information needed for time transfer. The software decodes this integer epoch counter (the integer part of LGRS time) and use the current state of the PRN code tracking to provide unambiguous pseudorange estimates to the GRAIL spacecraft.

Description	GRAIL-A	GRAIL-B
USO Freq. (MHz)	4.832	4.832099
Approximate TX Freq. (MHz)	2032	2207
Chipping Rate (chips/sec)	966400	1017284
Data Rate (bps)	50	50
PRN Code	GPS C/A PRN1	GPS C/A PRN2
Transmit Power (mW)	79.4	79.4
Transmit Antenna Gain (dBiC)	11.8	10.9

TABLE II

S-BAND TTS SIGNAL PROPERTIES

II. MOTIVATION

In order to solve for the offset between LGRS time and UTC, the GRAIL spacecraft provides a 'time correlation' packet in the downlink telemetry. When a TTS packet arrives via serial port at the flight computer, it gets timestamped, transmitted down to Earth and then timestamped again in UTC. After removing one-way light time, an offset of LGRS and UTC can be obtained at the 10-100 millisecond level.

This experiment attempts to reduce the time transfer accuracy to the sub micro-second level by directly measuring the TTS ranging code on Earth and timestamping with UTC.

III. EXPERIMENTAL SETUP

In order to intercept the TTS signal on Earth, two main points need to be considered:

- Does the geometry allow Earth to be in the main beam of the TTS antenna
- How much gain is needed on the receive antenna to allow for sufficient SNR to decode the GRAIL data bits.

Once it is established with the given geometry and receive antenna size that enough signal power is present to decode data bits, we will discuss the receiver setup, signal processing and delay calibration.

A. Moon-to-Earth Geometry

Both spacecraft are in near-polar, near-circular orbits around the moon, with a mean altitude of 55km for the science phase and 20km for the extended mission science phase. The spacecraft orbital period is slightly less than 2 hours. With this in mind, one can imagine the spacecraft orbit being 'dead on' when viewed from Earth roughly every half lunar orbit (13.6 days). When the moon has orbited 1/4 of a cycle (6.8 days) from these positions, the GRAIL spacecraft will trace out near-circular orbits as viewed from Earth, and the TTS antenna will always be at right-angles with any Earth antenna, making it very difficult to track due to the relatively low gain of the transmit antenna. A visualization of the geometry where the TTS antenna illuminates the Earth is depicted in Figure 2.

The transmit antenna gain pattern for both spacecraft is no more than 13dB below peak gain at 30 degrees off boresight, this number was picked when scheduling tracking time with the JPL Deep Space Network (DSN). This leads to tracking opportunities roughly every 13 days.

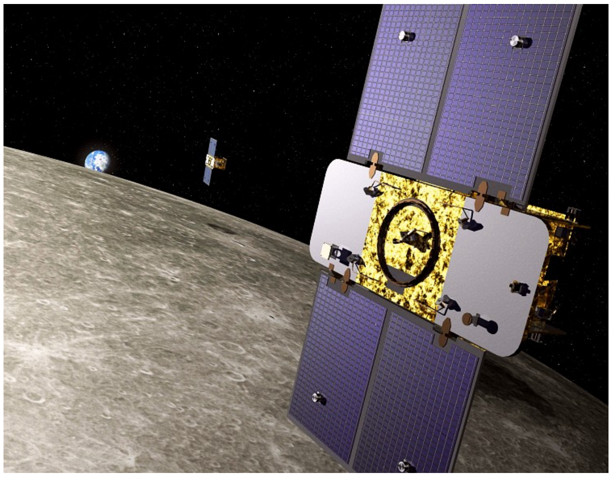

Fig. 2. GRAIL-to-Earth Geometry: Every 13 to 14 days the orbits of GRAIL align with the Earth such that GRAIL's TTS antenna illuminates the Earth, making it possible to track the signal on Earth.

B. Link Budget

DSS24, a 34 meter beam waveguide antenna was already used to track the GRAIL S-band telemetry and X-band beacon. It was thus natural to perform a link budget calculation using DSS24 parameters to see if this station will have sufficient gain. Table III has a quick derivation of link budget.

These link budgets assume worst case scenario, eg. the Moon is in full daylight (400 Kelvin noise contribution) as well as at its furthest distance from the Earth. Making these assumptions, the carrier to noise-density ratio (C/No) will be in the range of 34 dB-Hz to 48 dB-Hz depending on the angle the transmit antenna makes with Earth (30 and 0 degrees off boresight, respectively). It is thus quite feasible to track the GRAIL signal using a 34 meter antenna on Earth.

C. Receiver and Signal Processing

The JPL radio science team provided a Portable Radio Science Receiver [3] (PRSR) for this work. This is a flexible

Description	**GRLA**	**GRLB**	Notes
Transmitter EIRP (dBm)	27.4	26.6	At boresight
Path loss, Perigee (dB)	-210.4	-209.6	Range approx. 405696 km
34m Antenna Gain (dB)	55.3	54.6	55% efficiency
Signal Power (dBm)	-127.7	-128.4	At input to LNA
System Temperature (K)	212	212	Moon dominates at 400K
Noise Density (dBm)	-175.3	-175.3	At input to LNA
SNR (dB-Hz)	**47.6**	**46.9**	0 deg off boresight
SNR (dB-Hz)	**34.6**	**33.9**	30 deg off boresight

TABLE III

LINK BUDGET CALCULATION FOR GRAIL-A AND GRAIL-B. DEPENDING ON VIEWING ANGLE WITH EARTH, SNRS WILL RANGE FROM 34 TO 48 DB-HZ DURING MOON PERIGEE.

receiver with programmable bandwidths, sample rates, tuning frequencies, etc. Since the GRAIL-A TTS frequency (2032 MHz) is outside of the DSN operating band, instrument was installed at the DSS24 pedestal, allowing for direct access to the waveguide.

This receiver has three inputs:

- Intermediate Frequency (IF) input: 100-600 MHz
- 100 MHz input: Used for creating the 1.28 GHz sample clock for ADC
- 1 PPS input: Used to select the correct 100 MHz clock edge to indicate integer second epoch.

The PRSR does not directly accept the GRAIL S-band frequencies (2 GHz), thus a mixer, filter, amplifier stage was added before the PRSR to mix with 1700 MHz (coherent with 100 MHz reference) in order to present the PRSR with an IF of 332 MHz (GRAIL-A) and 507 MHz (GRAIL-B).

The PRSR was configured to save 3.2 MHz of bandwidth centered at each spacecraft IF frequency with 4-bit resolution. Even though the receiver is capable of higher bandwidths and 16-bit resolution, this would be overkill when sampling signals that are below the thermal noise floor. The JPL team installed 3 USB drives with 3 Terabyte capacity. The write speed for USB is limited around 20 MBytes/second, this was another factor when selecting bandwidth and resolution. With two GRAIL channels running in parallel at 6.4 MBytes/second, there is plenty of margin left.

D. Signal Processing

The signal processing consists of a handful of programs written in C and C++, using Python to glue them together (as demonstrated in Table IV). The observable extraction very closely follows signal processing in the TurboRogue [4] [5] receiver.

Name	**Language**	**Description**
fft_acquire	C	Performs FFT acquisition
prn_track	C	Carrier and Code tracking
decodeGrail	C++	Decodes data bits, same code running on GRAIL
fitter	C	Fits quadratics to 1sec epocs
signalTracker	Python	Glues together above programs

TABLE IV

THE SOFWARE RECEIVER COMPONENTS

The level 1 output is 1 second time-tagged phase, range and transmit time observables. The latter observable is used by the GRAIL science team to solve for the clock offset between GRAIL and UTC. Below is an example output file:

```
# $Revision: 89 $, Data Date:2012 65 19238...
# utc_offset:s,Phase:s, Range:s, txtime:s
11.0 -0.000059798586 -0.003164565876 1615072.742544763023
12.0 -0.000065250047 -0.003170027799 1615073.742550225462
13.0 -0.000070702738 -0.003175469676 1615074.742555667180
14.0 -0.000076156656 -0.003180926119 1615075.742561123333
```

The 4th column, txtime, is in units of seconds, this is the transmit time as decoded by the software timestamped with UTC (eg 11 seconds offset from year 2012, day of year 65, second of day 19238). Tracking of PRN code alone yields an ambiguity of approximately 1ms, it is up to the *decodeGrail* software to use the ambiguous output of *prn_track*, decode data bits, and report an unambiguous GRAIL time. In the example above, at 11 seconds the GRAIL time was 1615072.742544763023 seconds. **This is time as received on Earth**. To obtain actual time onboard GRAIL, one needs to correct for one-way light time.

E. Delay Calibration

The purpose of this experiment is to determine absolute time offset, careful note must be taken of absolute delays. This includes path delays at the DSS24 facility. Table V contains a summary of all station delays. The internal PRSR delay was measured by tracking a BPSK modulated signal at the GRAIL-A IF frequency (332 MHz). This BPSK modulation was coherent with both the PRSR 1PPS and 100MHz reference signals.

Note, the DSN distributes its own timescale [6] and tracks the offset of UTC(Goldstone) (as realized by the station master clock) to UTC(NIST). All PRSR timestamps are in UTC(PRSR), not UTC(NIST). First the path delay corrections τ_{total} need to be applied to correct UTC(PRSR) to UTC(DSS24/Goldstone), then the DSN provided offset of UTC(Goldstone) to UTC(NIST) need to be applied.

Timestamp adjustment from UTC(PRSR) to UTC(DSS24) can be calculated by differencing the microwave path delay and timing path delay (from Table V):

$$\begin{aligned}\tau_{total} &= \tau_{RF} - \tau_{timing} \\ &= 292.21ns - 131.84ns \\ &= 160.37ns \pm 15ns\end{aligned}$$

Note the error bars on this measurement is ±15 nanoseconds. Most of this error is due to the uncertainty of when the

Symbol	Delay (ns)	Description	Method
Td,down	34.48	Antenna aperture plane to DSS reference location	Computed
Tc	204.13	Antenna aperture to horn phase center	Computed
T4	10.74	Horn phase center to range calibration coupler	Computed
	35.71	Range calibration coupler to the rack	Estimated
	7.14	Rack, R.F/mixer/IF	Estimated
	0	PRSR internal RF delay (Measured RF-PPS delay)	Measured
τ_{RF} **(Total RF delay)**	**292.21**	**Path delay, DSS24 reference location to PRSR**	
Ttct	112.24	1PPS and 100MHz Delay from TCT to PRSR input	Measured
Tint	19.6	PRSR internal timing delay	Measured
τ_{timing} **(Total timing delay)**	**131.84**	**Path delay, DSS24 reference location to PRSR**	

TABLE V
RF AND TIMING DELAY MEASUREMENTS

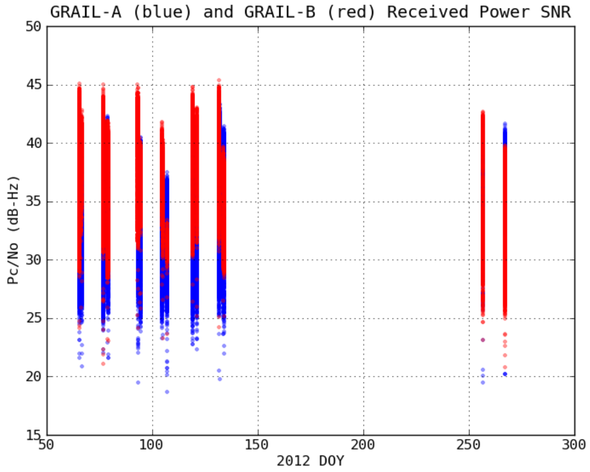

Fig. 3. GRAIL carrier to noise-density ratio for March 2012 to September 2012. For each pass, the C/No varies from approximately 45 dB-Hz to 25 dB-Hz. Tracking stops when the Moon occults the TTS signal or when the TTS antenna is at right angles with Earth.

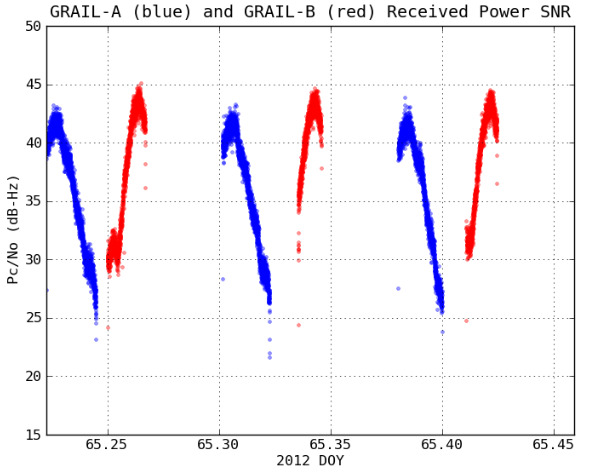

Fig. 4. GRAIL 2012/65 (5 March 2012) C/No. GRAIL-A tracked first, followed by GRAIL-B.

1pps and 100 MHz edges occur. As the 1pps and 100MHz edges drift apart, the PRSR can end up choosing a different 10ns edge.

IV. RESULTS

This section describes results of the GRAIL TTS DTE experiment. As of the writing of this paper, GRAIL is in its extended mission with TTS DTE observations ongoing.

A. *Carrier to Noise-Density Ratio (C/No)*

To get an idea of the range of C/No over multiple DSN tracks, refer to Figure 3. This shows C/No for the entire track, peak observed C/No is right around 45 dB-Hz, close enough the estimated values in Table III). The C/No difference from one observation to the next (usually only a day or two apart) is due to the change in angle of the transmit antenna to the receive antenna. The observations of 2012/104 and 2012/106 stands out particularly due to low C/No, this was traced back to a DSS24 pointing issue.

A zoomed in view of the first track TTS track (5 March 2012) and the third TTS extended mission track (22 September 2012) can be seen in Figures 4 and 5 respectively. The structure in C/No is due to the transmit antenna gain pattern. Notice in Figure 4 how GRAIL-A is tracked first, followed by a few minute gap until GRAIL-B is tracked, followed by approximately one hour of no signals (while the Moon is occulting both spacecraft). This delicate dance is reversed in Figure 5, indicating the spacecraft have switched positions for the extended mission.

B. *Pseudorange*

An example of the GRAIL-A pseudorange can bee seen in Figure 6. GRAIL-A was tracked from a few seconds after the occultation ended until the TTS antenna was nearly orthogonal to Earth, this geometry change is evident in the pseudorange by observing the spacecraft moving towards the Earth, but slowing down until 1900 seconds into the observation where the pseudorange is changing very slowly.

To get a better understanding of the noise on this measurement, pseudorange minus phase, also known as code minus carrier, is plotted in Figure 7. Consistent with a C/No ranging from 42 dB-Hz down to 25 dB-Hz, notice the 1σ scatter increasing from about 4ns to 25ns. A similar pseudorange minus phase plot for GRAIL-B can be seen in Figure 8. The GRAIL-B range scatter decreases over time as the angle off boresight (as viewed from Earth) decreases.

C. *S-band minus X-band*

A quick sanity check can be performed by comparing TTS S-band doppler to the radio science beacon X-band doppler. The carrier transmitted by the X-band beacon is tracked

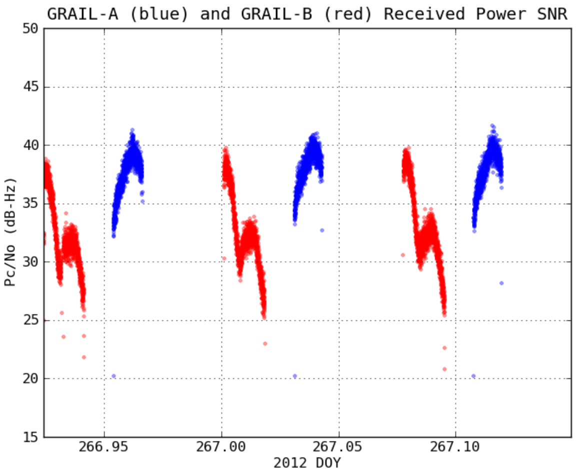

Fig. 5. GRAIL 2012/266 (22 September 2012) C/No.GRAIL-B tracked first, followed by GRAIL-A. The spacecraft switched positions for the extended mission.

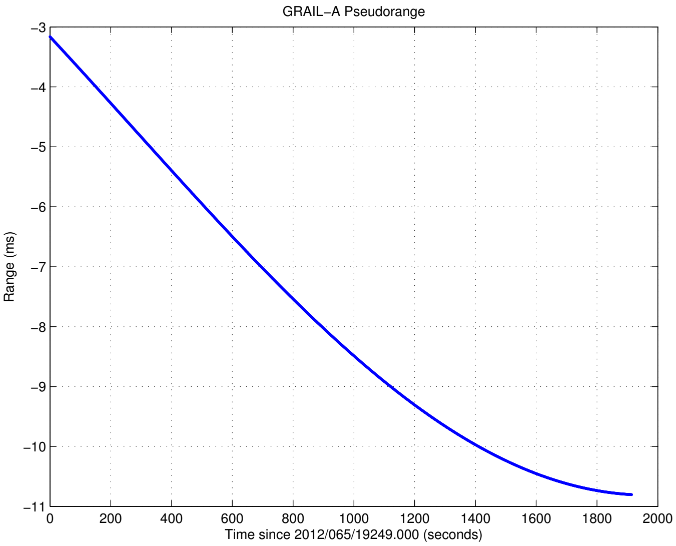

Fig. 6. GRAIL-A Pseudorange for 2012/65. The spacecraft is initially moving towards Earth, this rate slows down until the spacecraft motion (and transmit antenna) is nearly orthogonal with Earth

simultaneously at DSS24 with another PRSR synchronized to the same station master clock. The residual after differencing GRAIL-A X-band from S-band can be seen in Figure 9.

There is a bias of 1 mm/s between the two measurements. This is also the minimum offset obtainable by shifting time-tags in any direction, indicating further investigation is necessary in understanding the bias between the two measurements. It is conceivable this is due atmospheric effects between the two frequencies, but it's hard to imagine these effects causing a constant bias of 1 mm/s.

D. Absolute timing

The main purpose of this experiment was to determine the offset between the GRAIL clocks (LGRS time) and TDB. By tracking the PRN codes on Earth, one can obtain LGRS

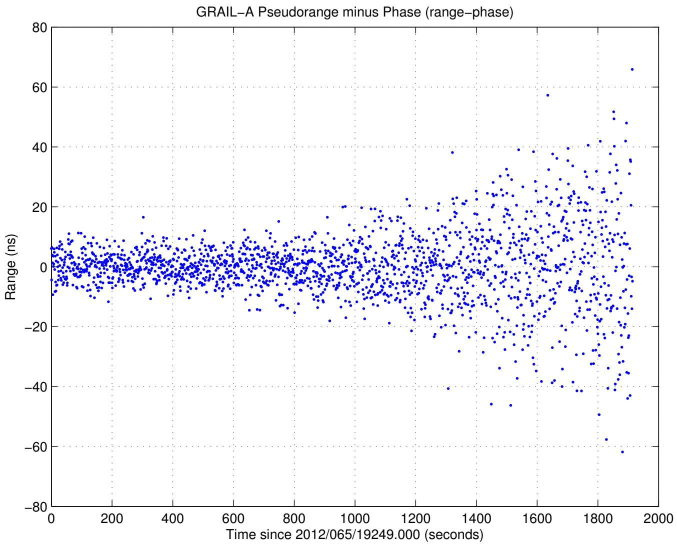

Fig. 7. GRAIL-A Pseudorange-Phase for 2012/65. Range scatter (1σ) increases from 4ns to about 25ns as the C/No decreases.

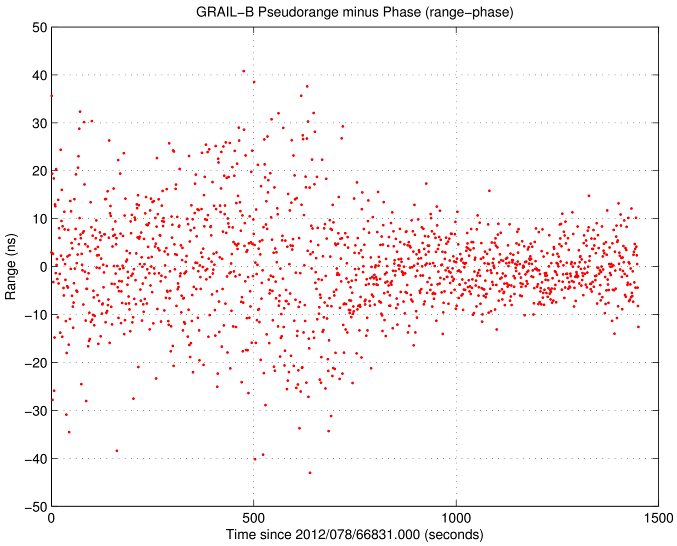

Fig. 8. GRAIL-B Pseudorange-Phase for 2012/65. Range scatter (1σ) decreases from 10ns to about 4ns as the C/No increases.

time modulo approximately 1 millisecond (PRN code repeat period). By decoding the data bits and obtaining the 'epoch count', this ambiguity can be removed. This observable is time as *r*eceived, and the one-way light time needs to be corrected for to obtain time at the spacecraft. This was performed by the Gerhard Kruizinga and his inner-planet navigation team at JPL, results are plotted in Figure 10.

The dominant effect in this plot is clock rate offset. Both GRAIL clocks are intentionally offset from nominal by a few nanoseconds per second, with GRAIL-A running slightly slower than nominal and GRAIL-B running slightly faster. The absolute timing plots are not densely filled because observations were sparse (10 hours observing approximately every 13 days). The three discontinuities observed are due to reboots of the a spacecraft, causing loss of integer epoch counter (or loss of time), resulting in synchronizing the local

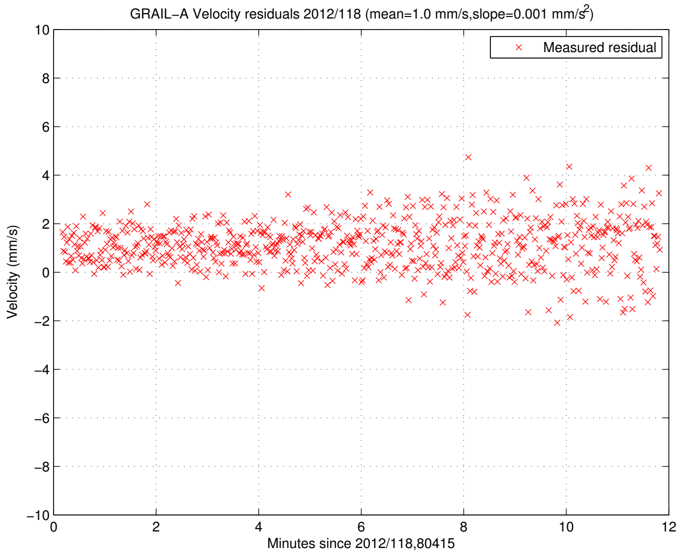

Fig. 9. GRAIL-A S-band minus X-band velocity. The 1 mm/s bias can't be explained yet and need further investigation. This bias does not get smaller when timetags are shifted in either direction

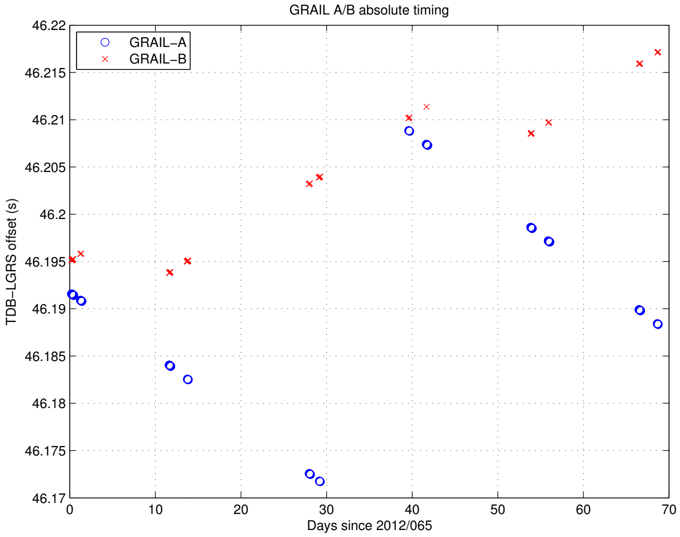

Fig. 10. Absolute Timing: This plot shows pseudorange with the one-way light time removed. The dominant effect is clock rate offset. Both GRAIL spacecraft has their clocks intentionally offset from nominal. The discontinuities are due to spacecraft rebooting (loosing its sense of time) and resynchronizing to the other spacecraft

clock to the other spacecraft's clock via the time transfer subsystem.

This LGRS-TDB offset is used as an input to solve for the Moon's gravity field.

V. CONCLUSION

A 34 meter antenna at JPL's Deep Space Network at Goldstone, California, USA was used to eavesdrop on the GRAIL inter-spacecraft time-transfer crosslink signal (at S-band). This signal was successfully tracked and demodulated to provide unambiguous pseudorange and phase timestamped in UTC. After correcting for one-way light time, the JPL inter-spacecraft navigation team obtained absolute clock offset between GRAIL clocks and Earth clocks at the sub microsecond level.

This absolute time offset is used as input to solve for the Moon's gravity field.

ACKNOWLEDGEMENTS

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

Thanks to Kamal Oudrhiri for overseeing this experiment. Thanks to Dong Shin, who designed the L-band to IF assembly and helped install this experiment in the DSS24 pedestal. Thanks to Gerhard Kruizinga and his team for producing one-way light time models used to generate the absolute timing offset plot. Thanks to Danny Kahan for helping with scripting of the PRSR.

REFERENCES

[1] D.G. Enzer, R.T. Wang, and W.M. Klipstein. GRAIL - a microwave ranging instrument to map out the lunar gravity field. In *Frequency Control Symposium (FCS), 2010 IEEE International*, pages 572 –577, june 2010.

[2] J.B. Thomas. An analysis of gravity-field estimation based on intersatellite dual-1-way biased ranging. In *JPL Publication 98-15*. JPL, 1999.

[3] Stephen Rogstad, Robert Navarro, Susan Finley, Charles Goodhart, Robert Proctor, and Sami Asmar. The portable radio science receiver (rsr). In *InterPlanetary Network Progress Report*. JPL, 2010.

[4] J.B. Thomas. Signal-processing theory for the turborogue receiver. In *JPL Publication 95-6*. JPL, 1996.

[5] J.B. Thomas. Functional description of signal processing in the rogue gps receiver. In *JPL Publication 88-15*. JPL, 1988.

[6] R.L. Tjoelker, M. Calhoun, P.F. Kuhnle, J. Lauf, and R. L. Sydnor. Master clock and time distribution system for the nasa deep space network part i. In *InterPlanetary Network Progress Report*. JPL, 2006.