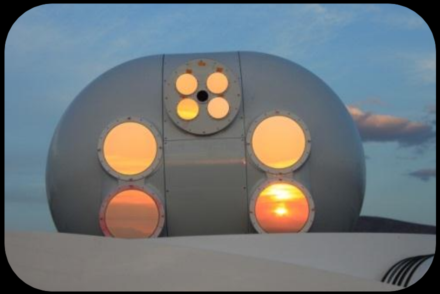
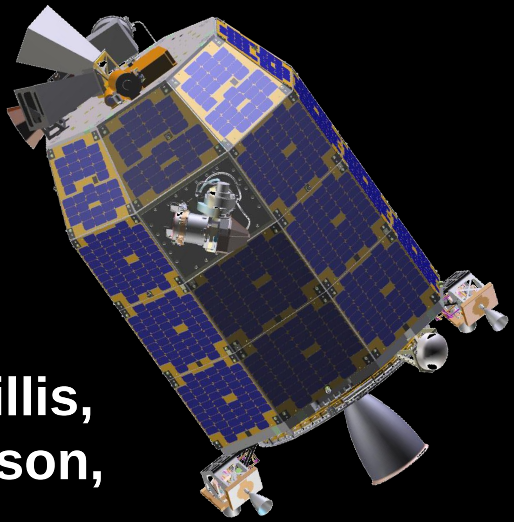
LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Time-of-Flight and Ranging Experiments on the Lunar Laser Communication Demonstration





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Stanford PNT Symposium
12 November 2015

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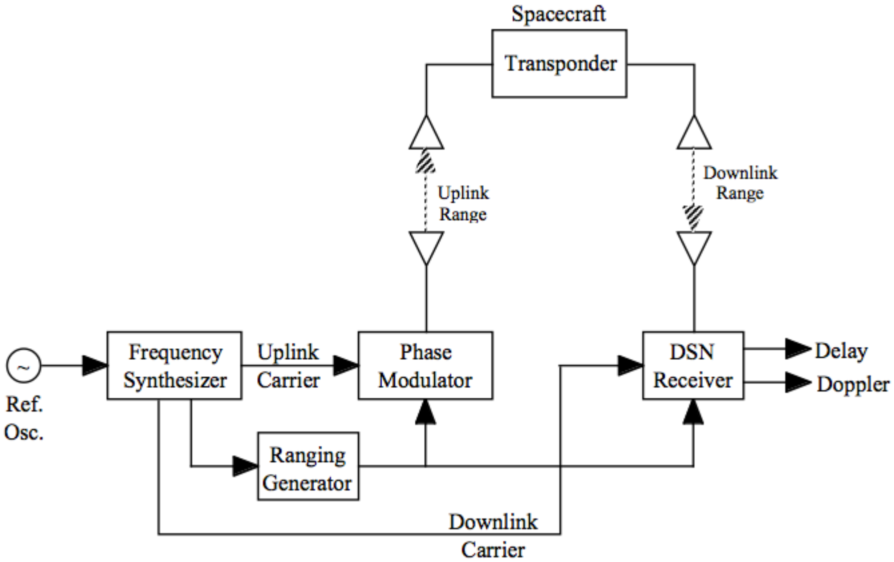
NASA Metric Tracking System

- RF satellite ranging performed using specialized 1-MHz waveforms applied to communication loop-back links
- Precision ranging requires dedicated measurements performed over a period of several hours
- Range accuracies of the order of 10 meters are achievable

White Sands
S-Band Tracking Antenna

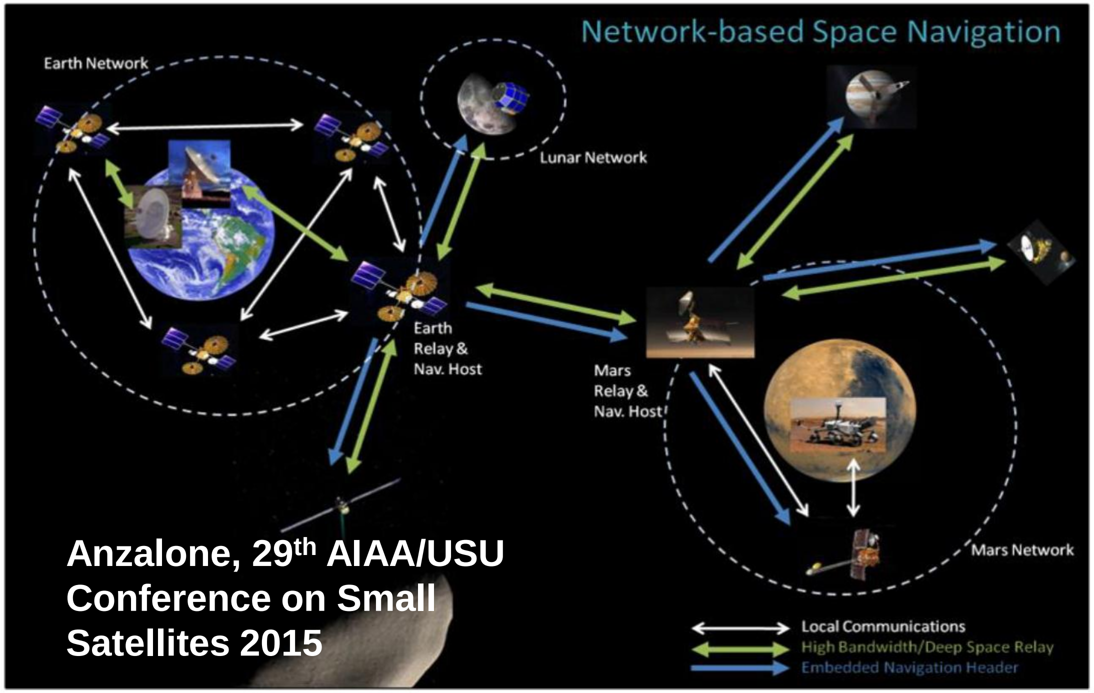


Loop-Back Configuration

Autonomous Navigation Concept

- **NASA MSFC is developing a system architecture for solar-system wide navigation using embedded headers in comm links**
- **LEO cubesat demo concept in development**

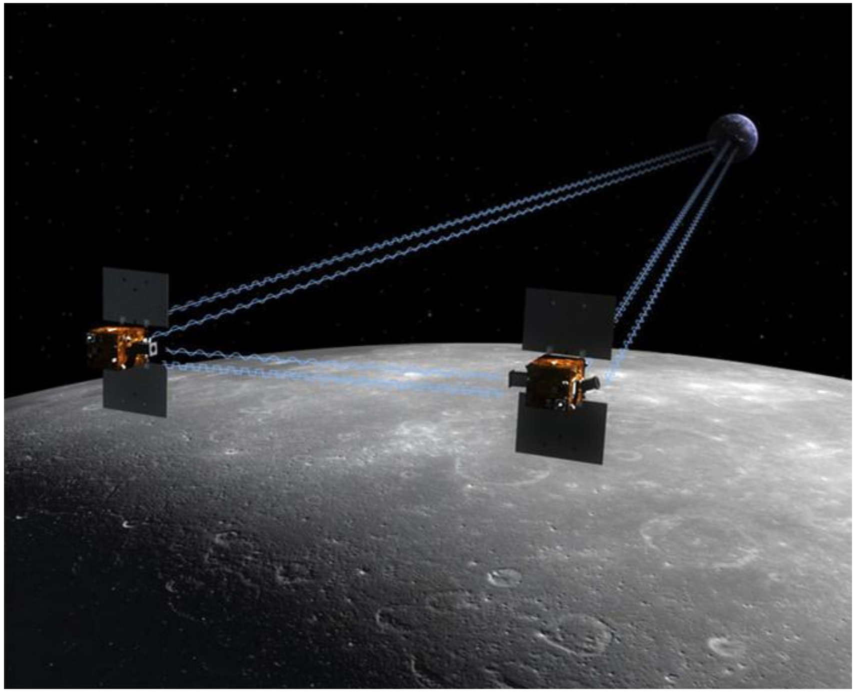
NASA's Multi-spacecraft Autonomous Positioning System



Anzalone, 29th AIAA/USU Conference on Small Satellites 2015

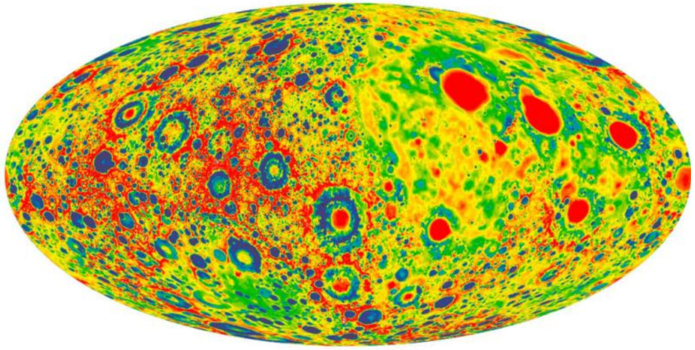
TOF Enables Planetary Science

- **Time-of-Flight (TOF) measurements are an enabler for:**
  - **Planetary science, gravity, internal structure of planets, moons**



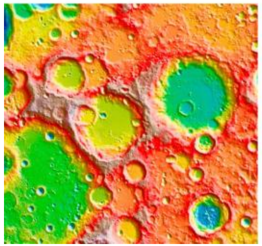
GRAIL: Gravity Recovery and Interior Laboratory
LOLA: Lunar Orbiter Laser Altimeter

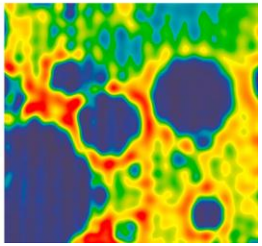
Mollweide Projection of Lunar Gravity Anomalies



Far side **Near side**

LOLA laser altimeter



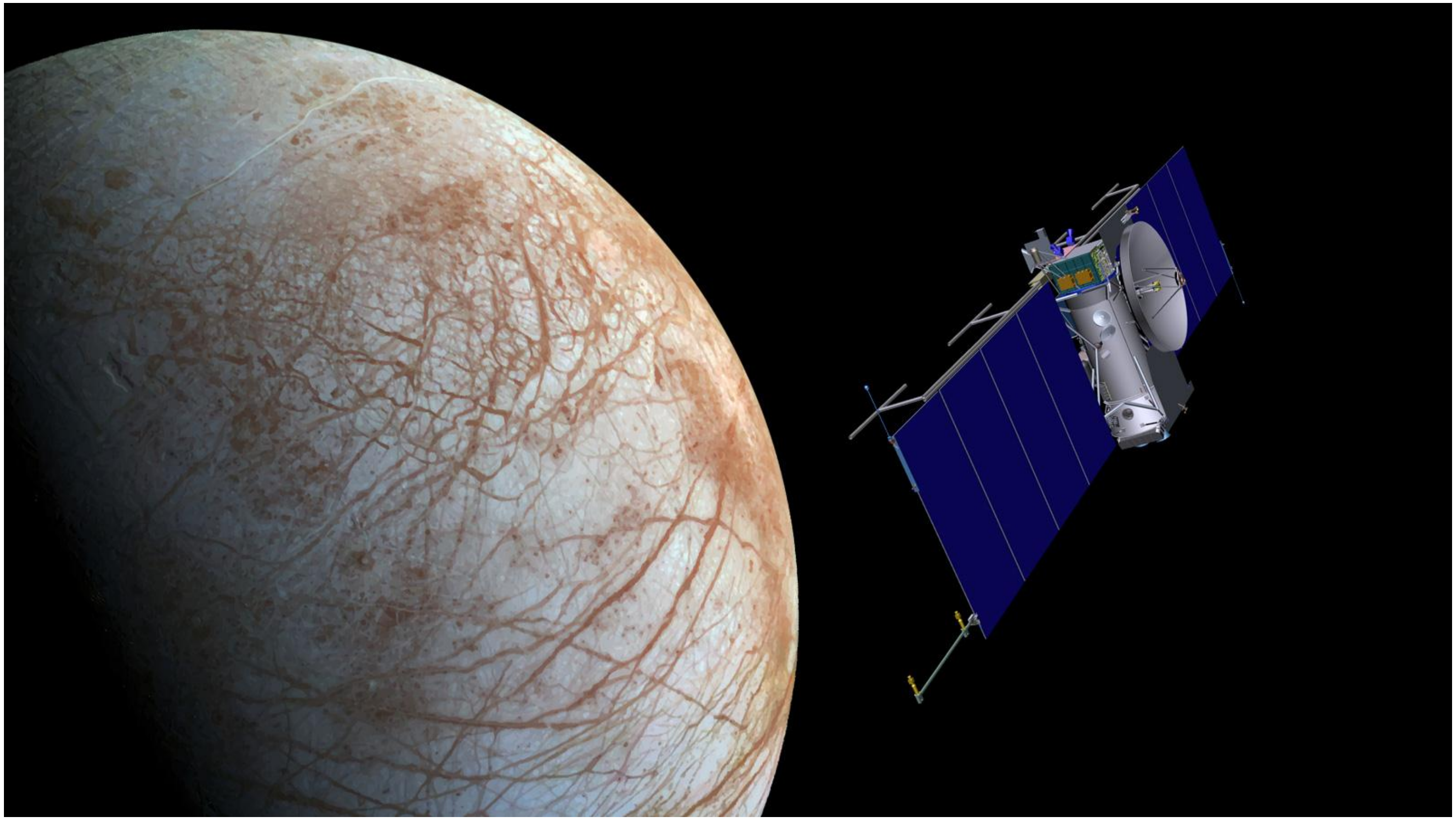


GRAIL gravity anomalies

Lemoine, et al.
"High Degree GRAIL Gravity Models"
Journal of Geophysical Research: Planets (2013)

Europa Clipper Mission

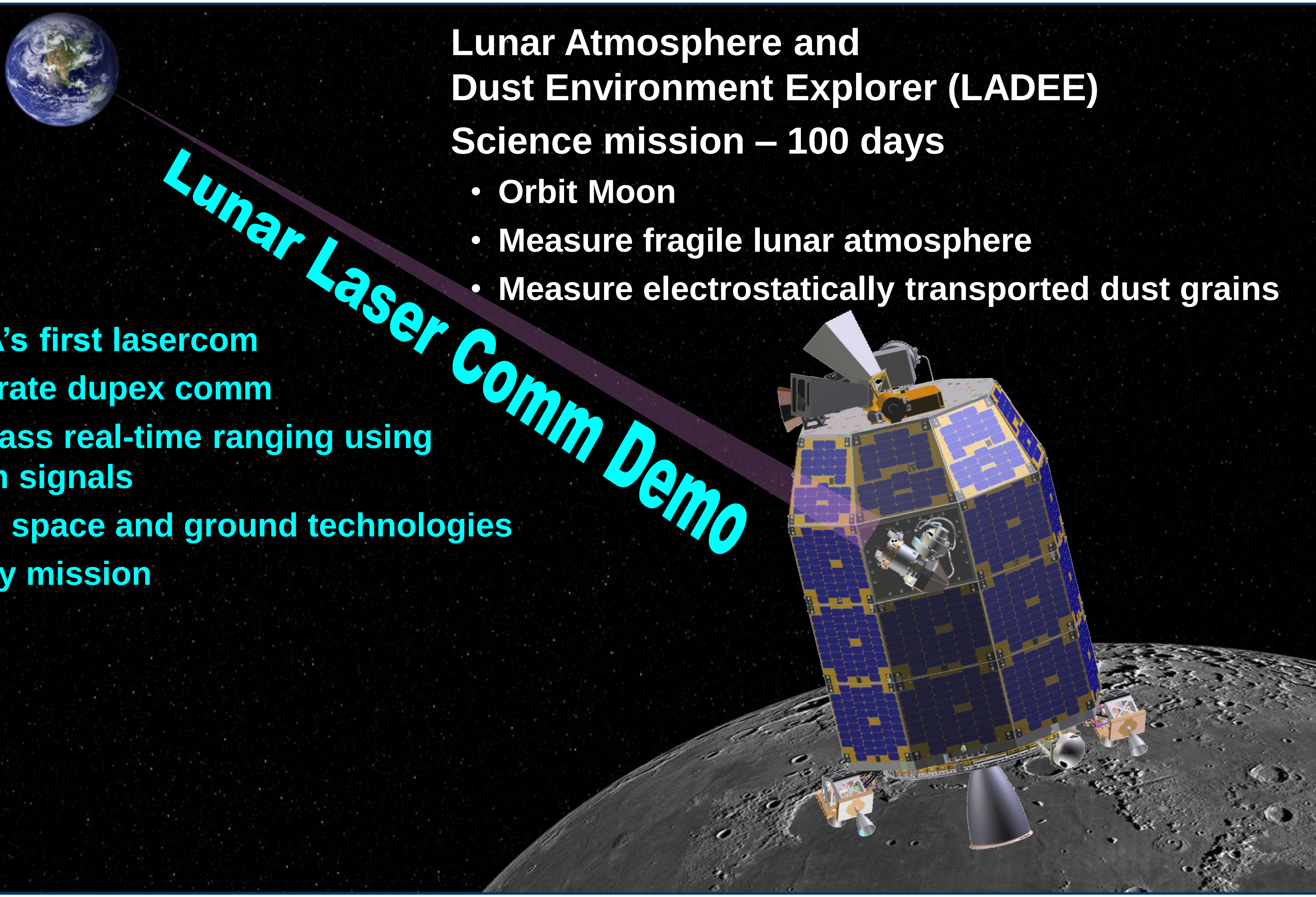
- **Primary mission: measure Europa gravity**
  - **Look for tidal changes indicative of a liquid ocean that might harbor life**



Outline

- LLCD Mission
- TOF System Architecture
- TOF Data

LLCD and LADEE



Lunar Atmosphere and Dust Environment Explorer (LADEE)

Science mission – 100 days

- Orbit Moon
- Measure fragile lunar atmosphere
- Measure electrostatically transported dust grains

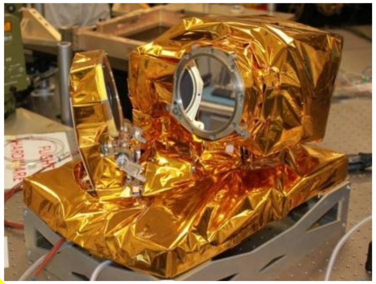
LLCD

- NASA’s first lasercom
- High-rate dupex comm
- cm-class real-time ranging using comm signals
- Novel space and ground technologies
- 30-day mission

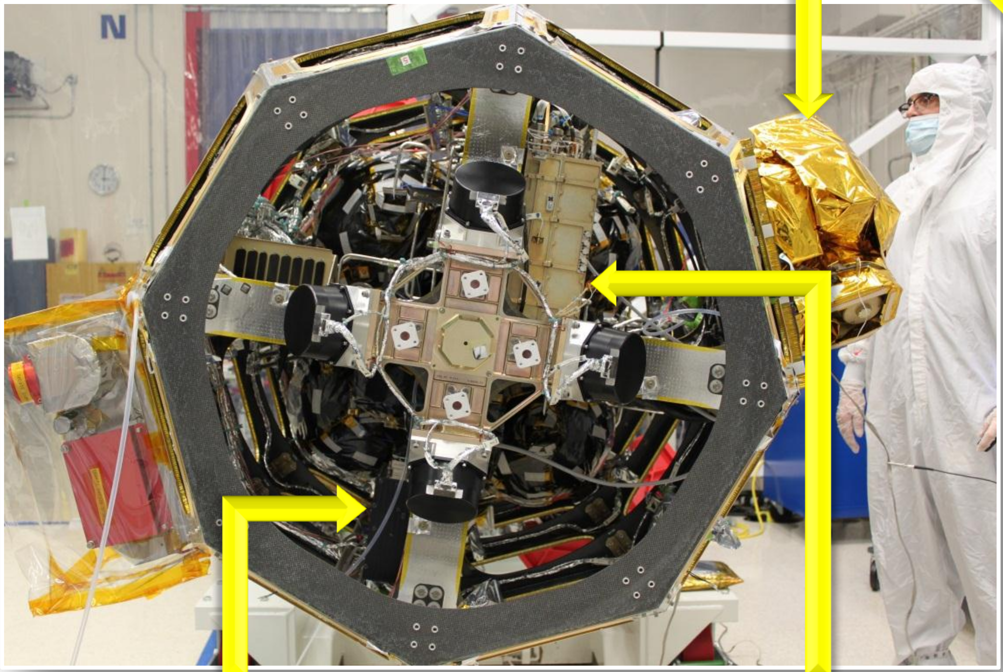
LLCD Space Terminal on LADEE

Modular design allowed for balanced placement in small spacecraft. Units fiber- and cable-connected.

LLCD Optical Module



0.5-W transmitter
4-inch telescope
Fully-gimballed
Inertial
stabilization



LLCD Controller Module **LLCD Modem Module**

Space Terminal: mass ~ 30 kg; power ~ 90 W

Primary LLCD Ground Terminal (LLGT)

at White Sands

Ground Terminal Design

- Single gimbal
- Four 16-inch receive telescopes
- Four 6-inch transmit telescopes
- All fiber-coupled superconducting nanowire single-photon detectors
- Air-conditioned globe for optics
- Clamshell dome for weather protection

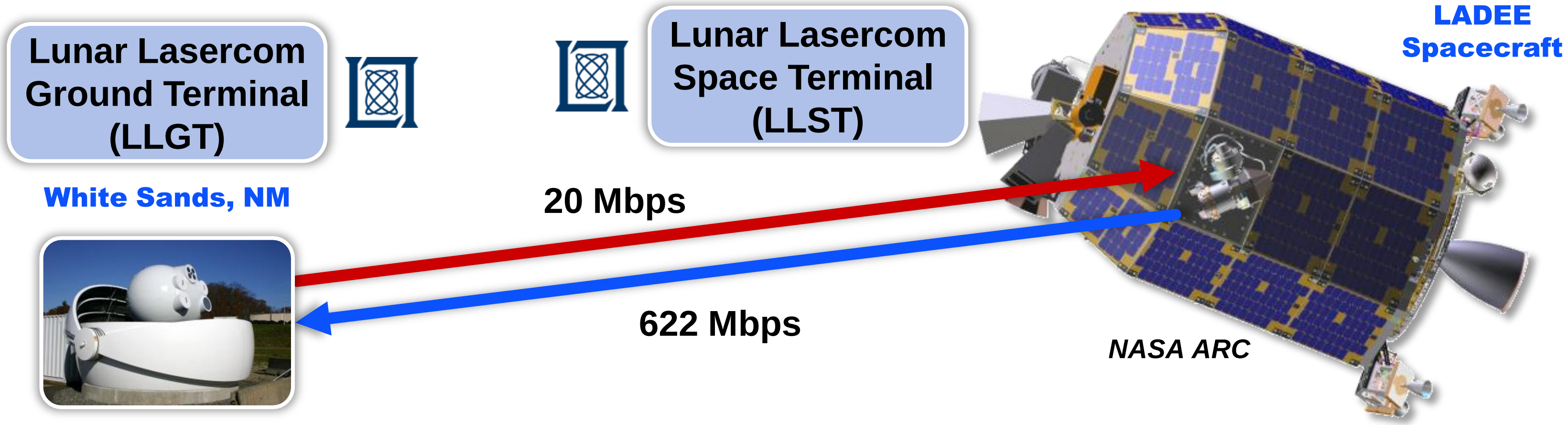
Transportable Design

- Novel architecture allows transportability
- Shipping container houses modem, computers, office
- Transported to White Sands NASA site

19-meter antennas in background
LLGT gimbal on pedestal is ~4-meters tall

Major Accomplishments

- **Longest laser communication link ~400,000 km**
- **Highest data rates ever demonstrated to/from moon**
  - **20 Mbps up, 622 Mbps down**
- **Operation through the atmosphere under a wide range of conditions**
  - **Including thin clouds**
- **Real-time reliable command and data delivery via Lasercom**
  - **Demonstrated RF-free operation**
  - **Entire spacecraft buffer downlinked in minutes**
  - **Loopback of multiple high-rate video streams and other file transfers**



Lunar Lasercom Ground Terminal (LLGT)

White Sands, NM

Lunar Lasercom Space Terminal (LLST)

LADEE Spacecraft

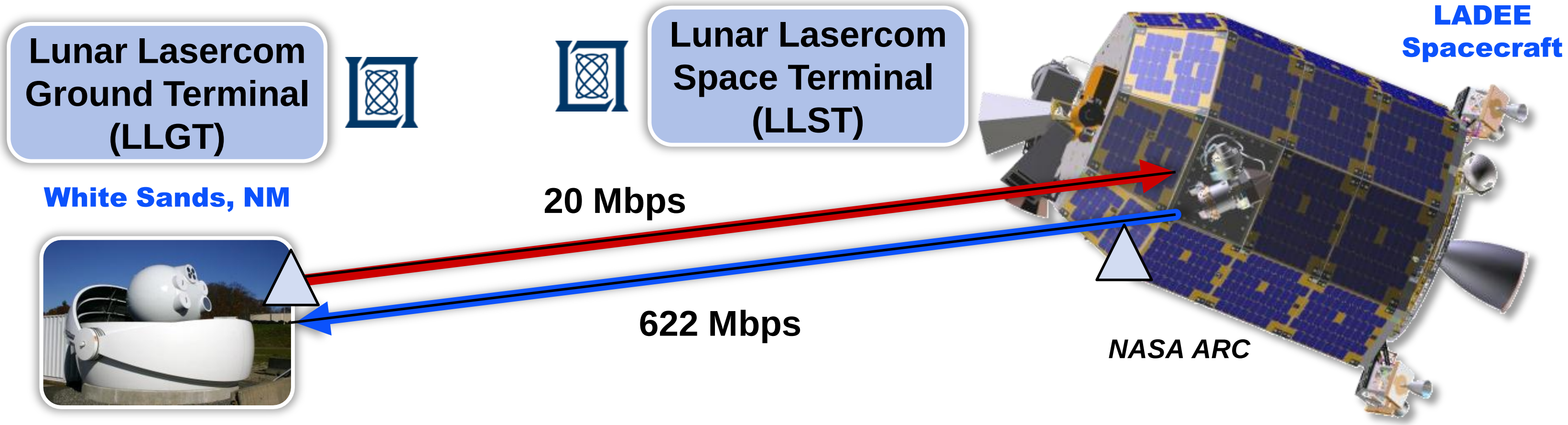
20 Mbps

622 Mbps

NASA ARC

… and Time-of-Flight

- Time-of-Flight (TOF) of signals using high-rate uplink and downlink communication system clocks
- In addition to duplex communication, 2-way TOF requires:
  - Common time reference on forward and return links
  - Downlink phase-locked to received uplink in space terminal
  - High-stability time reference for measuring two-way time-of-flight



Lunar Lasercom Ground Terminal (LLGT)

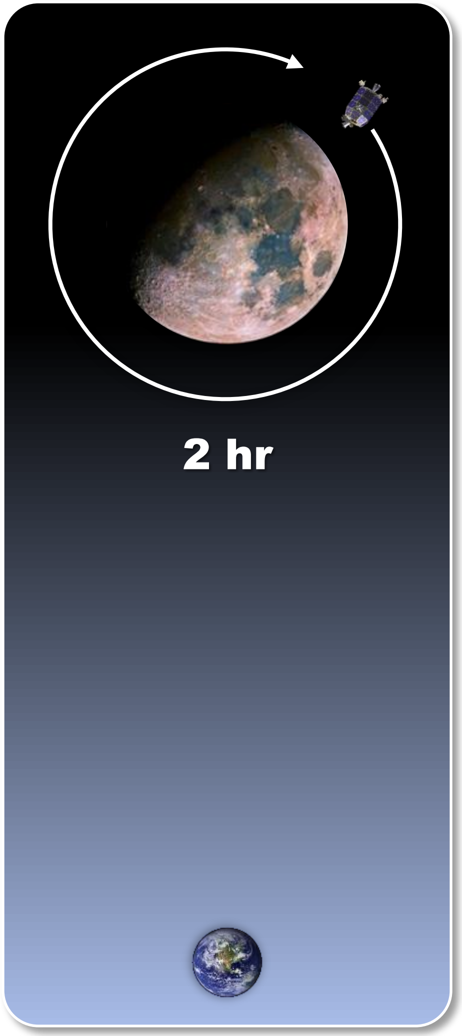
White Sands, NM

Lunar Lasercom Space Terminal (LLST)

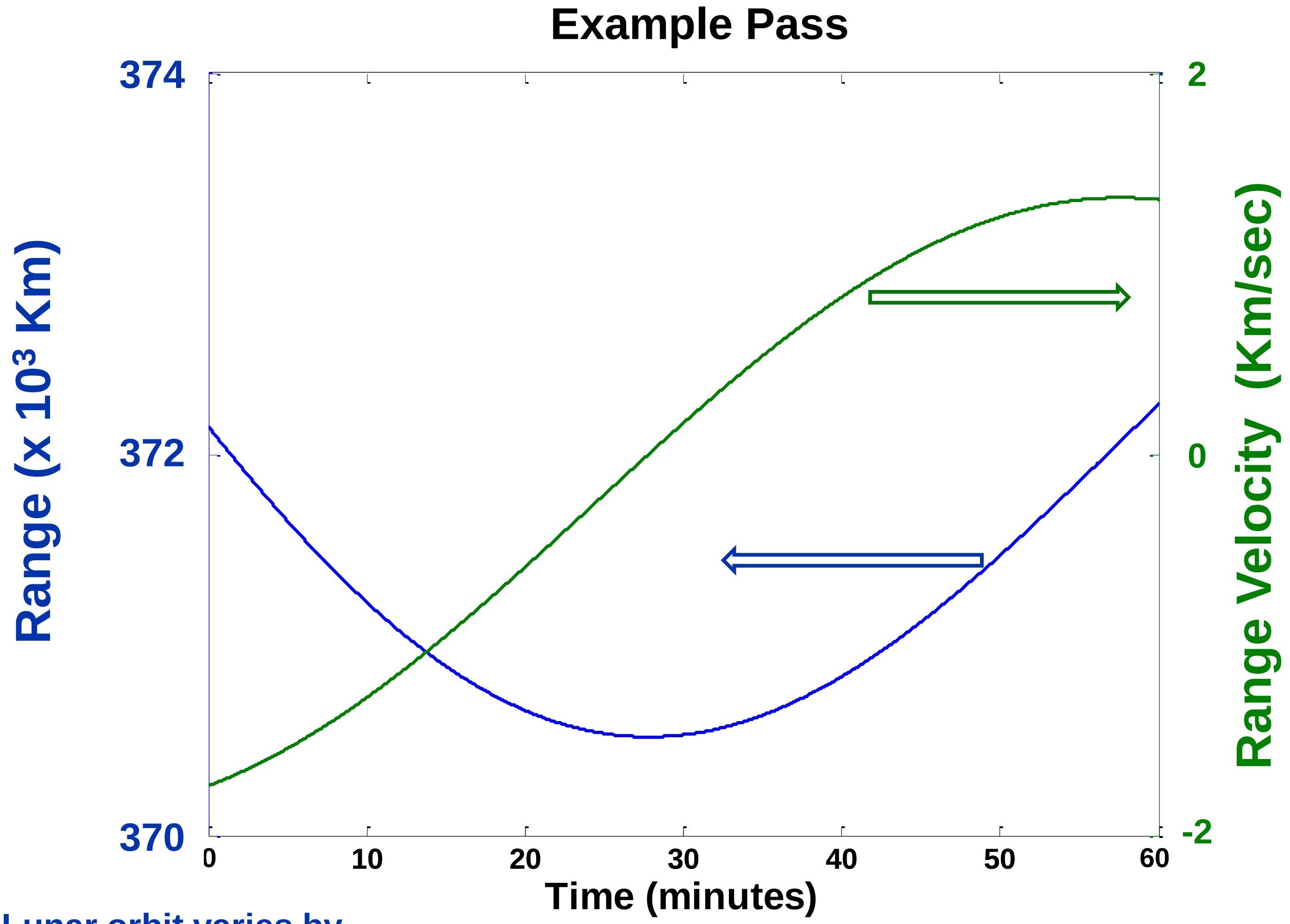
LADEE Spacecraft

LADEE / LLCD Mission Parameters

- **LADEE orbital period ~ 2 hrs**
  - **Visible from earth for about half of orbit**
- **Communication links available when LADEE is visible**
  - **Duplex phase-locked communications required for LLCD TOF**
- **Lasercom intervals limited to ~20 minutes by power and temperature**
  - **100 passes, 135 intervals of duplex comm (14.2 hours)**
- **LADEE ephemeris (orbit parameters) measured using NASA’s Satellite Tracking Network in dedicated ranging sessions**



LLGT-LADEE Range and Doppler in Lunar Orbit



Doppler (one-way)

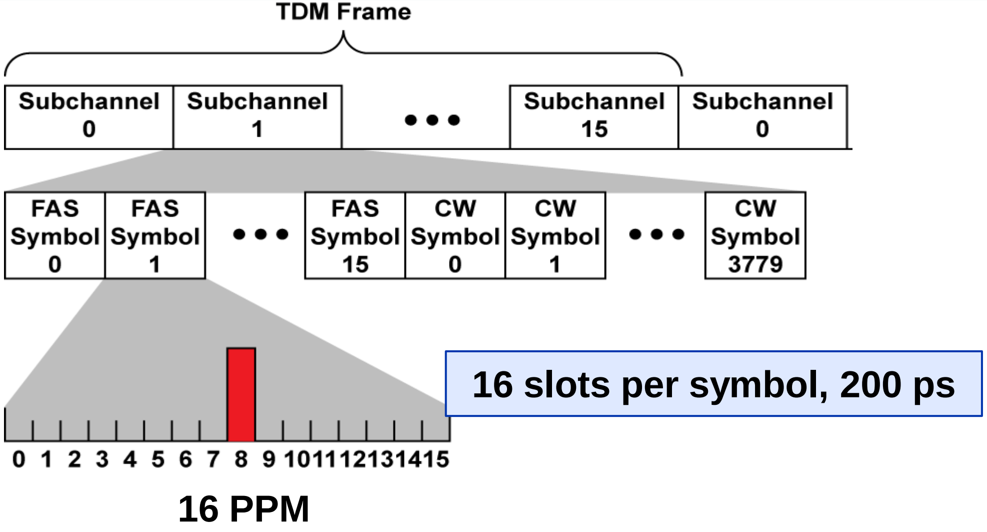
relative	± 6.7 ppm
carrier	± 1.3 GHz
DL slot clock	± 33 kHz
UL slot clock	± 2.1 kHz

Lunar orbit varies by 40,000 km over month

Outline

- **LLCD Mission**
- ➡ **TOF System Architecture**
- **TOF Data**

Ranging Based on Communication Synchronization

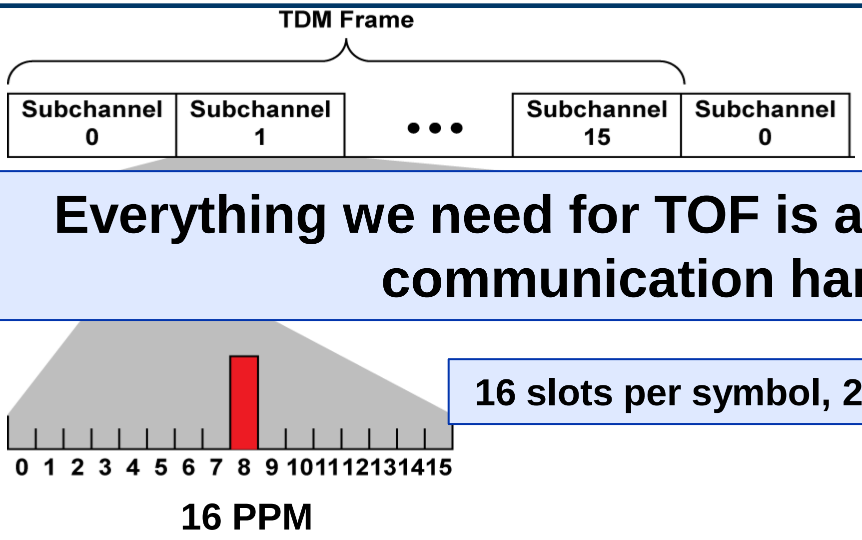


16 slots per symbol, 200 ps

FAS	**Frame Alignment Sequence**
CW	**Codeword**

- **Need perfect bit-alignment of symbols, codewords, frames, to have any communication**
- **Slot timing errors typically reduced to where communication loss is < 0.1 dB**
  - **Usually only a few % of a slot time**
- **Phase- and frequency-locking loops are designed as part of communication receivers**
  - **Designed to track through Doppler, fades, clock imperfections, delay variations, etc**
- **Symbol, codeword, and frame synchronization often accomplished using embedded symbols as part of communication signaling**

Ranging Based on Communication Synchronization



Everything we need for TOF is already built into the communication hardware

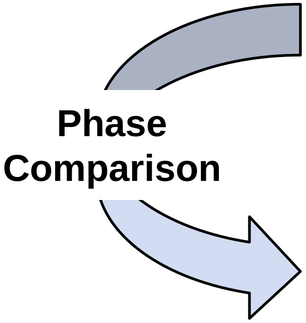
16 slots per symbol, 200 ps

FAS	Frame Alignment Sequence
CW	Codeword

- Need perfect bit-alignment of symbols, codewords, frames, to have any communication
- Slot timing errors typically reduced to where communication loss is < 0.1 dB
  - Usually only a few % of a slot time
- Phase- and frequency-locking loops are designed as part of communication receivers
  - Designed to track through Doppler, fades, clock imperfections, delay variations, etc
- Symbol, codeword, and frame synchronization often accomplished using embedded symbols as part of communication signaling

Communication System Time Scales

- Uplink and Downlink clocks are phase locked and fractionally related
  - 1 uplink slot (3.2 ns) = 16 downlink slots (200 ps) = 1 downlink symbol
  - Phase difference measured, integrated phase yields change in distance
- Synchronous UL / DL frame clocks compared at ground terminal
  - Time delay measurement yields absolute distance offset



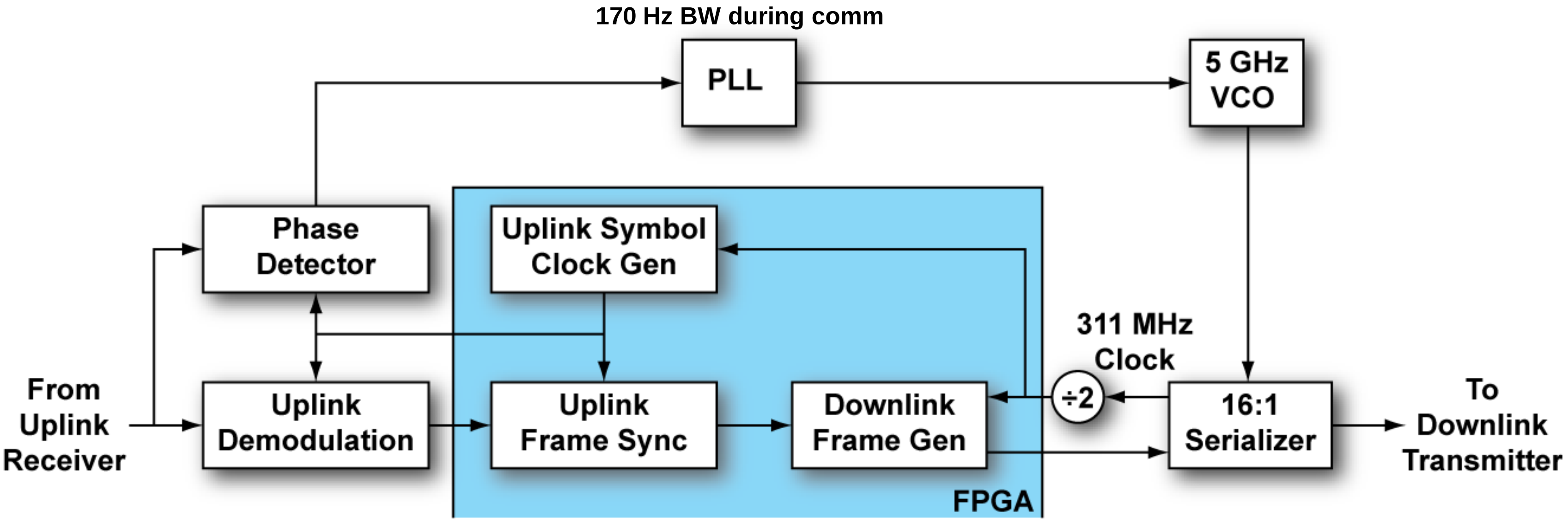
Phase Comparison

LLCD Designs	Frequency	Duration	Distance
Downlink			
Slot	4.977 GHz	200 ps	6 cm
Symbol	311 MHz	3.2 ns	96 cm
Codeword	81.9 kHz	12.2 us	3.7 km
TDM Frame	5.1 kHz	195.27 us	58.5 km
Uplink			
Slot	311 MHz	3.2 ns	96 cm
Symbol	19.4 MHz	51.4 ns	15.4 m
Codeword	2.5 kHz	390 us	117 km
TDM Frame	160 Hz	6.25 ms	1873 km

Comm requires accuracy to << 200 ps

Coarse Range ambiguity

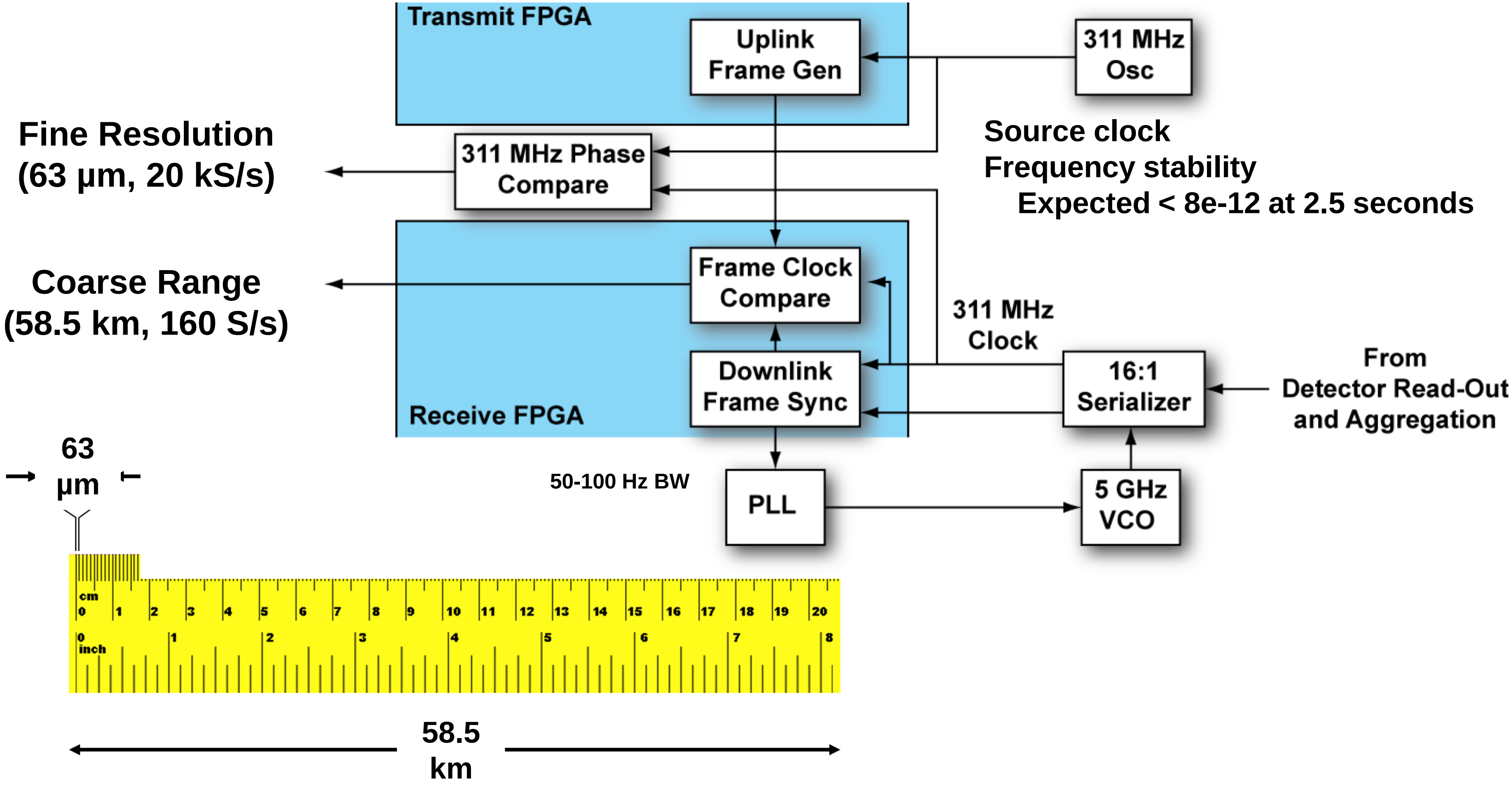
Space Terminal Clock Architecture



- Downlink clock is phase locked to received uplink clock
- Downlink frame is synchronized to uplink frame by command for absolute distance measurements
  - 39 measurement intervals synchronized by command
  - Automated synchronization possible in future missions

Single master clock locks downlink to uplink

Ground Terminal Time-of-Flight Systems



Transmit FPGA

Uplink Frame Gen

311 MHz Osc

Fine Resolution
(63 µm, 20 kS/s)

311 MHz Phase Compare

Source clock
Frequency stability
Expected < 8e-12 at 2.5 seconds

Coarse Range
(58.5 km, 160 S/s)

Frame Clock Compare

311 MHz Clock

Downlink Frame Sync

Receive FPGA

16:1 Serializer

From Detector Read-Out and Aggregation

63 µm

50-100 Hz BW

PLL

5 GHz VCO

58.5 km

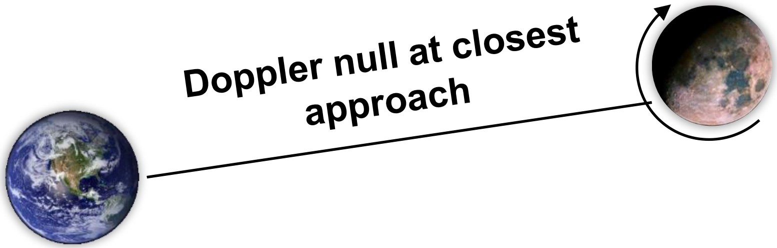
- Measured and archived all system performance metrics
  - 12.6 GB of fine and coarse resolution TOF data

Outline

- **LLCD Mission**
- **TOF System Architecture**
- **TOF Data**

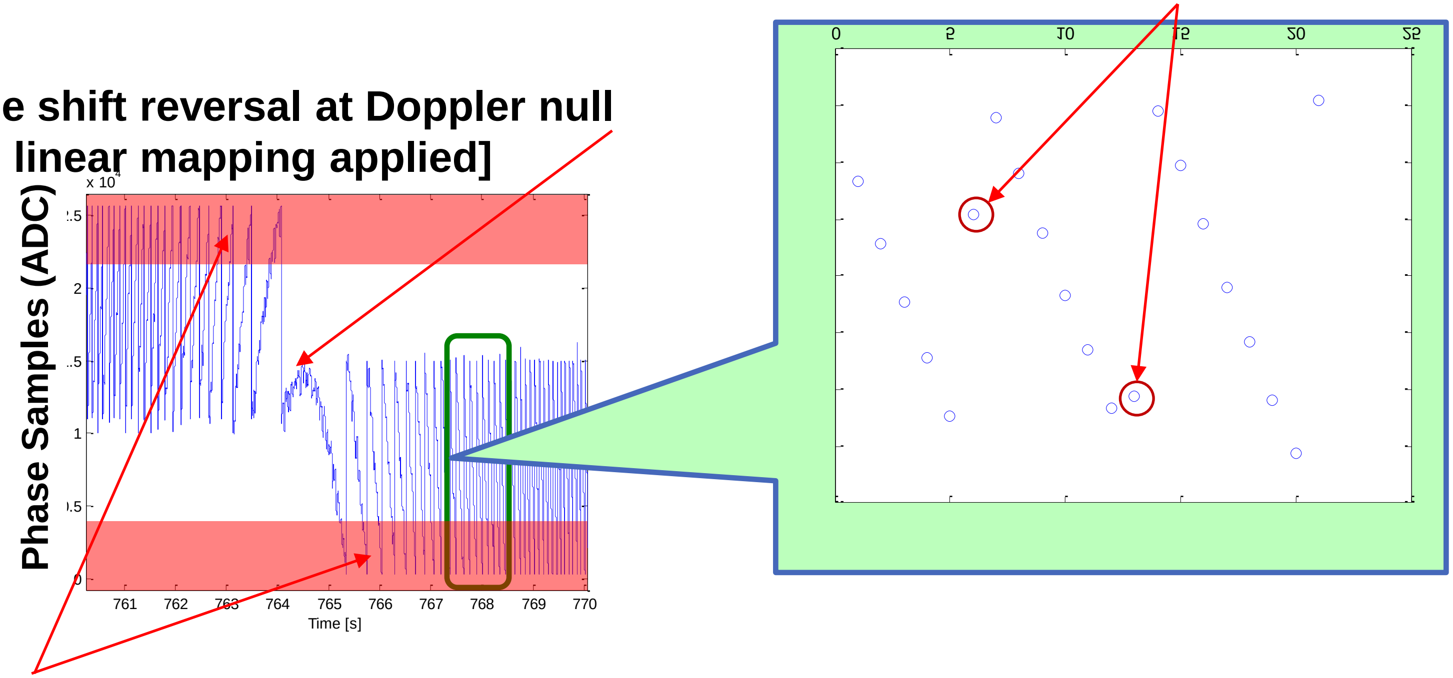
Processing Issues of TOF Phase Data

- **Each sawtooth is one cycle (360º) of 311.04 MHz**



2. Samples in rollover regions result in phase errors [straight-line fit correction applied]

1. Phase shift reversal at Doppler null [simple linear mapping applied]

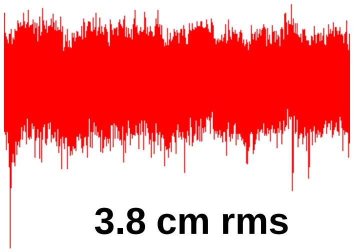


3. Slight non-linearity of detector results in residual beat-frequency noise in data [removed with filter]

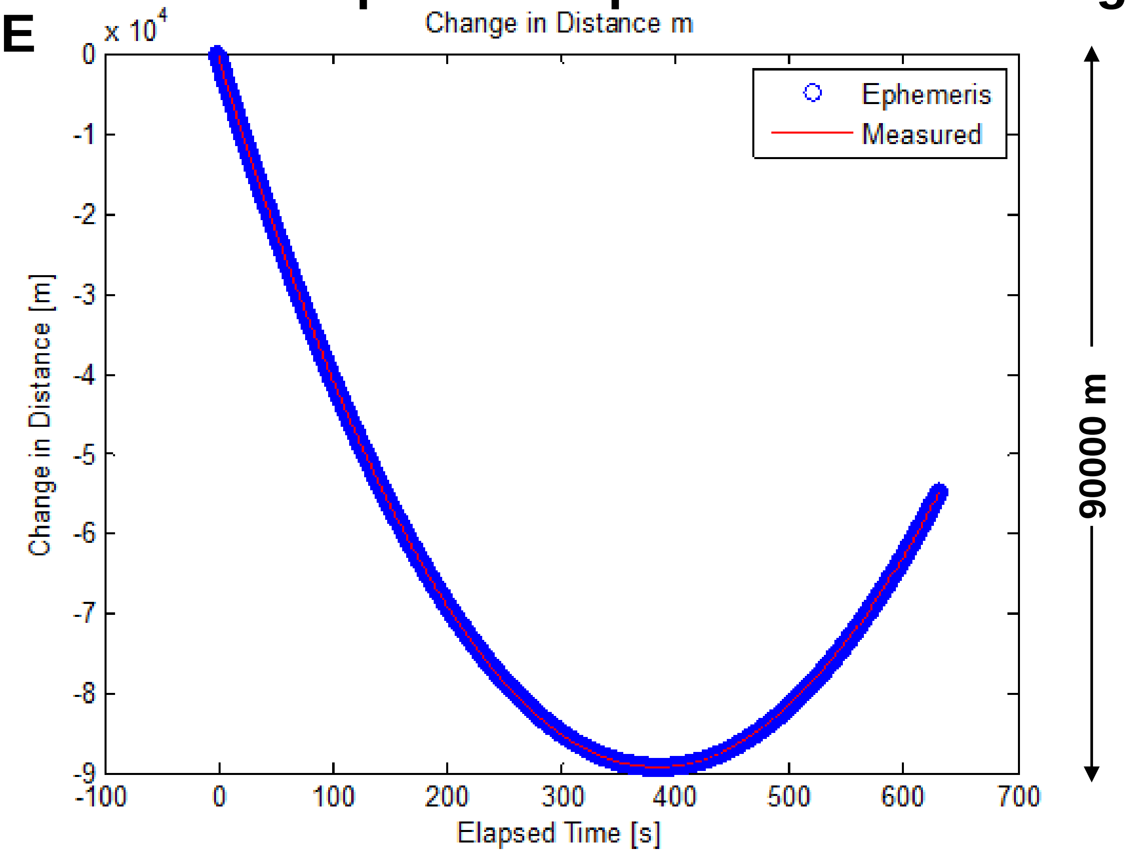
Relative Change in Distance

- **Using only fine data**
- **Measured and ephemeris set to zero at start**
- **Comparison of measured to ephemeris prediction at time light arrives at LADEE**

Residual Noise After Removing Polynomial Fit

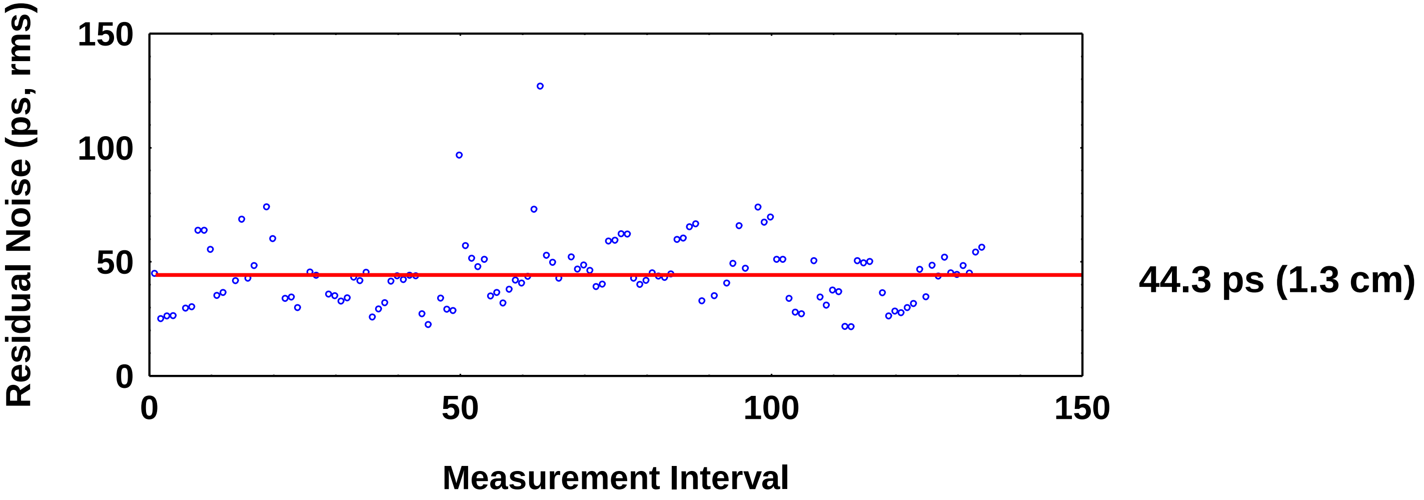


3.8 cm rms



Mission TOF Engineering Data

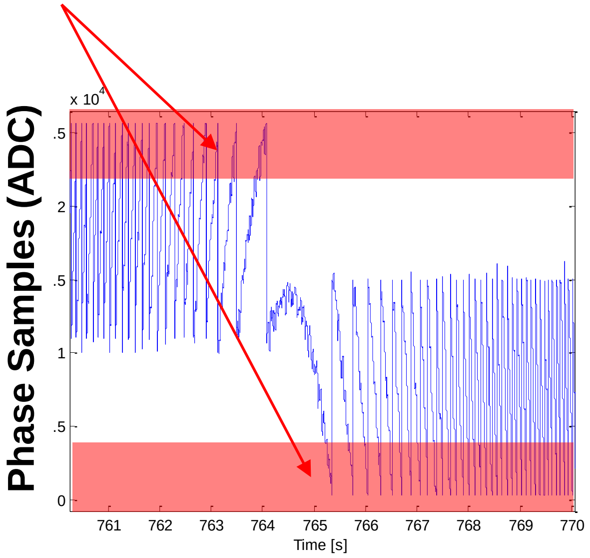
- **Two-way time-of-flight residual noise measured**
  - **Standard deviation in 1 s blocks calculated**
  - **Averaged over all data**
  - **σ = 44.3 ps (1.3 cm)**
    - **Very close to expected**
    - **Much better than 200ps promised**
- **Data archives, extraction and processing software sent to NASA science and navigation teams**

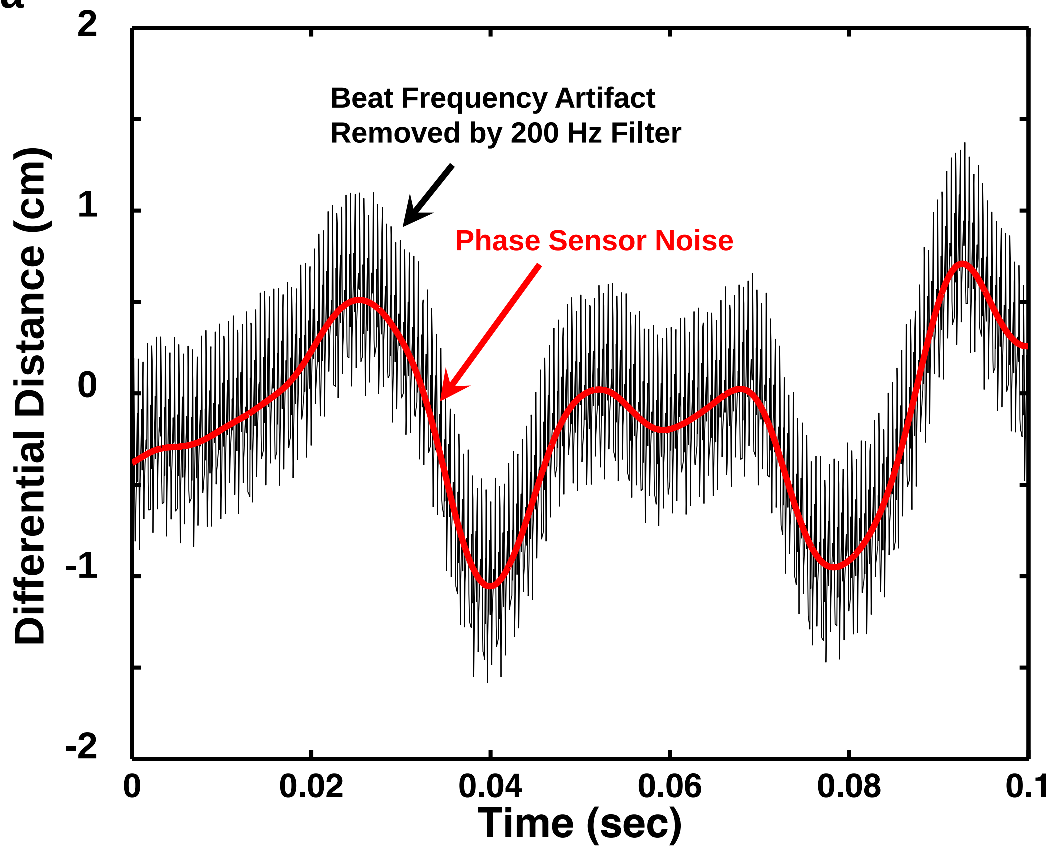


Detector Non-Linearity

- **Each sawtooth is one cycle (360º) of 311.04 MHz**

Slight non-linearity of detector results in residual beat-frequency noise in data





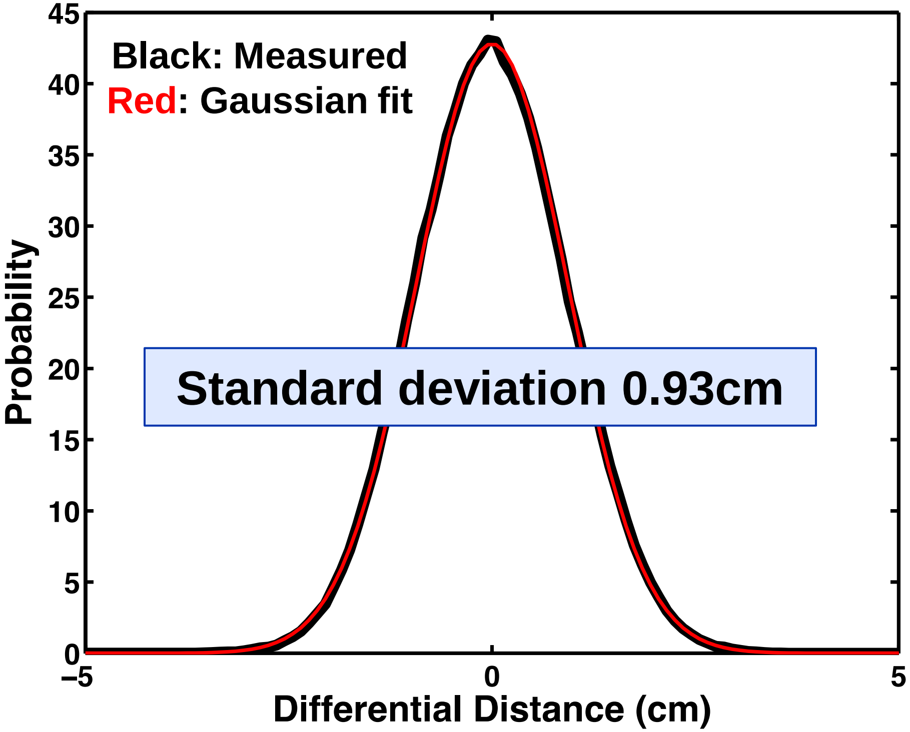
Beat Frequency Artifact Removed by 200 Hz Filter

Phase Sensor Noise

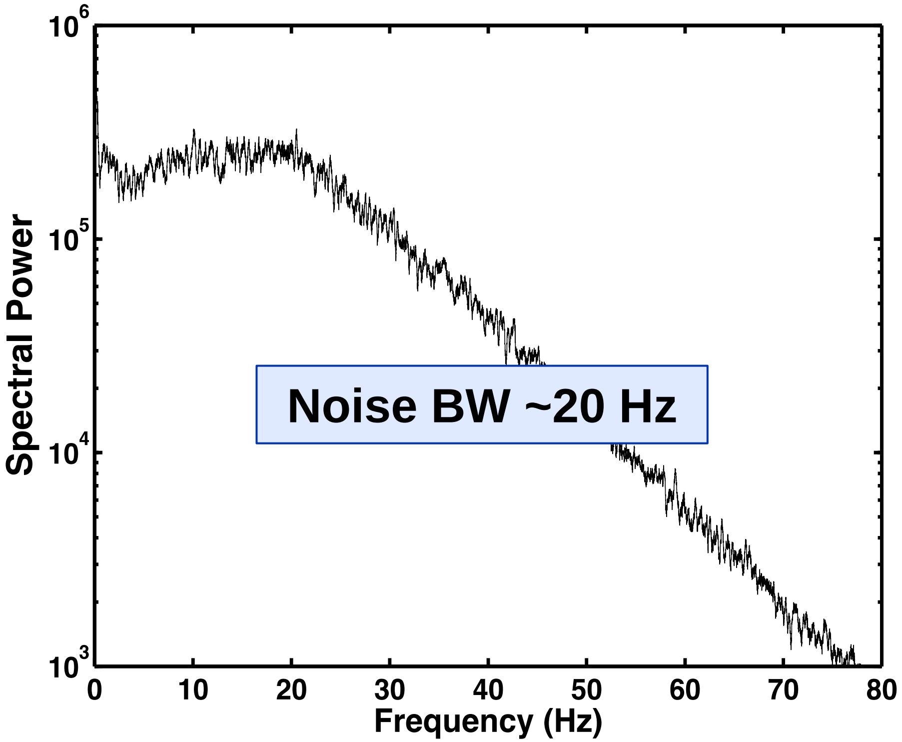
Residual beat-frequency noise removed with post-processing filtering

One-way Residual Gaussian Noise

Gaussian fit to filtered noise



Standard deviation 0.93cm

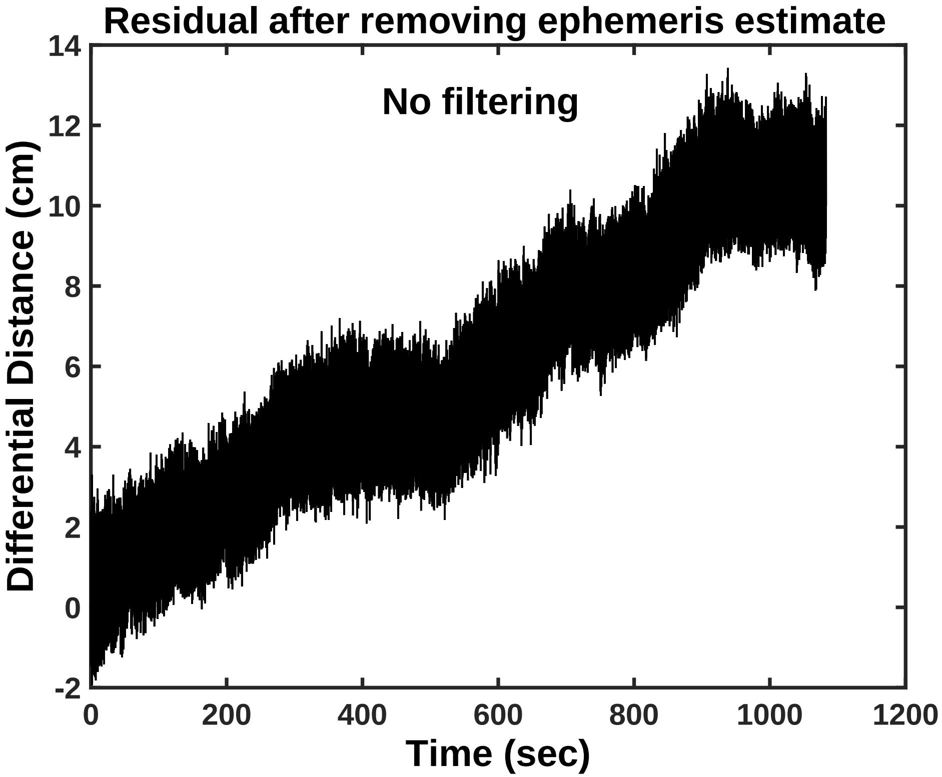


Noise BW ~20 Hz

LLCD TOF precision is 2 orders of magnitude finer than RF ranging systems currently in use

Low-Frequency Variations

- Some measurements show low-frequency variations
- Possible causes
  - Measurement noise
  - Platform movement
    - Roll, pitch, yaw
  - Temperature or signal power
  - Real orbital disturbance
- Resolution pending further analysis



Is this noise or real orbital disturbance?

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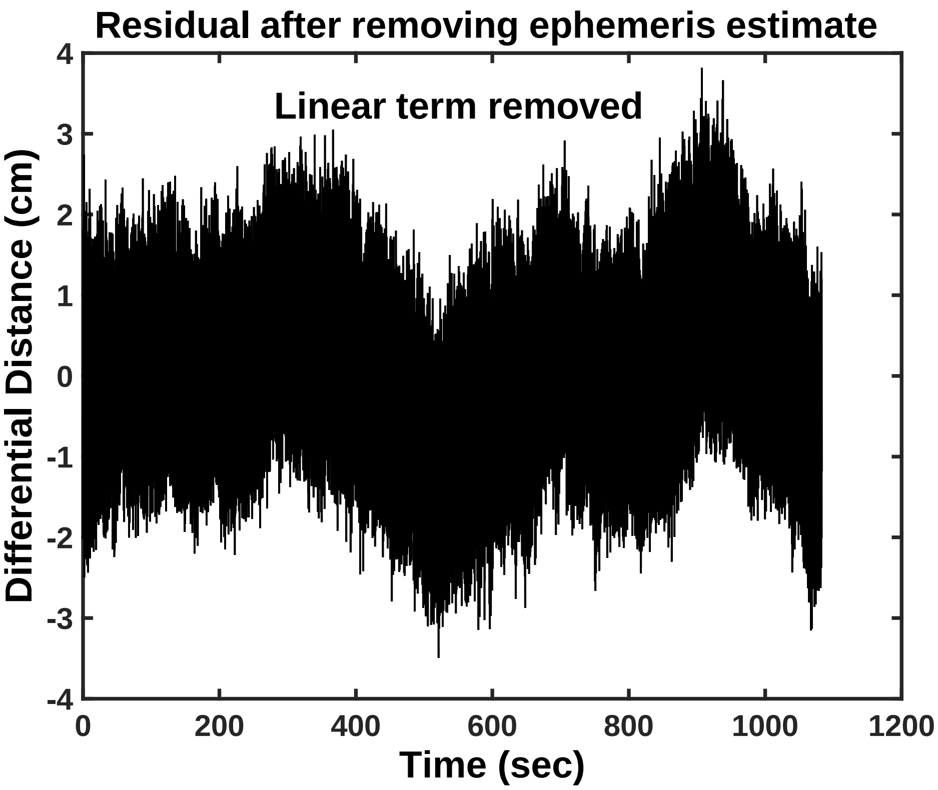

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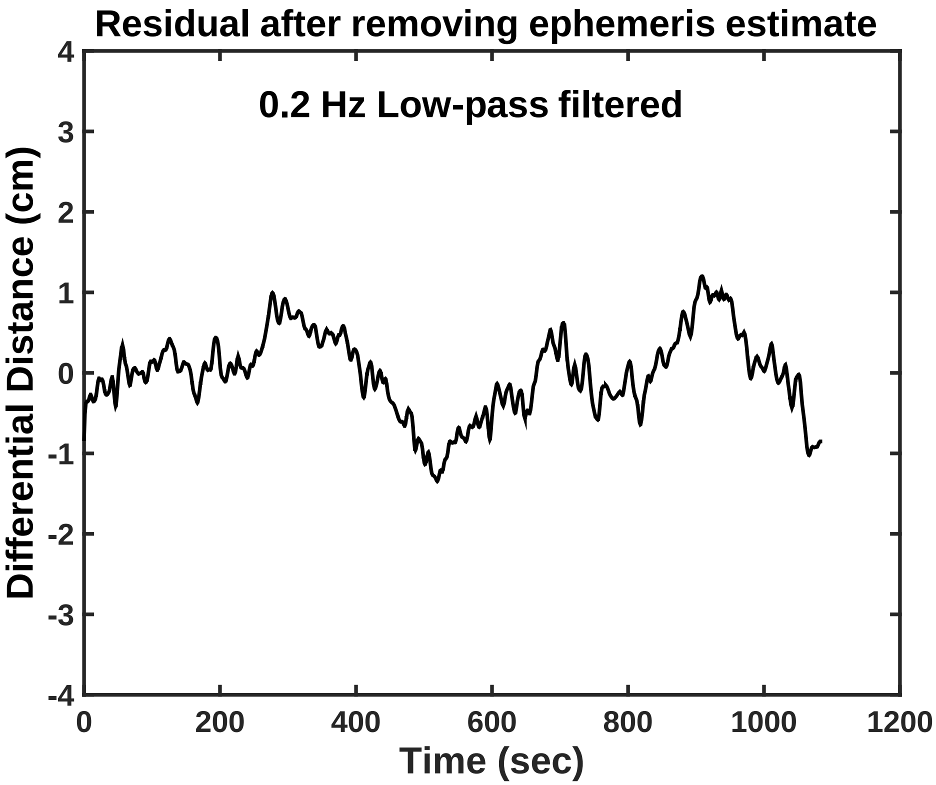

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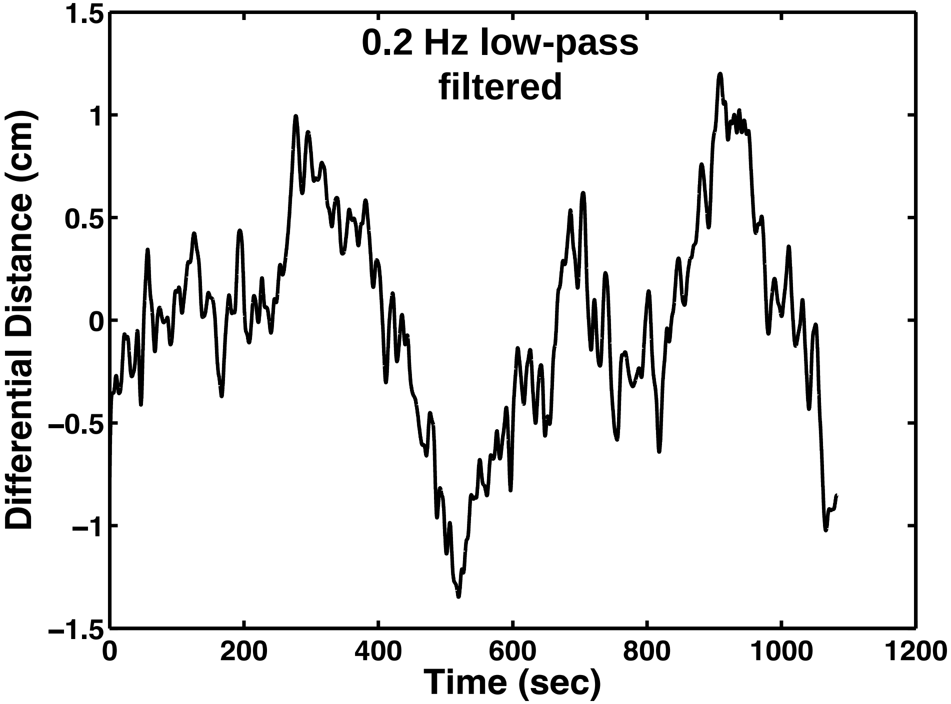
Residual after removing ephemeris estimate



Is this noise or real orbital disturbance?

Summary

- **LLCD included a measurement of time-of-flight using the high-speed clocks in the communication system**
- **Mission completed 100 passes**
  - **14.2 hours of duplex comm**
  - **12.6 GB of TOF data**
  - **Standard deviation of residual noise in 2-way TOF = 44.3 ps (1.3 cm)**
- **Preliminary ranging estimates show:**
  - **Centimeter precision of one-way relative distance**
  - **Gaussian residual noise with typical standard deviation of 0.93cm**
  - **Two orders of magnitude better than RF ranging systems in use**
- **NASA science and navigation teams are performing fine analysis of ranging**

We believe that high-rate communication-signal-based time-of-flight systems could be highly useful in future navigation and science missions

References

We believe that high-rate communication-signal-based time-of-flight systems could be highly useful in future navigation and science missions

- **D.M. Boroson, B.S. Robinson, D.A. Burianek, D.V. Murphy, F.I. Khatri, J.M. Kovalik, Z. Sodnik, Overview and results of the Lunar laser communication demonstration. Proc. SPIE 8971 (2014)**
- **B.S. Robinson, D.M. Boroson, D. Burianek, D. Murphy, F. Khatri, A. Biswas, Z. Sodnik, J. Burnside, J. Kansky, D. Cornwell, *"The NASA Lunar Laser Communication Demonstration—Successful High-Rate Laser Communications to and from the Moon"; Space Ops* (2014)**
- **Willis, M.M.; Robinson, B.S.; Stevens, M.L.; Romkey, B.R.; Matthews, J.A.; Greco, J.A.; Grein, M.E.; Dauler, E.A.; Kerman, A.J.; Rosenberg, D.; Murphy, D.V.; Boroson, D.M., "Downlink synchronization for the lunar laser communications demonstration," in *Space Optical Systems and Applications (ICSOS), 2011 International Conference on* , vol., no., pp.83-87, 11-13 May 2011**