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Flight Center

Optimetrics for Precise Navigation

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1. Overview of Radiometrics for Navigation

Radiometrics and Optimetric Parameters for Navigation

- Ranging (distance via time of flight)
- Doppler (velocity via frequency shift or carrier phase)

Radiometrics in RF Communication (over RF carrier)

- PN ranging; Tone ranging
- Carrier Doppler

Optimetrics in Optical Communication (over Optical Carrier)

- Data frame and clock ranging
- Data Clock Doppler
- *Come with signal pointing angles*

Radiometrics Accuracy Limiting Factors

Parameter	Limit (Allan Deviation)	Condition	Comments
Clock Stability	10^{-13}	Space Qualified crystal with 1000s average [4]	Optical frequency standard can reach [5] **10^{-18}**
Frequency Standard	10^{-15}	Hydrogen Maser	Optical frequency standard can reach [5] **10^{-18}**
Plasma Introduced group delay variation	20cm - 60 cm	X-band in Ionosphere [4]	**Dt = k/f^2** Higher Optical Frequency (10^{14}Hz) than X-band (10^{10}Hz), reduces this noise by **8 orders** of magnitude
Plasma Introduced group delay variation	1m- 75m	X-band in interplanetary medium [4]	

2. Tracking Examples

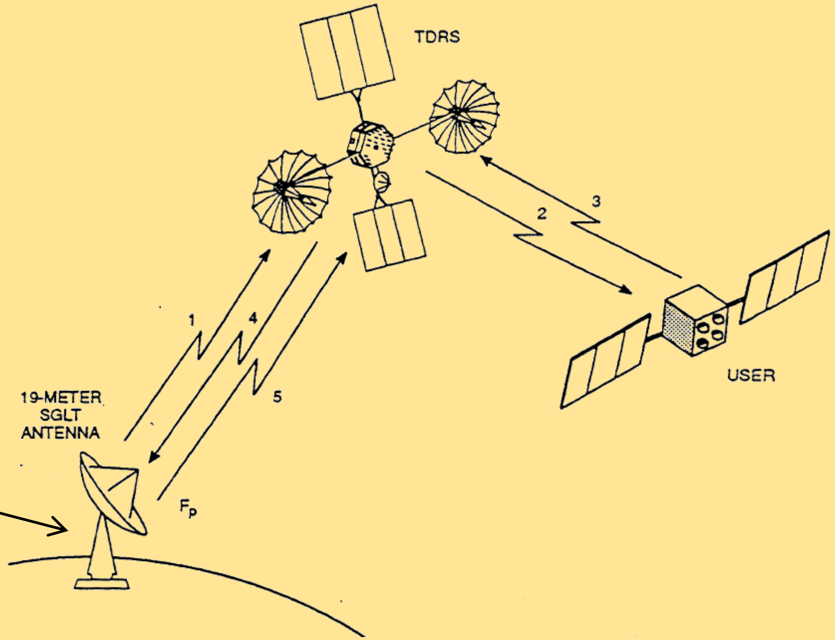
Tracking and Data Relay Satellite System (TDRSS)

Tracking and Data Optical Relay Satellite (TDORS)

Traditional TDRSS Radiometrics

1. Tracking and Data Relay Satellite System (TDRSS) provides two-way coherent range (PN ranging) and range rate (carrier Doppler) observations
2. The signal path transverses 4 paths (legs 1 – 4) during the observation
3. The TDRS payload is coherent to the Telemetry, Tracking, and Command (TT&C) uplink (leg 5), which is coherent to a common time and frequency source (CTFS)
4. Knowledge of absolute time onboard *the TDRS* is unnecessary to support TDRSS radiometrics
5. Range and Doppler observations are referenced to the ground system/modem, and are time tagged according to the CTFS
6. Calibrations of the ground system and TDRS payload are necessary to mitigate delays introduced by ground and spacecraft electronics

Observations referenced to the ground



Range and Doppler Goal over (Tracking and Data Optical Relay Satellite) TDORS

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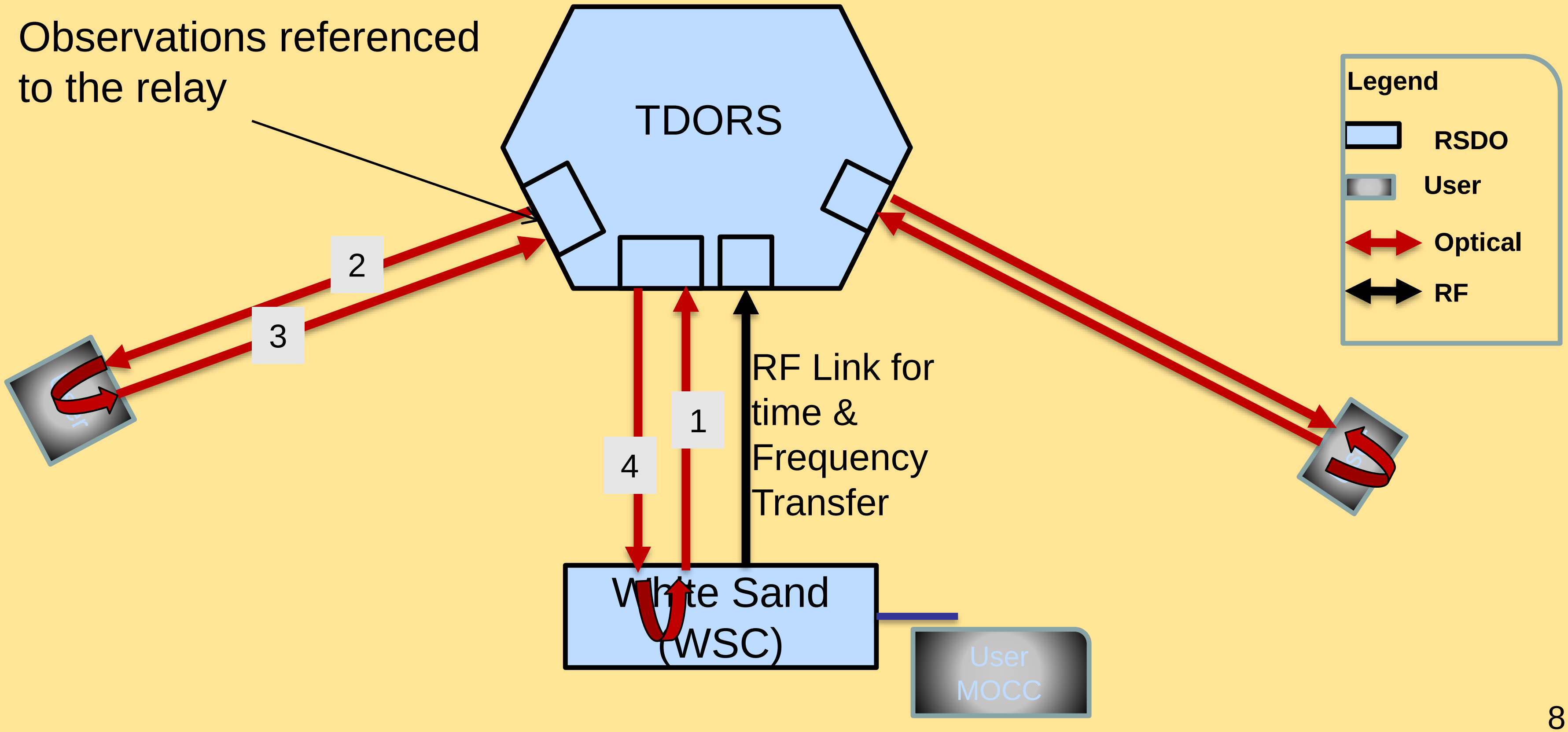
1. The Range and Doppler observations are referenced to the Relay system/modem.
2. The Measurements are time tagged
3. Measurements of leg 1&4 are between Relay and Ground
4. Measurements of leg 2&3 are between Relay and User
5. The Relay station movement contribution are common to both 1&4 and 2&3, and the measurements are conducted at the same time
6. User to ground measurement (like TDRSS) can be mathematically constructed by subtracting common contributions from the Relay.



3. Optimetric Measurements Implementation

Missions with Radiometrics or Optimetric

Area	Missions	Carrier
Formation Flying for Gravitational scientific measurements	GRACE, GRAIL	RF
Space Doppler Tracking via Radio Science Beacon	Cassini, GRAIL	RF/OpNav
Doppler and Ranging for Spacecraft Navigation	All navigation	RF
Optical Ranging and Doppler Demo	LLCD [1]	Optical

Optical Tracking Current Status

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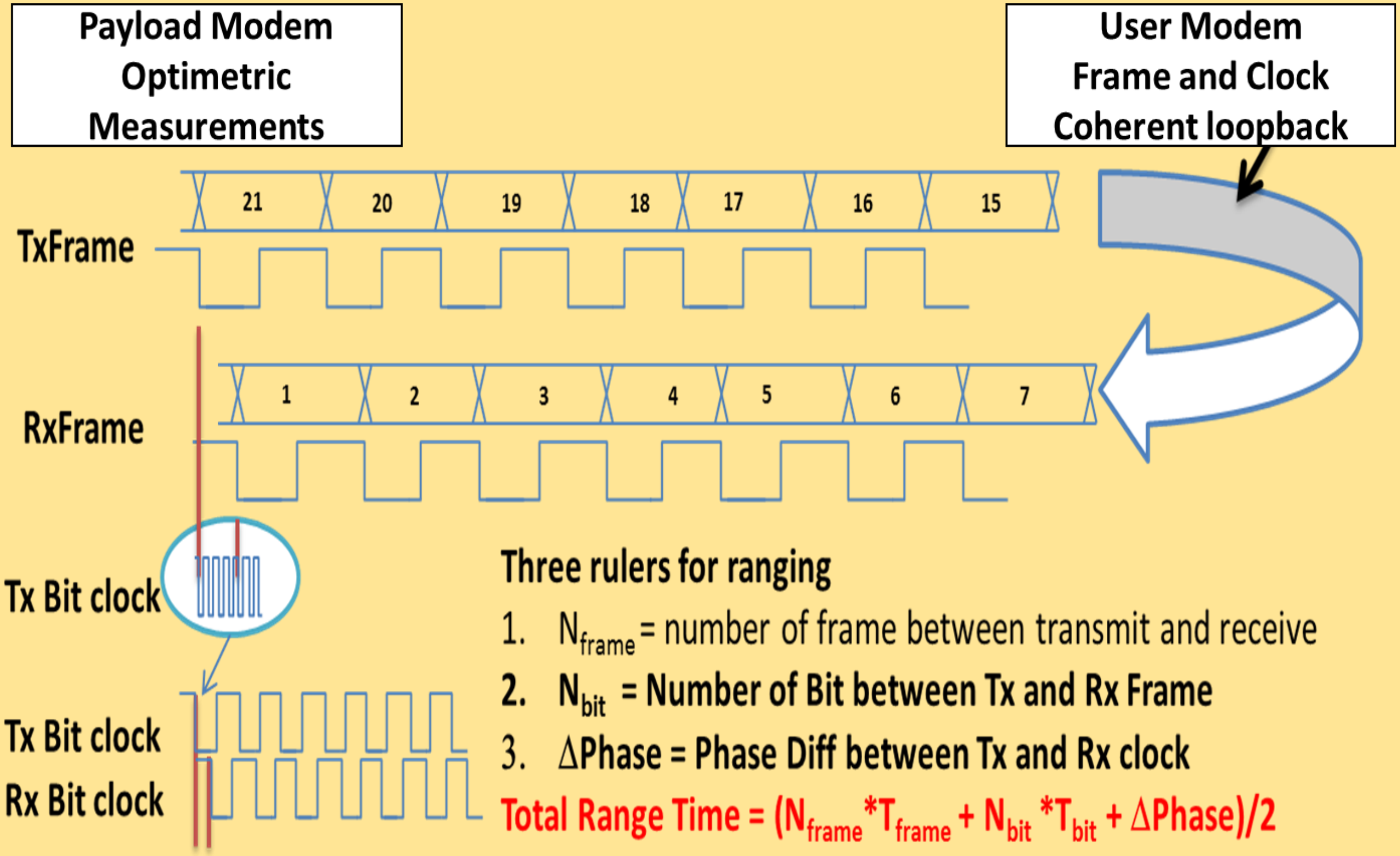
- LLCD demonstrated two-way coherent range and Doppler measurements [3]
- Current LCRD payload doesn’t support coherent clock and frame loopback.
- Future TDORS requires Optimetric measurements be implemented

Optimetric over Optical Communication



Three rulers for ranging

1. N_{frame} = number of frame between transmit and receive
2. **N_{bit} = Number of Bit between Tx and Rx Frame**
3. **ΔPhase = Phase Diff between Tx and Rx clock**

Total Range Time = $(N_{frame} * T_{frame} + N_{bit} * T_{bit} + \Delta Phase)/2$

Experimental Setup [2,3]

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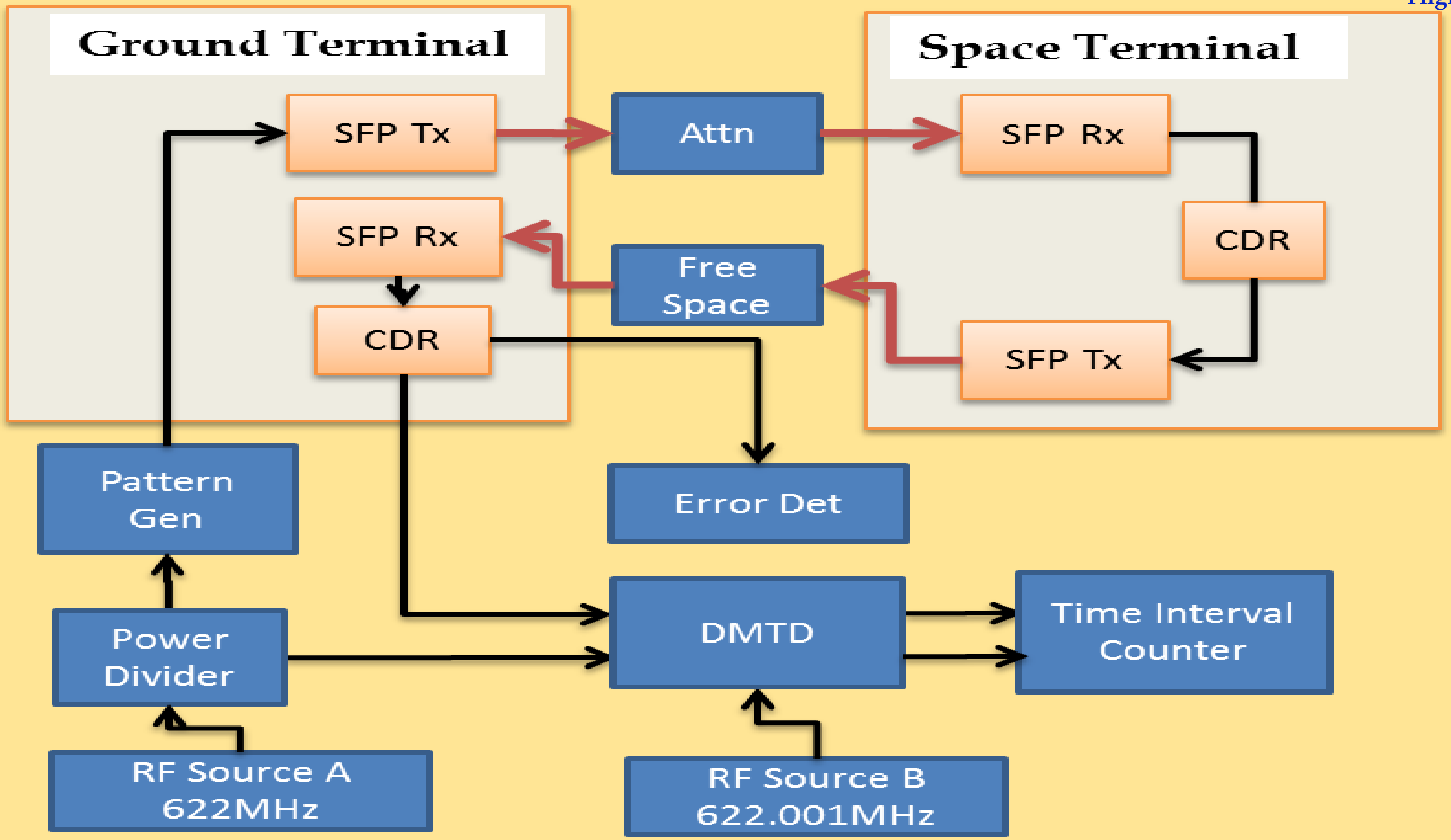
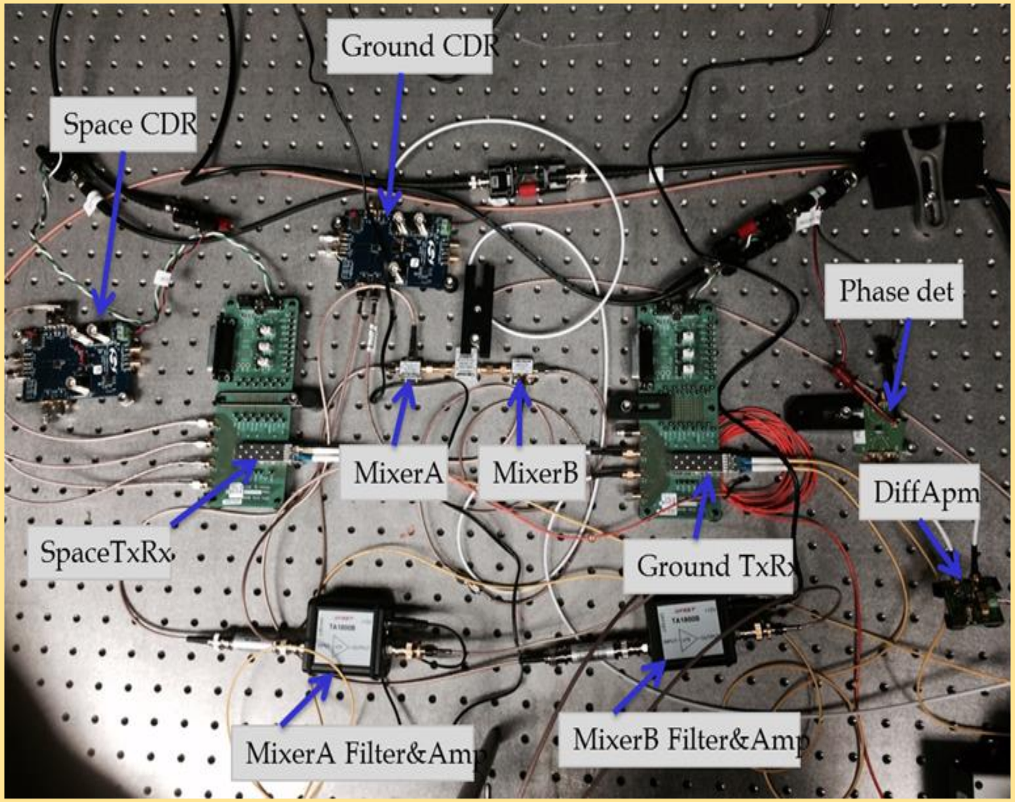


SFP	**Small Form-factor Pluggable optical transceiver**
CDR	**Clock Data Recovery ,**
DMTD	**Dual Mixer Time Difference phase measurement**

Breadboard and Test Equipment



Breadboard

Test Equipment

Instrument Noise Floor (Continuous Phase at 1KHz sampling rate)

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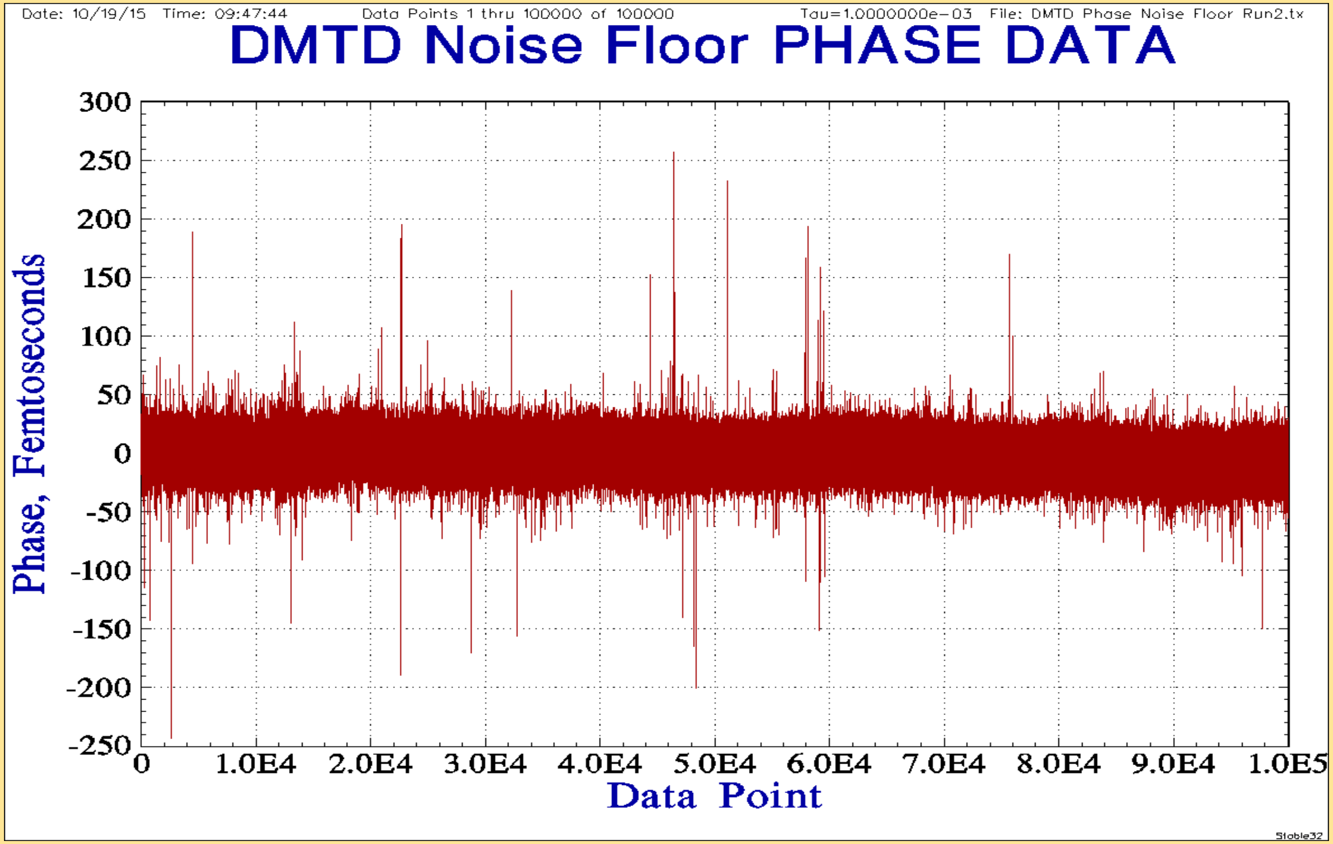
With DMTD phase measurement, the instrument noise is improved by three orders of magnitude from **20 ps** (HP time interval counter) to **50 fs**



Space Terminal and Ground Terminal Closed Loop Performance Data Rate at 622MBPS

Transmit clock, recovered data, and recovered clock waveforms captured in scope plots

Payload Terminal Received Data

Payload Terminal Transmit Clock

Payload Terminal Received Clock

Tone Modulation at 622MHz

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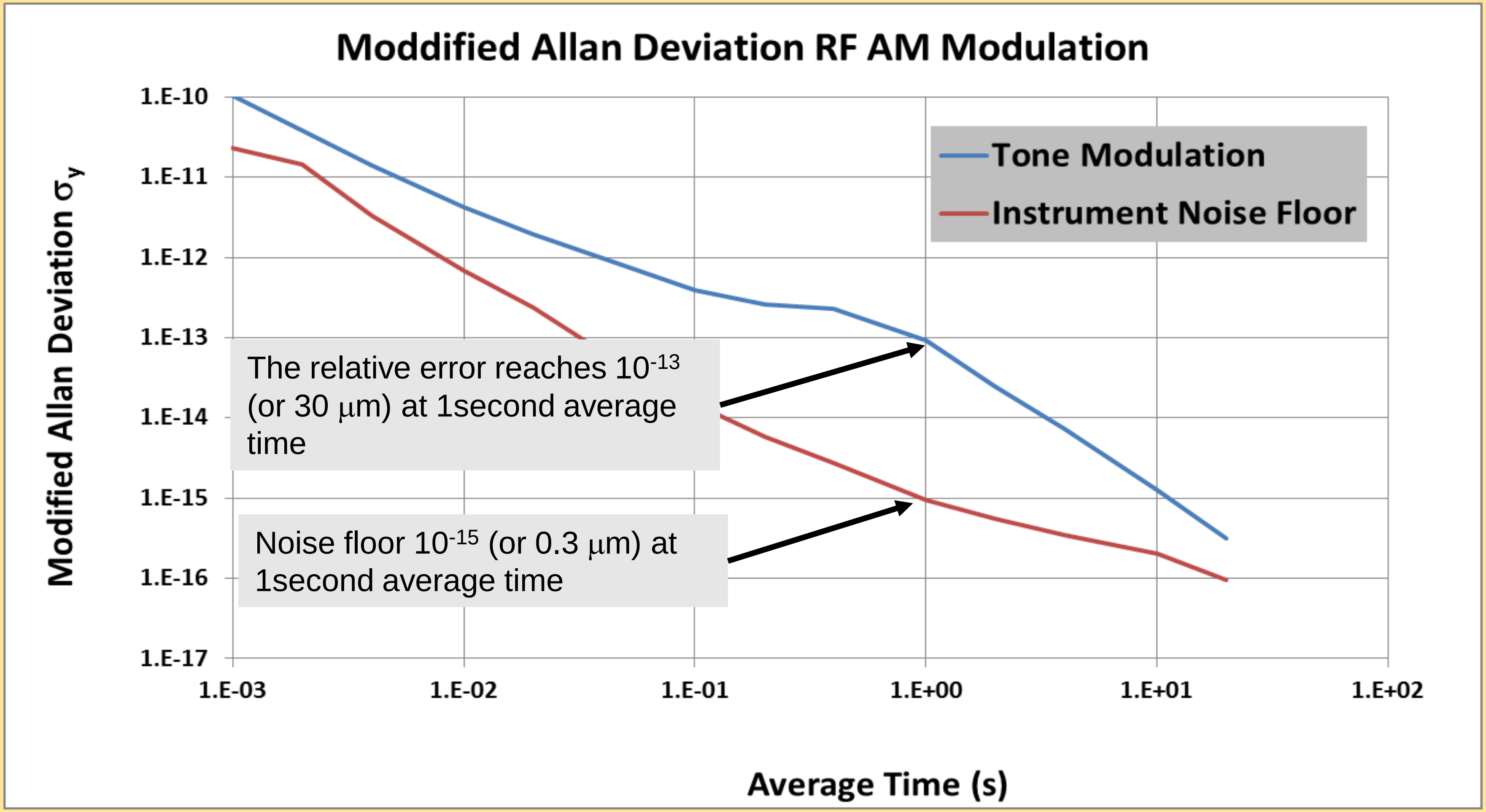

Data Modulation at 622 MBPS

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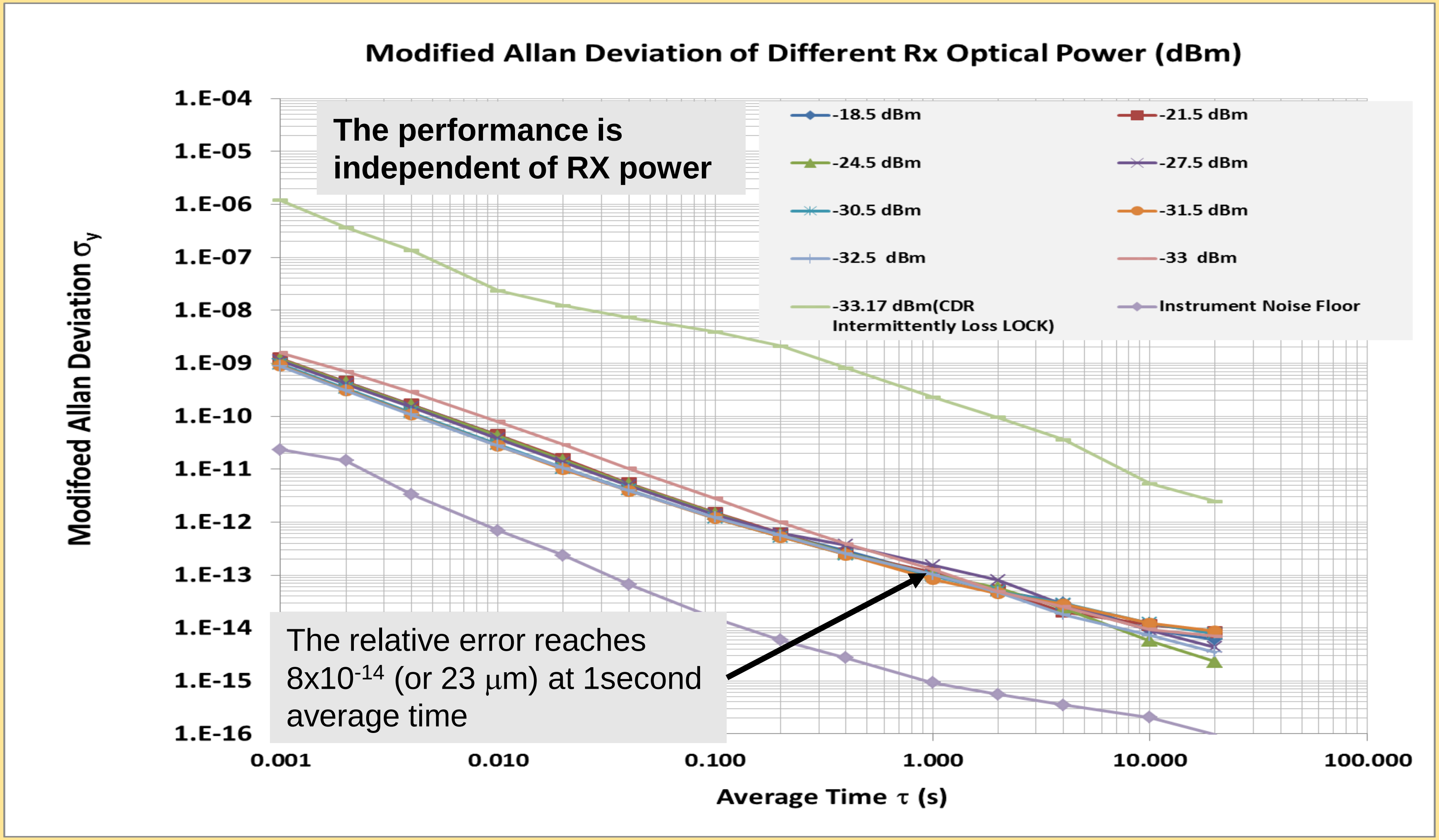

Range Rate Accuracy over BER

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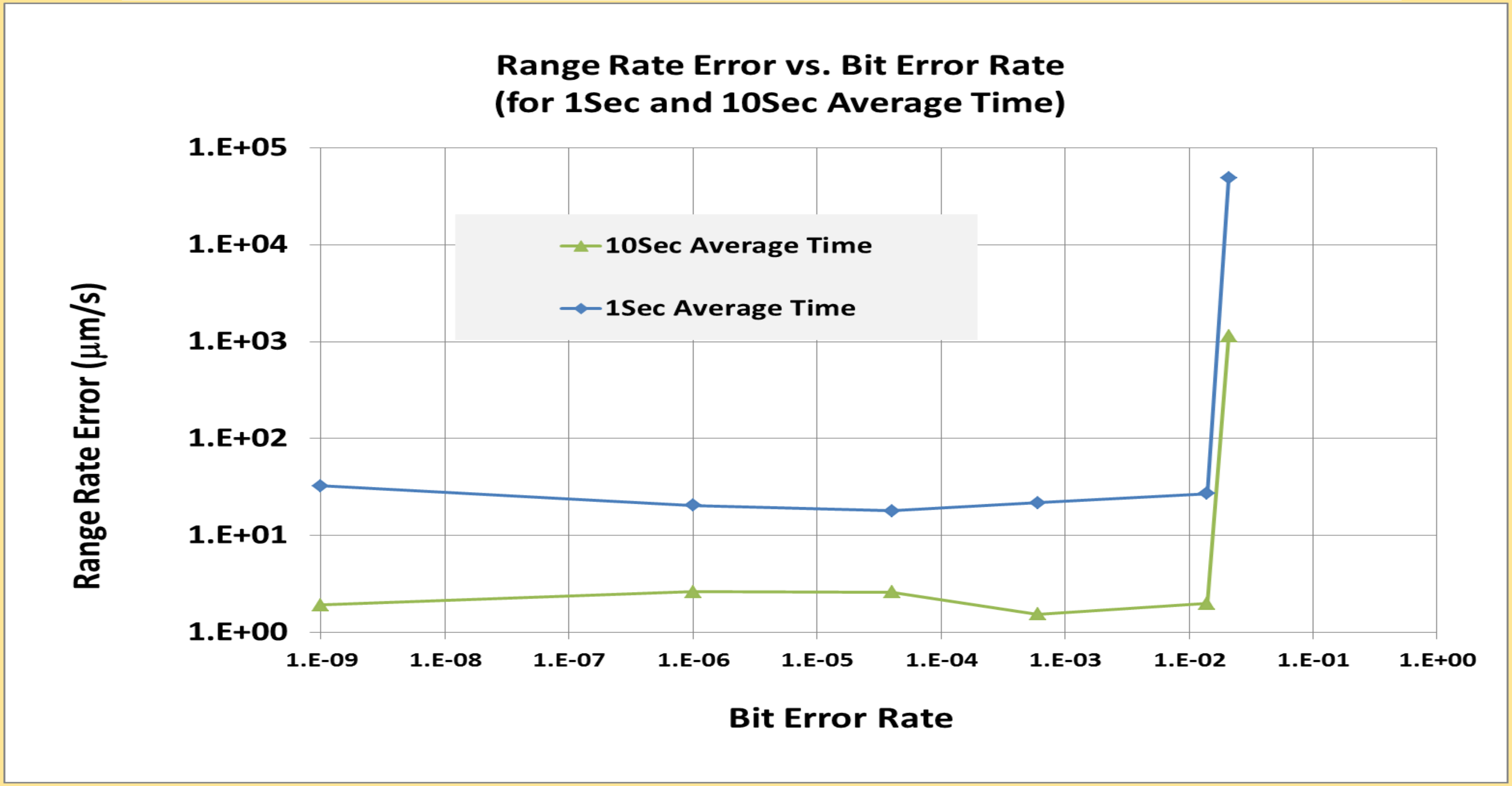
The measurement accuracy is not dependent on the Rx power, or Bit error rate. The performance is two orders of magnitude better than TDRSS



Ranging and Range Rate Accuracies [2,3]

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Average Time (s)	Range Rate Accuracy (μm/s)		
	Instrument Noise Floor	622MHz Tone AM Modulation	622MBPS Data Communication
1	0.28	19.74	23.1
10	0.06	0.27	2.1

Average Time (s)	Ranging Accuracy (μm)		
	Instrument Noise Floor	622MHz Tone AM Modulation	622MBPS Data Communication
1	0.28	19.74	23.10
10	0.62	2.67	21.00

4. Summary

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Advantages of Optimetric

- **High Optical Frequency enables**
  - Immunity from ionosphere and interplanetary Plasma noise floor, which is a performance limitation for RF tracking
  - High antenna gain reduces terminal size and volume, enables high precision tracking in Cubesat, and in deep space Smallsat.
- **High Optical Pointing Precision provides spacecraft orientation**
- **Minimal additional hardware to implement Precise Optimetrics over optical comm link (TRL>6)**
- **Continuous optical carrier phase measurement will enable the system presented here to accept future optical frequency standard with much higher clock accuracy (10^{-18})**

Conclusions and Future Works

Achievements:

- Achieved 2.7 mm range accuracy for average window size of 10s
- Achieved 0.27 mm/s range rate accuracy for average window size of 10s
- Demonstrated range and range-range accuracy are independent of optical communication link noise bit error rate.

Future work

- Implementation of Optimetrics in TDORS
- Research on continuous optical phase measurement Optimetrics in coherent optical communication
- Engage with planetary and earth scientists for application of this technology
- Engage with the next NASA laser comm mission, Laser Communication Relay Demonstration (LCRD) to study infusing optimetrics into their system.

5. References

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[1]. SPIE Photonic West Proceeding (2016), M. L. Stevens etc "The Lunar Laser Communication Demonstration time-of-flight measurement system: overview, on-orbit performance and ranging analysis"

[2]. SPIE Photonic West Proceeding (2016), Guangning Yang etc, :Innovative free space optical communication and navigation system with high data rate communication, precision ranging, range rate measurements, and accurate spacecraft pointing"

[3]. IEEE Aerospace Conference (2016), Guangning Yang etc. "High-Precision Ranging and Range-Rate Measurements over Free-Space-Laser Communication Link"

[4]. Catherine L. Thornton and James S. Border, JPL DEEP-SPACE COMMUNICATIONS AND NAVIGATION SERIES "Radiometric Tracking Techniques for Deep-Space Navigation"

[5]. David B. Hume* and David R. Leibrandt, PHYSICAL REVIEW A 93, 032138 (2016) "Probing beyond the laser coherence time in optical clock comparisons"

Backups

Abstract

"Optimetrics for Precise Navigation" will implemented on existing optical communication links. The ranging and Doppler measurements are conducted over communication data frame and clock. The measurement accuracy is two orders of magnitude better than TDRSS. It also has other advantages of:

The high optical carrier frequency enables

- Immunity from ionosphere and interplanetary Plasma noise floor, which is a performance limitation for RF tracking
- High antenna gain reduces terminal size and volume, enables high precision tracking in Cubesat, and in deep space smallsate.

High Optical Pointing Precision provides spacecraft orientation

Minimal additional hardware to implement Precise Optimetrics over optical comm link

Continuous optical carrier phase measurement will enable the system presented here to accept future optical frequency standard with much higher clock accuracy.

Navigation Products

Two Primary navigation functions

1. Orbit Determination (OD)
2. Guidance

Two Relevant Tracking Techniques for Discussion

1. Radiometric based range and Doppler (earth based radio frequency tracking)

   Optimetric Provides similar measurements with higher precision

2. Optical Based Navigation (optical image of the target or satellite against the known star background)

Dual Mixer Time Difference Phase Measurement

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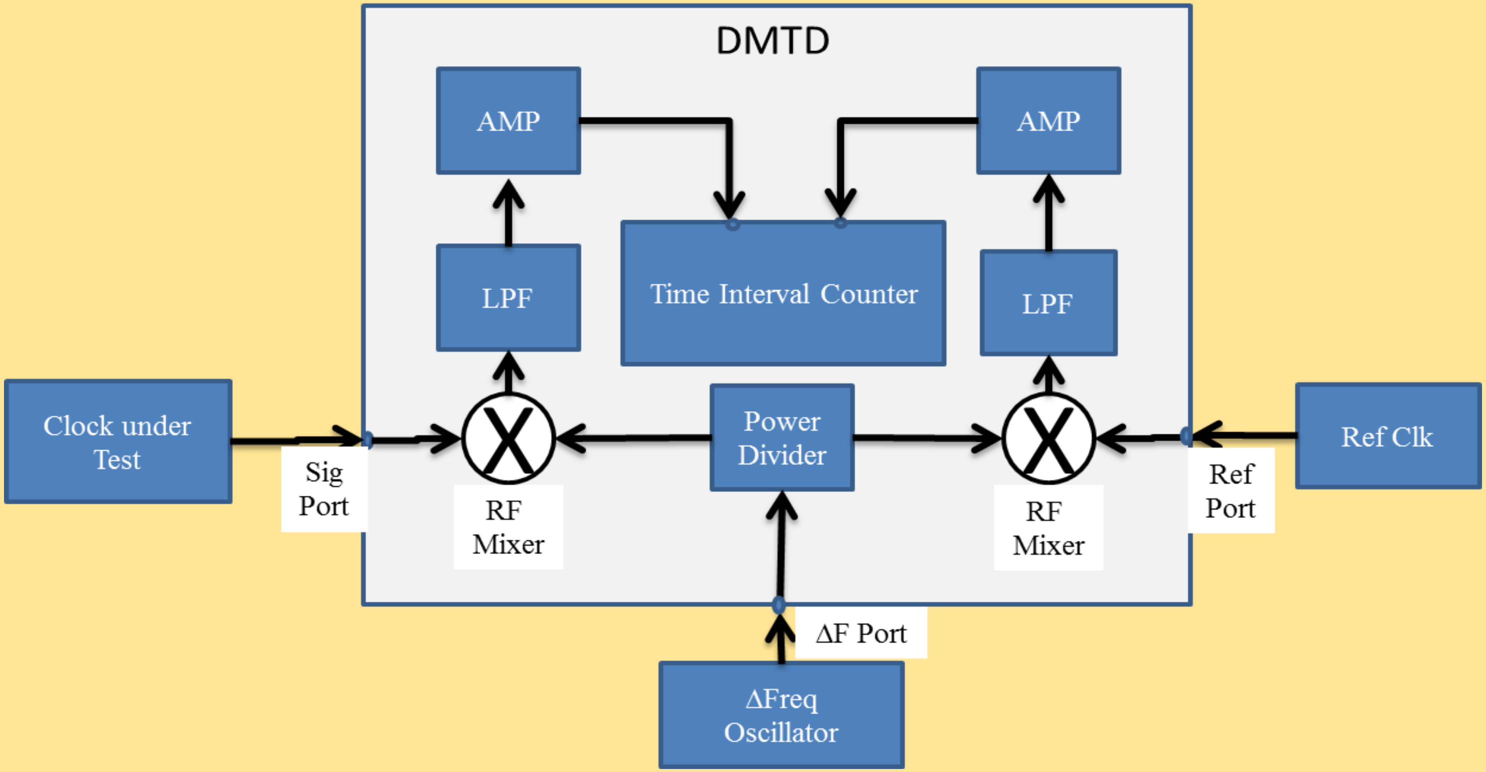
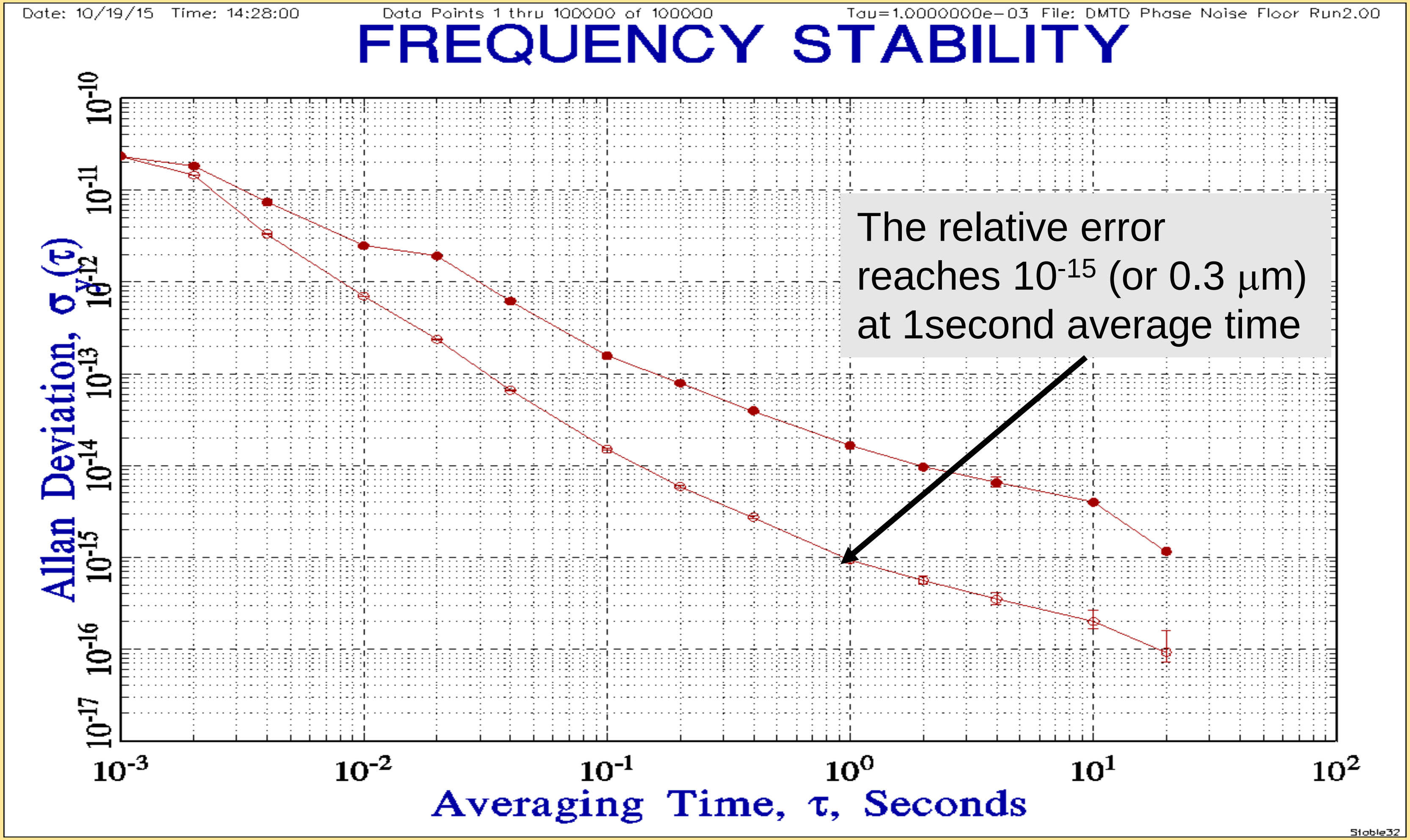


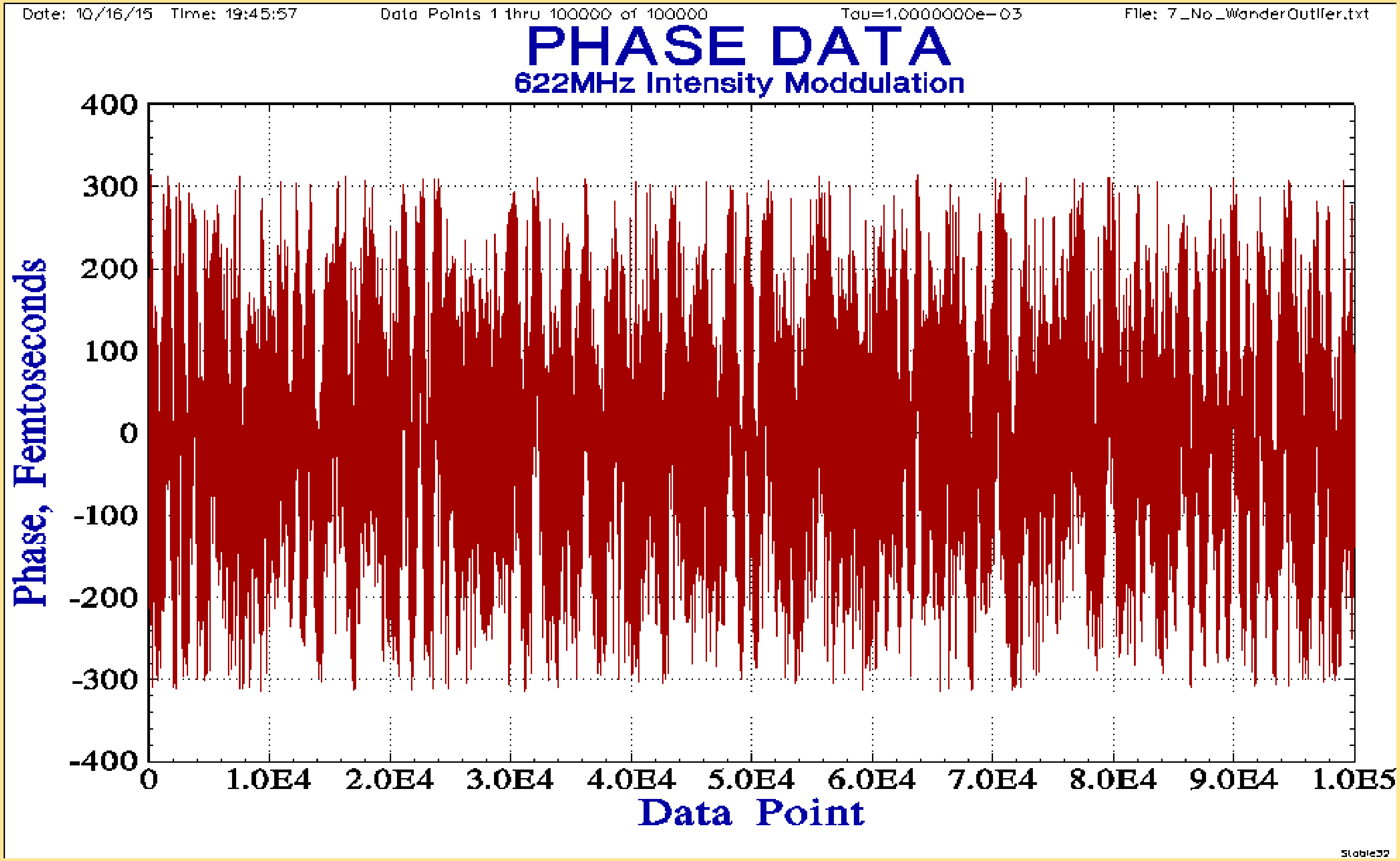
Dual Mixer Time Difference (DMTD) phase measurement setup. To Increase the measurement sensitivity by heterodyne mixer gain

Instrument Noise Floor
(Allan and Modified Allan deviation)



Continuous Phase Error, 622MHz AM modulation (sampling rate 1KHz)

622MHz AM modulated optical signal presents a zero-to-peak noise at 300 fs



Phase Measurement with 1KHz Sampling Rate

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622MHz Data (Pattern PRBS31-1) modulated optical signal presents a zero-to-peak noise at 2 ps