Simultaneous Two-Way Doppler and Ranging for Multiple Spacecraft at Mars: Flight Radio Tracking System Design and Performance Simulations

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Outline

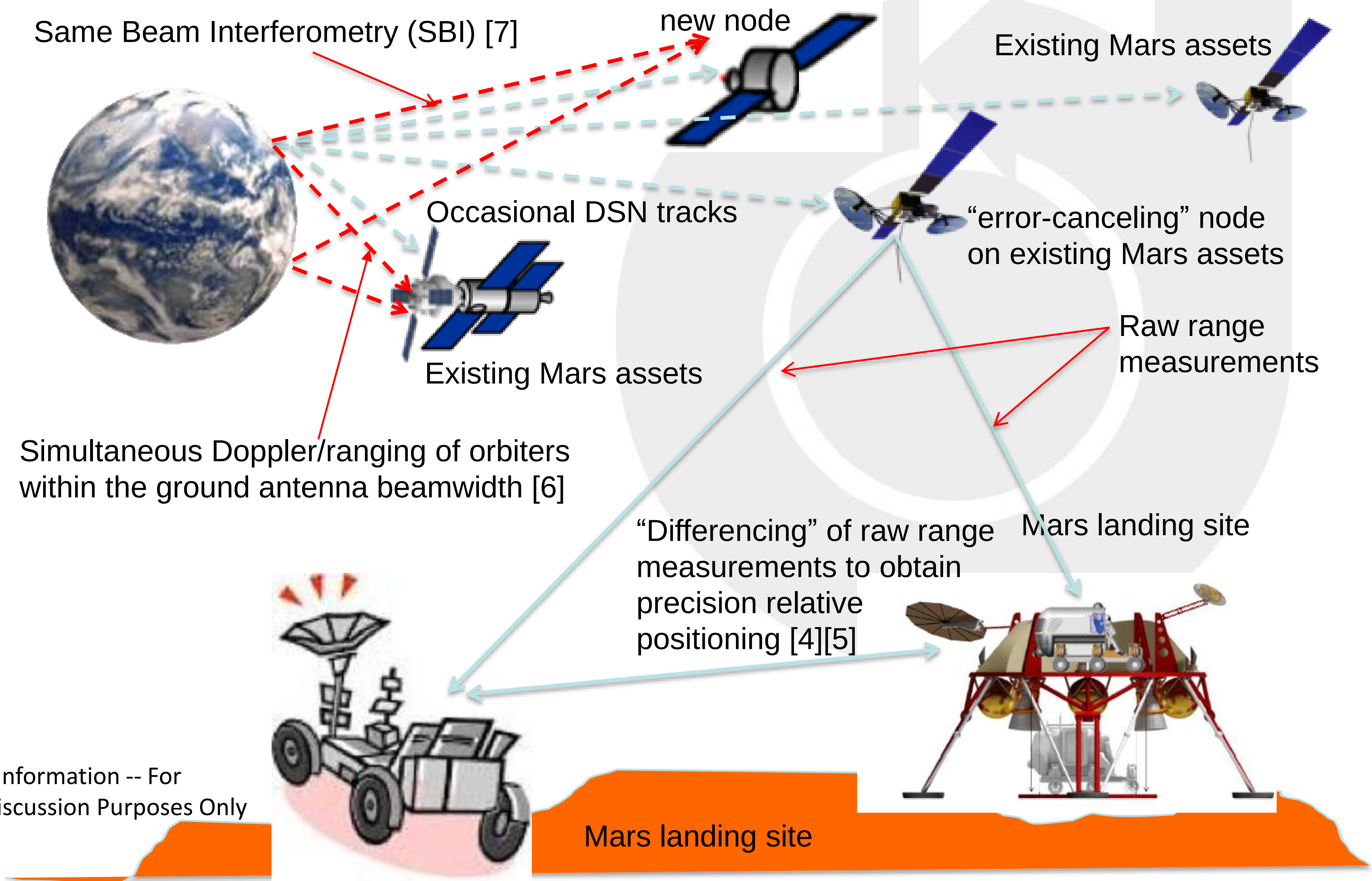
- Background and System Concept
  - Overview of the Proposed Mars Regional Navigation Satellite System (MRNSS)
  - Importance of Accurate Navigation Orbit Determination (OD)
  - Challenges of Deep Space Tracking/Navigation for Multiple Spacecraft
- Simultaneous 2-Way Doppler/Ranging
  - System Approach: A Collaborative Flight-Ground Architecture
  - Different Doppler and Doppler Rate of Mars Assets
  - Flight Radio Upgrade: Smart Sweeping Algorithm
  - Tracking Performance Simulation
- Conclusion

Part 1: Background and System Concept

Proposed Mars Regional Navigation Satellite System (1)

- We have been working on the system concept of a low-cost low-maintenance Mars Regional Navigation Satellite System (MRNSS) [1] with the following key principles
  - Capitalize on the build-up of orbiting and surface infrastructures on Mars during the human Mars exploration era [2][3][4]
  - Leverage on a new geometric trilateration method that simultaneously performs absolute positioning and relative positioning [5][6]
  - Introduce the concept of using relative positioning that provides regional navigation services in the vicinity of a human Mars landing site (~100 km), thereby relieving the stringent requirements on orbit determination (OD) of Mars navigation satellites

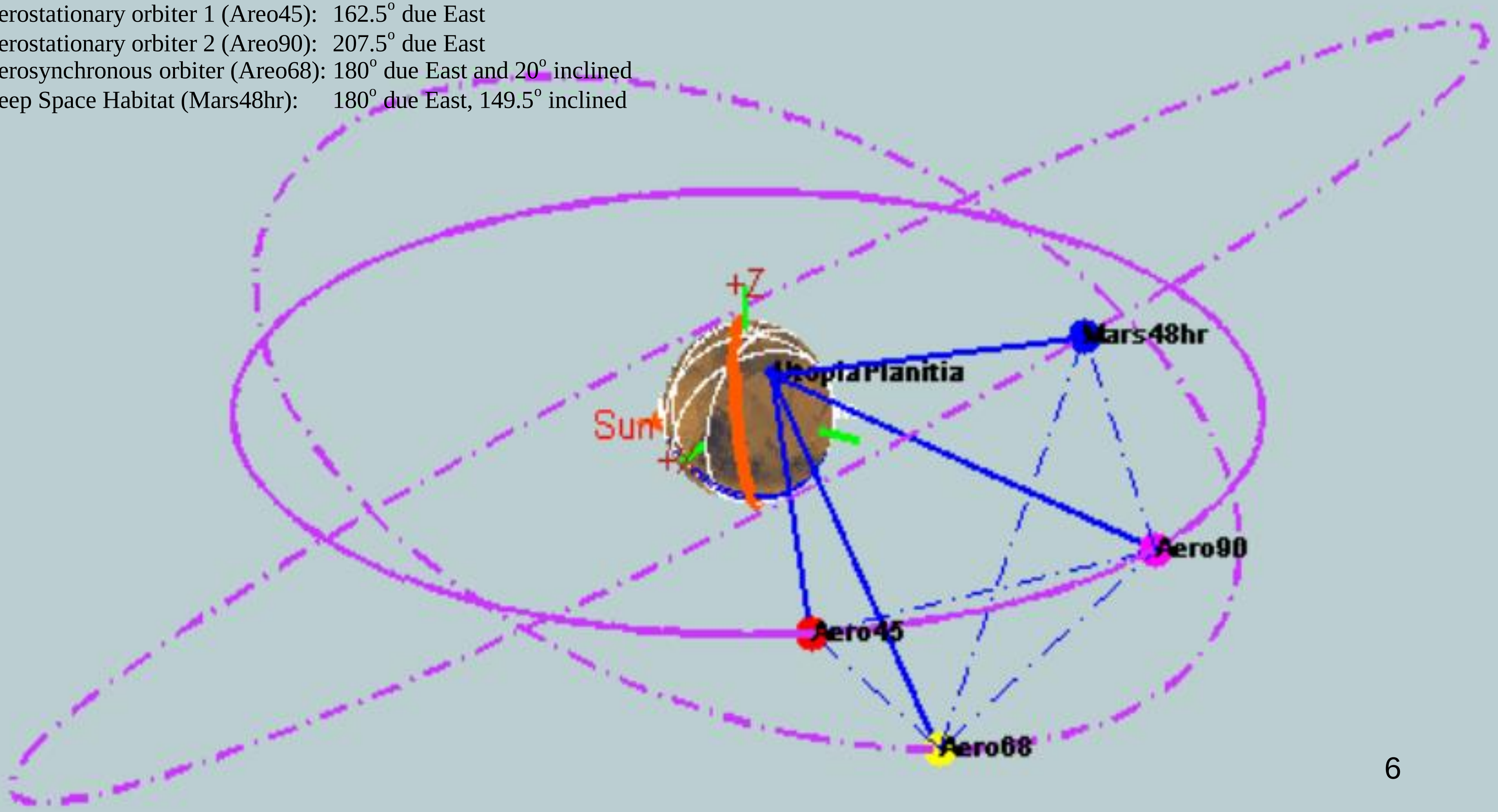
Proposed Mars Regional Navigation Satellite System (2)



Proposed Mars Regional Navigation Satellite System (3)

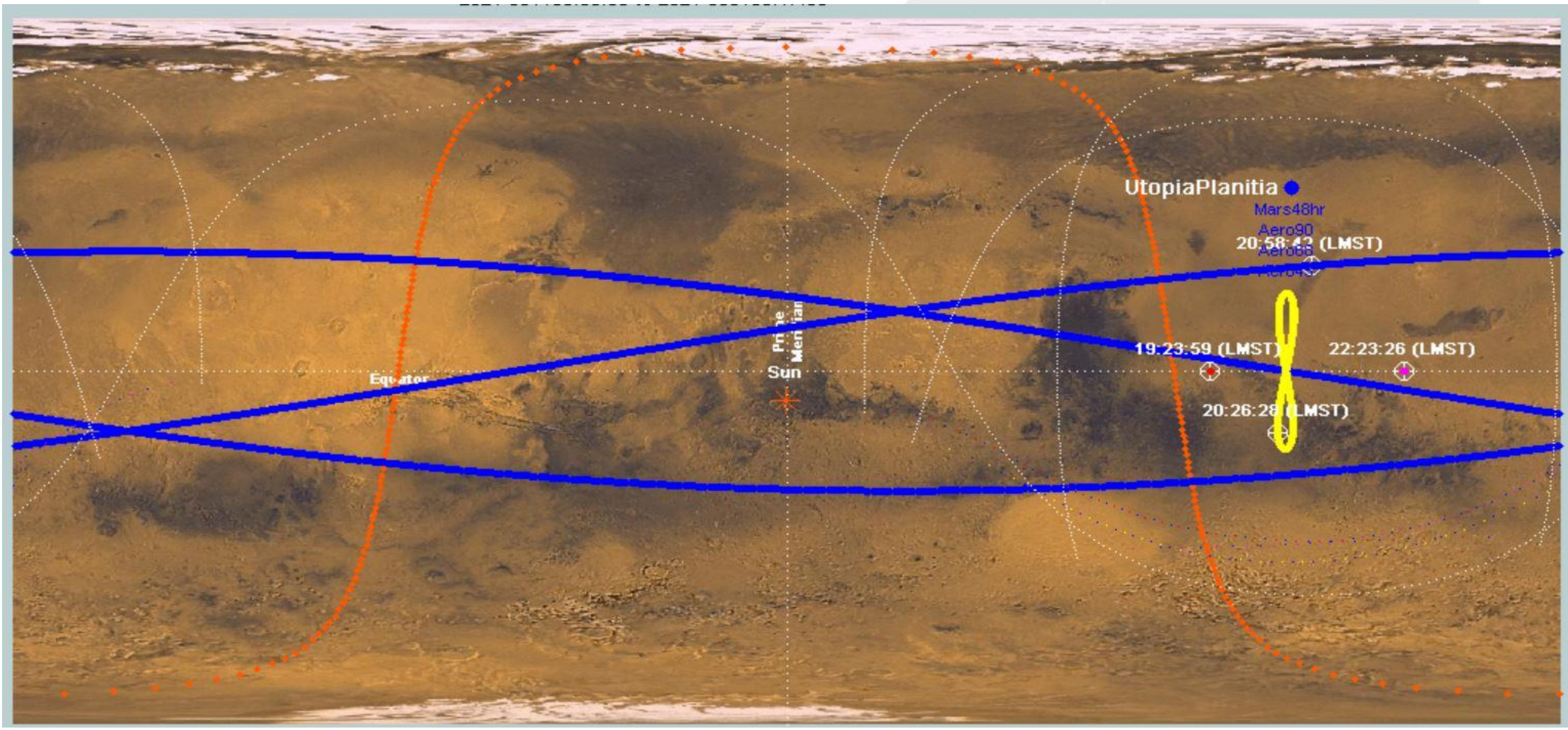
Orbits of the Notional Mars Navigation Nodes (3-D View)

Utopia Planitia:	182.5° due East, 46.7° due North
Aerostationary orbiter 1 (Areo45):	162.5° due East
Aerostationary orbiter 2 (Areo90):	207.5° due East
Aerosynchronous orbiter (Areo68):	180° due East and 20° inclined
Deep Space Habitat (Mars48hr):	180° due East, 149.5° inclined



Proposed Mars Regional Navigation Satellite System (4)

Orbits of the Notional Mars Navigation Nodes Projected on Mars Surface (3-D View)



Importance of Accurate Navigation Satellites Orbit Determination

Our Proposed Scheme		GPS Satellite Position Error							
		0m	0.5m	1m	2m	5m	10m	30m	35m
Pseudo-range error	0 cm	0.00	3273.85	6547.69	13095.39	32738.48	65476.99	196431.3	229169.9
	0.10 cm	11.27	3273.70	6547.54	13095.23	32738.32	65476.82	196431.1	229169.7
	0.25 cm	28.19	3273.56	6547.35	13095.01	32738.08	65476.58	196430.9	229169.5
	0.50 cm	56.37	3273.51	6547.12	13094.69	32737.71	65476.19	196430.5	229169.1
	1.00 cm	112.74	3274.15	6547.03	13094.24	32737.04	65475.45	196429.7	229168.3
	2.00 cm	225.48	3278.35	6548.30	13094.06	32735.98	65474.10	196428.1	229166.7
	5.00 cm	563.71	3313.95	6563.76	13099.34	32735.15	65471.23	196423.9	229162.4

Table 1. S_{3D} Absolute Localization Error standard deviation (cm) of the New Scheme. PDOP=113.17.

Our Proposed Scheme		GPS Satellite Position Error							
		0m	0.5m	1m	2m	5m	10m	30m	35m
Pseudo-range error	0 cm	14.43	21.57	35.07	65.44	160.06	319.04	956.04	1115.33
	0.10 cm	21.59	26.82	38.47	67.27	160.75	319.32	956.05	1115.32
	0.25 cm	42.77	45.58	53.22	76.58	164.76	321.27	956.58	1115.75
	0.50 cm	81.89	83.33	87.69	103.45	178.67	328.48	958.82	1117.63
	1.00 cm	161.95	162.62	164.84	173.62	226.38	356.41	968.34	1125.72
	2.00 cm	323.00	323.28	324.34	328.78	359.12	452.05	1006.71	1158.71
	5.00 cm	806.95	806.99	807.34	808.99	821.36	865.36	1246.30	1371.59

Table 2. S_{3D} Relative localization Error standard deviation (cm) of the New Scheme.
Distance between reference and target = 100 km. Sigma = 100 m. Delta = 100 m.

Our Proposed Scheme		GPS Satellite Position Error							
		0m	0.5m	1m	2m	5m	10m	30m	35m
Pseudo-range error	0 cm	0.14	1.59	3.18	6.35	15.87	31.73	95.20	111.07
	0.10 cm	16.03	16.10	16.32	17.20	22.47	35.45	96.42	112.10
	0.25 cm	40.08	40.10	40.18	40.53	42.99	50.93	103.02	117.79
	0.50 cm	80.15	80.16	80.19	80.36	81.59	85.99	123.99	136.48
	1.00 cm	160.31	160.30	160.32	160.39	160.97	163.19	185.83	194.34
	2.00 cm	320.62	320.61	320.61	320.63	320.89	321.95	333.77	338.52
	5.00 cm	801.54	801.53	801.52	801.52	801.58	801.93	806.47	808.38

Table 3. S_{3D} Relative localization Error standard deviation (cm) of the New Scheme.
Distance between reference and target = 10 km. Sigma = 100 m. Delta = 100 m.

200 – 400 folds improvement in RMSE accuracy

Sigma: media delay
Delta: clock bias

Challenges of Deep Space Tracking/Navigation for Multiple SC

- Traditional deep space tracking techniques include Doppler, ranging, and Delta Differential One-Way Ranging (ΔDOR)

- 2-Way Doppler/ranging requires tight coordination between ground and flight (Doppler compensation), and one ground station tracking one spacecraft (1-to-1)

- ΔDOR is 1-way, but requires two ground station tracking one spacecraft (2-to-1)

- Tracking requires tying up an antenna for a long time [7]. When number of missions increase, and for missions with multiple spacecraft, there might not be enough DSN antenna assets to meet missions' communications and tracking needs

- There is a desire to extend the current deep space tracking techniques to support multiple spacecraft in a beam to improve the antenna usage efficiency

Part 2: 2-Way Simultaneous Doppler/Ranging

A Collaborative Flight-Ground Architecture (1)

- Assume Doppler/ranging in X-band, which supports low rate commands/telemetry
- The Mars orbiters all lie within the same beamwidth of a DSN 34-m BWG antenna
- For *N* orbiters, the downlinks operate in *N* allocated frequency bands separated by *N-1* guard bands to prevent interference
- Collaborative flight-ground architecture:
  - The *N* orbiters time-share a single uplink; commands differentiated by SCID
  - The ground "Doppler-compensates" the uplink signal in either way:
    - With respective to the Mars center
    - With respective to the average (centroid) of Doppler's of *N* orbiters

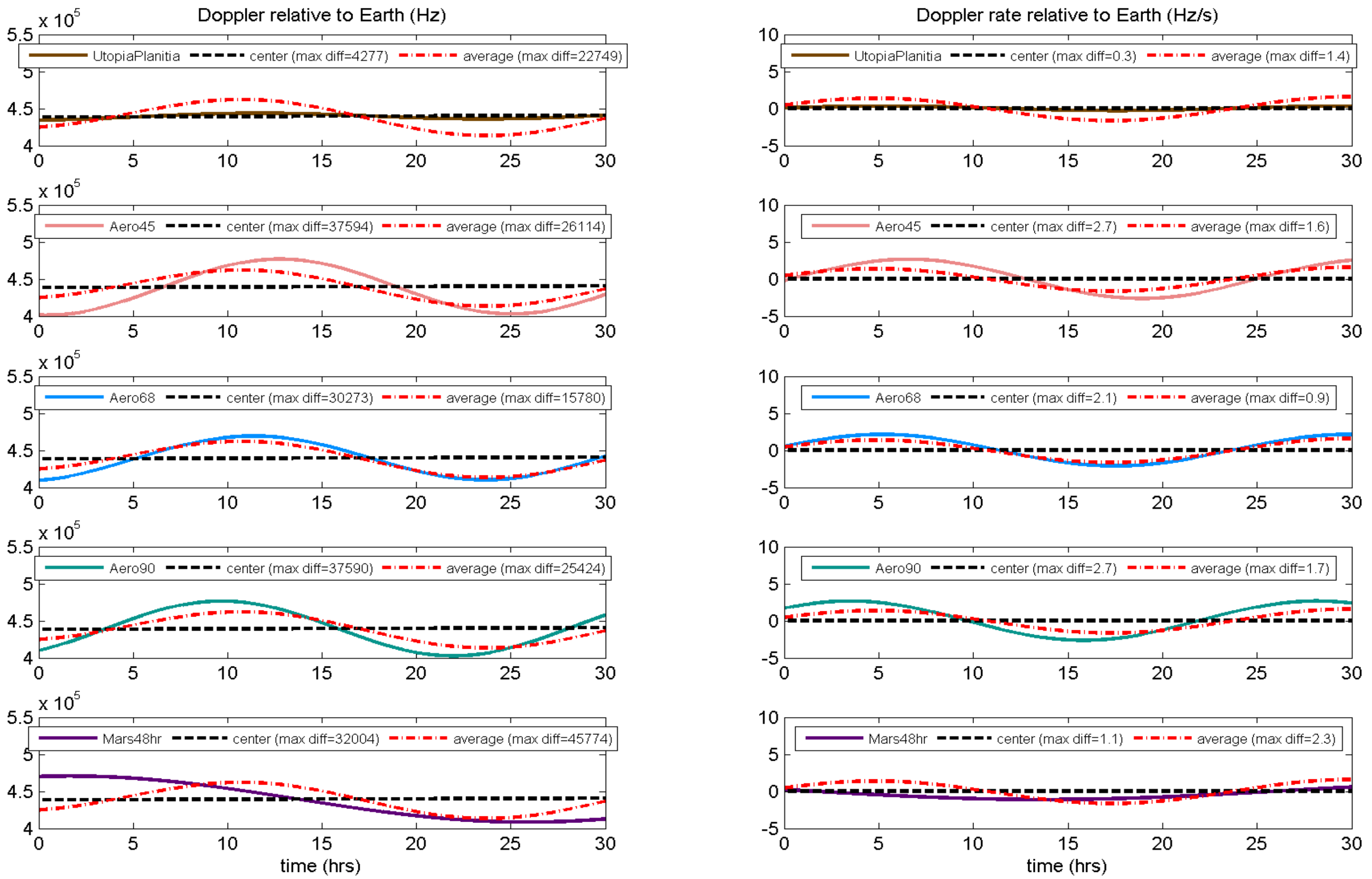
    Guard bands must be wide enough to accommodate the residual Doppler. Preliminary simulations: residual Doppler and Doppler rate are bounded by 45 KHz & 2.6 Hz/s

A Collaborative Flight-Ground Architecture (2)

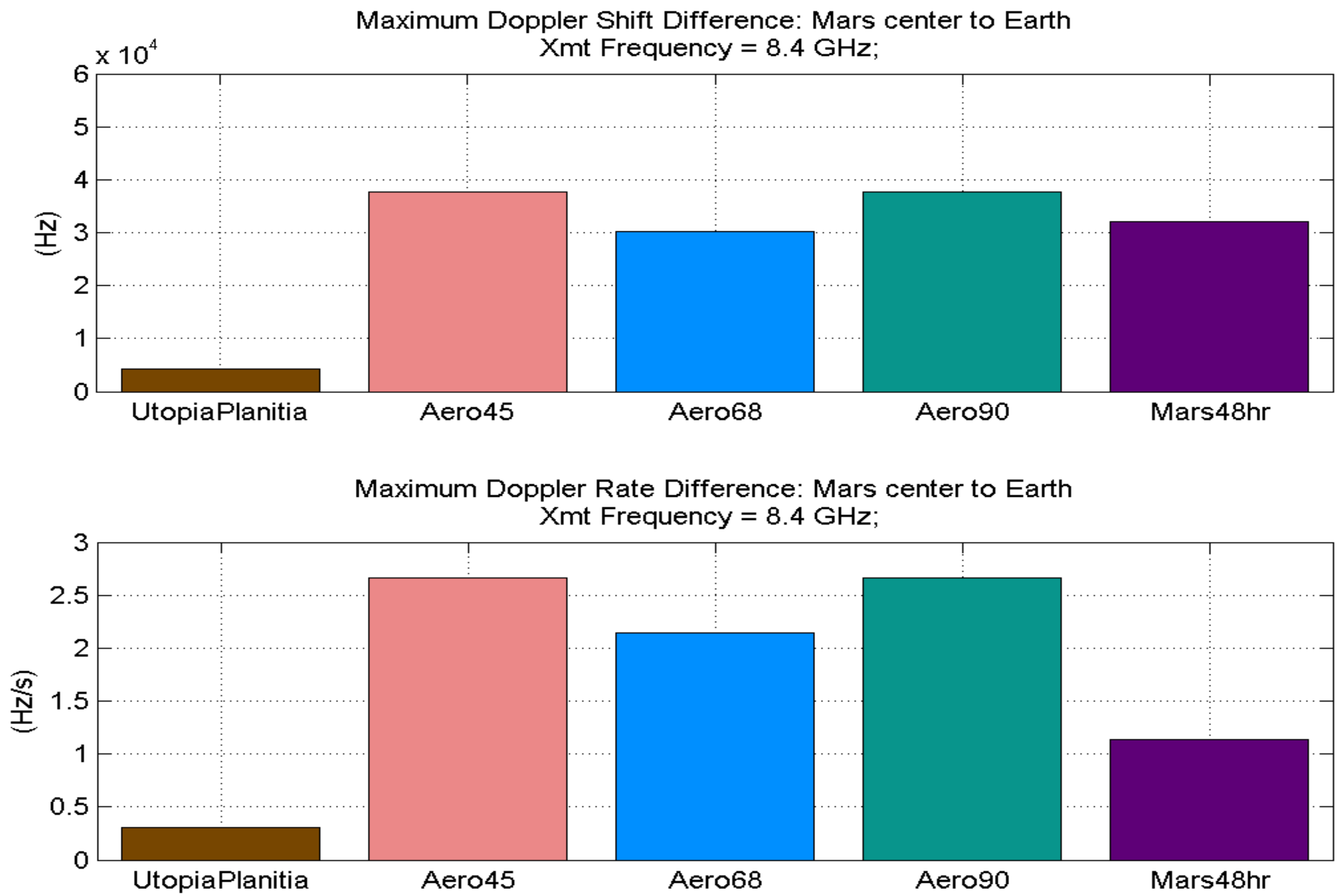
- Flight radio upgrades:
  - A different turn-around-ratio for each spacecraft so the same uplink would be coherently “turned-around” to modulate the telemetry and ranging signals on a different allocated downlink frequency
  - A well-designed tracking loop that can sweep, acquire, and track the unknown uplink carrier phase and high residual Doppler frequency

- Ground upgrades (not discussed in this paper):
  - One ground antenna receives all *N* downlink signals with different carrier frequencies via Multiple Spacecraft Per Aperture (MSPA)
  - Each signal stream is extracted via band-pass filtering and down-converted to IF for telemetry, Doppler, and range processing

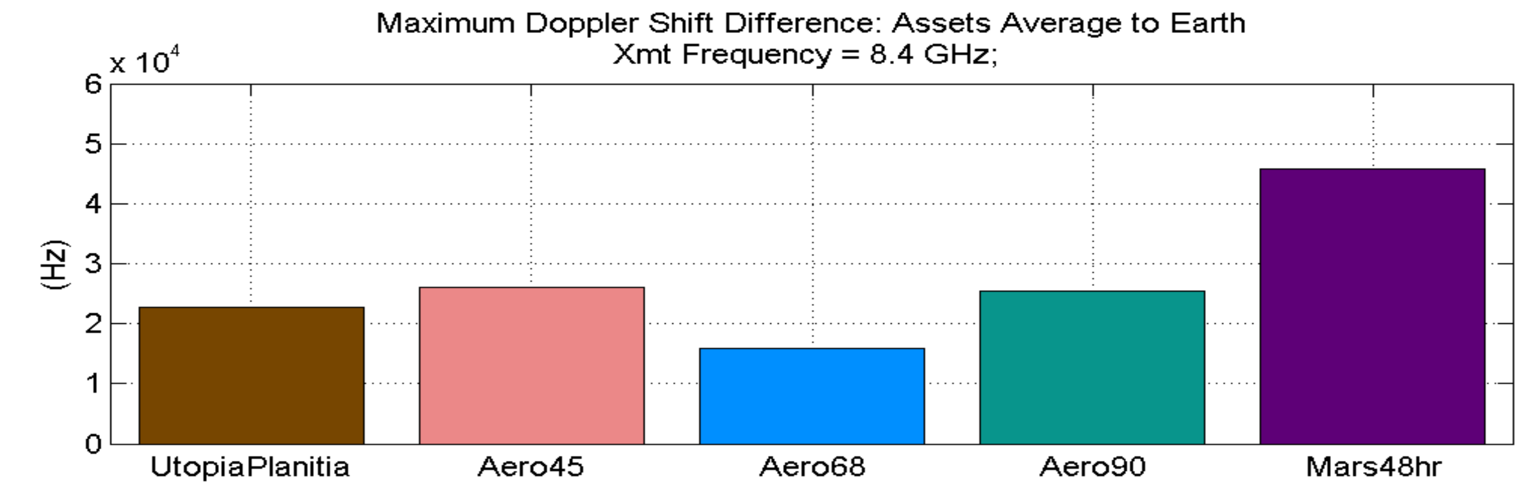
Doppler and Doppler Rate Profiles

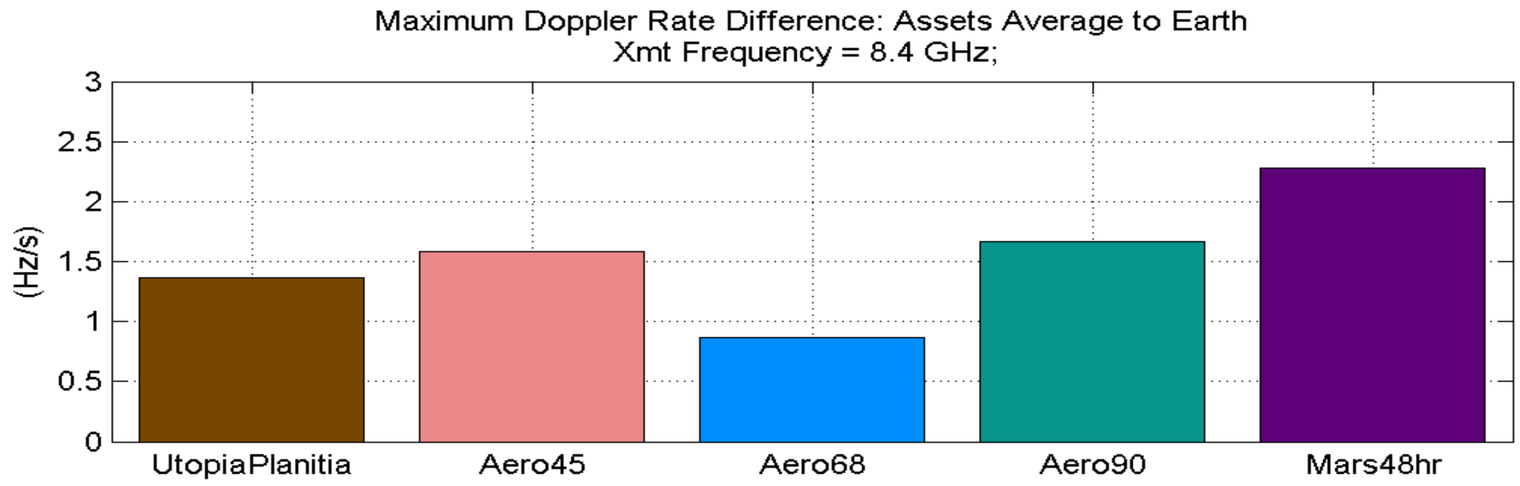


Doppler and Doppler Rate Residuals for Mars Center Strategy

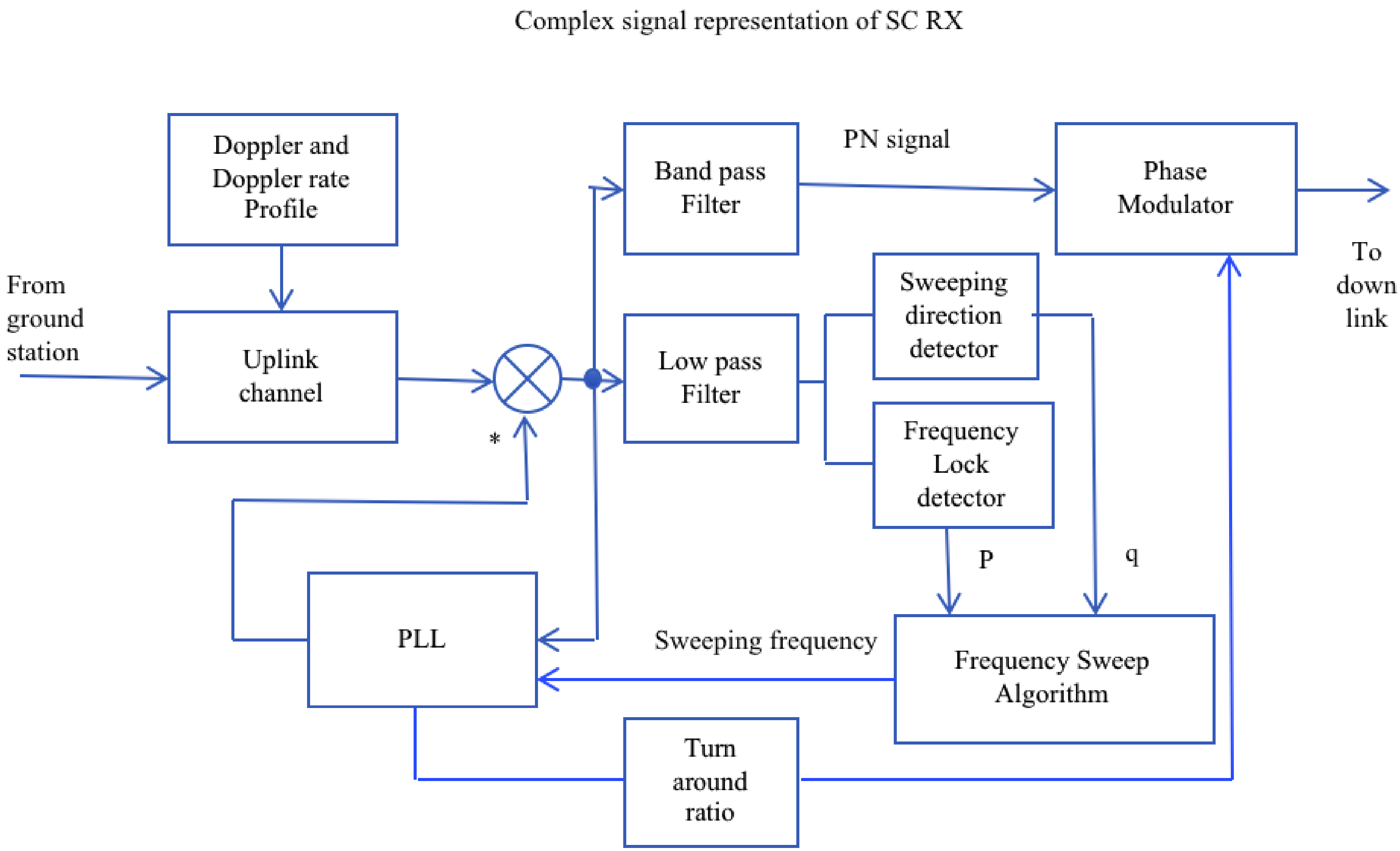


Doppler and Doppler Rate Residuals for Frequency Centroid Strategy

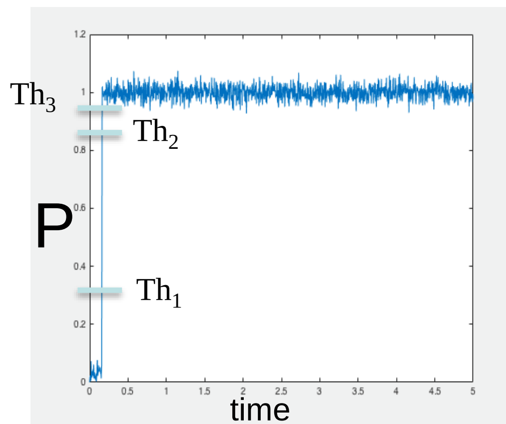


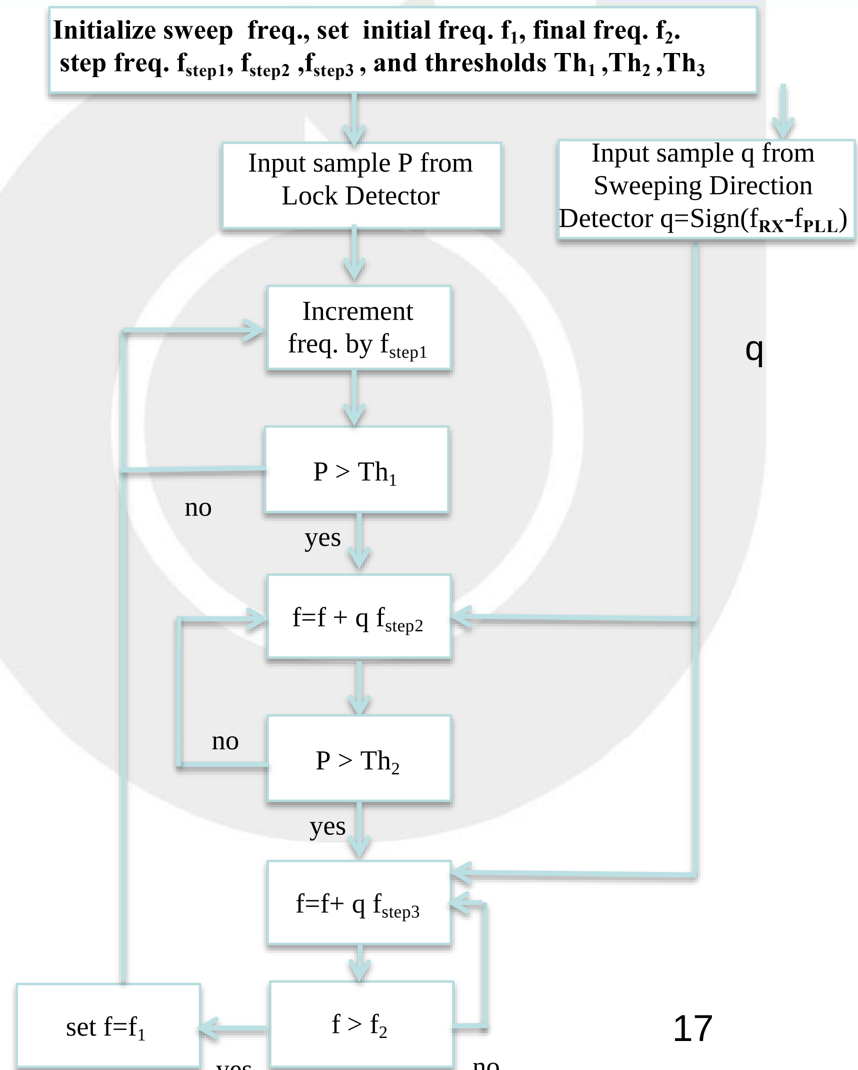


Spacecraft Radio Schematics



Flight Radio Smart Frequency Frequency Algorithm



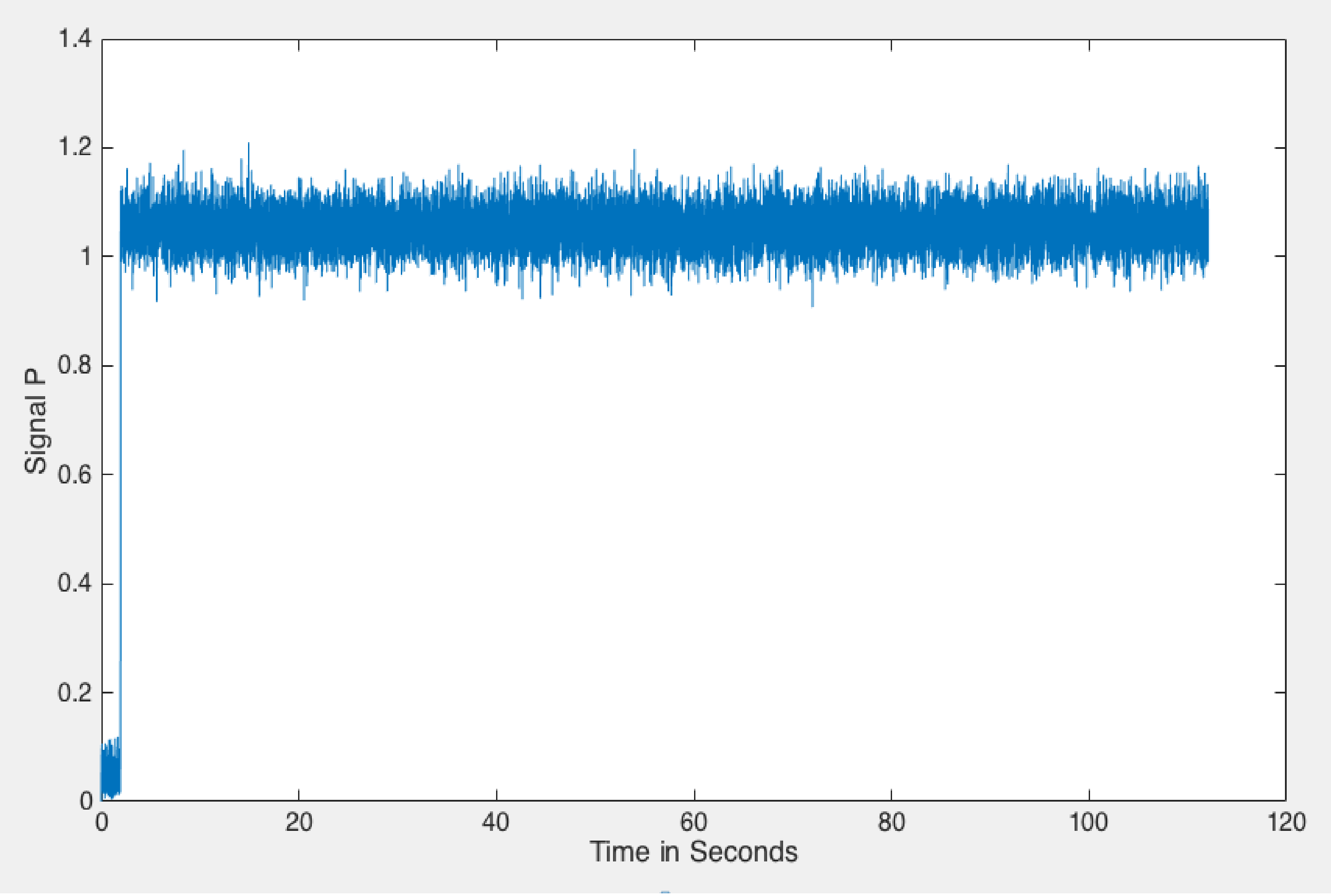


Dynamic sweeping circuit

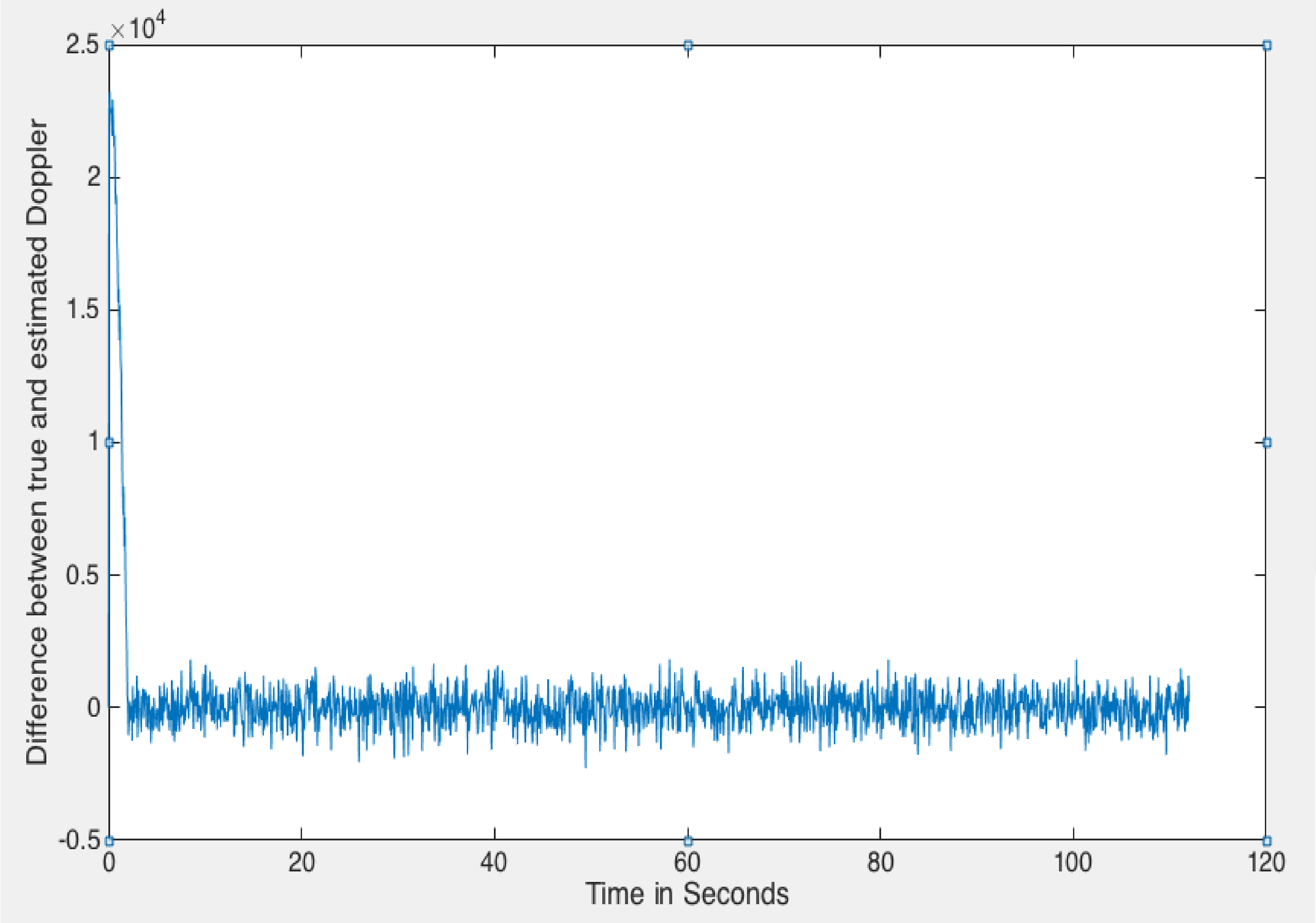
Uniqueness:

- It uses multiple thresholds and changes the frequency step size when the signal P is greater than a threshold
- It detects whether the received Doppler frequency is greater than the estimated Doppler frequency by PLL (q=+1) or is lower (q=-1) to determine the sweeping direction – either increase or decrease the sweeping frequency

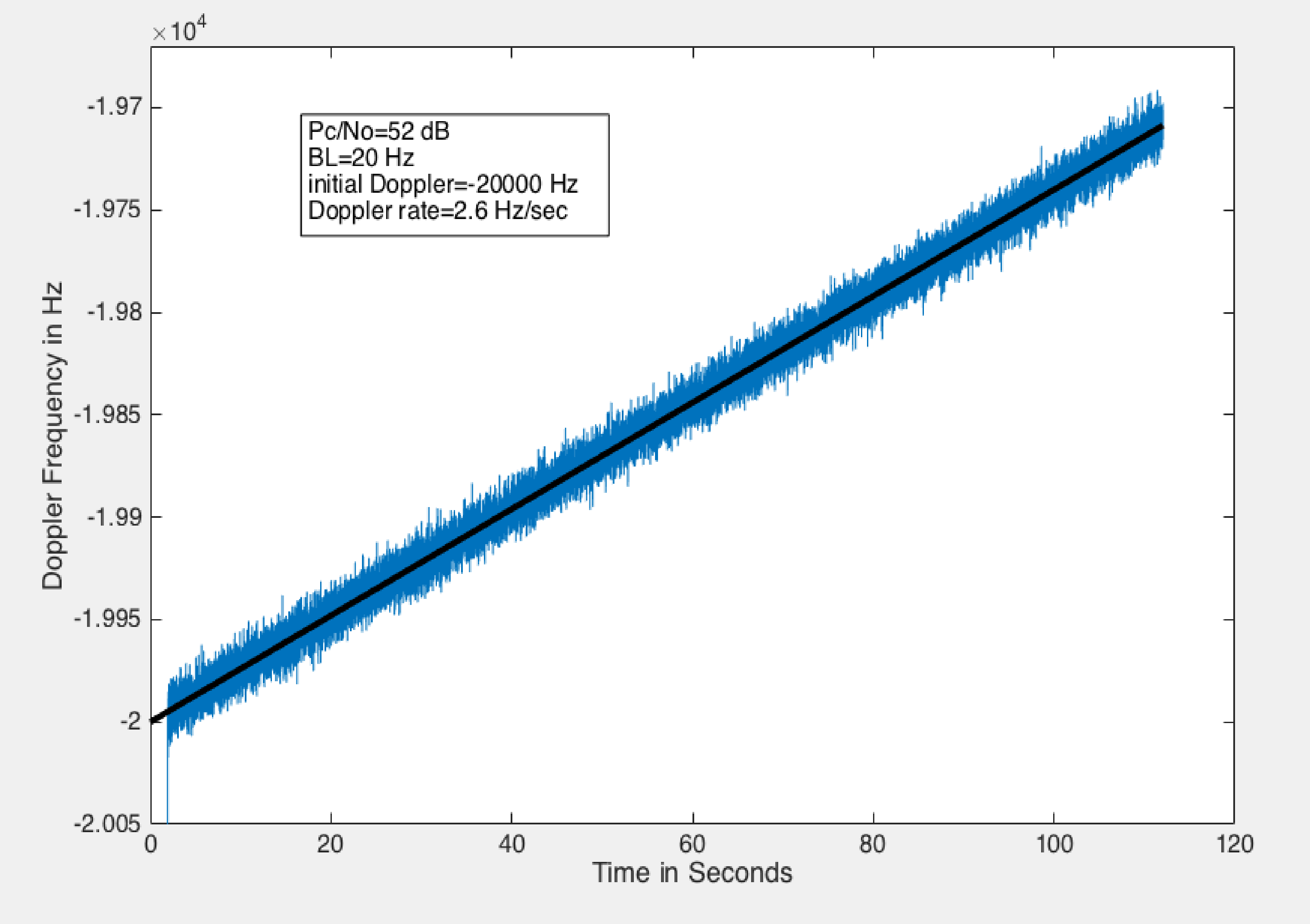
Lock Detection Signal P During Frequency Acquisition/Tracking



Difference between Doppler and Estimated Doppler



Time Profiles of Doppler and Estimated Doppler



Conclusion

- We describe a collaborative flight-ground architecture that performs two-way Doppler and ranging for navigation tracking for multiple orbiting spacecraft at Mars
- This scheme does not require any changes to the current DSN ground signal processing, and only needs multiple copies of the Receiver Ranging Processors (RRPs) at the ground station
- We introduce a smart frequency sweeping algorithm that acquires and tracks the more dynamic uplink signals experienced by each spacecraft
- We illustrate the application of this scheme to support simultaneous OD for the Mars orbiters of a notional Mars Regional Navigation Satellite System (MRNSS)
- This scheme is extensible to the Lunar scenarios

References

- [1] K.Cheung, C. Lee, “In-Situ Navigation and Timing Services for a Human Mars Landing Site Part 1: System Concept,” September 2017, 68th International Astronautical Congress, Adelaide, Australia.
- [2] H. Price, J. Baker, F. Naderi, A Scenario for a Human Mission to Mars Orbit in the 2030s: Thoughts Toward an Executable Program – Fitting Together Puzzle Pieces & Building Blocks, Jet Propulsion Laboratory, California Institute of Technology. Presented at the Future In-Space Operations (FISO) Telecon, May, 2015.
- [3] Mars Architecture Steering Group, Human Exploration of Mars Design Reference Architecture 5.0, Technical Report, NASA, 2009.
- [4] D. Bell, R. Cesarone, T. Ely, C. Edwards, S. Townes, MarsNet: A Mars Orbiting Communications & Navigation Satellite Constellation, IEEE Aerospace Conference 2000, March 2000, Big Sky, Montana.
- [5] K.Cheung, C. Lee, A Trilateration Scheme for Relative Positioning, IEEE Aerospace Conference 2017, Big Sky, Montana, March 2017.
- [6] K. Cheung, C. Lee, A Trilateration Scheme for GPS-Style Localization, Interplanetary Network Progress Report, 42-209, May 15, 2017.
- [7] P. Romero, B. Pablos, G. Barderas, “Analysis of Orbit Determination from Earth-Based Tracking for Relay Satellites in a Perturbed Areostationary Orbit,” Acta Astronautica 136 (2017) 434-442, April 4, 2017.

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