In-Situ Navigation & Timing Services for a Human Mars Landing Site Part 1: System Concept

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Introduction – Summary of Results

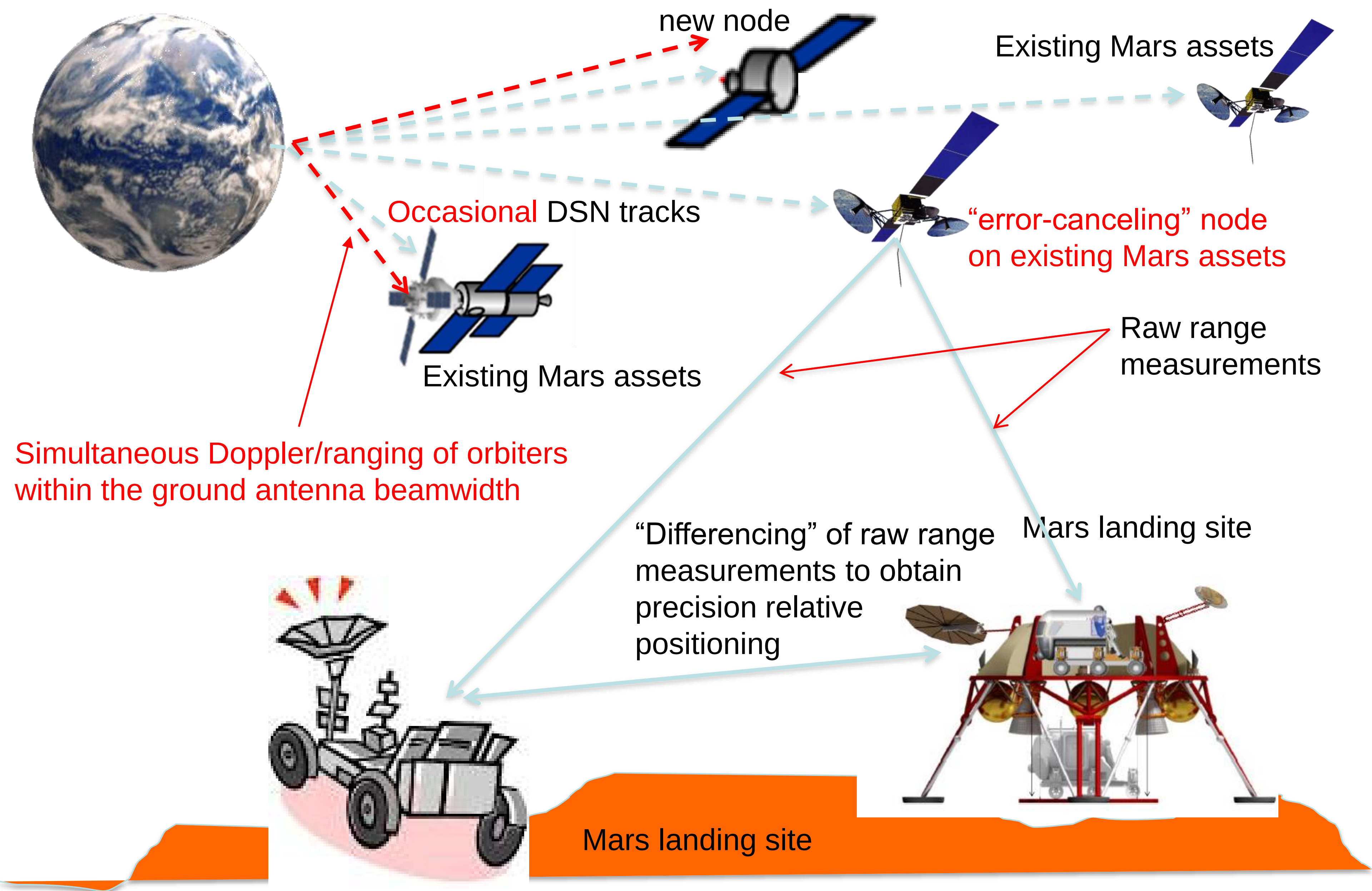
- The United States' Global Positioning System (GPS) has an estimated development and deployment cost of $33 billion and the annual operation cost of $1 billion, and this is on Earth

- This paper describes a system concept that enables a low-cost low-maintenance Mars Regional Navigation Satellite System (MRNSS):
  - Capitalize on the build-up of orbiting and surface infrastructures on Mars during the human Mars exploration era [1][2][3]
  - Leverage on a new geometric trilateration method that simultaneously performs absolute positioning and relative positioning [4][5]
  - 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
  - Extend current DSN's tracking approaches of pairing one or two dedicated ground stations to one spacecraft for a period of time to simultaneously tracking of multiple Mars orbiters
    - Simultaneous Doppler/ranging [6]
    - Same Beam Interferometry (not discussed in this paper)

Introduction – Needs for Mars In-Situ Navigation

- Examples of human Mars exploration activities that require positioning support
  - Localizing discoveries and returning to sites
  - Construction and assembling of structures and habitats
  - Entry/descend/landing
  - Approach/rendezvous/docking
  - Mars ascent/orbit insertion
- Traditional deep space tracking methods are Earth-based, and are limited by the speed of light
  - At Mars distance, the one-way-light-time (OWLT) is between 4 and 24 minutes
  - During the final and critical phase of Mars approach when the spacecraft is about to enter the Martian atmosphere, the ground network would not be able to provide timely navigation updates to the spacecraft
- Earth-based tracking cannot cover Mars landing site when it is not in-view of Earth
- Traditional Doppler/ranging is "one-on-one", and Delta DOR is "two-on-one"
  - Number of orbiting and surface elements is in the order of 10's
  - Traditional methods that require pairing one or two ground stations with one spacecraft for a period of time to generate tracking measurements becomes impractical

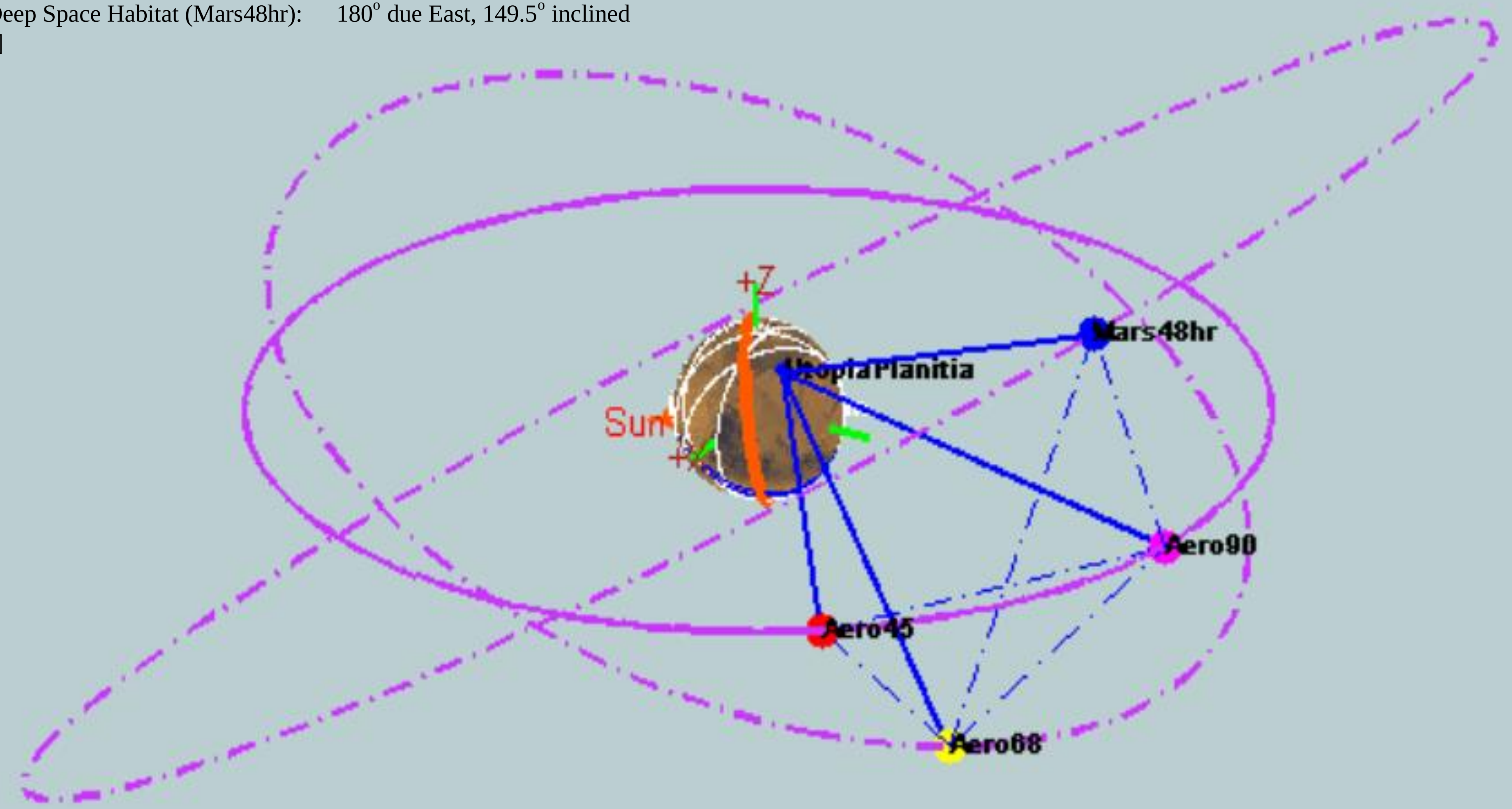
System Concept – Problem Formulation (1 of 3)



System Concept – Problem Formulation (2 of 3)

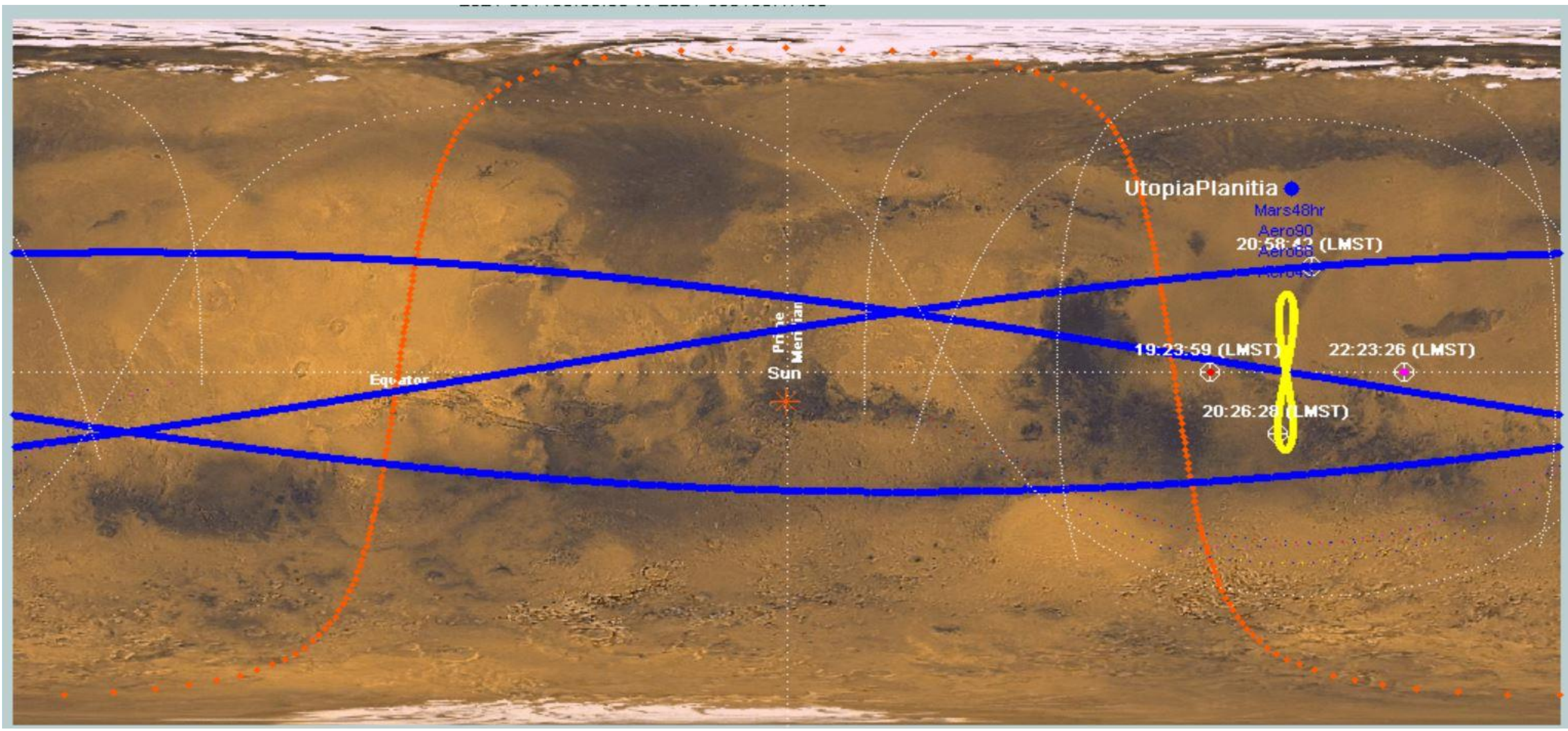
Orbits of the Notional Mars Navigation Nodes (3-D View)

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



System Concept – Problem Formulation (3 of 3)

Orbits of the Notional Mars Navigation Nodes Projected on Mars Surface (2-D View)



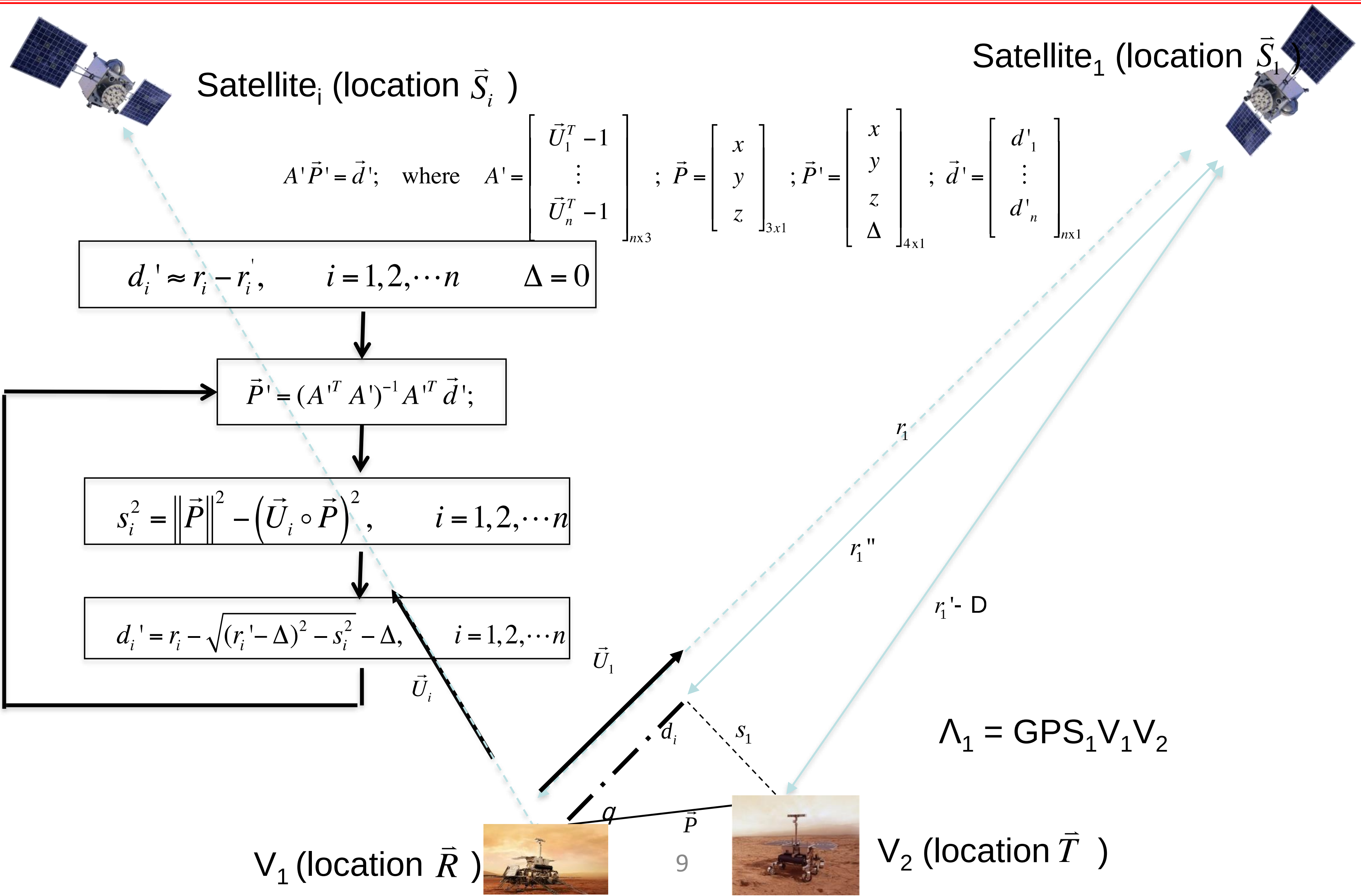
System Concept – Challenges & Possible Solutions

Black: problem statement
Blue: proposed solution

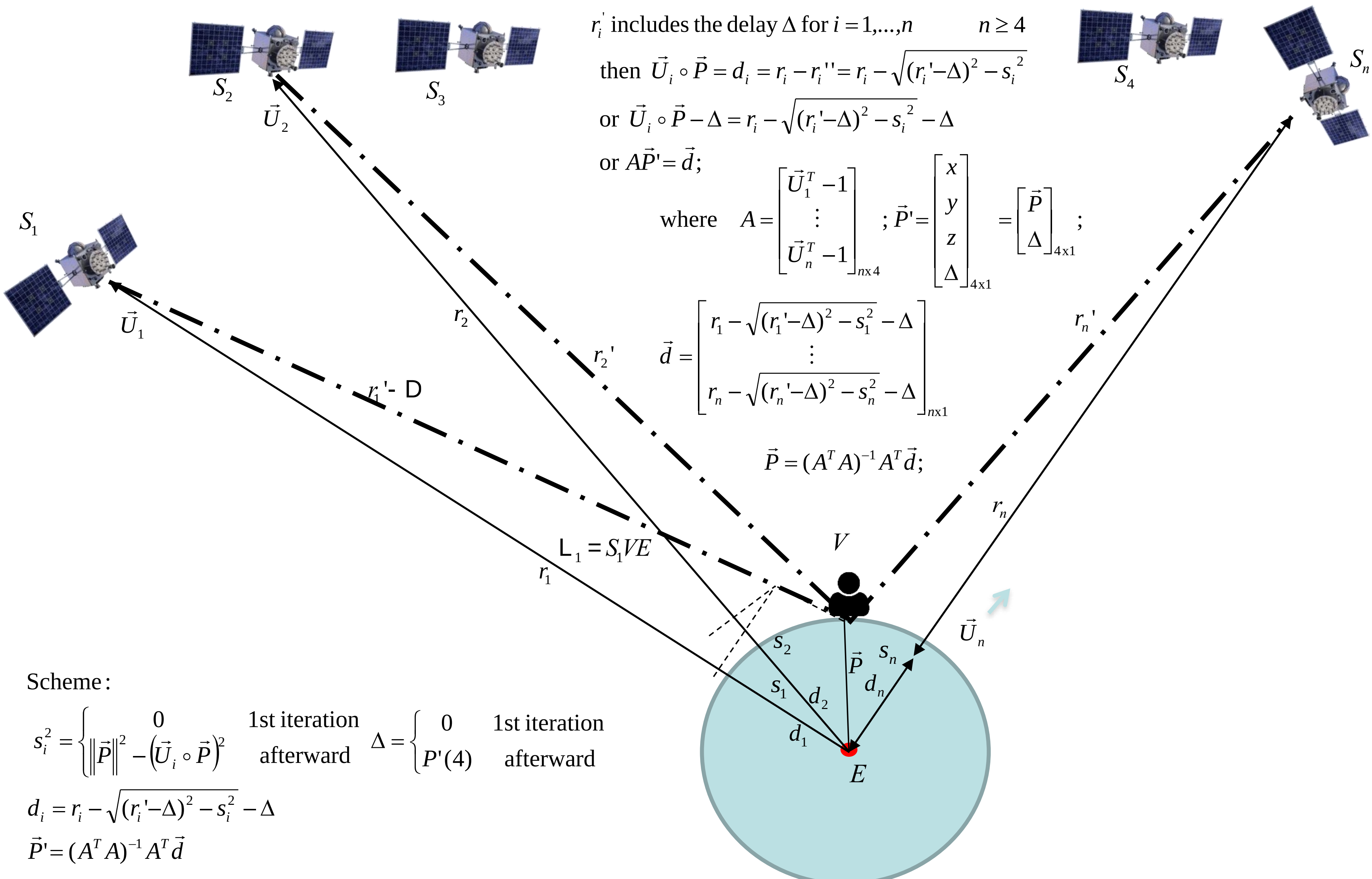
- An in-situ Mars navigation satellite system requires 4+ orbiters
  - Leverage on the build-up of orbiting and surface infrastructures on Mars in the human exploration era

- Need near-continuous tracking of multiple Mars navigation orbiters from Earth's ground antenna for orbit determination (OD) [7]
  - Traditional 1-on-1 & 2-on-1 tracking methods are impractical; DSN is a shared resource
  - Current OD accuracy of 5m (after multiple days of tracking) is too high for most standard GPS positioning applications
  - Use relative positioning for Mars landing site to reduce the orbit determination (OD) requirements (thus ground antenna tracking time) of Mars navigation satellites
    - "Differencing" of range measurements to eliminate common ephemeris error
  - Develop simultaneous (same beam) Doppler and ranging techniques and system concept that allow one ground antenna to cover multiple Mars navigation orbiters
  - "Re-invent" Same Beam Interferometry (SBI) whose data type compliments Doppler and ranging measurements, thus further reduce the ground antennas' tracking time burden (Part 2 results, not discussed in this paper)

Technical Details – New GT Scheme (Relative Positioning)



Technical Details – New GT Scheme (Absolute Positioning)



r_i' includes the delay Δ for $i = 1,\dots,n$ $\quad n \ge 4$

then $\vec{U}_i \circ \vec{P} = d_i = r_i - r_i'' = r_i - \sqrt{(r_i' - \Delta)^2 - s_i^{\,2}}$

or $\vec{U}_i \circ \vec{P} - \Delta = r_i - \sqrt{(r_i' - \Delta)^2 - s_i^{\,2}} - \Delta$

or $A\vec{P}' = \vec{d}$;

$$\text{where} \quad A = \begin{bmatrix} \vec{U}_1^T & -1 \\ \vdots & \\ \vec{U}_n^T & -1 \end{bmatrix}_{nx4} ; \vec{P}' = \begin{bmatrix} x \\ y \\ z \\ \Delta \end{bmatrix}_{4x1} = \begin{bmatrix} \vec{P} \\ \Delta \end{bmatrix}_{4x1};$$

$$\vec{d} = \begin{bmatrix} r_1 - \sqrt{(r_1' - \Delta)^2 - s_1^2} - \Delta \\ \vdots \\ r_n - \sqrt{(r_n' - \Delta)^2 - s_n^2} - \Delta \end{bmatrix}_{nx1}$$

$$\vec{P} = (A^T A)^{-1} A^T \vec{d};$$

Scheme:

$$s_i^2 = \begin{cases} 0 & \text{1st iteration} \\ \left\|\vec{P}\right\|^2 - \left(\vec{U}_i \circ \vec{P}\right)^2 & \text{afterward} \end{cases} \qquad \Delta = \begin{cases} 0 & \text{1st iteration} \\ P'(4) & \text{afterward} \end{cases}$$

$$d_i = r_i - \sqrt{(r_i' - \Delta)^2 - s_i^2} - \Delta$$

$$\vec{P}' = (A^T A)^{-1} A^T \vec{d}$$

Technical Details – Simultaneous Doppler/Ranging

- 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
- Flight and ground upgrades:
  - 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
  - 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 residual Doppler frequency

Preliminary Performance Results (Prelude for Part 2)

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

Conclusion and Future Work

- We propose a low-cost, low-maintenance Mars regional navigation satellite system (MRNSS) architecture that provides in-situ navigation and timing services in the vicinity of the Mars landing site
- We introduce a number of flight and ground improvements that would enable the MRNSS system concept, both technically and fiscally
- In an upcoming paper [9], we will discuss
  - In-depth simulations to evaluate the performance of the absolute and relative positioning schemes under different combinations of error conditions - 3-D ephemeris errors of the navigation satellites, random pseudo-range measurement errors, and clock biases
  - Detailed analysis to derive mathematical insights as to how the trilateration algorithm would “cancel out” in real-time most of the common errors
  - Incorporation of Same Beam Interferometry (SBI) to reduce ground antenna tracking time and to improve OD performance

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