Navigation Using Deep-Space Optical Communication Systems

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SPACE 2016, September 13 – 16, 2016
Long Beach, CA

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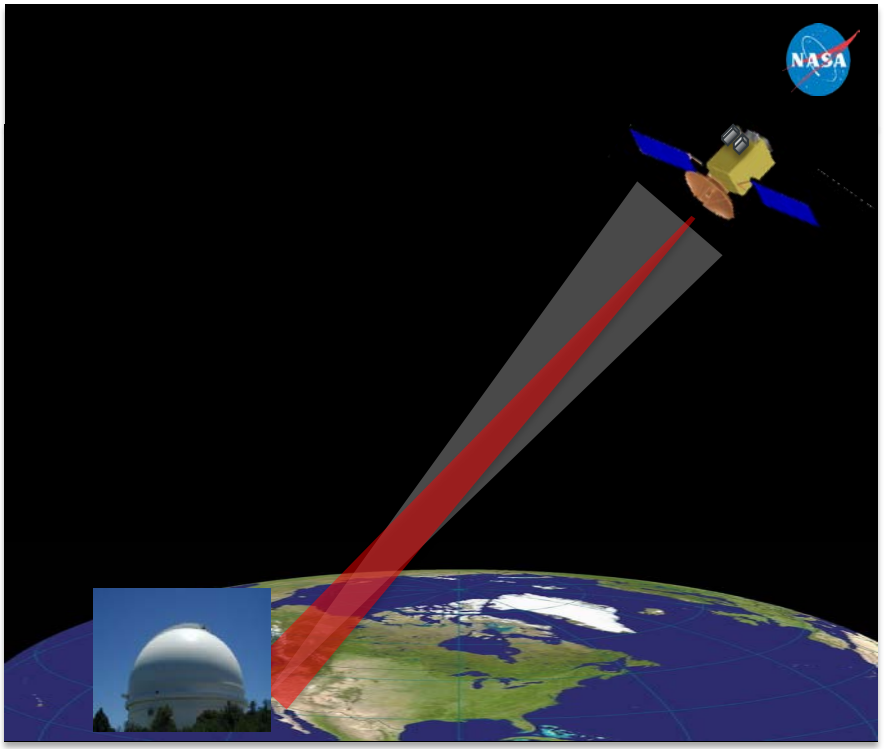
California Institute of Technology

Overview

- Introduction & Background
- Measurement models
- Analysis Results
- Conclusions



Simplified optical communication schematic

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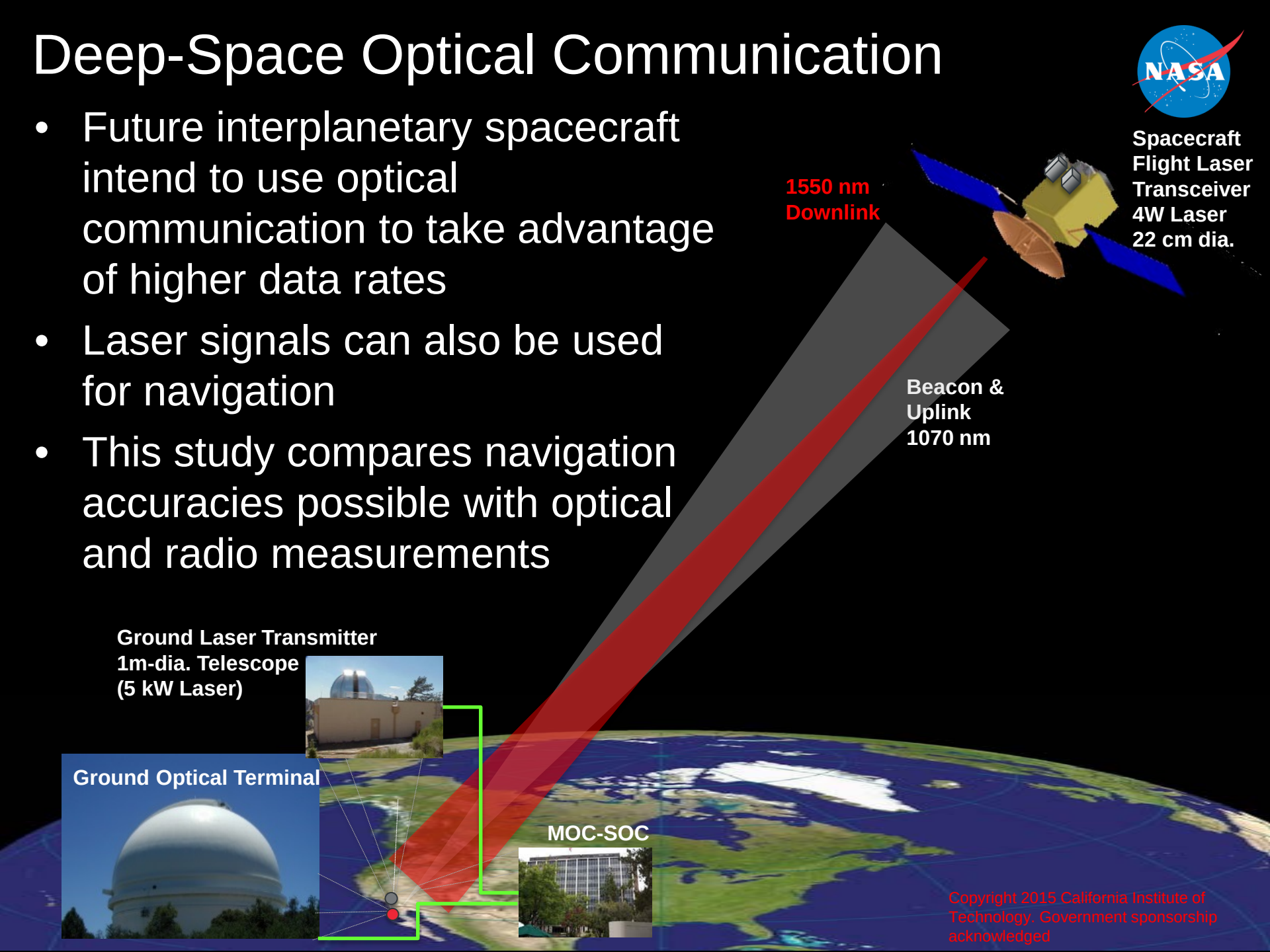
Deep-Space Optical Communication

- Future interplanetary spacecraft intend to use optical communication to take advantage of higher data rates
- Laser signals can also be used for navigation
- This study compares navigation accuracies possible with optical and radio measurements



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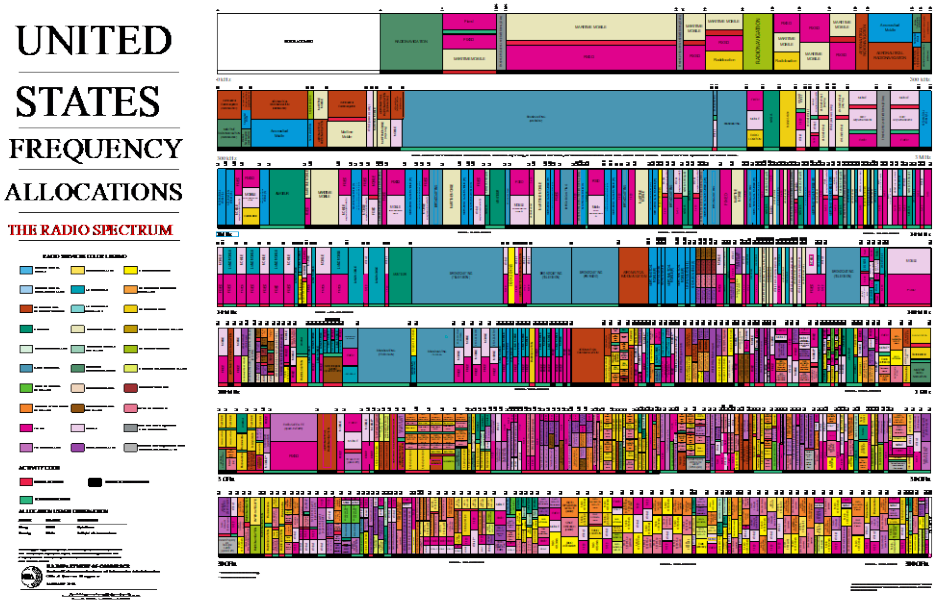
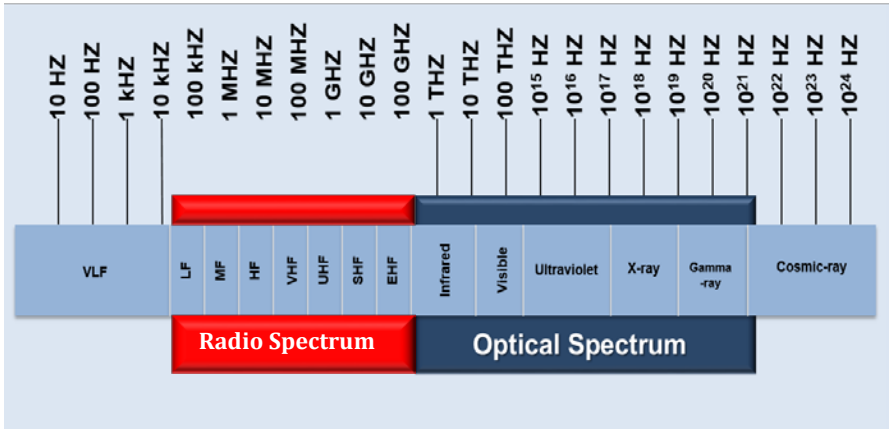
The Case for Optical Communication Systems

- Higher bandwidth—up to 20x increase in data rate
- No allocation limitations
- Smaller on-board infrastructure



Radio spectrum allocations as of January 2016. Image courtesy of National Telecommunications & Information Administration, U.S. Department of Commerce



Electromagnetic spectrum

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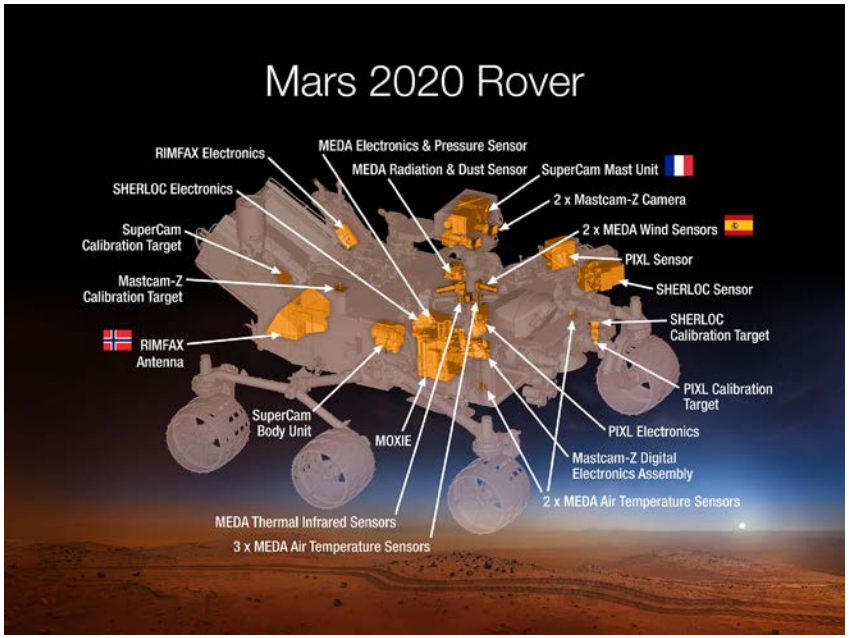
Analysis Background

- Radio and optical data types simulated
- Different mission scenarios considered
  - Mars lander case based on Mars 2020
  - Mars orbiter case based on Mars Atmosphere and Volatile EvolutioN (MAVEN)



Mars 2020 schematic. Image courtesy of NASA.

MAVEN at Mars. Image courtesy of NASA.

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Comparing optometrics and radiometrics

	Radiometrics	Optometrics
Data Types	Two-way Doppler, two-way SRA range, ΔDOR	Optical range, ground-based astrometric measurements of angular position
Data uncertainties	Doppler: 0.10 mm/sec (0.00562 Hz) SRA: 21.0 RU (2.99 m) ΔDOR: 0.06 ns (2.25 nrad)	Range: Depends on integration time Astrometry: Depends on elevation angle, sky brightness, angle between Sun, spacecraft, and Earth
Error sources	Earth orientation, station location, ephemeris, GMs, clock	
	Troposphere + Ionosphere	Troposphere only
		Star catalog

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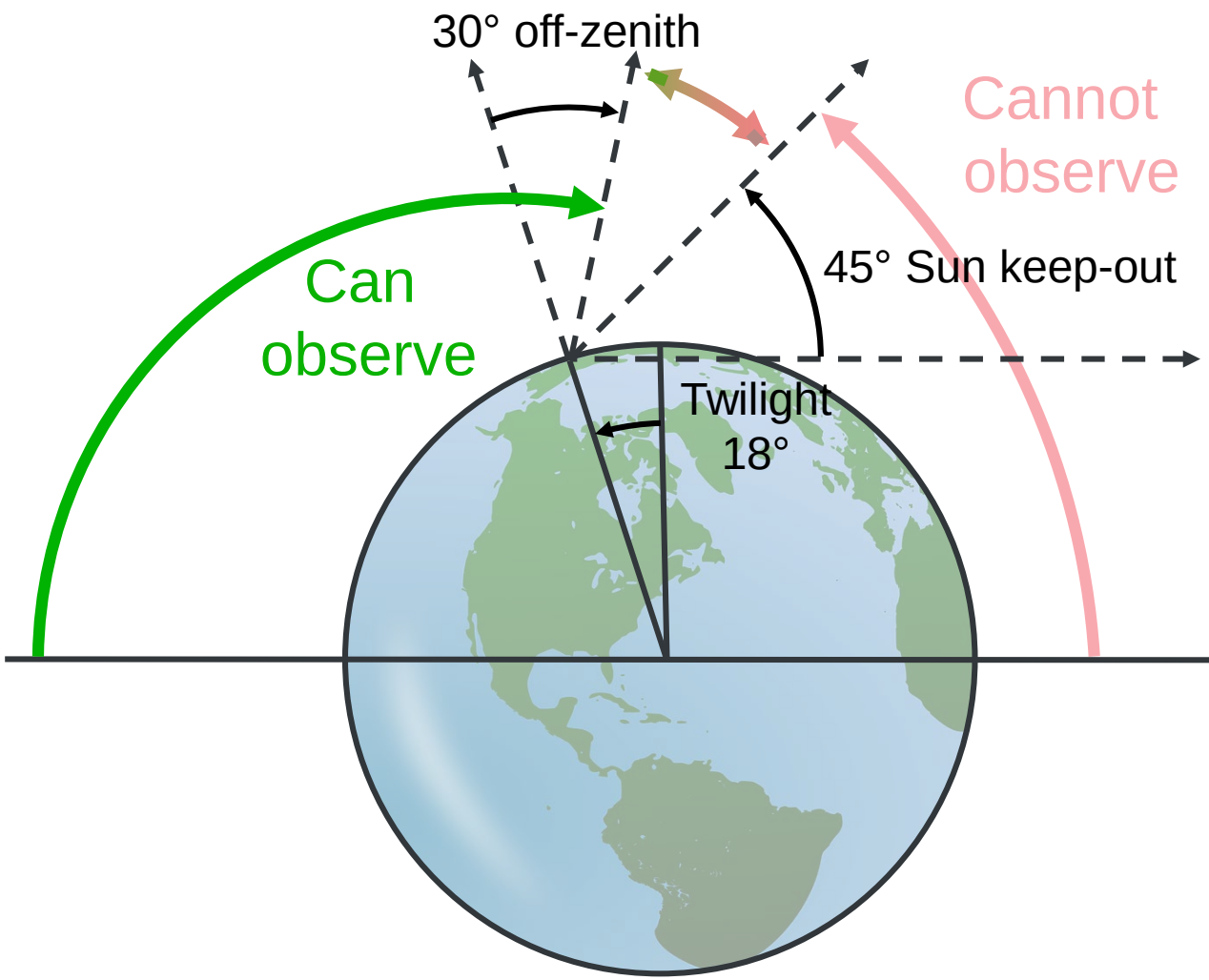
Optical Astrometry Constraints



- Elevation: within 30° of zenith
- Brightness: astronomical twilight (18°) observed
- Sun-Earth-S/C: Solar keep-out zone of 45°

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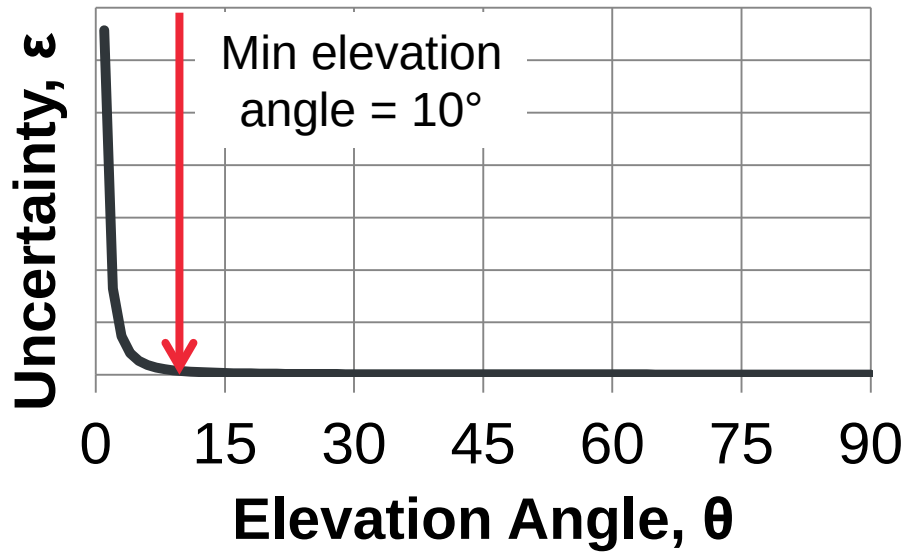
Optical astrometry measurement weights

- Varies with sky brightness
- Improves with higher elevation angle



$$\epsilon_{\text{day}}^2 = a_{\text{day}} + \frac{b_{\text{day}}}{\sin^2\theta_{el}} + c_{\text{day}}\cos^2\theta_{el}$$

$$a_{\text{day}} \sim 6.6\left(\frac{1\text{ hour}}{T}\right)\text{mas}^2, b_{\text{day}} \sim \left(\frac{1\text{ hour}}{T}\right)\text{mas}^2, \text{ and } c_{\text{day}} \sim 3.6\left(\frac{1\text{ hour}}{T}\right)\text{mas}^2$$

$$\epsilon_{\text{night}}^2 = a_{\text{night}} + \frac{b_{\text{night}}}{\sin^2\theta_{el}}$$

$$a_{\text{night}} \sim 0.75\left(\frac{1\text{ m}}{D}\right)^2\left(\frac{1\text{ hour}}{T}\right)\text{mas}^2, b_{\text{night}} \sim 0.25\left(\frac{1\text{ m}}{D}\right)^2\left(\frac{1\text{ hour}}{T}\right)\text{mas}^2$$

$$\epsilon_{\text{twilight}}^2 = \epsilon_{\text{day}}^2\left(1 - \frac{\theta_{sbh}}{18^\circ}\right) + \epsilon_{\text{night}}^2\frac{\theta_{sbh}}{18^\circ}$$

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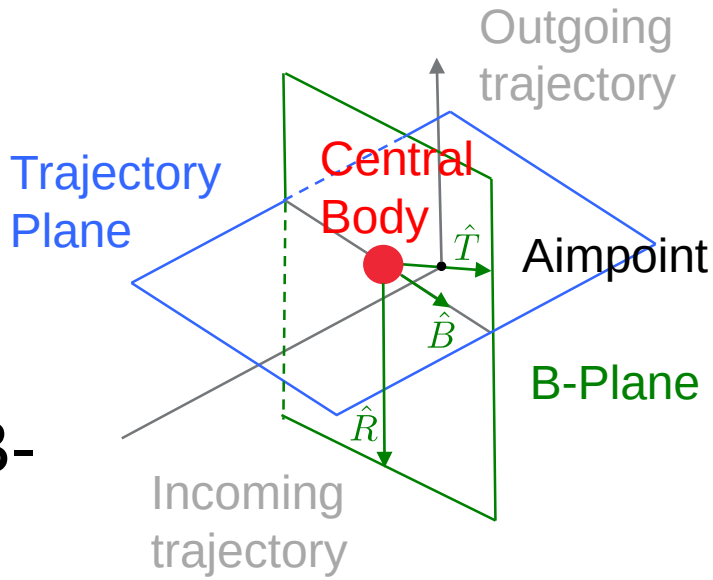
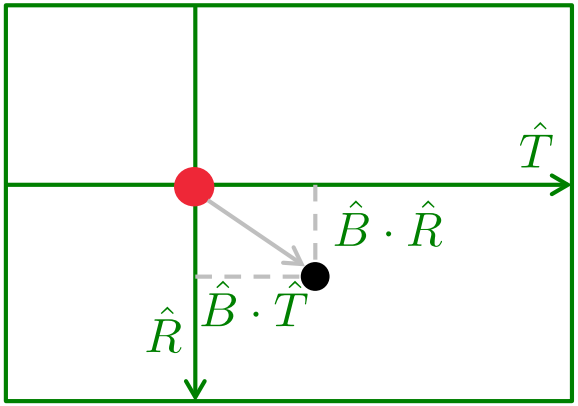
Analysis Metrics

- Mars Lander
  - Position and velocity covariance mapped to B-Plane
- Mars Orbiter
  - Position and velocity covariance norm of reconstructed trajectory
  - Orbital elements for predicted trajectory



B-Plane schematics



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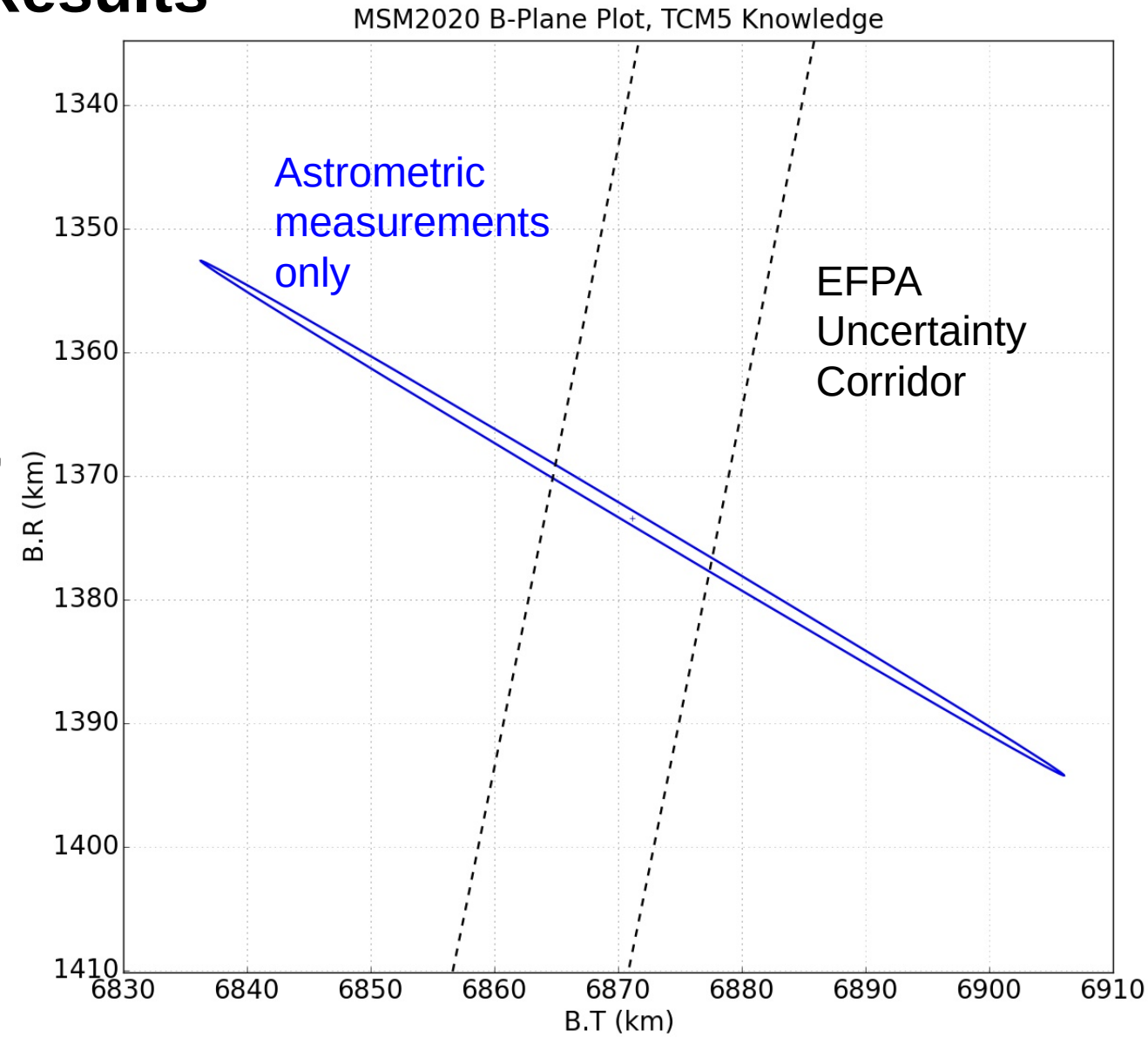
Mars Lander Results

- Columbia Hills landing site example
- Using only astrometric measurements, simulation does not meet EFPA requirement



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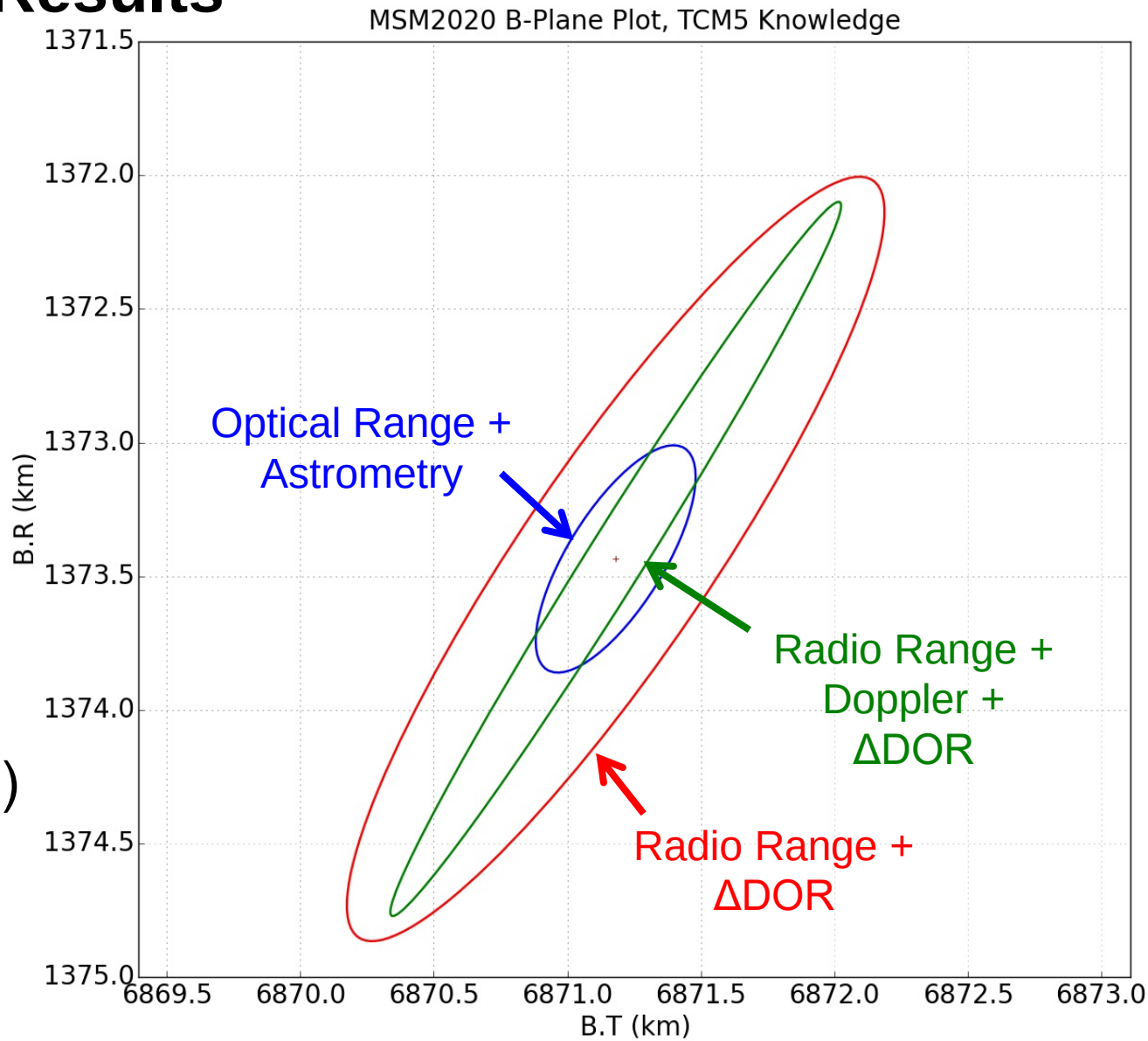
Mars Lander Results

- Optical outperforms traditional radiometric tracking data
- Optical outperforms direct radiometric analog (Radio range + ΔDOR)
- Meets EFPA requirement



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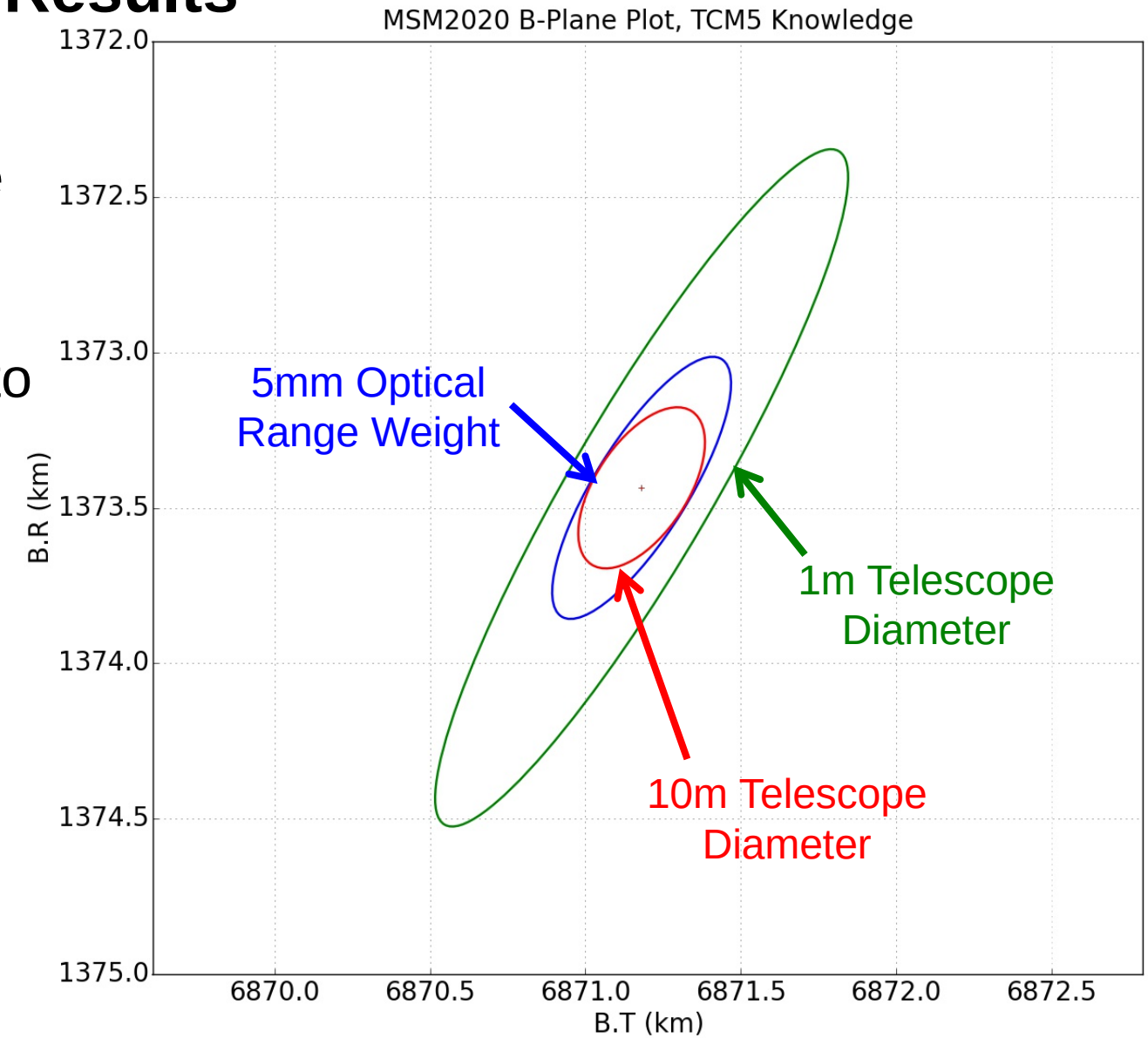
Mars Lander Results

- Optical data most sensitive to telescope diameter
- Not sensitive to frame effects
- Meets EFPA requirement



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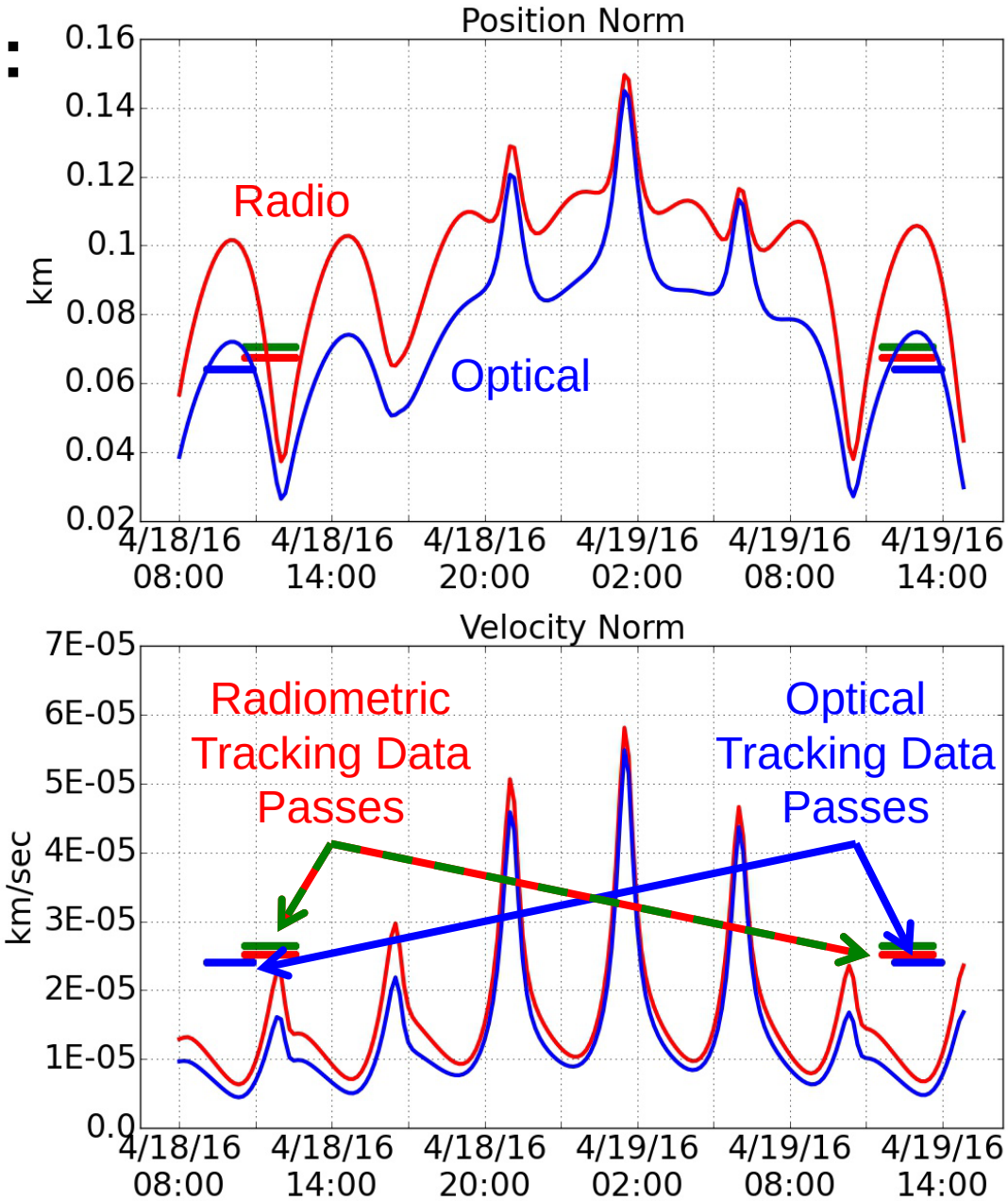
Mars Orbiter Results: April 18 – 19, 2016

- Based on MAVEN, currently in orbit at Mars
- Reconstruct orbit to within 3.0 km
- Optical outperforms radio during tracking passes & tracking gaps



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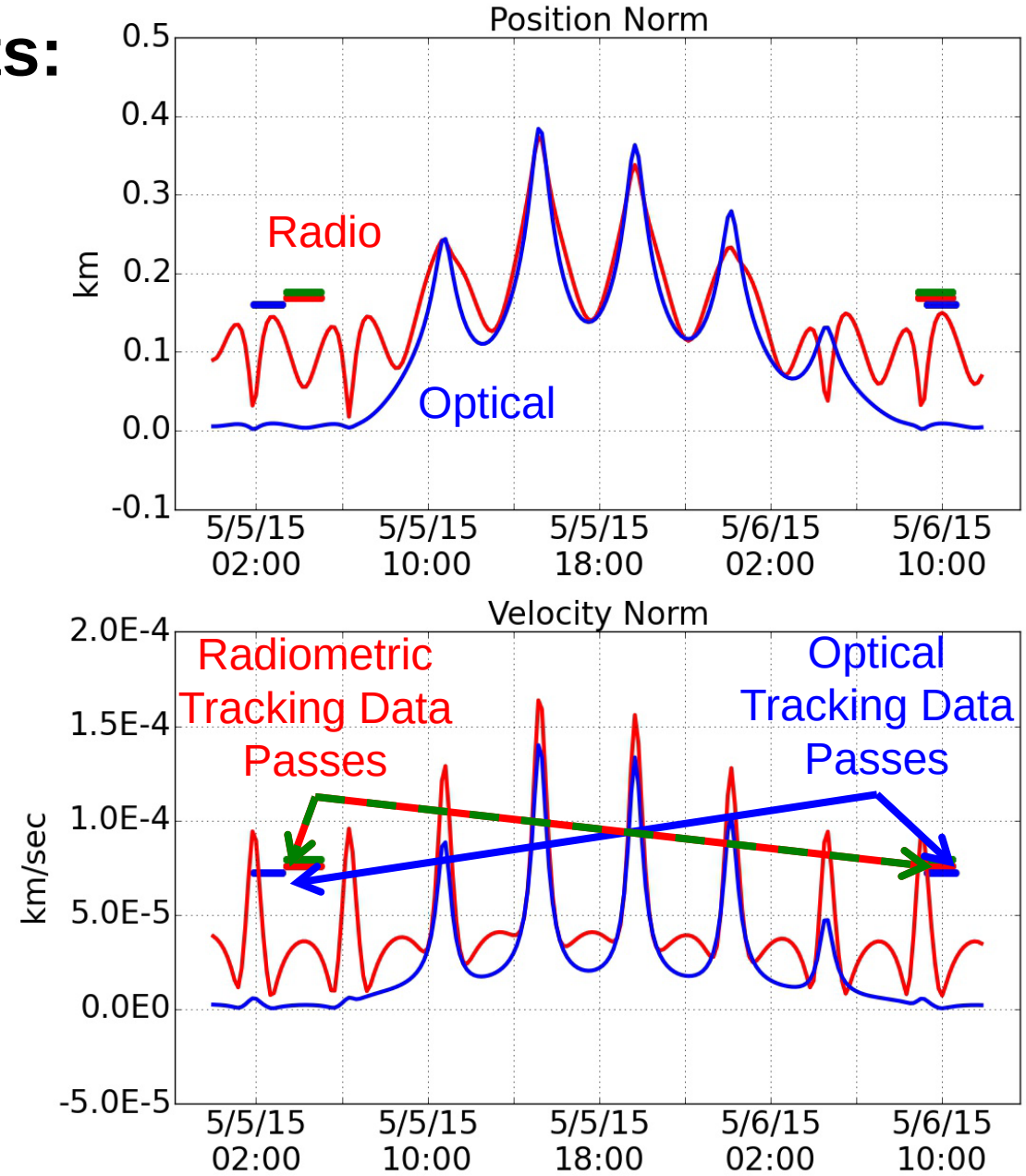
Mars Orbiter Results: May 5 – 6, 2015

- Degraded OD performance due to occultations
- Optical outperforms radio during tracking passes but not tracking gaps
- Still meet requirement



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Mars Orbiter Results: Summary

- Improvement of optical over radiometric tracking data types
- RMS across whole arc

Parameter	Position Norm	Velocity Norm	Radial Norm	Tangential Norm	Normal Norm
April 18 – 19, 2016	20%	15%	4%	21%	29%
May 4 – 6, 2015	15%	31%	-8%	-4%	94%

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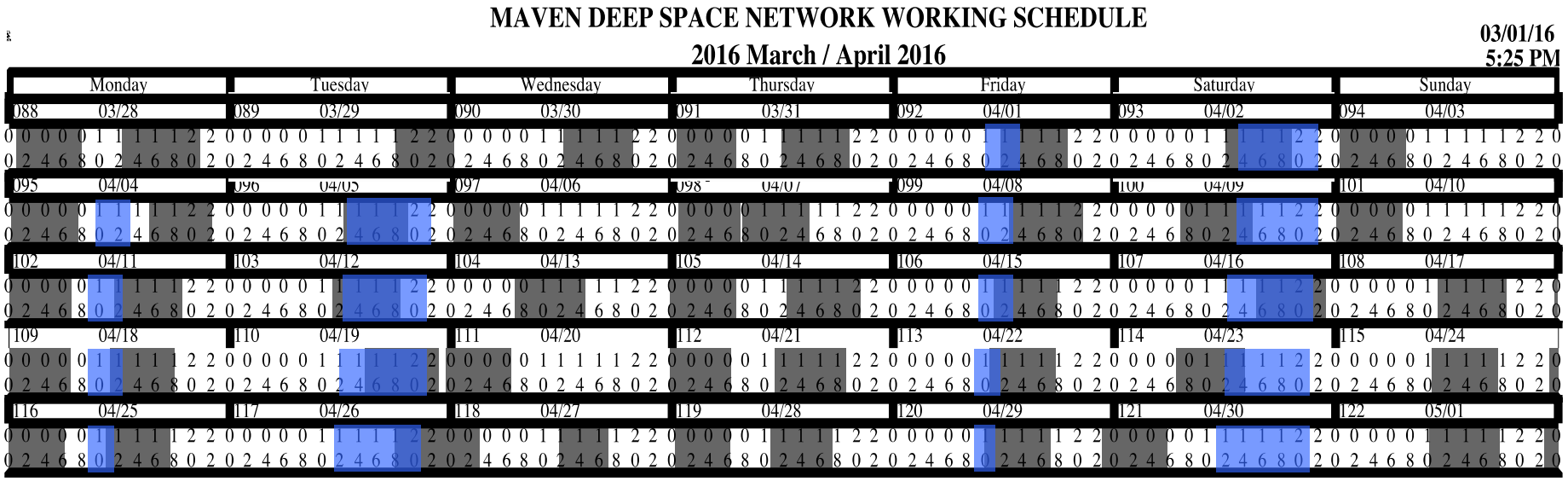
Orbiter Operational Constraints

- Pass duration
- Pass frequency
- Antenna pointing

MAVEN tracking schedule;
Simulated optical passes in blue.



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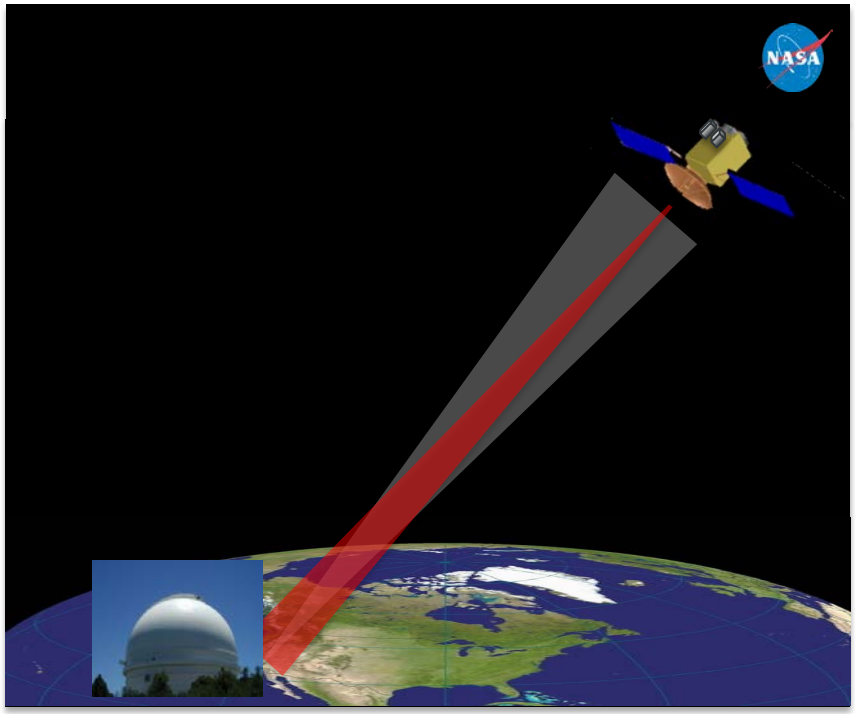
Conclusions

- Optical tracking data types viable alternative to radiometric data types; meets requirements for both mission scenarios
- Pass frequency and duration important
- Additional operational constraints for optical tracking data types



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Acknowledgements

The navigation work described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Copyright 2016. California Institute of Technology.

Backup

Radio Measurement Model Assumptions

Based on Mars 2020 Lander

Lander Baseline Orbit Determination Error Assumptions

Error Source	Estimate or Consider	A Priori Uncertainty (1σ)	Correlation Time	Update Time	Comments
Epoch state position	Est.	1000 km	-	-	
Epoch state velocity	Est.	1 km/s	-	-	
X-Band 2-way Doppler	-	0.1 mm/s	-	-	0.0056 Hz
Range	-	3 m	-	-	21.03 RU, low SNR during late cruise
ΔDOR	-	60 ps	-	-	~2.4 nrad
Doppler Bias	Est.	0.002 mm/s	0	Per pass	Residual error from spin bias estimation
Range Bias	Est.	2 m	0	Per pass	DSN performance
Station Locations	Con.	Full 2003 cov.	-	-	
Quasar Locations	Con.	1 nrad	-	-	
Pole X, Y	Est.	1-4 cm	48 hr	6 hr	Slope 2 days before EOP to EOP + 12 hr
UT1	Est.	1.7-15 cm	48 hr	6 hr	Slope 6 days before EOP to EOP + 12 hr
Ionosphere day/night	Est.	55/15 cm	6 hr	1 hr	S-band units; use 6x (iono) and 2x (trop) apsig when no actuals; subsequent passes uncorrelated
Troposphere wet/dry	Est.	1/1 cm	6 hr	1 hr	
Mars and Earth Ephemerides	Con.	DE423 Covariance	-	-	
Mars GM	Con.	2.80×10^{-4} km^3/s^2	-	-	~10x MGS95J formal error
Solar Pressure					High-fidelity model
Radial (Gr)	Est.	5%	7 days	1 day	Correlation broken at turns. Gr and Gx estimated as both a bias and a stochastic
Tangential (Gx)	Est.	5%	7 days	1 day	
Out of plane (Gy)	Est.	1%	-	-	
Non-gravitational Accelerations	-	0 km/s^2	-	-	Accommodated in SRP model
ACS Event ΔV	Every 7 days from L+15 days until E-2 days				Conservative assumption
Per axis	Est.	2 mm/s before E-45 days 1 mm/s after E-45 days	-	-	Flight system requirement
Maneuver execution errors					Range of values for current set of cases
TCM-4 (E-8d)	Est.	2.32-2.43 mm/s	-	-	5% proportional error and 4 mm/s fixed error (3σ), vector mode maneuver
TCM-5 (E-2d)	Est.	1.910-1.912 mm/s	-	-	

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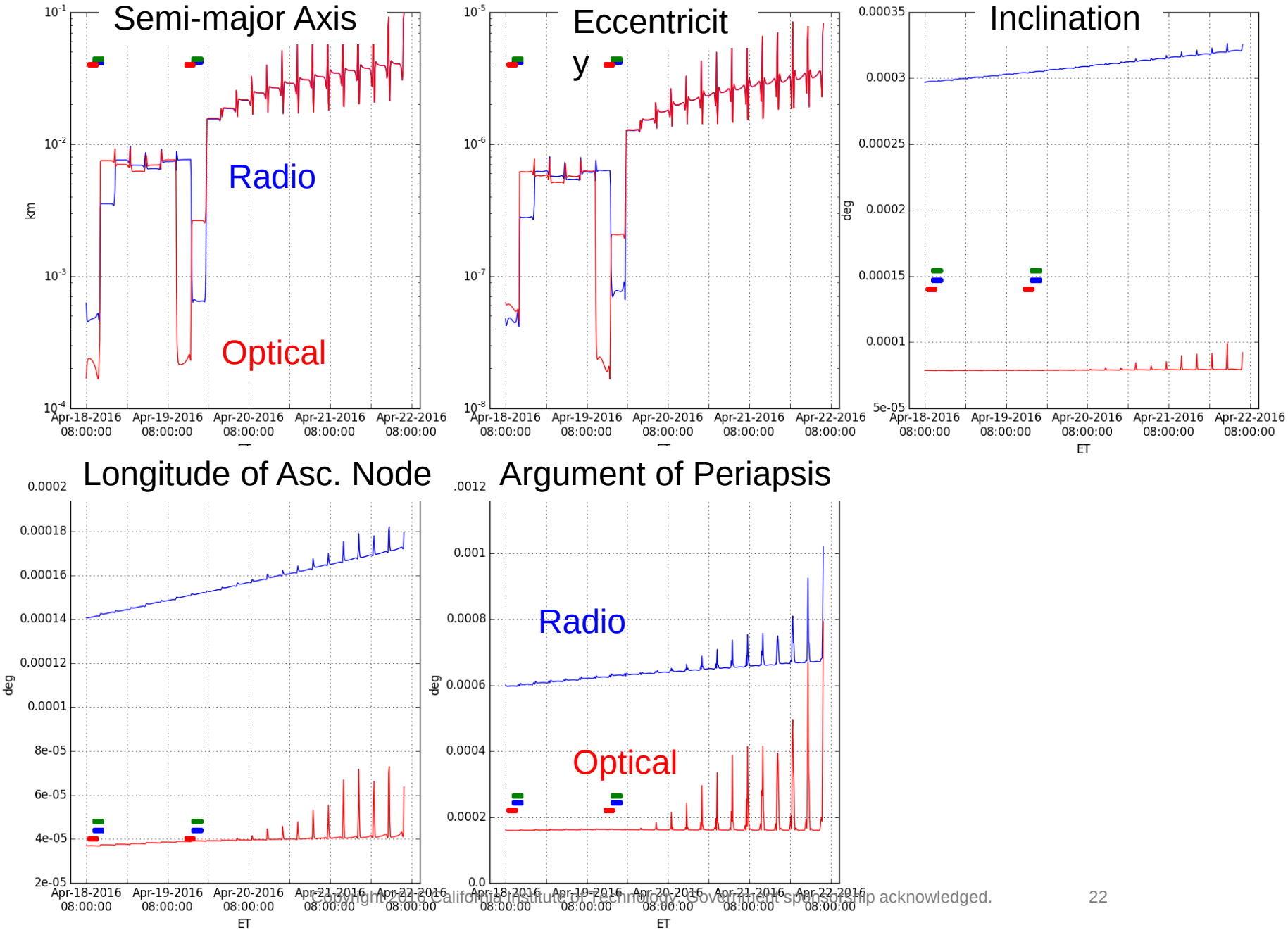
Mars Orbiter Results: April 18 – 22, 2016



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Historical applications

- Orbit determination for Earth-orbiting spacecraft
- Astrometry of orbital debris
- Deep space laser ranging experiments
- Spacecraft dockings?
- None of these systems sufficient to replace radio-frequency tracking systems

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