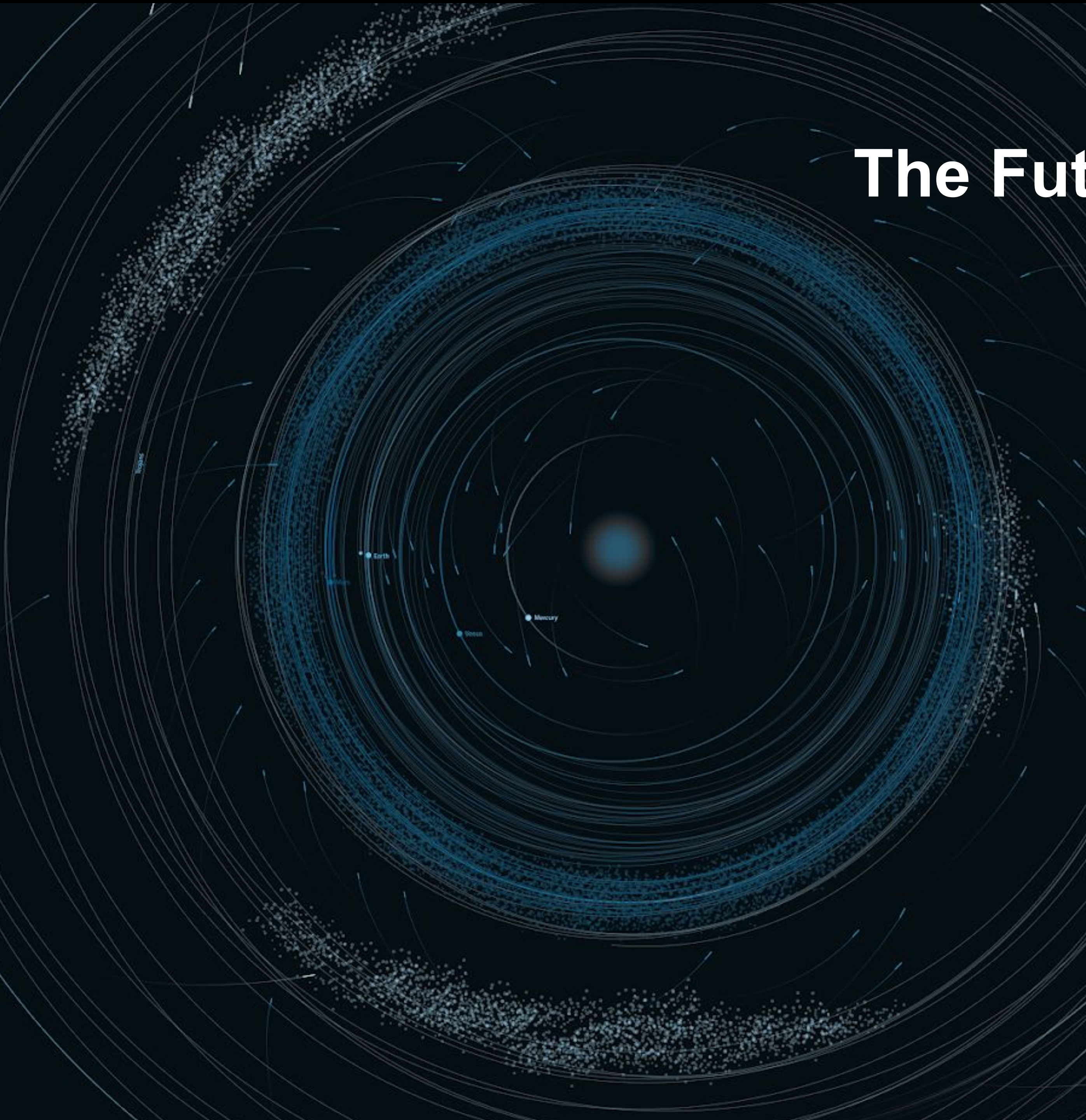


The Future (and Present) of Solar System Science

Michael Watkins

With significant input from Ryan Park and the Solar System Dynamis Group (JPL)

Introduction

- As we look toward the prospects of ILTN, let's first look back on how we have been learning about solar system dynamics (planetary ephemerides, planetary structure, etc)

- The NASA Deep Space Network has been the primary tool – sometimes called the "world's largest scientific instrument"

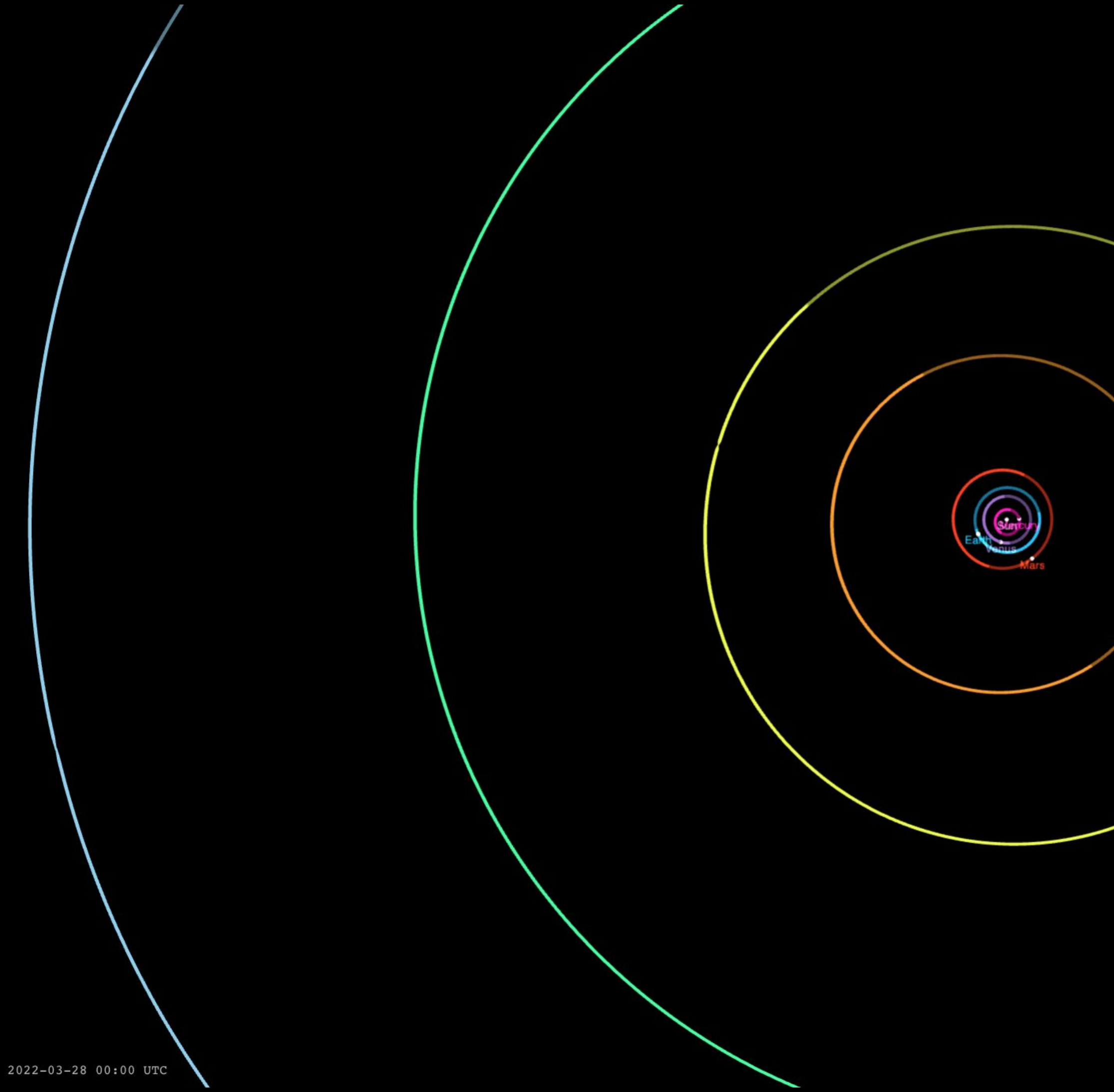
- DSN tracking of orbiting spacecraft have provided an ever increasing wealth of information about the solar system

Let's start with the planetary ephemerides…

Planetary and Lunar Ephemerides

What is it and who uses it?

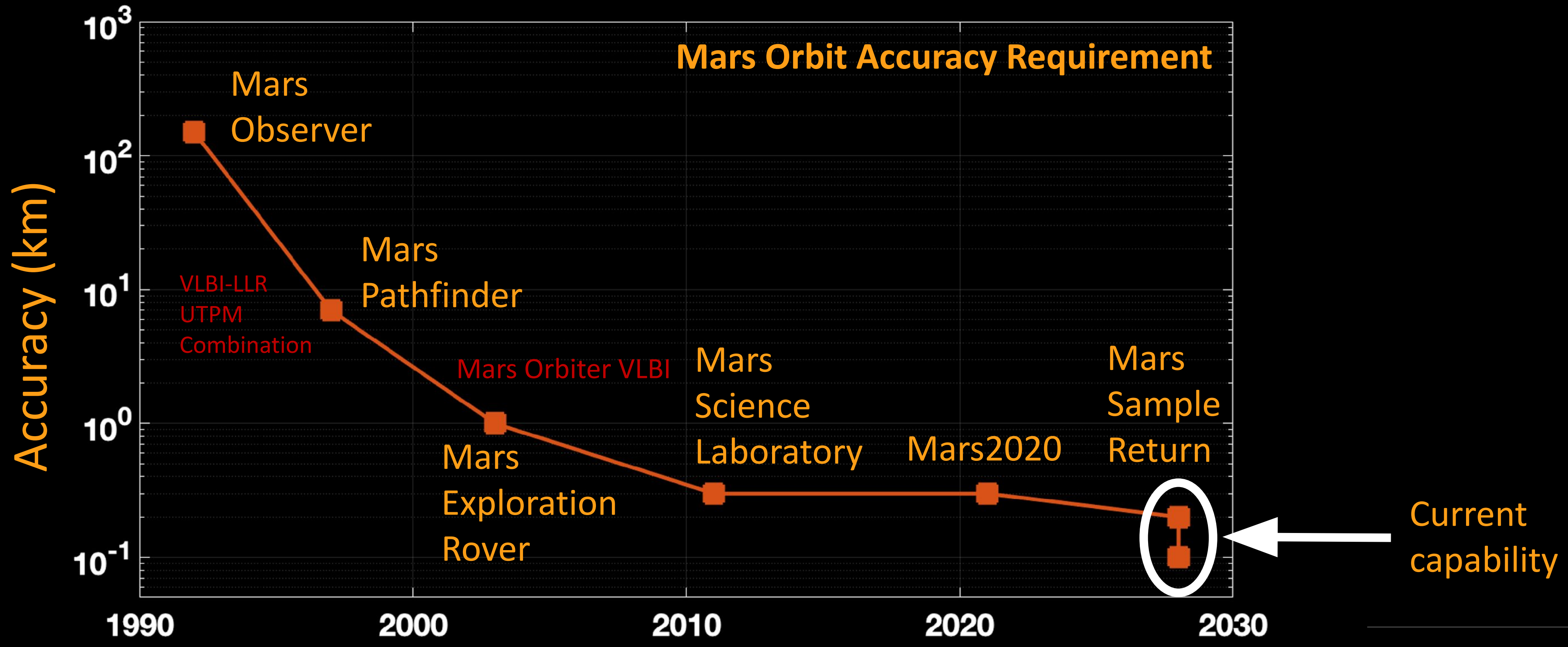
- Provides the position and velocity data of
  the Sun, 8 planets, Moon, Pluto, and orientation of the Moon (e.g., DE440).
- It serves as the foundation for studying the dynamics of Solar System objects,
  e.g., asteroid orbit prediction, spacecraft navigation, astrometry, planetary science, fundamental science, planetary defense, etc.
- All NASA and most, if not all, international (ESA, JAXA, ISRO, etc.) flight projects use the JPL planetary ephemeris,
  e.g., Juno, MESSENGER, LRO, OSIRIS-REx, MRO/Odyssey, Hayabusa-1&2, Chandrayaan, PSP, DART, etc.
- Used by researchers/astronomers around the world and by the general public.



Planetary and Lunar Ephemerides

JPL has a 4-decade of track record of improving the ephemeris in order to support more ambitious missions:

- Improved accuracy allows targeting more interesting/precise Mars landing sites.
- Current Earth-Mars orbit accuracy is <300 m (3-D) for ~one-year prediction.
- Used by several Mars lander missions (latest one being Mars2020)

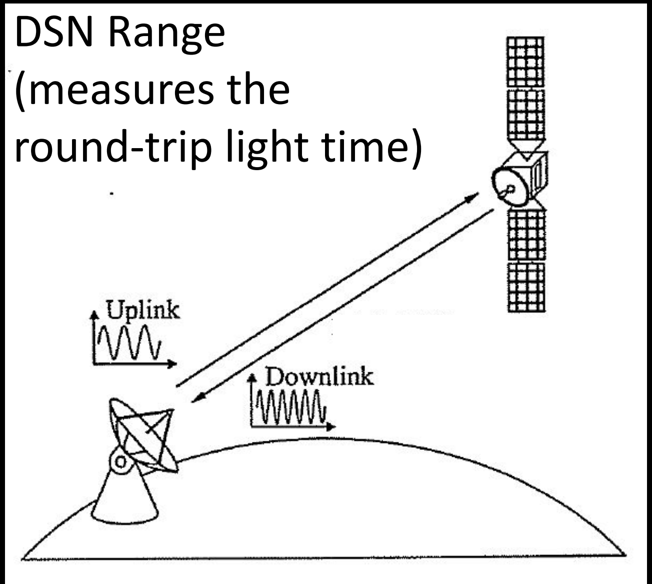


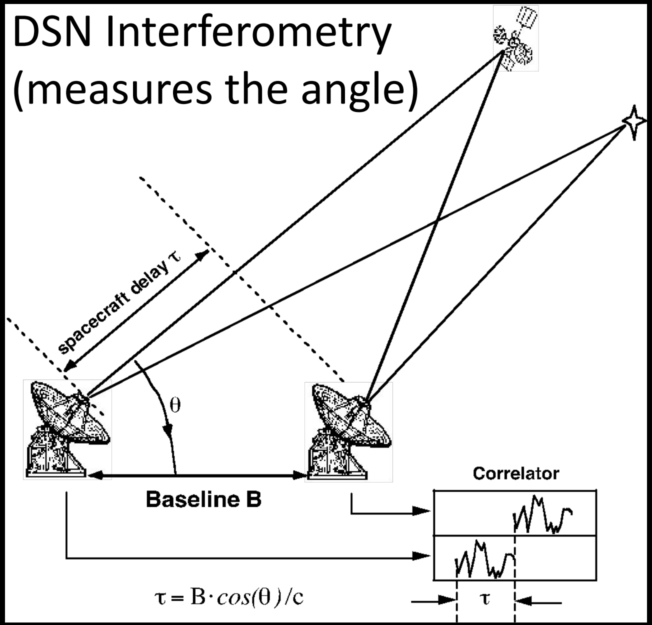
Planetary and Lunar Ephemerides

How do we compute it?

- Computed by fitting numerically integrated orbits to ground-based and space-based observations collected over a century.
- Data types include:
  - DSN Range (measures the Earth-relative distance)
  - DSN Doppler (measures the Earth-relative speed)
  - DSN Interferometry (measures the plane-of-sky angles)
  - Astrometry (measures angles in an inertial frame)
  - Lunar Laser Ranging (measures Earth-moon distance)
- The DSN data determines the accuracy of the modern-day planetary ephemeris.

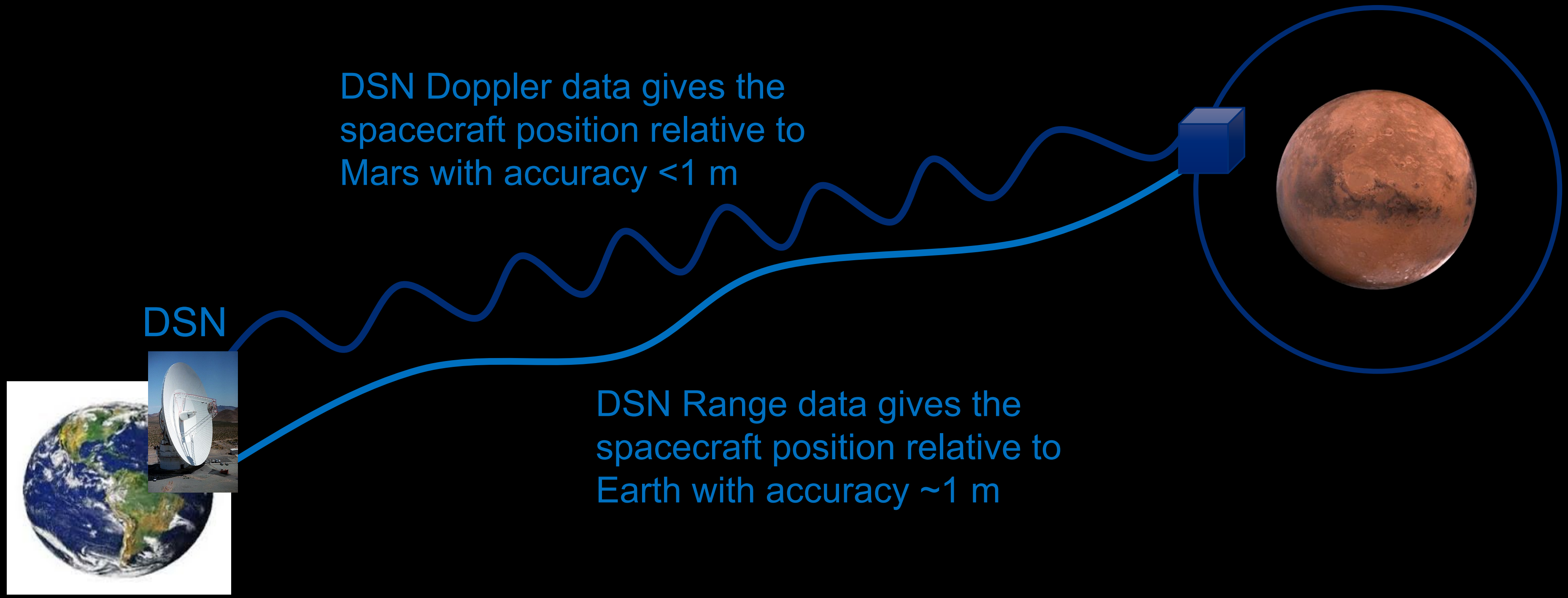
The Development Ephemeris 440 (DE440) is the latest-available general planetary and lunar ephemerides file.



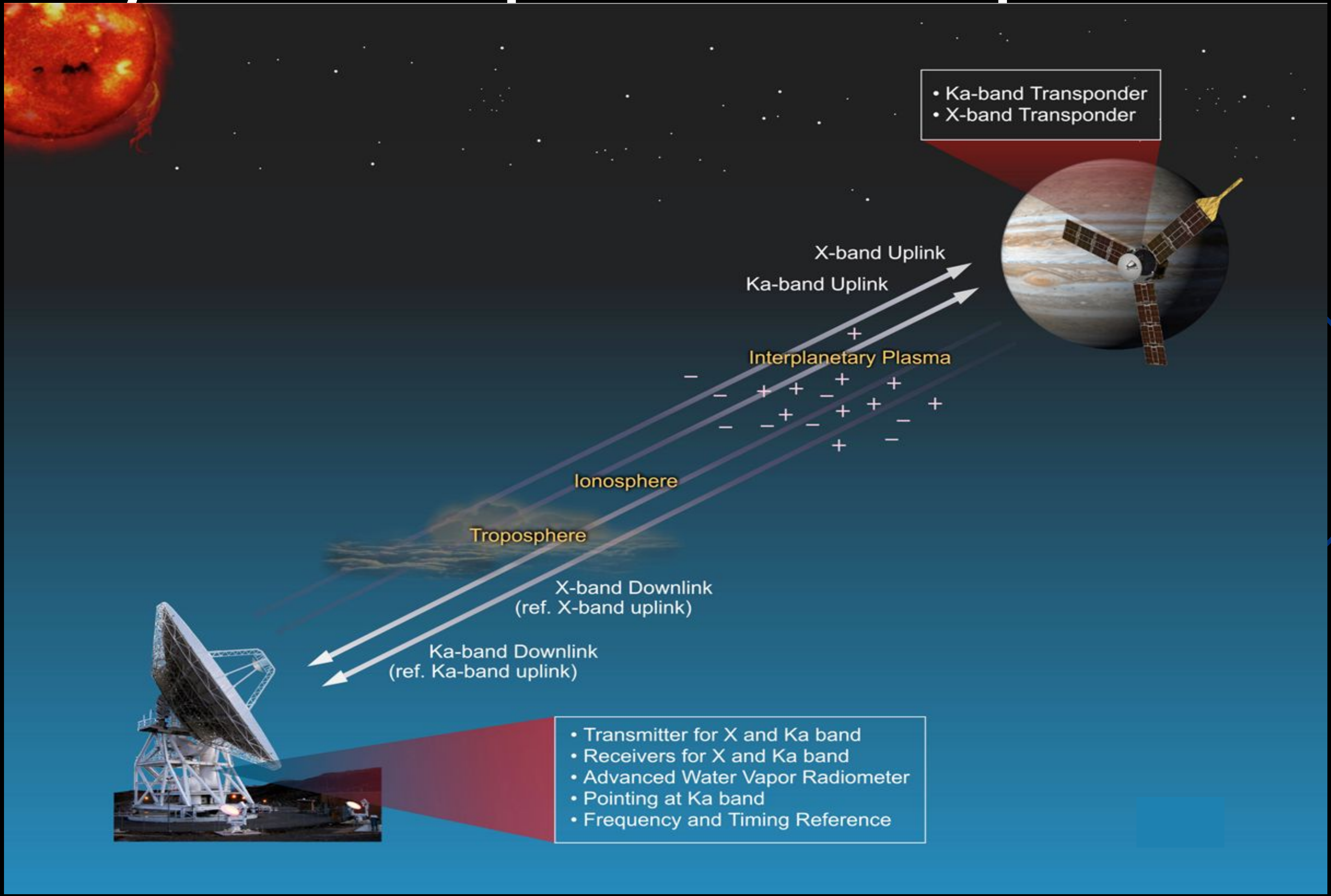


Planetary and Lunar Ephemerides Computation Procedure

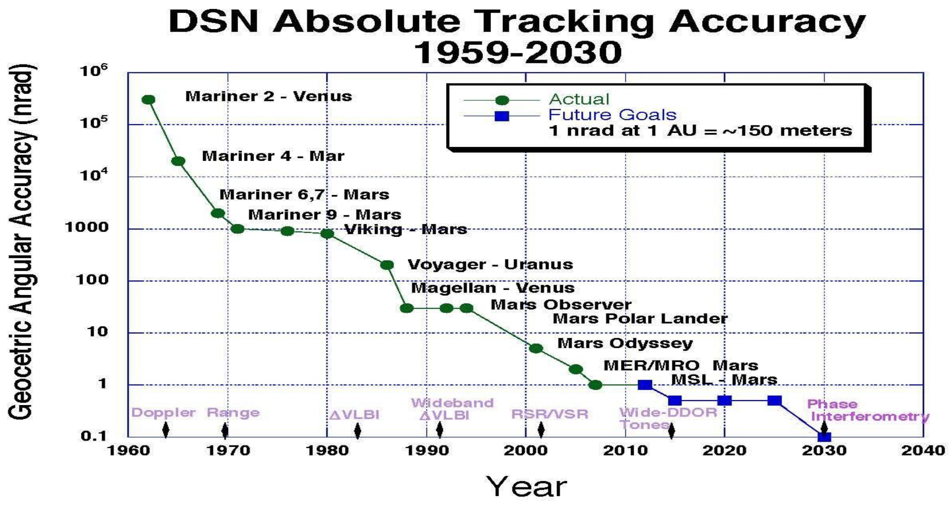
The accuracy of the modern-day planetary ephemeris is dominated by the DSN range, Doppler, and interferometry data.



Planetary and Lunar Ephemerides Computation Procedure



Tracking and Navigation Accuracy

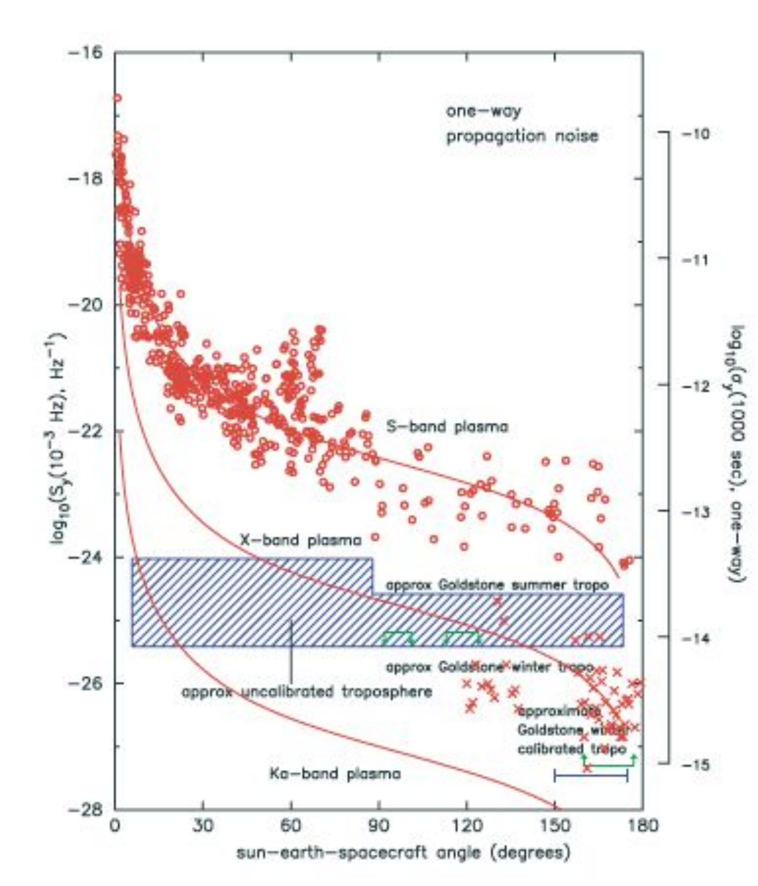


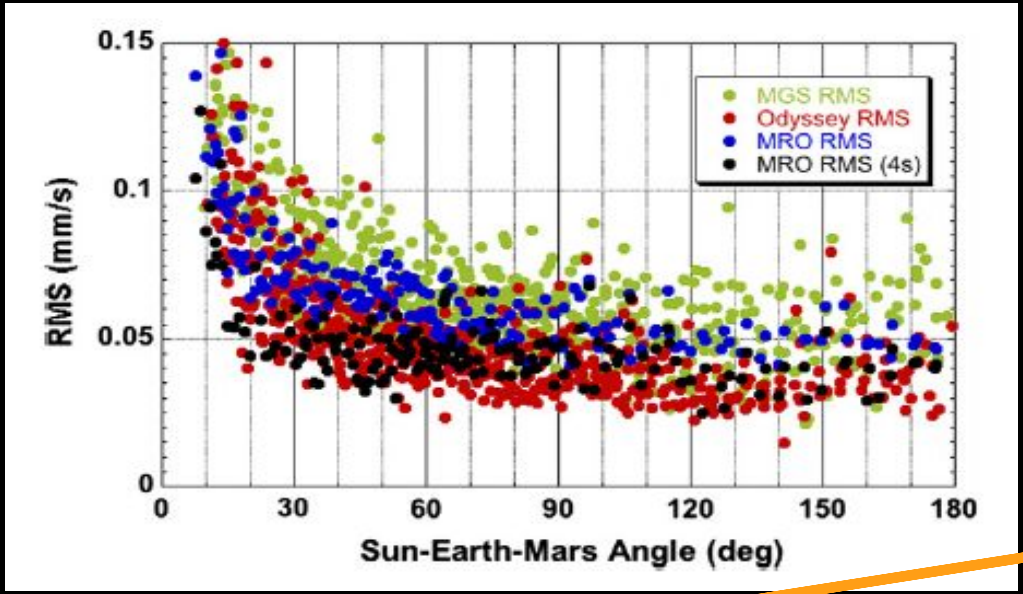
Slightly outdated but useful slide showing how far we have come in 60 years!

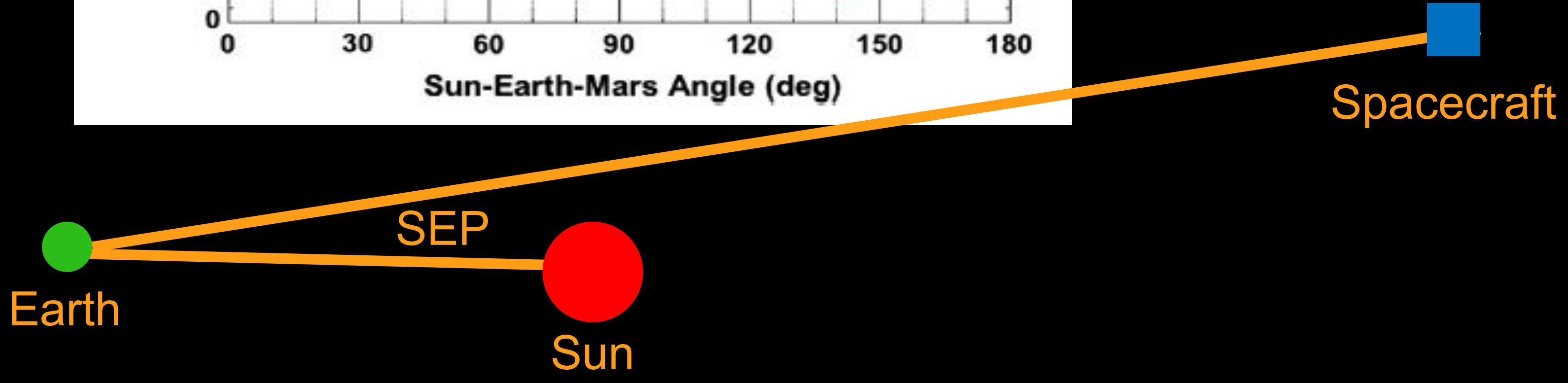
Errors in DSN radio data

- The DSN radio data are sensitive to electrons and water particles in the path.
  - Earth troposphere: calibrated from GPS data
  - Earth ionosphere: calibrated from GPS data
  - Solar plasma: calibrated depending on the solar activity

Typical X-band accuracies :
- Doppler: 0.03-0.1 mm/s (60s sample)

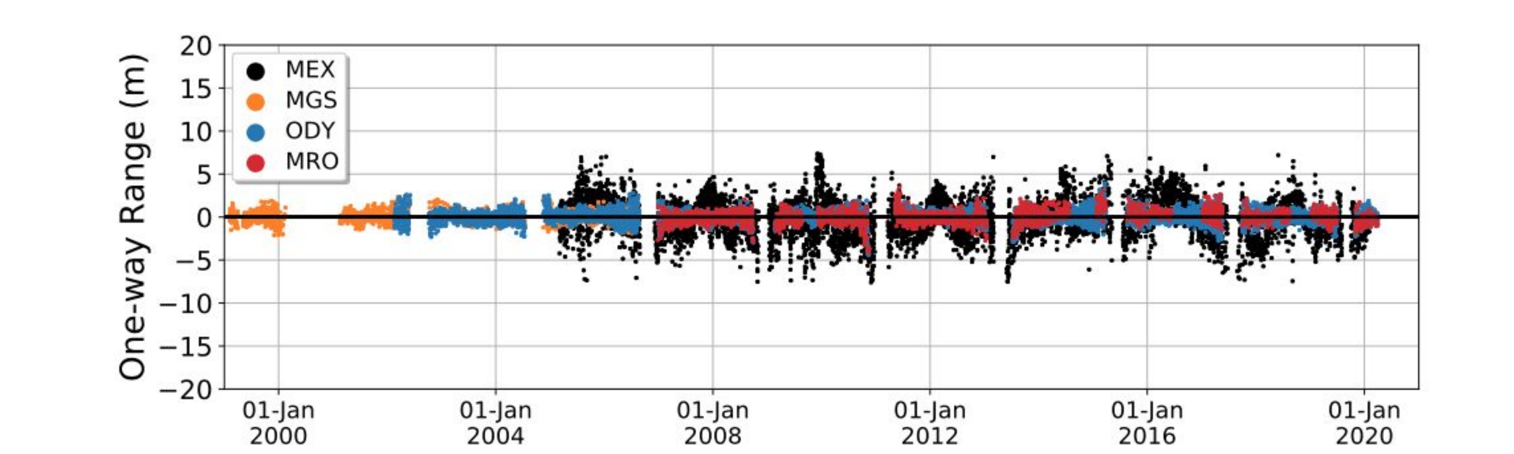






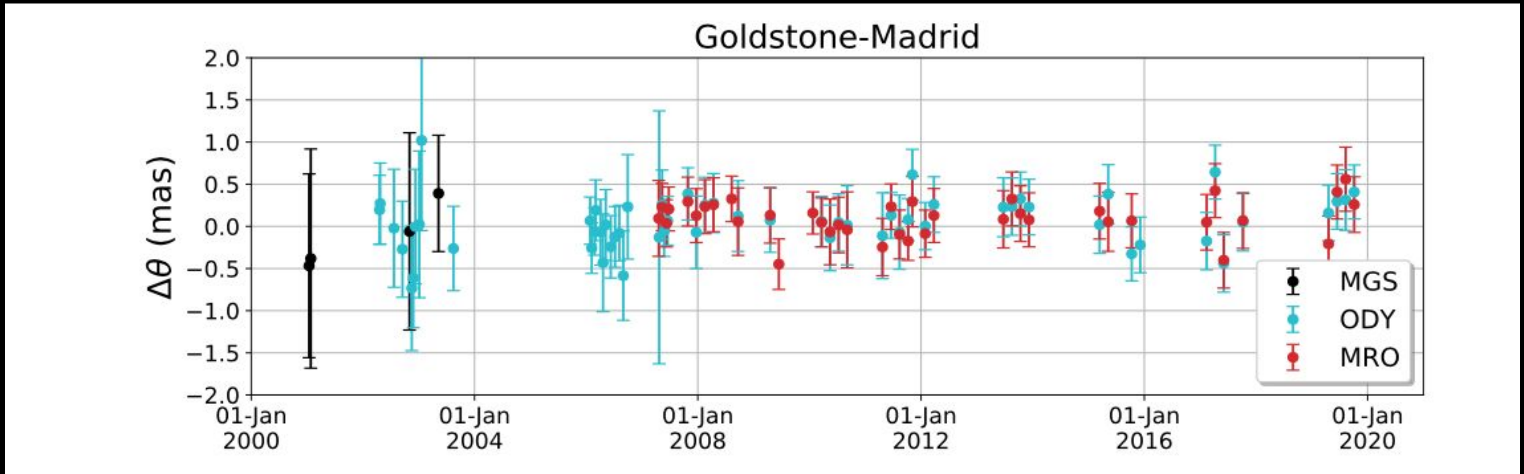
Mars residuals from DE440

Mars ranging data (measures distance)



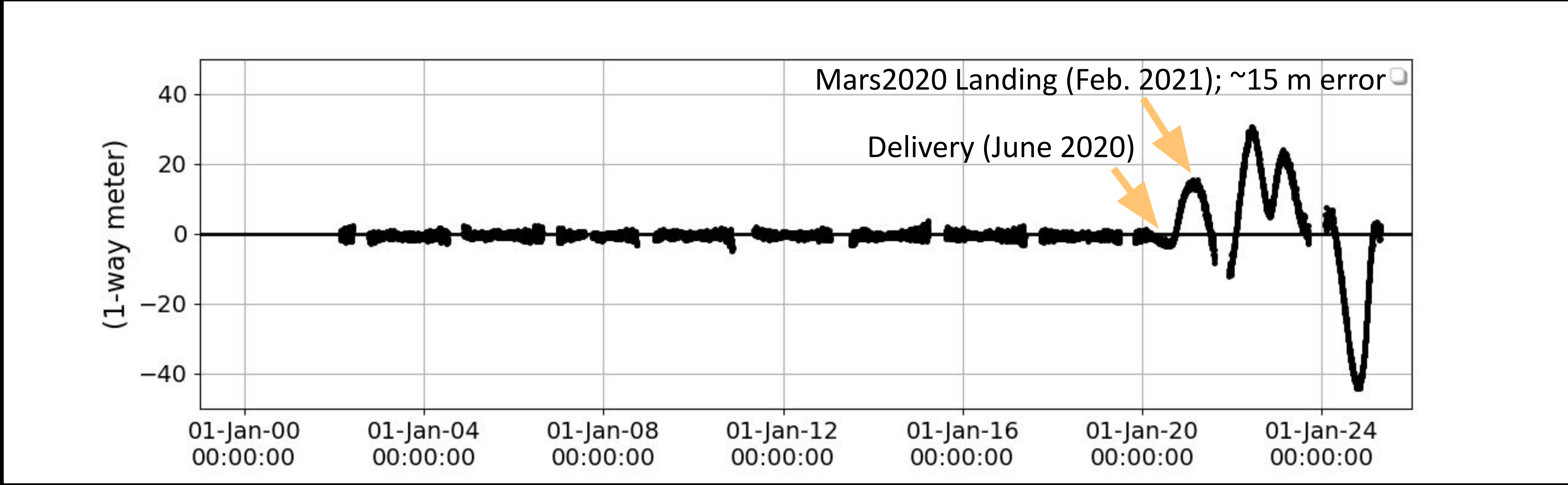
Data fit good to ~1m

Mars interferometry data (measures the plane-of-sky angles)

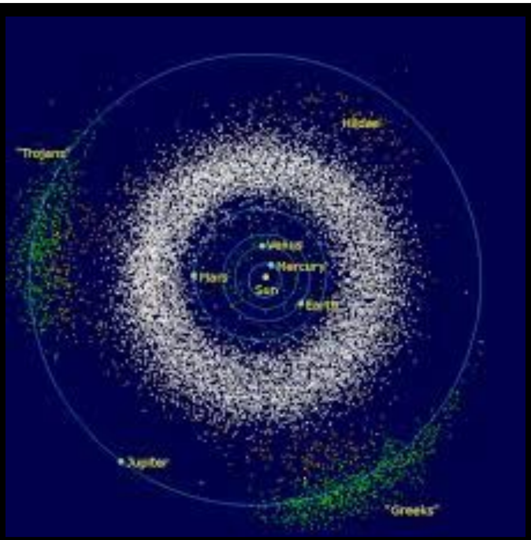


Data fit good to ~0.25 mas (200-300 m)

Delivery accuracy of DE440 for Mars2020 Landing

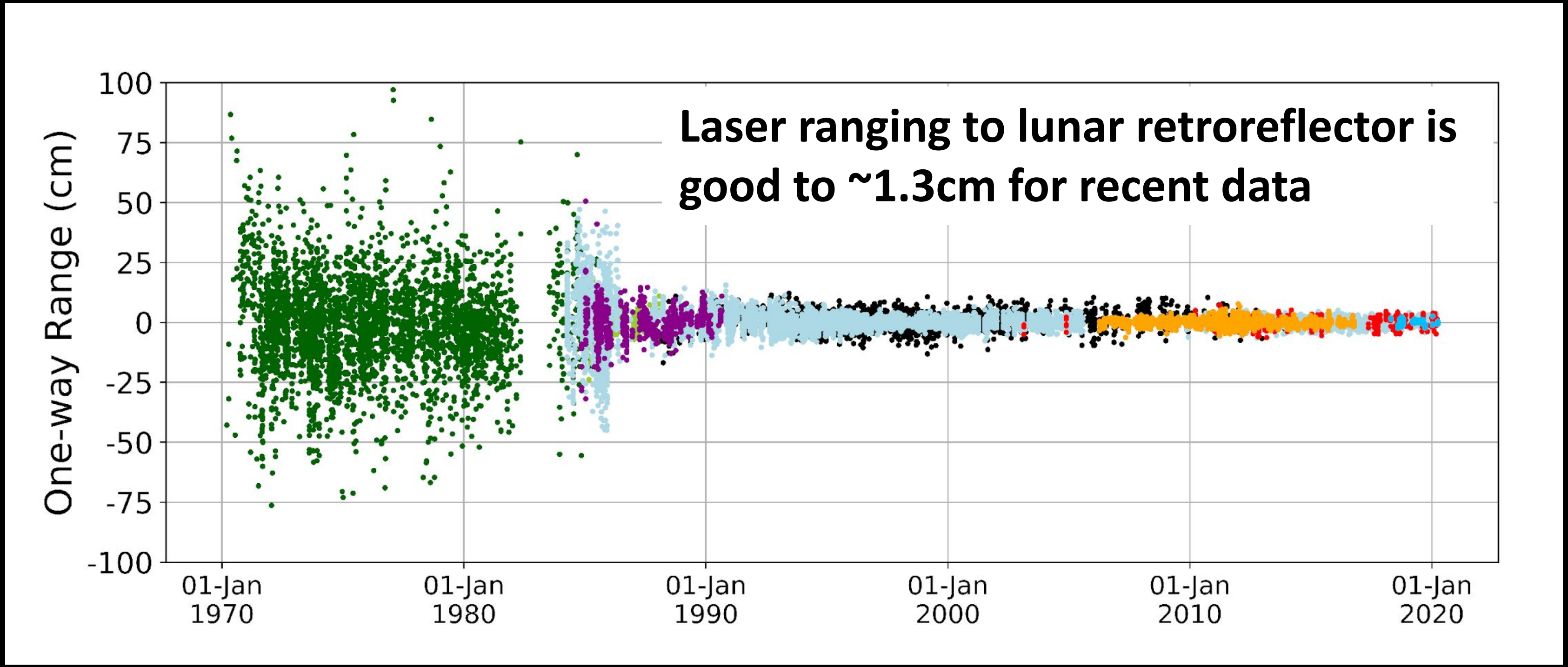


- The DE440 delivery was made to Mars2020 based on the data collected up to ~June 2020
- The range prediction error was ~15m (limited by the errors in asteroid masses)
- The angular prediction error was ~200m (limited by the accuracy of interferometry data)

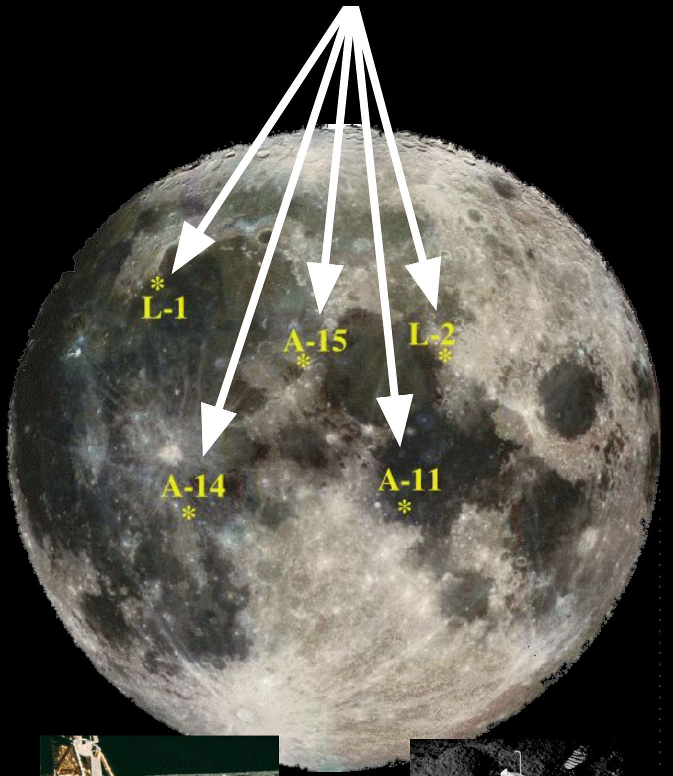


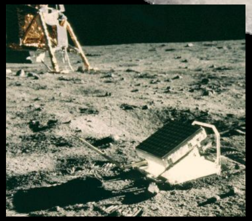
Many asteroid masses are unknown

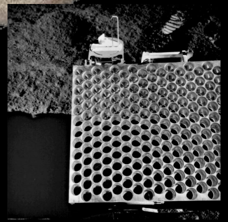
Accuracy of Lunar Orbit



5 lunar retroreflectors







- JPL has been providing lunar ephemeris and orientation for ~50 years.
- The current lunar orbit and rotational motion accuracy is ~1 m.
- Currently in discussion with NASA and other US government agencies for possible future needs that might be more demanding.

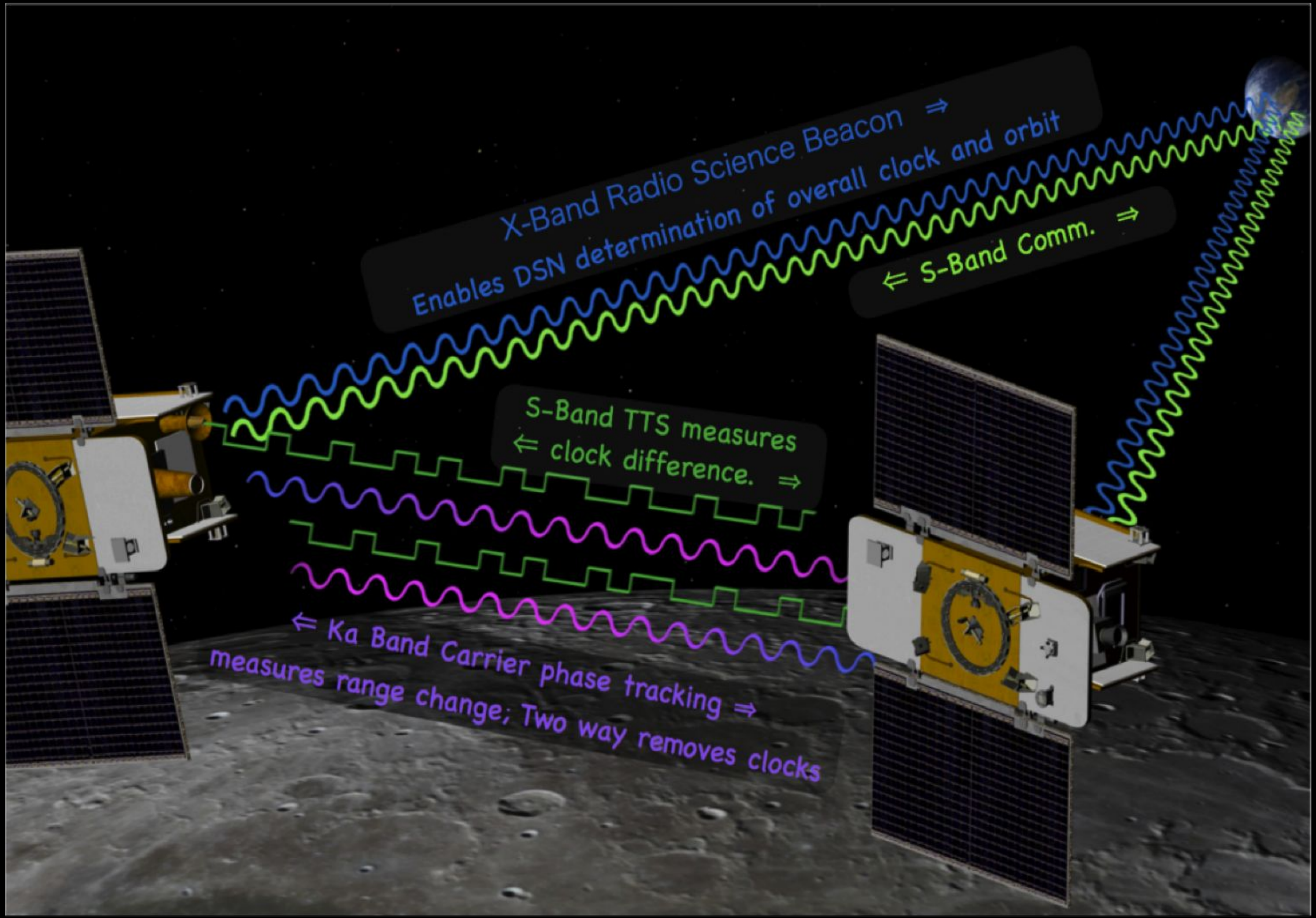
Gravity Field and Topography (examples)

- Precision tracking and analysis of DSN (or sat-sat data in the case of Earth and Moon) allow accurate determination of the gravity and topography (using laser altimetry or SAR)

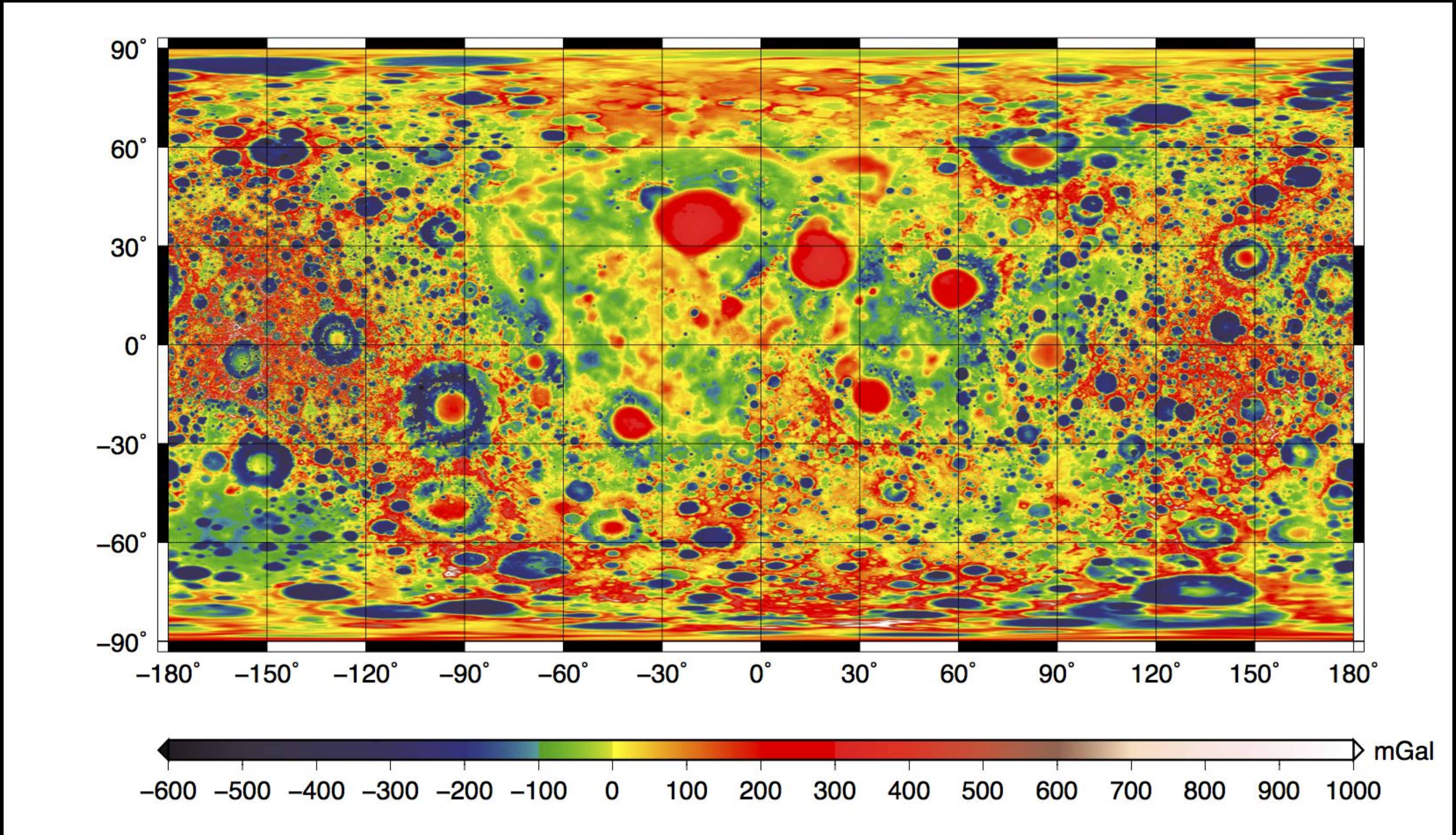
- This information has provided key constraints on planetary composition and evolution (including thermal history)

Lunar Gravity Field

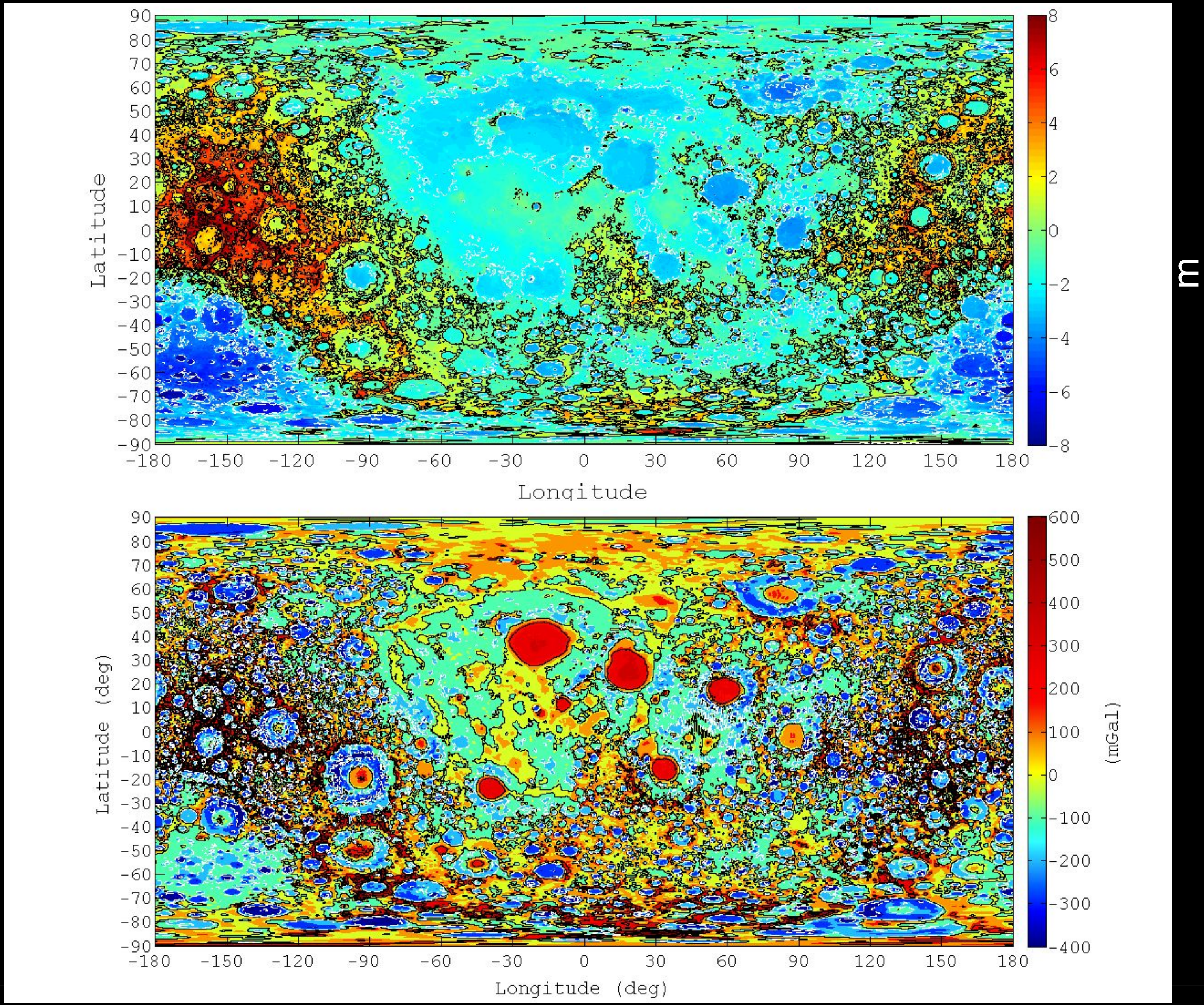
- The latest lunar gravity field is determined primarily by processing the GRAIL data.



Lunar Surface Gravity (Post-GRAIL)



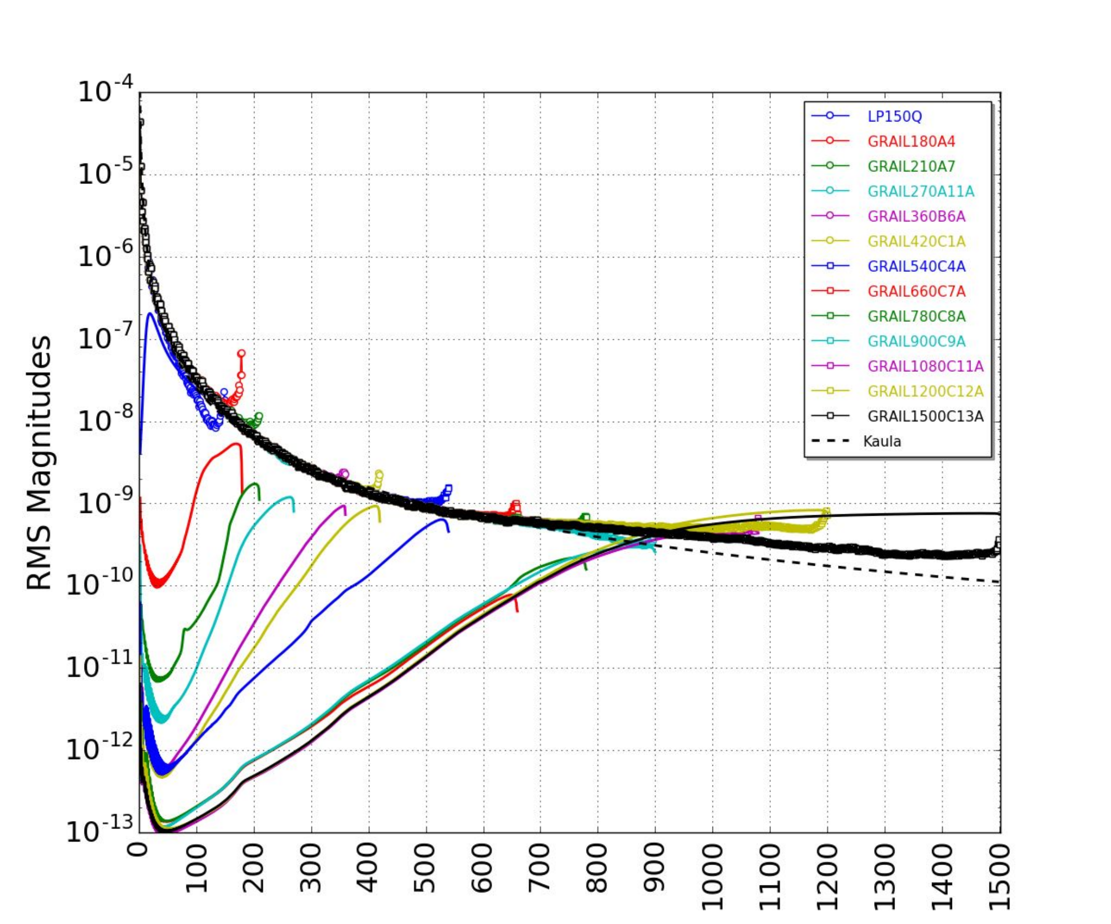
Maps of Lunar Topography and Gravity Field



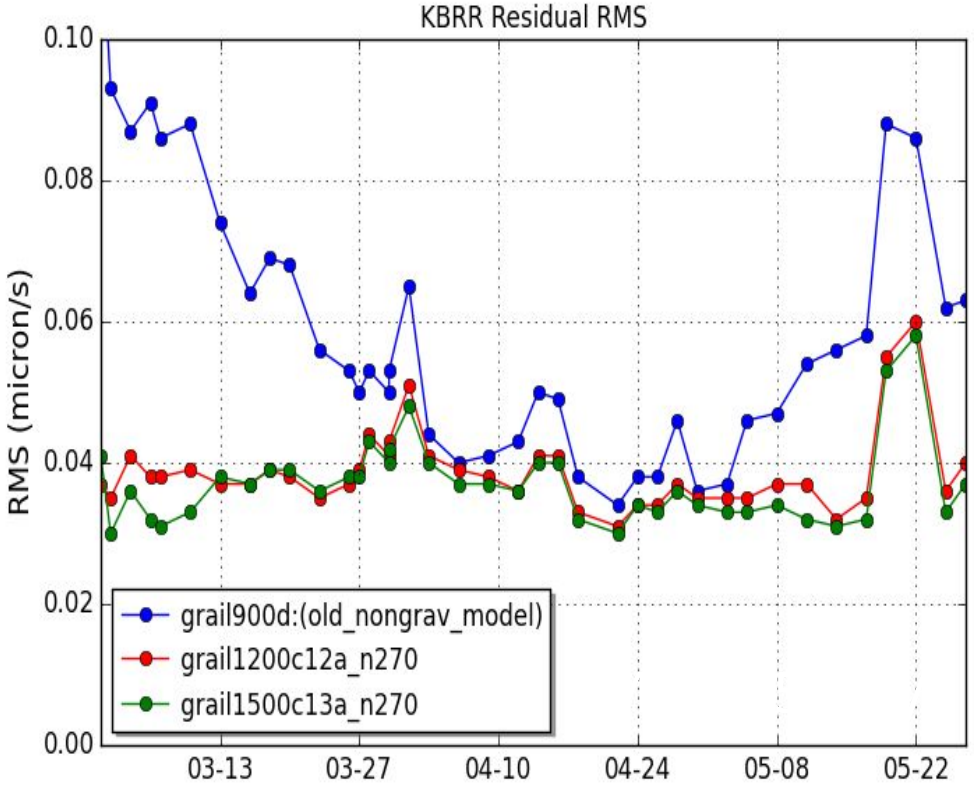
Lunar Gravity Field

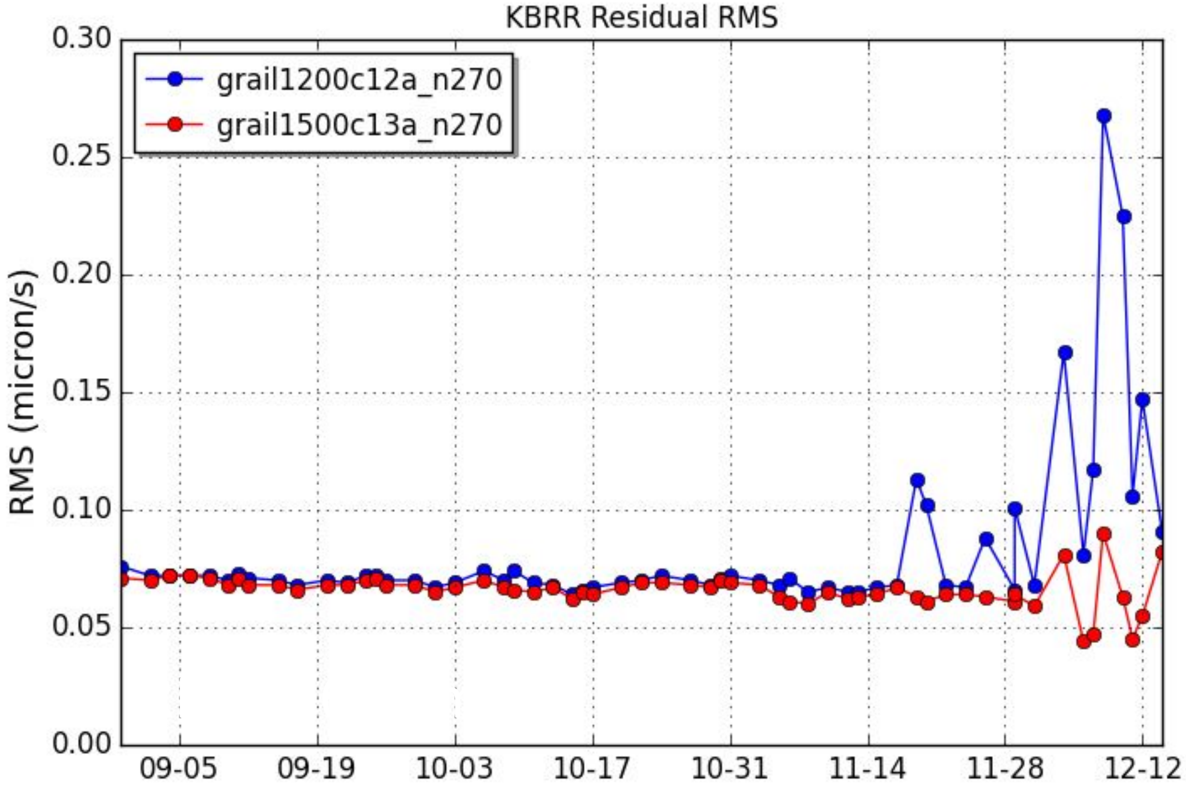
- The highest resolution lunar gravity field available to date is a degree-1500 field (available on PDS): https://pds-geosciences.wustl.edu/grail/
  - About ~2.3 million parameters are estimated
  - Half wavelength of 3.6 km
- The lunar gravity field is globally accurate to about n=850 (~6.4 km resolution)
- A degree-1800 lunar gravity field is in preparation.
- Historically, lunar gravity fields have been delivered in the PA frame, but for no particular reason.
- Due to growing interest in cis-lunar exploration and potential confusion when using multiple frame definitions, JPL has computed lunar gravity fields in both PA and ME frames with numerically equivalent accuracy

Degree RMS of Gravity Spectrum



Residuals of GRAIL S/C-to-S/C Data



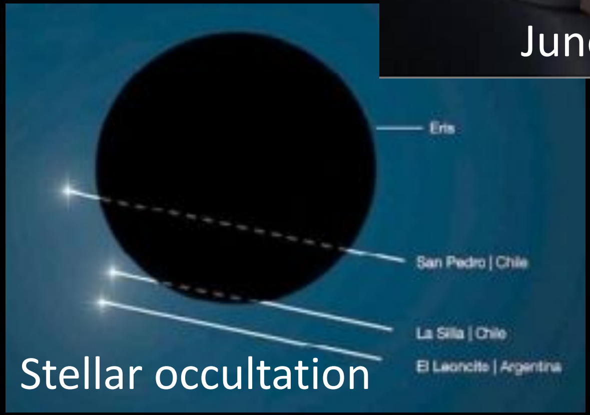


GRAIL-based lunar gravity field should be sufficiently accurate for all near-term practical needs.

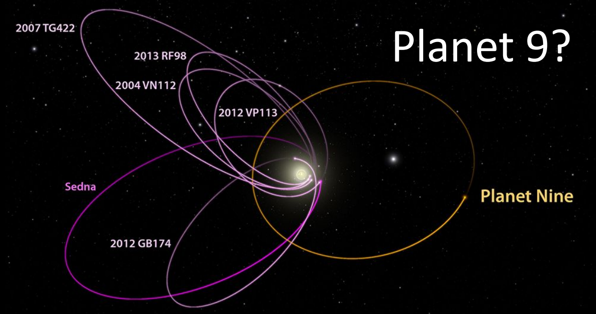
The Future with and without ILTN

- Continue to improve dynamical modeling, data calibration, data fusion, etc.
  - Without ILTN, generally getting asymptotic in accuracy due to systematic errors
  - ILTN improves data noise, plasma noise, enables additional observability due to planet-planet measurement
  - ILTN still subject to spacecraft orbit modelling, asteroid perturbations, etc
    - More detailed numerical simulations are needed to understand capability of ILTN
- Inner planets
  - Rely on improved information from planned orbiters
    - Bepi-Colombo for Mercury, upcoming Venus missions for topography
    - Hope for GRACE@Mars but not in planning for next decade
- Support planetary and fundamental science with ILTN
  - Search for potential distant planets – challenging without ILTN
  - Gravity waves (was tried unsuccessfully with Cassini X/Ka)
  - Dark matter?


Juno at Jupiter



Stellar occultation



Planet 9?

Summary

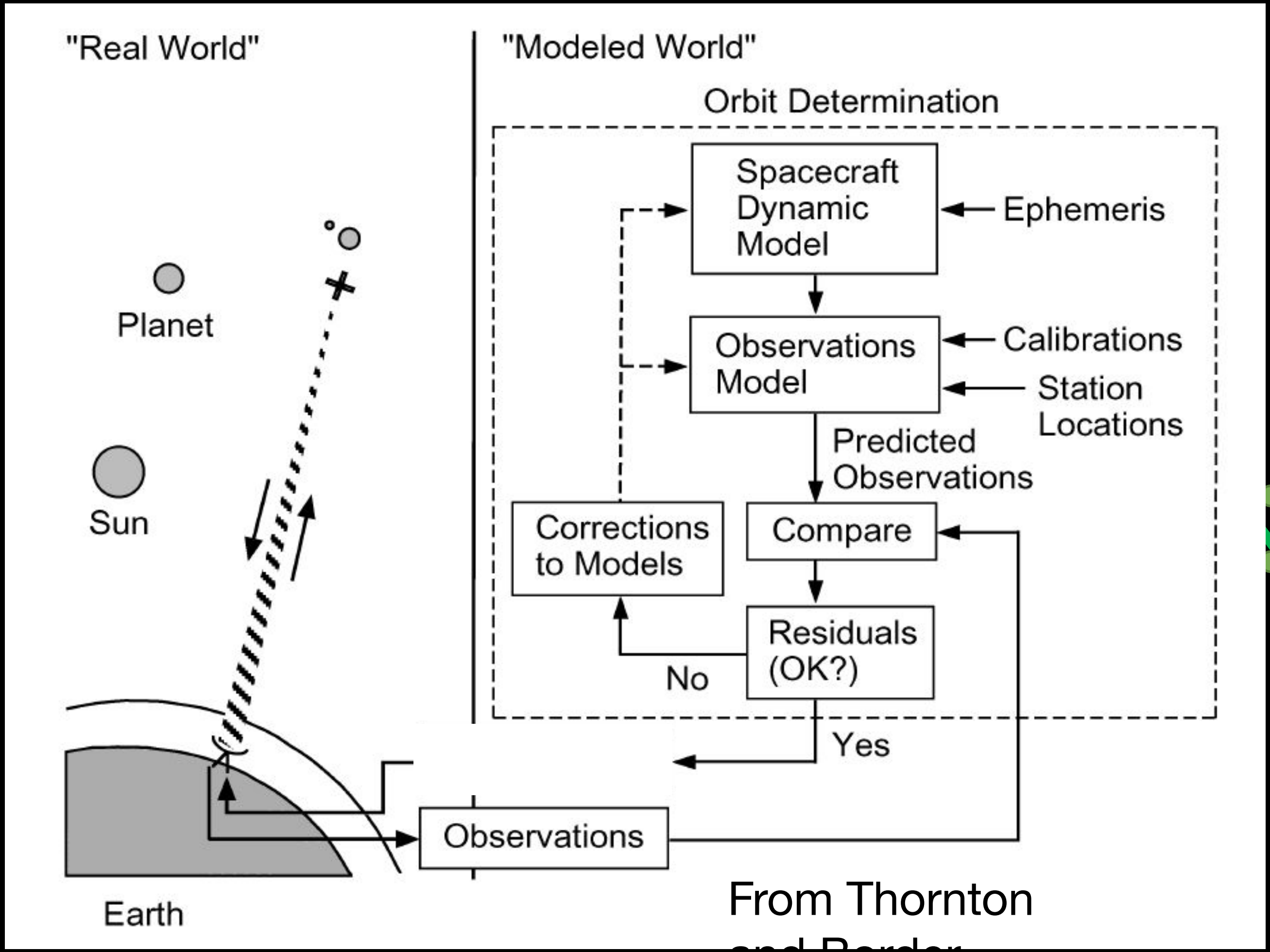
- Measuring and understanding the orbits and gravity of planetary bodies play a crucial role in planetary science and physics

- ILTN can be a key next step in Solar System Dynamics
  - Only proposed significant improvement in SSD measurements
  - High fidelity simulations are needed – these are key for mission acceptance

Thank you -

Questions?

Orbit Determination



From Thornton and Border

$$\ddot{\mathbf{r}}_i = \sum_{j\neq i} \frac{\mu_j(\mathbf{r}_j-\mathbf{r}_i)}{r_{ij}^{3}}\Bigg\{1-\frac{2(\beta+\gamma)}{c^2}\sum_{l\neq i}\frac{\mu_l}{r_{il}}-\frac{2\beta-1}{c^2}\sum_{k\neq j}\frac{\mu_k}{r_{jk}} + \gamma\left(\frac{\dot{s}_i}{c}\right)^2+(1+\gamma)\left(\frac{\dot{s}_j}{c}\right)^2-\frac{2(1+\gamma)}{c^2}\dot{\mathbf{r}}_i\cdot\dot{\mathbf{r}}_j - \frac{3}{2c^2}\left[\frac{(\mathbf{r}_i-\mathbf{r}_j)\cdot\dot{\mathbf{r}}_j}{r_{ij}}\right]^2+\frac{1}{2c^2}(\mathbf{r}_j-\mathbf{r}_i)\cdot\ddot{\mathbf{r}}_j\Bigg\} + \frac{1}{c^2}\sum_{j\neq i}\frac{\mu_j}{r_{ij}^{3}}\left\{[\mathbf{r}_i-\mathbf{r}_j]\cdot[(2+2\gamma)\dot{\mathbf{r}}_i-(1+2\gamma)\dot{\mathbf{r}}_j]\right\}(\dot{\mathbf{r}}_i-\dot{\mathbf{r}}_j) + \frac{3+4\gamma}{2c^2}\sum_{j\neq i}\frac{\mu_j\ddot{\mathbf{r}}_j}{r_{ij}}$$

Equations of motion

$$\begin{bmatrix}\ddot{\xi}\\ \ddot{\eta}\\ \ddot{\zeta}\end{bmatrix} = -\frac{\mu}{r^2}\Bigg\{\sum_{n=2}^{n_1} J_n\left(\frac{R}{r}\right)^n\begin{bmatrix}(n+1)P_n(\sin\phi)\\ 0\\ -\cos\phi P_n'(\sin\phi)\end{bmatrix} + \sum_{n=2}^{n_2}\left(\frac{R}{r}\right)^n\sum_{m=1}^{n}\begin{bmatrix} -(n+1)\ P_n^m(\sin\phi)\ [+C_{nm}\cos m\lambda+S_{nm}\sin m\lambda]\\ m\sec\phi\ P_n^m(\sin\phi)\ [-C_{nm}\sin m\lambda+S_{nm}\cos m\lambda]\\ \cos\phi\ P_n^{m\prime}(\sin\phi)\ [+C_{nm}\cos m\lambda+S_{nm}\sin m\lambda]\end{bmatrix}\Bigg\}$$

Extended body acceleration

Cost function

$$J = \frac{1}{2}\sum_{i=1}^{N}\frac{(\mathbf{z}_i^* - \mathbf{z}_i(\mathbf{x}_0))^2}{\sigma_i^2}$$

$$\sum_{i=1}^{N}\mathbf{\Phi}_i^T\mathbf{h}_{\mathbf{x}_i}^T\frac{1}{\sigma_i^2}\Delta\mathbf{z}_i = \left(\sum_{i=1}^{N}\mathbf{\Phi}_i^T\mathbf{h}_{\mathbf{x}_i}^T\frac{1}{\sigma_i^2}\mathbf{h}_{\mathbf{x}_i}\mathbf{\Phi}_i\right)\delta\mathbf{x}_0$$

Least-squares estimation