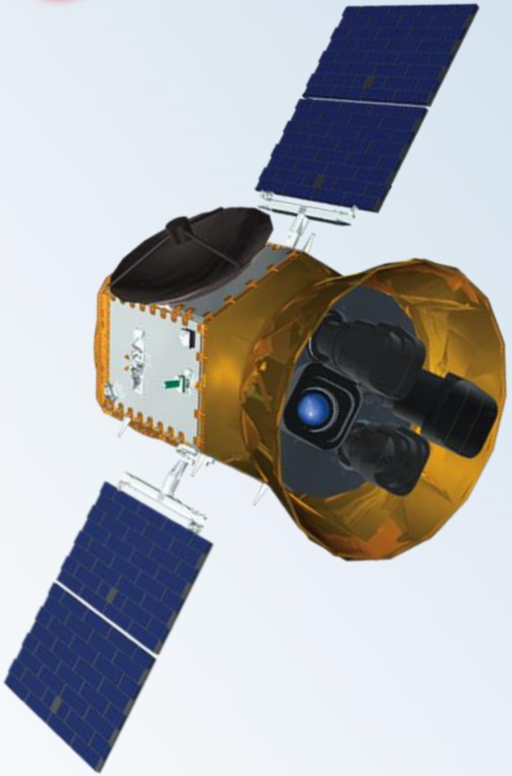
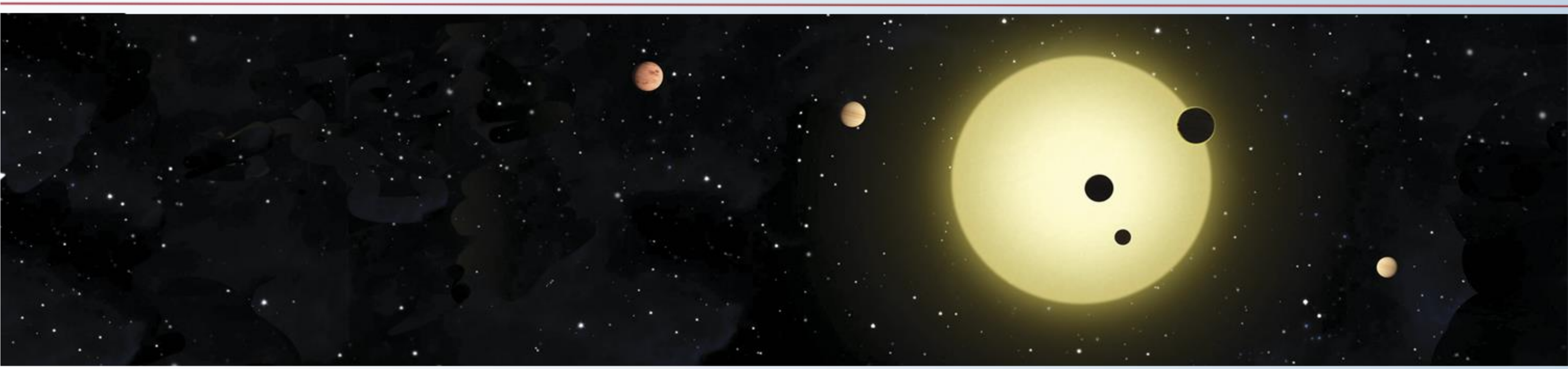


Transiting Exoplanet Survey Satellite (TESS) Flight Dynamics Commissioning Results and Experiences

Joel J. K. Parker	***NASA Goddard Space Flight Center***
Ryan L. Lebois	*L3 Applied Defense Solutions*
Stephen Lutz	*L3 Applied Defense Solutions*
Craig Nickel	*L3 Applied Defense Solutions*
Kevin Ferrant	*Omitron, Inc.*
Adam Michaels	*Omitron, Inc.*

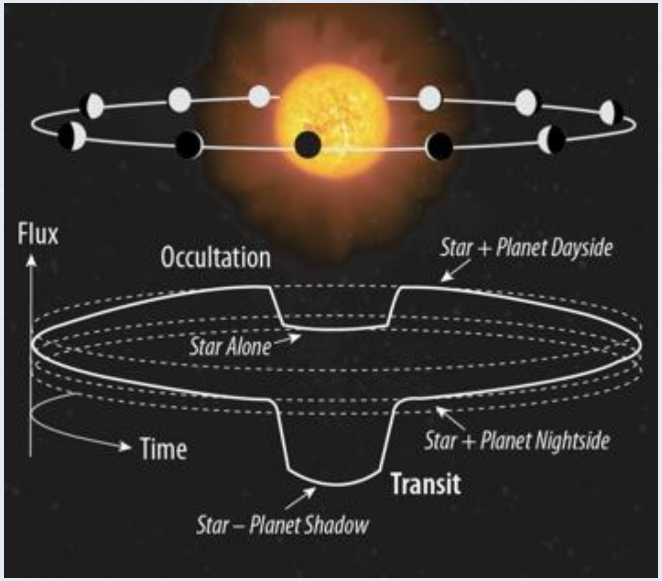
August 22, 2018



Contents

- Mission Overview
- Flight Dynamics Ground System
- TESS Commissioning
  - *Launch*
  - *Phasing Loops & Maneuver Execution*
  - *PAM & Extended Mission Design*
  - *Commissioning Results*
- Orbit Determination
- Conclusions

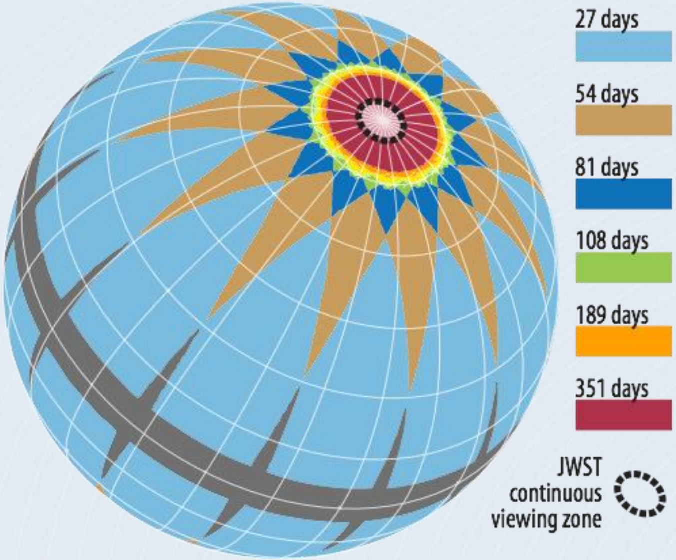
Mission Overview—Science Goals



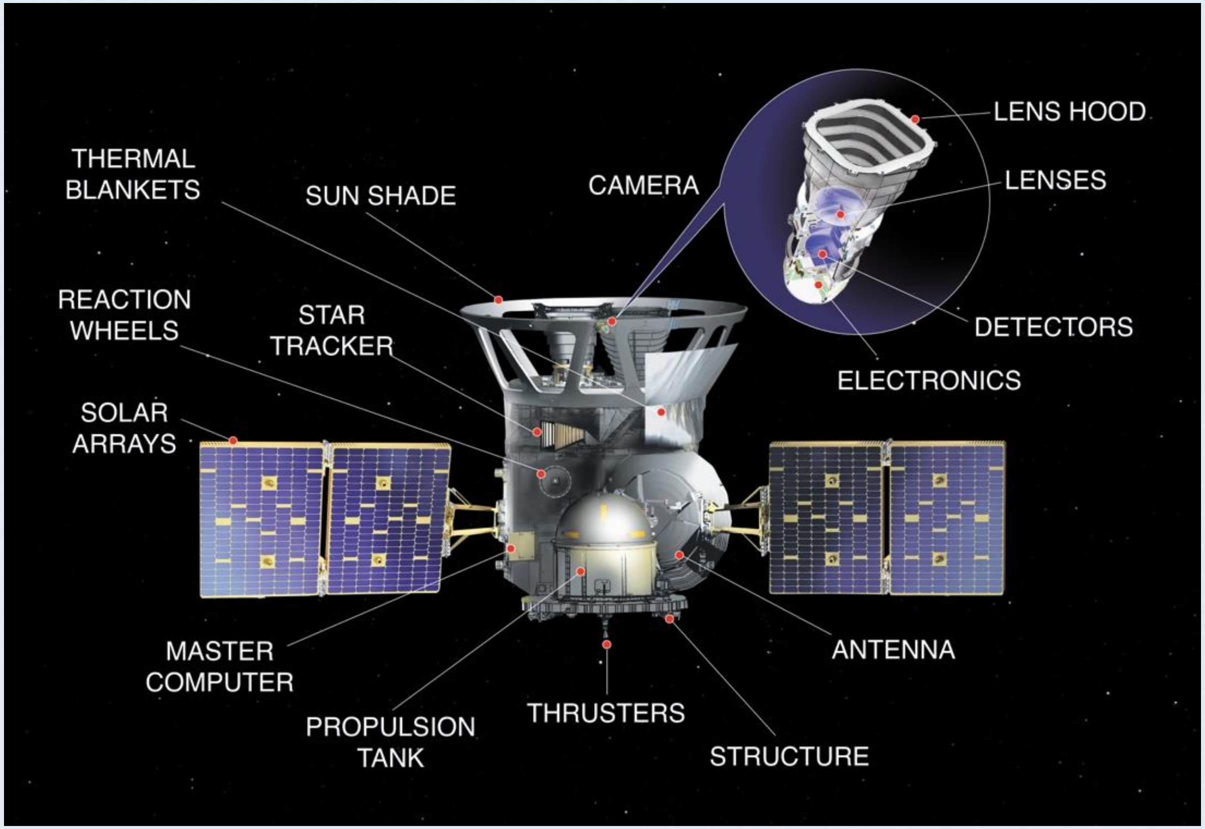
- **Primary Goal:** Discover Transiting Earths and Super-Earths Orbiting Bright, Nearby Stars
  - *Rocky planets & water worlds*
  - *Habitable planets*
- Discover the "Best" ~1000 **Small** Exoplanets
  - *"Best" means "readily characterizable"*
    - *Bright Host Stars*
    - *Measurable Mass & Atmospheric Properties*
- Unique lunar-resonant mission orbit provides long view periods without station-keeping

Large-Area Survey of Bright Stars

- *F, G, K dwarfs: +4 to +12 magnitude*
- *M dwarfs known within ~60 parsecs*
- *"All sky" observations in 2 years*
  - *All stars observed >20 days*
  - *Ecliptic poles observed ~1 year (JWST Continuous Viewing Zone)*

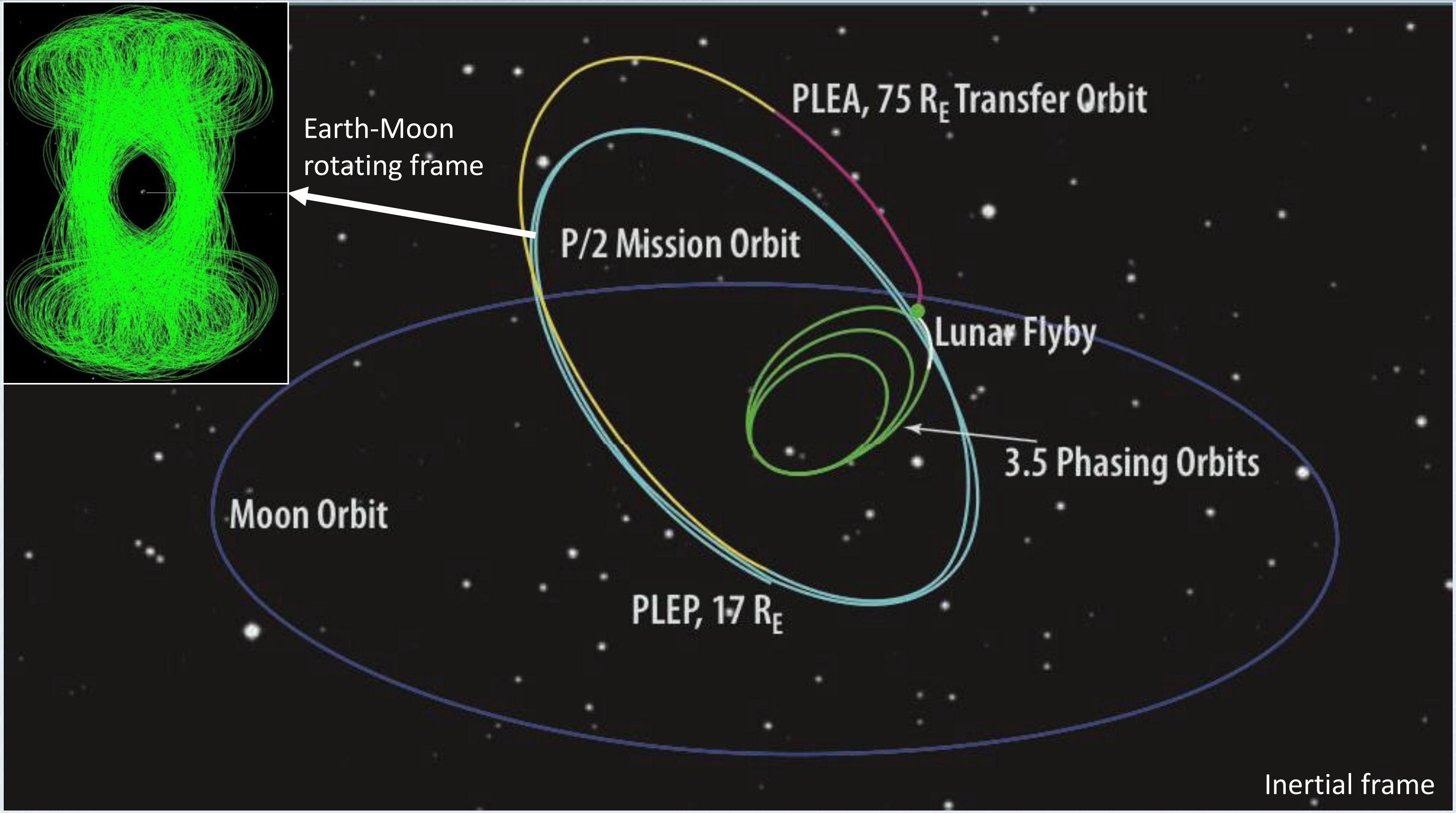


Mission Overview—Spacecraft



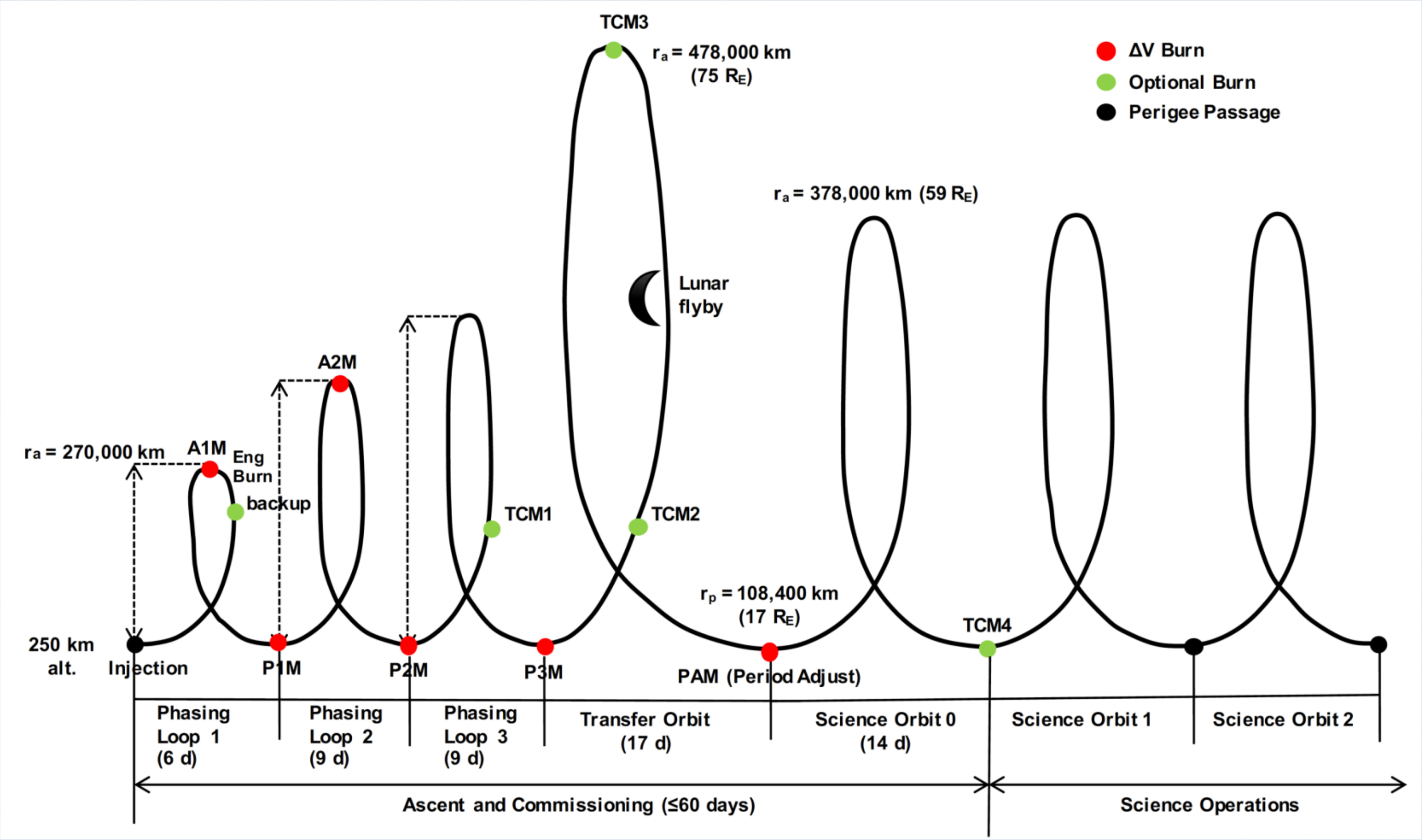
- Northrop Grumman LEOStar-2/750 bus
- **Propulsion**:
  - *1x 22N ΔV reaction engine assembly (REA)*
  - *4x 4.5N REA for attitude control*
- **Communications**:
  - *2x S-band omnidirectional antennas*
  - *1x Ka-band high-gain antenna (HGA)*
- **Attitude Control**:
  - *4x reaction wheel assemblies (RWAs), 2x star tracker assemblies, 10x coarse sun sensors*
  - *Keep-out zones associated with all sensors*
- **Instrument**:
  - *4x camera assemblies*
  - *30° by ± 50° rectangular keep-out zone*

Mission Overview—Trajectory Design



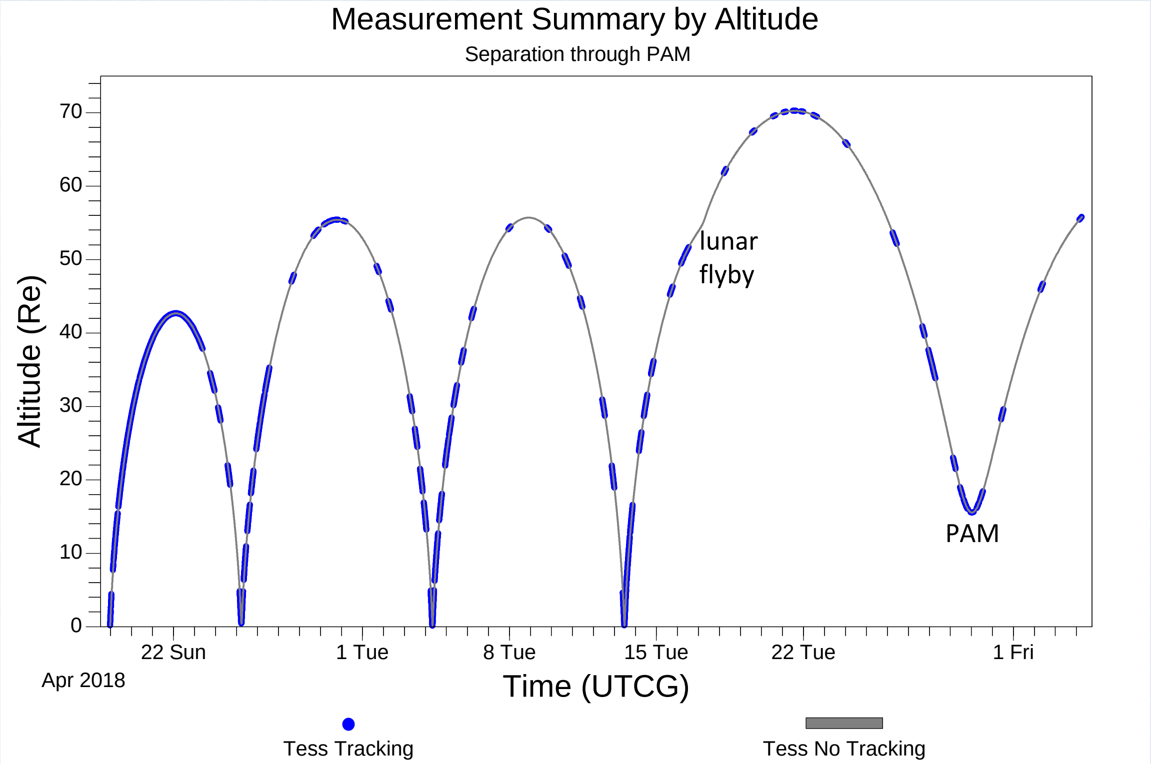
- Overall mission design:
  3.5 phasing loops → lunar flyby → transfer orbit → mission orbit
- Mission orbit features 2:1 lunar resonance (“P/2”), or 13.67 d mean orbit period

Mission Overview—Commissioning



- Overall commissioning is ≤60d process
- 6 planned maneuvers + 5 optional/backup maneuvers

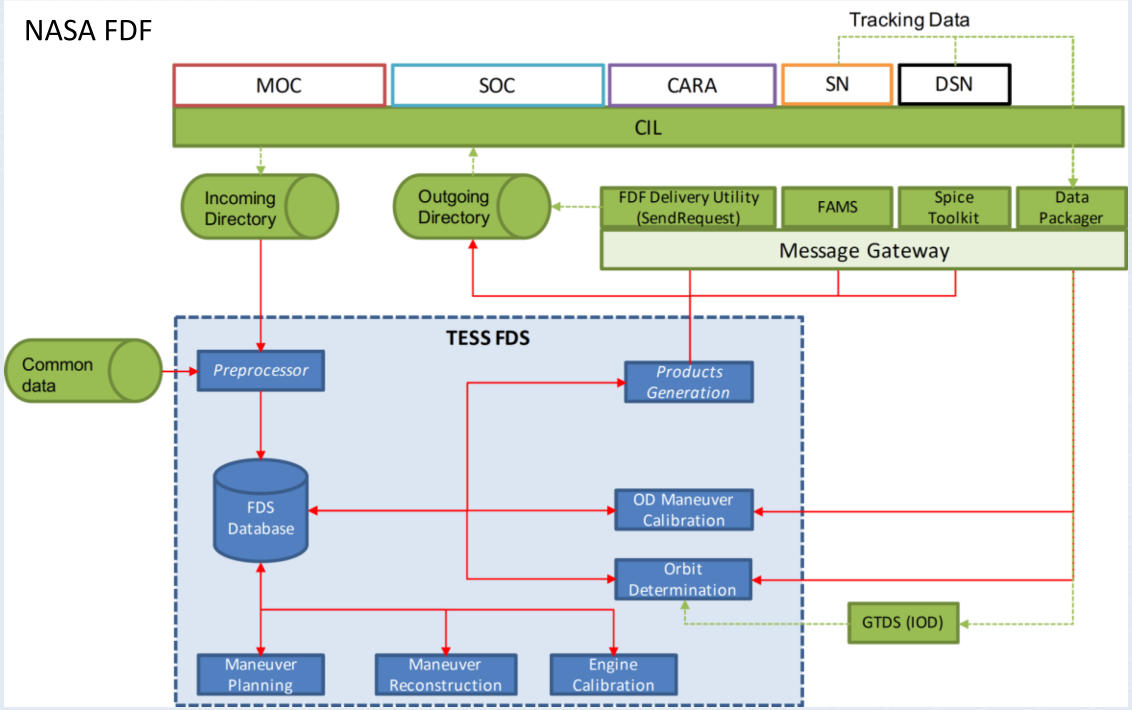
Mission Overview—Navigation



- Navigation support provided by NASA Deep Space Network (DSN) and Space Network (SN)
- SN post-separation acquisition at +1 min
- Handover to DSN by +1.5 hr
- Near-continuous tracking through first phasing loop, then scheduled to cover maneuvers and meet OD accuracy requirements
- Post-launch SN support scheduled around perigee maneuvers only

Flight Dynamics Ground System

- TESS Flight Dynamics Ground System:
  - *NASA Flight Dynamics Facility (FDF)*
  - *TESS Flight Dynamics System*
- FDF responsibilities:
  - *Facility/infrastructure*
  - *DSN/SN data interfaces*
  - *IOD external verification*
- FDS responsibilities:
  - *Maneuver planning*
  - *Orbit determination*
  - *Product generation*
  - *Maneuver reconstruction/calibration*



- Software utilized:

Software	Use
L3 ADS Flight Dynamics System (FDS)	Procedure Execution, Data Management
NASA General Mission Analysis Tool (GMAT)	Maneuver Planning, Ephemeris Generation
AGI Orbit Determination Tool Kit (ODTK)	Primary Orbit Determination
Goddard Trajectory Determination System (GTDS)	Backup Orbit Determination
SPICE Toolkit	DSN Acquisition Generation
AGI Systems Tool Kit (STK)	Analysis, QA, Visualizations
MATLAB	Analysis, Plotting

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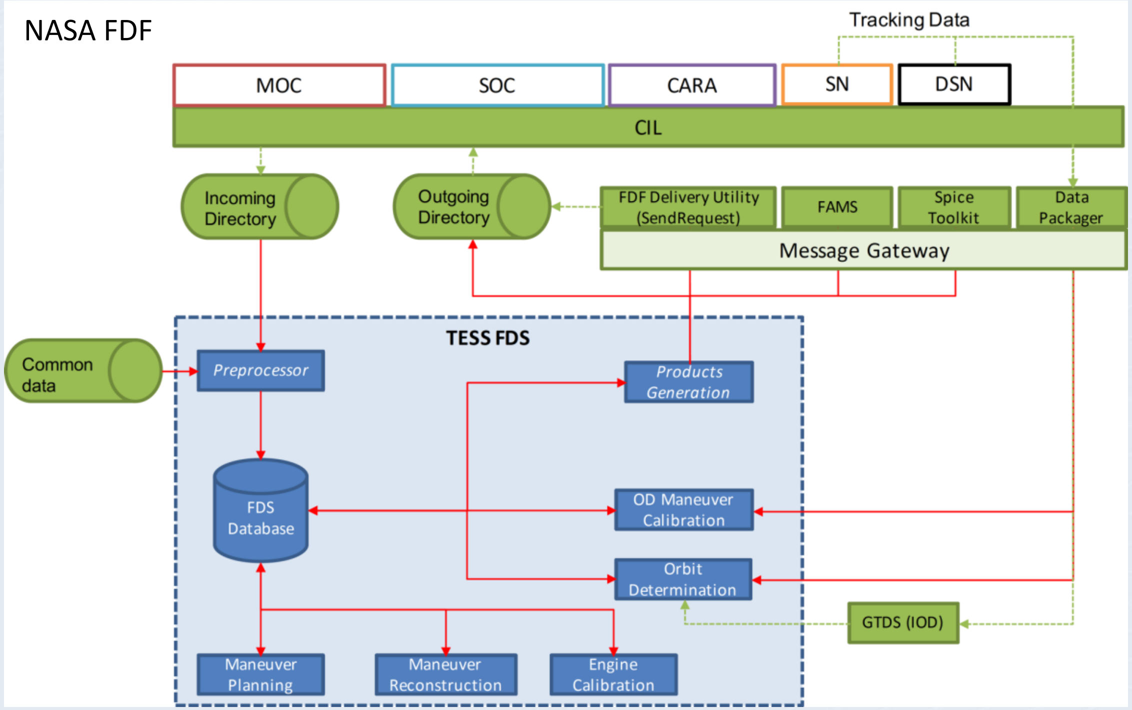

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MATLAB	Analysis, Plotting

First end-to-end use of GMAT in primary maneuver planning role

Launch Performance

Launch Date: April 18th 2018

Vehicle: SpaceX Falcon 9

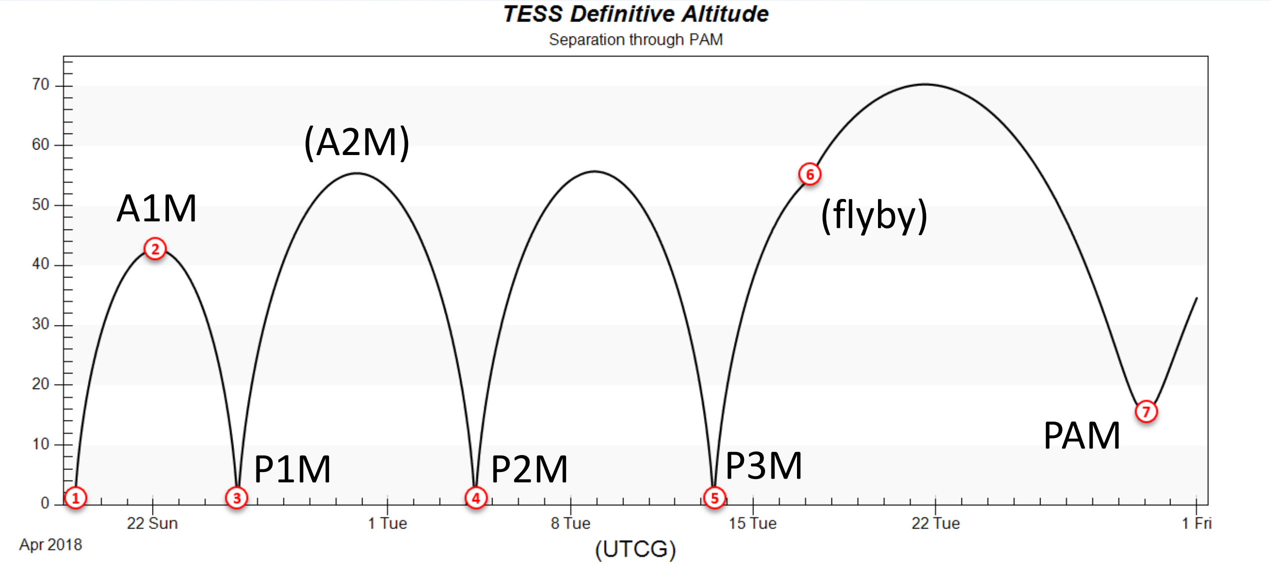
Location: Cape Canaveral Air Force Station, SLC-40

Event	Actual (UTC)	Delta (s)
Liftoff	22:51:30.498	-0.502
Separation	23:41:03.177	+2.177

Element*	Pre-Launch BET	OD	Delta	3σ Requirement	Sigma
Apogee Altitude [km]	268,622.397	269,330.228	707.831	± 20,000	0.11
Perigee Altitude [km]	248.456	248.755	0.299	± 25	0.04
Inclination [deg]	29.563	29.579	0.016	± 0.1	0.48
Argument of Perigee [deg]	228.111	228.088	-0.023	± 0.3	-0.23

*All elements at epoch: 18 Apr 2018 23:45:30.666 UTC

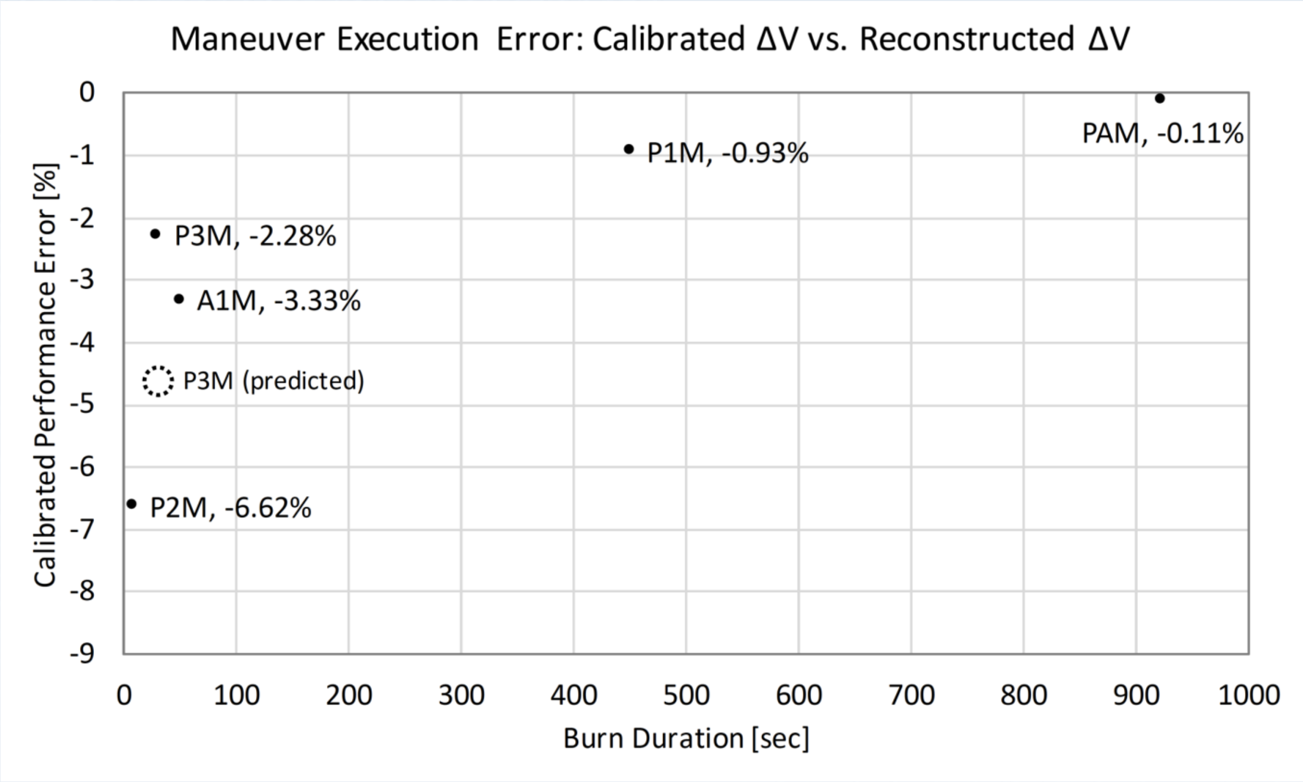
Phasing Loops



- All burns nominal
- A2M waived as unnecessary
- Performance error
  - *<7% worst-case*
  - *<1% for major maneuvers*

Maneuver	Epoch	Dur. (sec)	Calibrated ΔV (m/s)	Performance Error (%)	Mean Pointing Error (deg)
A1M	22 Apr 2018 01:59:06.628	50	3.915	-3.33	9.6
P1M	25 Apr 2018 05:36:42.053	449	32.265	-0.93	0.6
P2M	04 May 2018 08:05:46.650	7	0.430	-6.62	0.4
P3M	13 May 2018 11:37:48.648	29	1.862	+2.87	1.6
PAM	30 May 2018 01:20:23.149	923	53.409	-0.11	0.7

Maneuver Performance

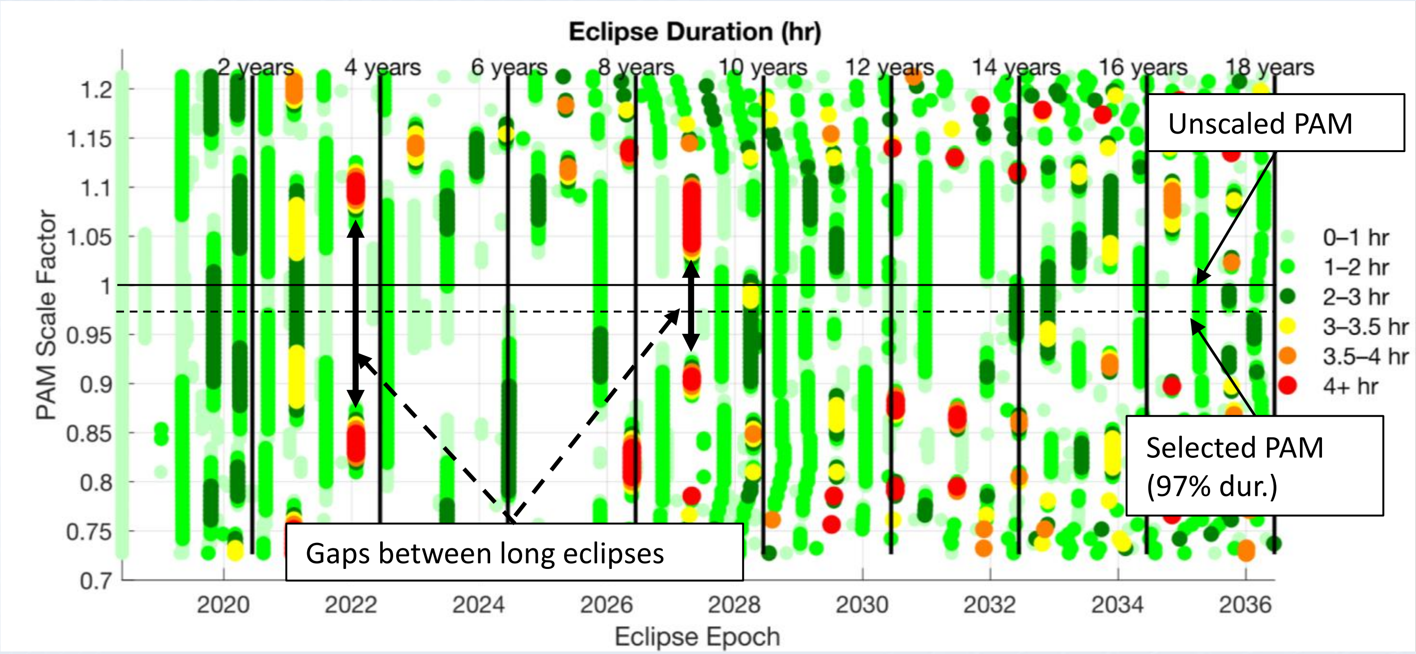


- Maneuver performance error trends with duration
  - *Shorter duration correlated with underperformance*
  - *Trend explained as an artifact of thermal ramp-up of propulsion system*
- Analysis through P2M was used to predict likely performance of P3M flyby-targeting maneuver
  - *Maneuver thrust scaled by 95% during P3M planning to better target desired flyby*

PAM Design & Extended Mission Design

- PAM: Period Adjust Maneuver
  - *Goal: Lower apogee to achieve 2:1 lunar resonance (approx. 13.67 day orbit period)*
  - *Secondary objectives:*
    - *Improve long-term eclipse profile*
    - *Maintain long-term orbit stability*
  - *Long-term extended-mission analysis performed to 18–25 years of mission life (to extent of prediction capability)*
- PAM was fine-tuned via parametric scanning process
  - *PAM start epoch fixes eclipse "trade space"*
  - *PAM duration chooses specific eclipse profile within trade space*
- Two major tools:
  - *Eclipse profile plots (a.k.a. "Napolean plots")*
  - *Mean orbit period plots*

Extended Mission Eclipse Profile



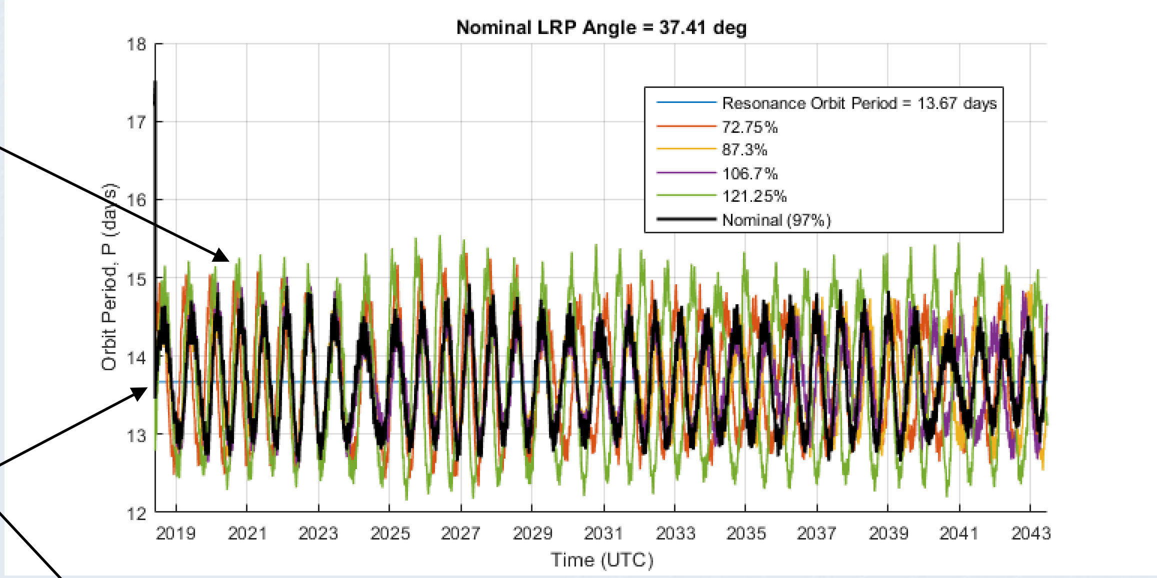
- "Napoleon plot": Each row shows eclipses over time for a trajectory associated with a given PAM duration (scale factor from nominal).
  - *Plot trade space is fixed with PAM start epoch (chosen by targeter)*
  - *Selected profile (row) is fixed with choice of PAM duration (scale factor)*
- Selected PAM duration was chosen to avoid 3+ hr eclipses in 2021 and 4+ hr eclipses in 2027
  - *Selected duration = 97% of nominal (923 s, 53.6 m/s)*
  - *Associated initial mission orbit period = 13.72 days*

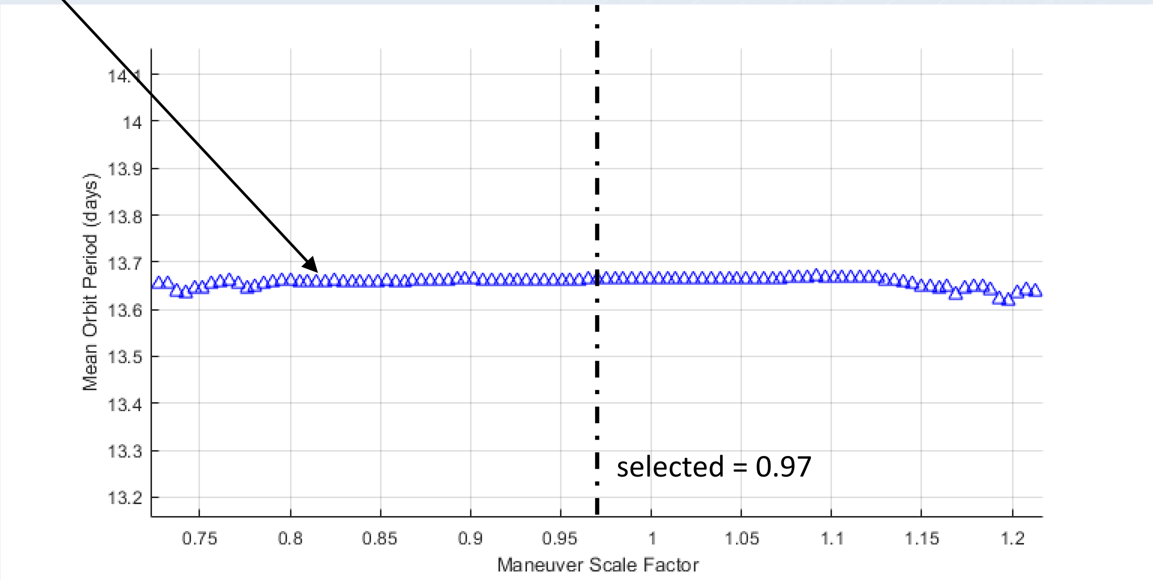
Extended Mission Stability

Each series = 1 PAM scaling value

25-year mean (above) is represented as one value (below)

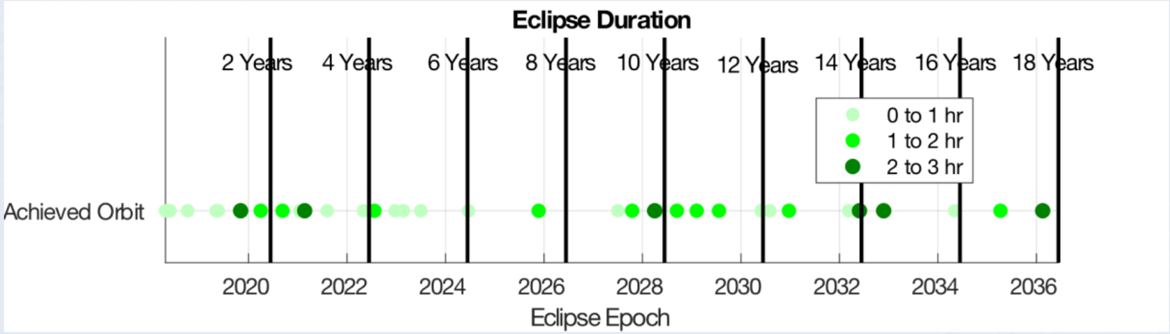
Mean should be approx. 13.67 days to indicate stability





Commissioning Results

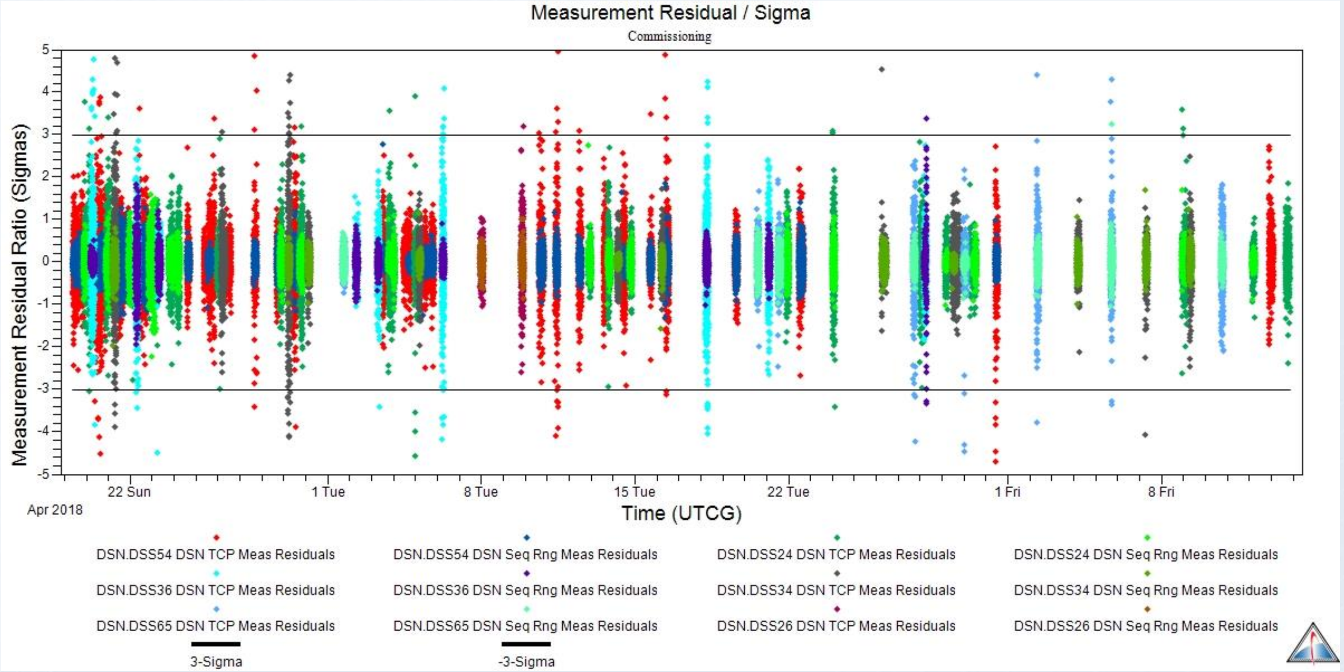
- PAM execution nominal; achieved long-term eclipse profile shows no eclipses >3 hr duration
- Achieved initial orbit period = 13.73 d
- Long-term stability and perigee/apogee altitude predictions meet expectations



- All commissioning mission requirements were met:

Requirement	Value	Achieved
Orbit Period	13.67 days (2:1 lunar resonance)	Achieved (orbit period oscillates about 13.67 days)
Maximum Perigee Radius	≤ 22 R_E	18.70 R_E
Maximum Apogee Radius	< 90 R_E	70.25 R_E
Maximum Total ΔV	≤ 215 m/s	91.19 m/s
Maximum Single Maneuver ΔV	≤ 95 m/s	53.41 m/s
Maximum Commissioning Duration	≤ 2 months	54.87 days
Eclipses	≤ 16 eclipses, ≤ 4 hours duration each (umbra + ½ penumbra)	10 eclipses in primary mission; longest = 2.5 hr
Orbit Determination Position Accuracy	≤ 6 km per axis	Achieved throughout commissioning
Orbit Determination Velocity Accuracy	≤ 7% of maneuver magnitude	Achieved throughout commissioning

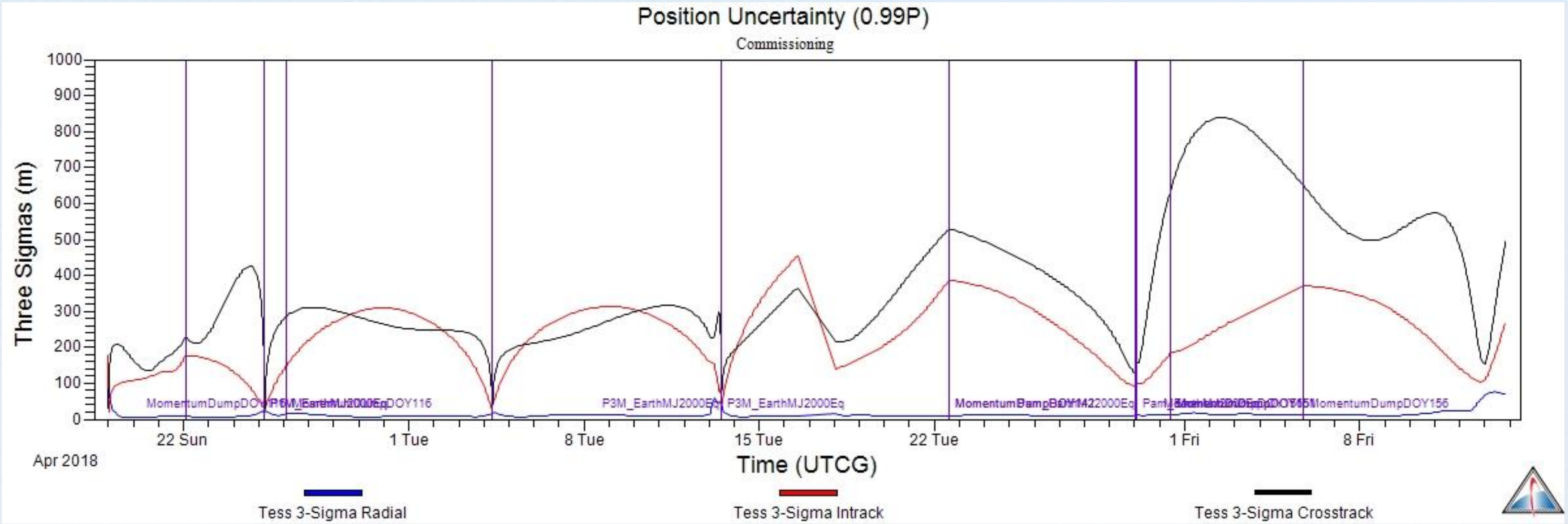
Orbit Determination



- Orbit determination was performed throughout commissioning
- Software: AGI Orbit Determination Toolkit (ODTK)
- DSN measurement types processed: TCP, Sequential Range
- TDRS 5L Doppler measurements were available, but not used in final solution

Measurement types	DSN TCP, DSN SeqRng, TDRS 5L Doppler
DSN antennas	DSS24, DSS26, DSS34, DSS36, DSS54, DSS65
TDRS satellites	TDRS-K, TDRS-L

Orbit Determination

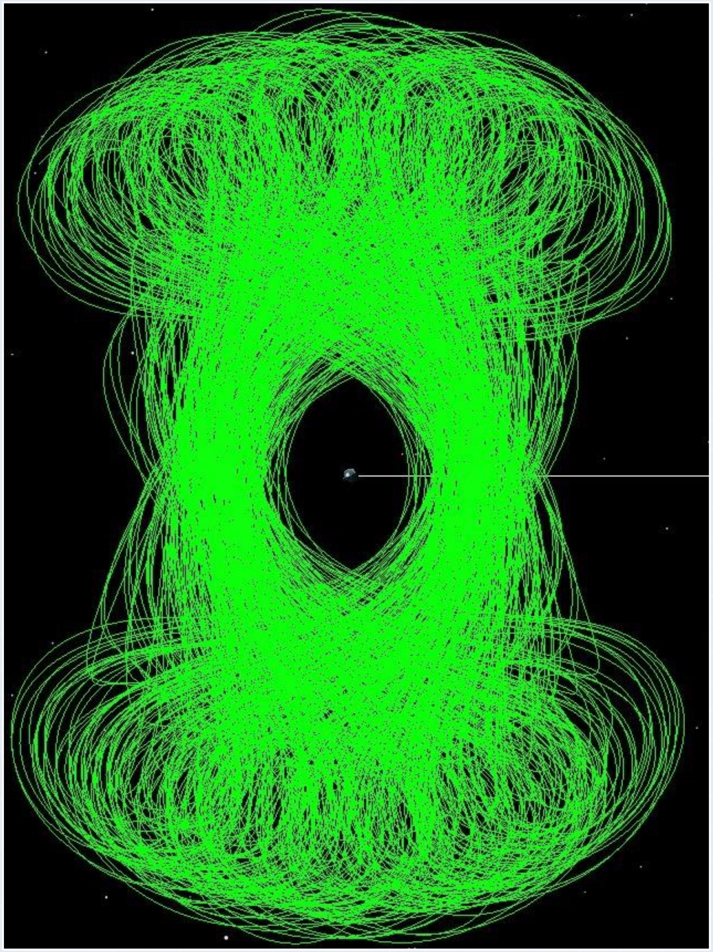


Parameter	Constant Bias	Bias 1σ	White Noise 1σ	Bias Half-life [min]
DSN TCP	-0.08	0.05	0.005	60
DSN SeqRng [m]	0	5	0.25	60
Spacecraft C_r	1.5	0.2	N/A	2880
Spacecraft C_d	2.2	Not Estimated		
Spacecraft Transponder Delay [ns]	5863.46	10	N/A	2880

- Minimal filter tuning was required
- Small injections of process noise were used sporadically to prevent collapse of covariance during perigee passes
- Overall 3σ position uncertainty < 900 m
  - *< 450 m through phasing loops*
- Filter-smoother consistency well-behaved, remains w/in ±3σ bounds

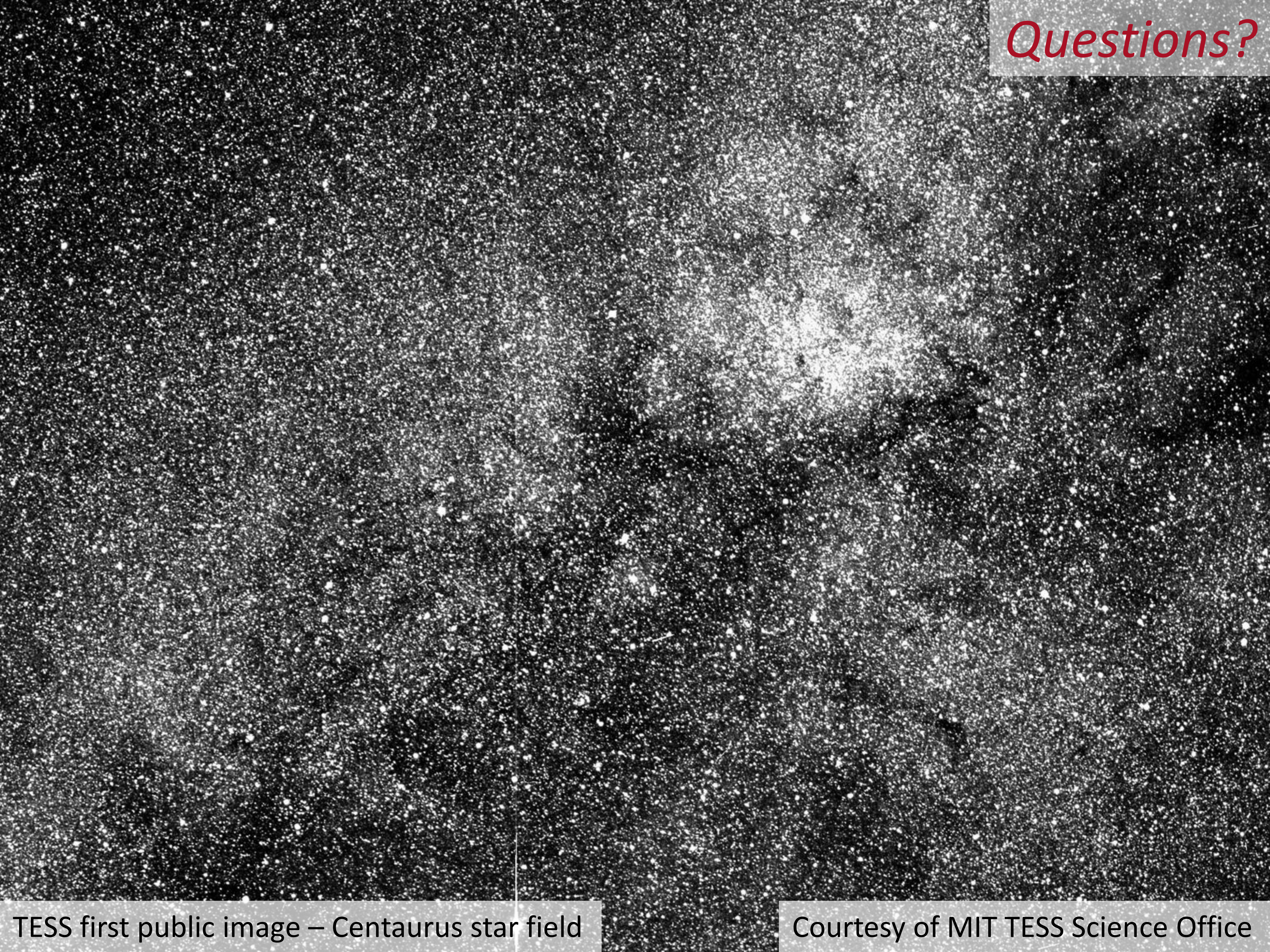
Conclusions

- TESS will perform the first-ever spaceborne all-sky survey of exoplanets transiting bright stars.
- TESS launched nominally on 18 Apr 2018, and successfully executed a 60-day flight dynamics commissioning phase.
- All maneuvers executed nominally or were waived as unnecessary.
- All commissioning and primary mission requirements were met or exceeded and are expected to continue to be met for 18+ years.
- Mission ”firsts”:
  - *First mission designed for resonant orbit in the primary mission*
  - *Use of innovative techniques for fine-tuning final maneuver for long-term characteristics*
  - *First application of NASA’s open-source GMAT in a primary role*



- TESS is now on-orbit and started science operations on July 25.

Questions?



TESS first public image – Centaurus star field

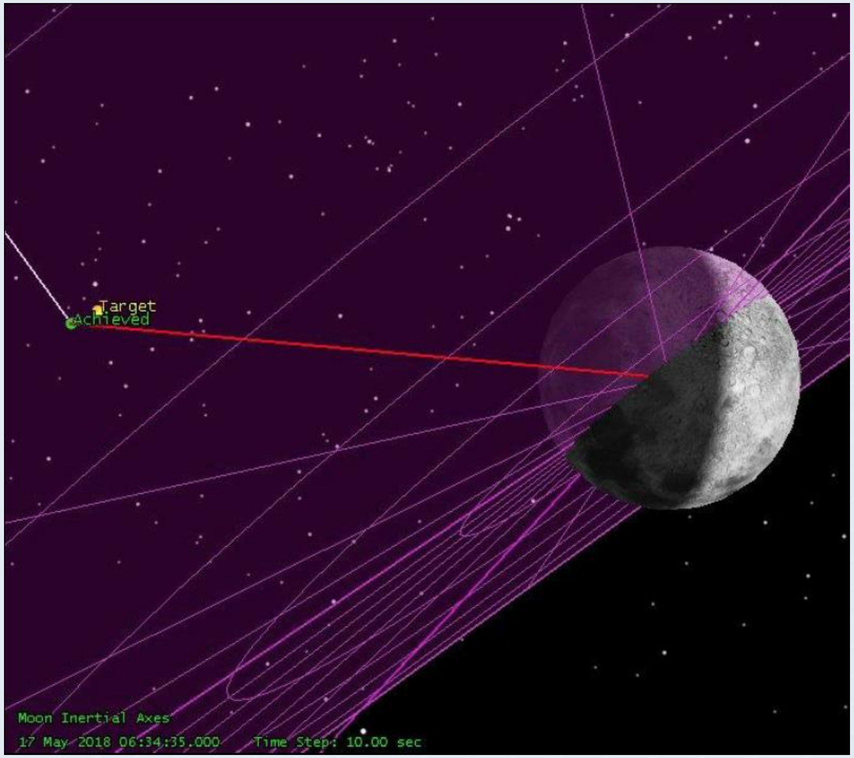
Courtesy of MIT TESS Science Office

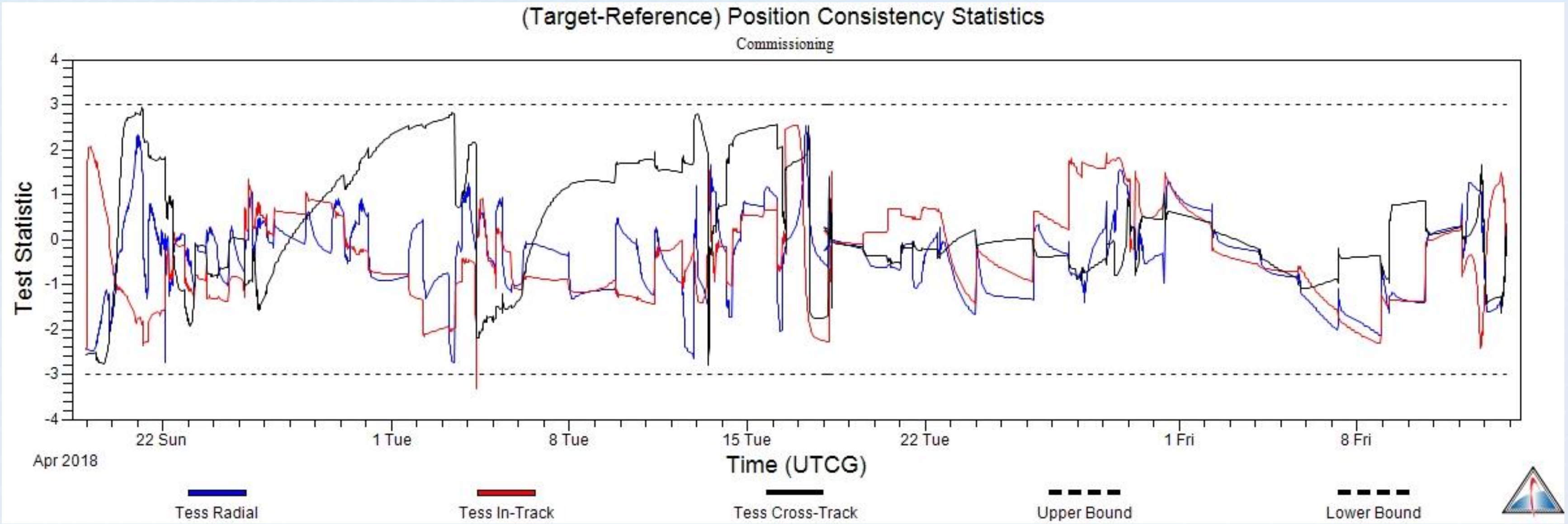
Lunar Flyby & Transfer Orbit

- **Lunar flyby: 17 May 2018**
- Performance as expected:

Event	Time (UTC)	Lunar Altitude (km)
Expected	06:33:06	8183 km
Observed	06:34:36	8254 km
Delta	90 s	71 km

Element	Pre-flyby	Post-flyby
Perigee Radius (R_E)	1.14	16.53
Apogee Radius (R_E)	56.23	72.61
INC (deg)	29.3	36.6
RAAN (deg)	37	286
AOP (deg)	230	356





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