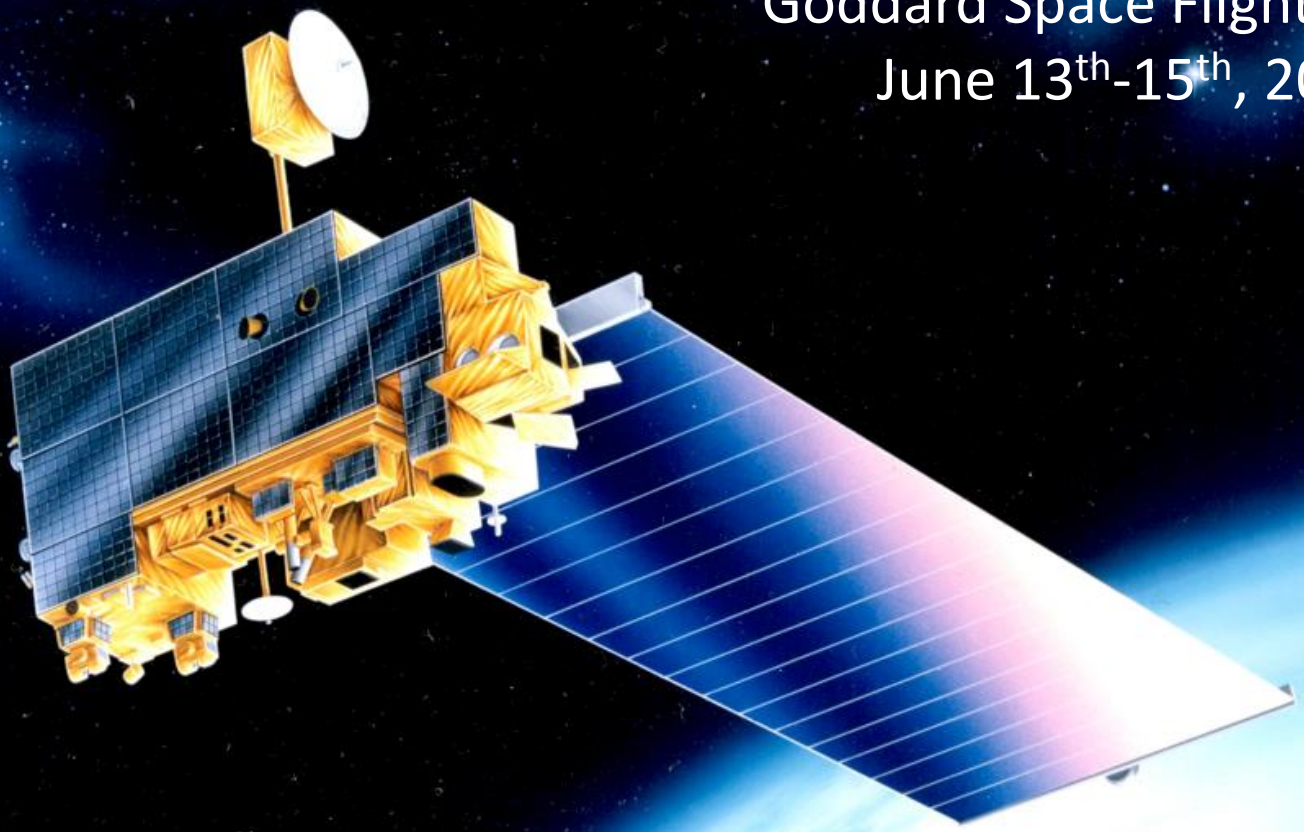
EOS Terra

Mission Status
Constellation MOWG

Goddard Space Flight Center

June 13th-15th, 2017



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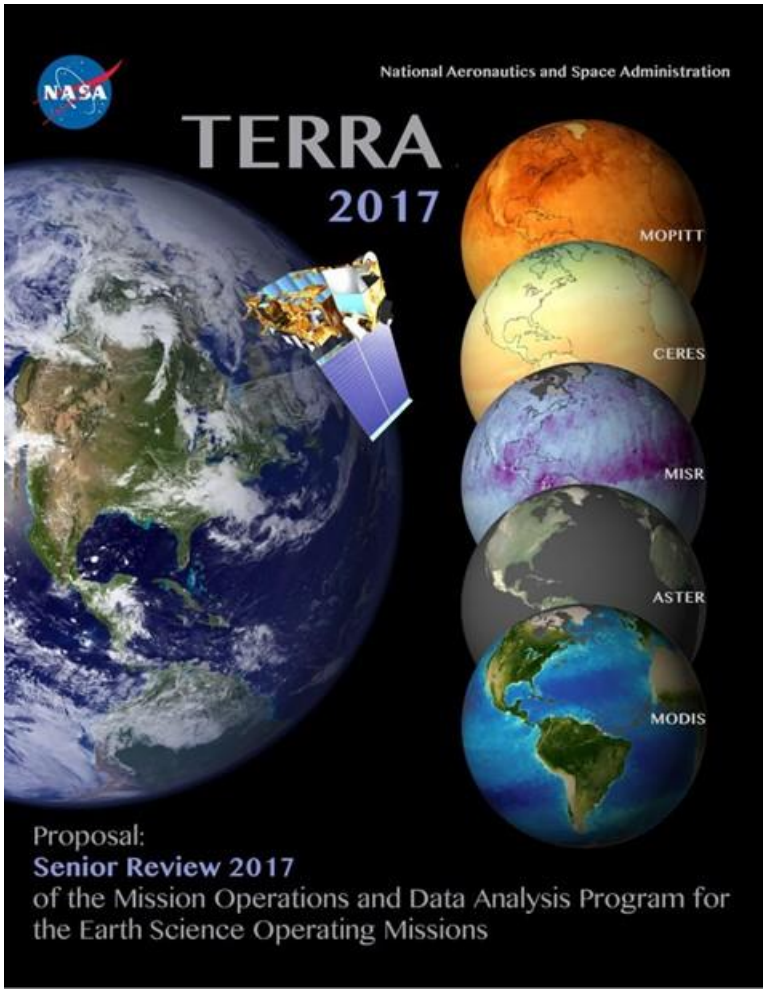
Topics

- Mission Summary
- Spacecraft Subsystems Summary
- Recent Activities
- Inclination Adjust Maneuvers
- Conjunction History
- End-Of-Mission Plan
- Future Plans
- Summary
- Backup Slides

EOS Terra Mission Summary

- **May 2017: Mission Extension Senior Review Proposal Panel Report**
  - Mission extension through FY22
  - Senior Review submission delivered in Mar 2017
- **2016-17 Inclination Adjust Maneuvers**
  - Spring 2016 Inclination Maneuvers
    - IAM #43 - February 18th
      - Aborted – Terra to Safehold
    - IAM #44 – March 3rd
    - IAM #45 – March 11th
  - Fall 2016 Inclination Maneuvers
    - IAM #46 – October 20th
  - Spring 2017 Inclination Maneuvers
    - IAM #47 – February 16th
    - IAM #48 – February 23rd
- **12/18/16: Terra 17-Year Anniversary**
  - 5-Year Design Life, 6 year goal
  - Reliability Estimates thru 2022+
  - Consumables through 2020+
- **January 2017: EOS Flight Operations Annual Review #11**



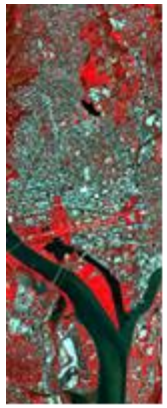
Terra Mission Overview

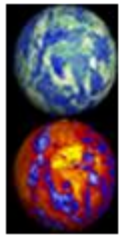
Terra Features

- **Launch Date:** *December 18,1999 (Atlas IIAS, VAFB)*
- **Orbit:** *705 km, Sun-synchronous polar, 98.2º Inclination, 10:30 AM MLT descending node*
- **Instrument Payload:**
  - **ASTER (*SWIR*, TIR & VNIR) -** *Advanced Spaceborne Thermal Emission and Reflection Radiometer* (Japan)
  - **CERES (Fore & Aft) -** *Clouds and the Earth's Radiant Energy System* (USA – Langley)
  - **MISR -** *Multi-angle Imaging Spectro-Radiometer* (USA – JPL)
  - **MODIS -** *Moderate Resolution Imaging Spectro-radiometer* (USA – GSFC)
  - **MOPITT -** *Measurement of Pollution in the Troposphere* (Canada)
- **Project Management:** *Earth Science Mission Operations (ESMO)*
- **Spacecraft Flight Operations:** *Contracted by GSFC to Honeywell / ASRC/JBS/AIMM team and supported by NASA NENs and TDRSS*
- **Instrument Operations and Science Data processing:** *Performed at respective Instrument Locations where developed*
- **Mission Duration:** *Successfully completed Prime mission of 5 years. Currently in Extended Operations.*
- **Distributed Active Archive Centers:** *LP DAAC – MODIS, ASTER; Langley DAAC – CERES, MISR, MOPITT*

Science

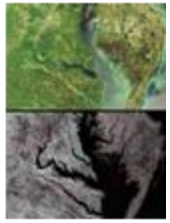
- *The primary objective of the Terra Mission is to simultaneously study clouds, water vapor, aerosol, trace gases, land surface and oceanic properties, as well as the interaction between them and their effect on the Earth's energy budget and climate.*

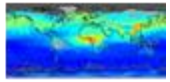

ASTER


CERES


Terra (EOS AM-1)


MODIS


MISR


MOPITT

Terra Spacecraft Status

No Change

All subsystems on Primary Hardware except as noted

- **Command & Data Handling** (CDH) – **Nominal**
  - Solid State Recorder (SSR) – holds ~1 orbit of data
  - 10 of 58 SSR Printed Wire Assembly tripped off resulting in reduced recording capacity
- **Communications** (COMM) – **Nominal**
  - DAS Modulator Failure on 05/29/2008 (Operating on Redundant)
  - Use K-Band primarily, X-Band as needed for Science Playback
- **Electrical Power System** (EPS) – **Good**
  - Battery Cell and Heater Controller Anomaly (10/13/2009)
  - 1 of 24 Solar Panel Failed (9/24/2000)
- **Flight Software** (FSW) – **Nominal**
- **Guidance, Navigation & Control** (GN&C) – **Nominal**
  - Minor loss of sensitivity in SSSTs – updated tracker biases to compensate
- **Propulsion** (PROP) – **Nominal**
- **Thermal Control System** (TCS) – **Nominal**
- **Instruments** (INST) – **Nominal**
  - Only ASTER SWIR failed, all other instruments are taking science

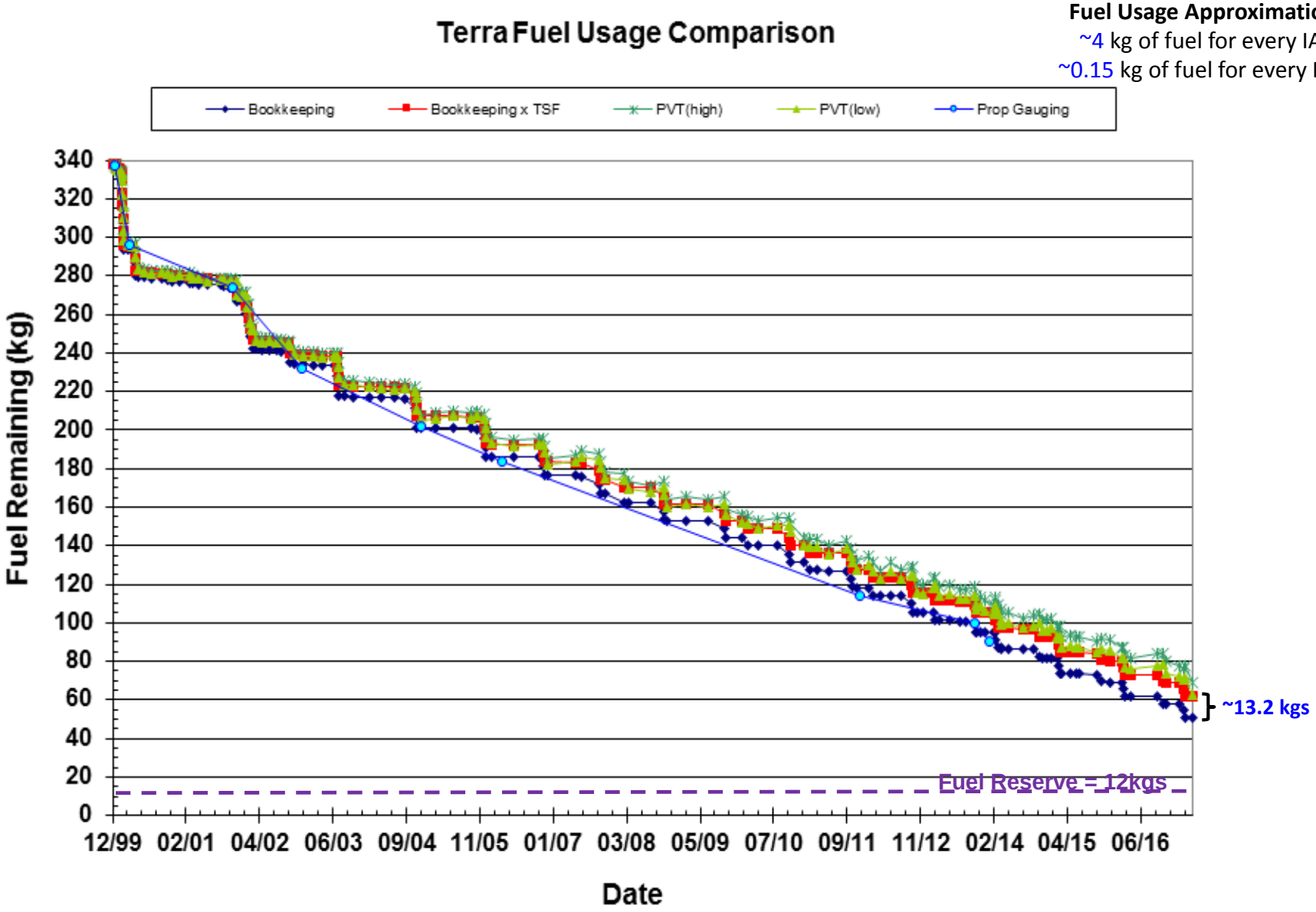
Spacecraft Component Status

No Change

Subsystem	Component	Design	Current	Capability	Comments
EPS	Solar Array	24 Shunts	23 Shunts	96%	Degradation is minimal. Fully capable of supporting mission thru 2020 unless future failures occur
	Batteries	108 Cells	107 Cells	99%	BBAT cell #50 failed on 10/15/09.
	Batteries	36 Heater Controls	28 Heater Controls	77%	BBAT heater control failed on 4 of 9 heater groups on primary, redundant, and survival. Battery cell charging/discharging and the remaining heater groups are preventing cells from freezing. PBAT heater control performance is nominal.
TCS	MOPITTCPHTS	2	2	Full	Performance is nominal
	SWIR CPHTS	2	2	Full	Performance is nominal
	TIR CPHTS	2	2	Full	Random temperature fluctuations. Performance within requirements.
SCC	SCC	2	2	Full	Performance is nominal
COMM	HGA	2	2	Full	MDA BITE failures occur 2-3/week due to SEU. Recoverable
	X-Band	2	1	75%	DAS Modulator 1 failed (50%). Solid State Power Amplifier redundancy still available (100%).
	CTIU	2	2	Full	Performance is nominal
	OMNI	2	2	Full	Performance is nominal
CDH	MO	2	2	Full	Drift rate changes have occurred since 10/3/10. Performance is within requirements.
	SFE	2	2	Full	SFE SEU occur 1-2/year. Recoverable
	SSR	59 PWA	49 PWA	83.1%	Recycle of Data Memory Unit likely to recover all Printed Wire Assemblies
GNC	IRU	3	3	Full	Performance is nominal. 2 for 3 redundancy
	TAM	2	2	Full	Performance is nominal
	SSST	2	2	Full	Minor loss of sensitivity in SSSTs – tracker biases updated
	CSS	2	2	Full	Performance is nominal
	ESA	2	2	Full	Performance is nominal
	FSS	1	1	Full	Performance is nominal. Not currently used
	RWA	4	4	Full	Performance is nominal. 3 for 4 redundancy
	MTR	3	3	Full	Performance is nominal
Prop	REAs	16	16	Full	Performance is nominal
Instruments	ASTER - SWIR	2	2	0%	Cooler is unable to maintain detector temperature. Science Data is unusable (Fully Saturated) and is no longer being recorded. Still collecting and monitoring Engineering data.
	ASTER - TIR	2	2	Full	Performance is nominal
	ASTER - VNIR	2	2	Full	Performance is nominal
	CERES - Aft	1	1	Full	Performance is nominal
	CERES - Fore	1	1	Full	Performance is nominal
	MISR	2	2	Full	Performance is nominal
	MODIS	2	1	50%	Power Supply #2 failed, Formatter A degraded, cross-strapped. **All Science is nominal.**
	MOPITT	2	1	50%	Displacer B and Chopper Motor failed. **Loss of redundancy only. All Science is nominal.**

Lifetime Fuel Estimates

Fuel Usage Approximations:
~4 kg of fuel for every IAM
~0.15 kg of fuel for every DMU



Recent Activities

- **Propulsive Maneuvers**
  - Drag Make Up Maneuver (DMU) #97 executed on 09/15/16
  - Inclination Adjust Maneuver (IAM) #46 on 10/20/16
    - First IAM using modified IAM methodology
  - Drag Make Up Maneuver (DMU) #98 executed on 11/11/16
  - Drag Make Up Maneuver (DMU) #99 executed on 01/19/17
  - Inclination Adjust Maneuver (IAM) #47 on 02/16/17
  - Inclination Adjust Maneuver (IAM) #48 on 02/23/17
  - Drag Make Up Maneuver (DMU) #100 executed on 04/06/17
  - Drag Make Up Maneuver (DMU) #101 targeted for 05/25/17

- **Calibration Maneuvers**
  - MODIS Roll #167 executed on 09/20/16
  - MODIS Roll #168 executed on 10/19/16
  - MODIS Roll #169 executed on 11/18/16
  - MODIS Roll #170 executed on 12/17/16
  - MODIS Roll #171 executed on 01/16/17
  - MODIS Roll #172 executed on 02/15/17
  - MODIS Roll #173 executed on 03/16/17
  - MODIS Roll #174 executed on 04/16/17

- **11/04/16: MISR SFE Data Corruption Anomaly**
- **12/10/16: ASTER 1-sec data loss due to PB cut short on short contact**
- **12/18/16: Terra 17 year Anniversary**
- **12/31/16: Terra Leap Second @ 23:59:60z**
- **01/25/17 – 01/26/17: ESMO Annual Review**
- **02/01/17: FDIR RTCS 99 (OA -> Wheel Safe hold) Uplink**
- **02/02/17: CERES DSC Elevation Scan Profile Uplink**
- **02/15/17 – 02/16/17: TMON #1 Limit 4.5 -> 5 degs uplinked for IAM #47 (returned to 4.5 after IAM)**
- **02/26/17: Solar Eclipse #39**
- **03/06/17 – 03/17/17: MOPITT Decontamination and Hot Calibration**
- **03/13/17: Terra FOT LDSC Full Team Simulation**
- **03/15/17 – 03/16/17: ASTER IOT LDSC Working Group**
- **03/16/17: Terra ASTER IOT LDSC Full Team Simulation**
- **04/18/17 – 04/20/17: LDSC Sun Safe Recovery Simulation**
- **04/26/17: TAM data source (BDU -> ACE) switch (part 1) and initial onboard TAM Predict file test**
- **04/27/17: TAM Predict file test #2**

Inclination Adjust Maneuvers

- **Inclination Adjust Maneuvers used to maintain nominal spacecraft mean local time (descending node) of 10:30 AM**
  - 10/20/2016 IAM #46 (320 sec burn) executed successfully
  - 02/16/2017 IAM #47 (320 sec burn) executed successfully
  - 02/23/2017 IAM #48 (320 sec burn) executed successfully
  - October 2017 IAMs #49 & #50 planned

- **Predictions indicate need to perform 3-4 maneuvers per year**
  - **2017: (2 in Spring, 2 in Fall) to maintain 10:30am +/- 1 minute goal**
  - **2018: (1 in Spring, 2 in Fall)**
  - **2019: (2 in Spring, 1 in Fall)**
  - **2020: (2 in Spring, 0 in Fall) -- last inclinations for Terra mission**

Terra High Interest Events

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2016 (T1-T4)	1	2	1	1	2	1	1	1	1	0	0	0	11
Tier 3	0	0	0	1	0	1	1	0	1	0	0	0	4
Tier 4	0	0	0	0	0	0	0	0	0	0	0	0	0
2017 (T1-T4)	0	2	0	0									2
Tier 3	0	0	0	0									0
Tier 4	0	0	0	0									0

CARA Defines the 4 Tiers as: T1 – Notify (email/phone), T2 – Conduct Briefing, T3 – Plan Maneuver, T4 – Execute Maneuver

- **2005**: 4 HIEs – 1 Debris Avoidance Maneuver (DAM) performed on 10/21/2005: Terra vs. 14222 CA on 10/23
- **2006**: 1 HIE – 1 maneuver waived off due to CA. Maneuver originally planned for 01/12/2006: Terra vs. 1716 CA on 1/12@ 17:46z
- **2007**: 4 HIEs – 1 DAM performed on 06/22/2007: Terra vs. 31410 CA on 6/23
- **2008**: 2 HIEs – 1 DAM planned and waived off: Terra vs. 82832 CA on 10/28/2008 @ 06:17z
- **2009**: 2 HIEs – No DAMs planned or performed
- **2010**: 5 HIEs – 1 DAM performed on 01/22/2010: Terra vs. 34700 CA on 1/23 @ 20:46z
- **2011**: 20 HIEs – 2 DAM planned and waived off: (1) Terra vs. 26181 CA on 3/28/2011 @ 12:14z (2) Terra vs. 30440 Repeating CA 05/07-09/2011
- **2012**: 19 HIEs – 1 maneuver waived off due to CA. Maneuver originally planned for 05/31/2012: Terra vs. 37789 CA on 6/1 @ 22:49z
- **2013**: 17 HIEs – 7 that required significant action
- **2014:** 24 HIEs – 6 that required DAM execution or nominal maneuver waive-off and replan
- **2015:** 33 HIEs – 8 that required DAM execution or nominal maneuver waive-off and replanning
- **2016:** 11 HIEs – 0 that required DAM execution or nominal maneuver waive-off and replanning
- **2017 thru present: 2 High Interest Events (HIEs) – 0 that required DAM execution or nominal maneuver waive-off and replanning**

ESMO RMM Planning Automation

- **ESMO has updated its Close Approach (CA) Process Flow to move towards a more Automated approach**
  - Prepares for future increased object catalog w/ Space Fence
  - Reduces workload for each event
  - Keeps solution “at the ready” for short notice events
- **ESMO Flight Dynamics team is currently developing an autonomous ephem generation tool**
- **Ephems will be built off optimal and constrained cases solved for by the Collision Risk Management System (CRMS)**
- **CARA will accept delivery of these ephems and ship them to JSpOC for screening**
  - Delivery from FDS to CARA will be manual for some period as we become more familiar with which solutions are most valuable
  - Eventually delivery to CARA will be automatic based on logic built into the FDS ephem tool
- **Screening results will be automatically compiled and outputted via an email report from CRMS**
- **Target implementation is January of 2017**
- **Implemented on February 13th, 2017**

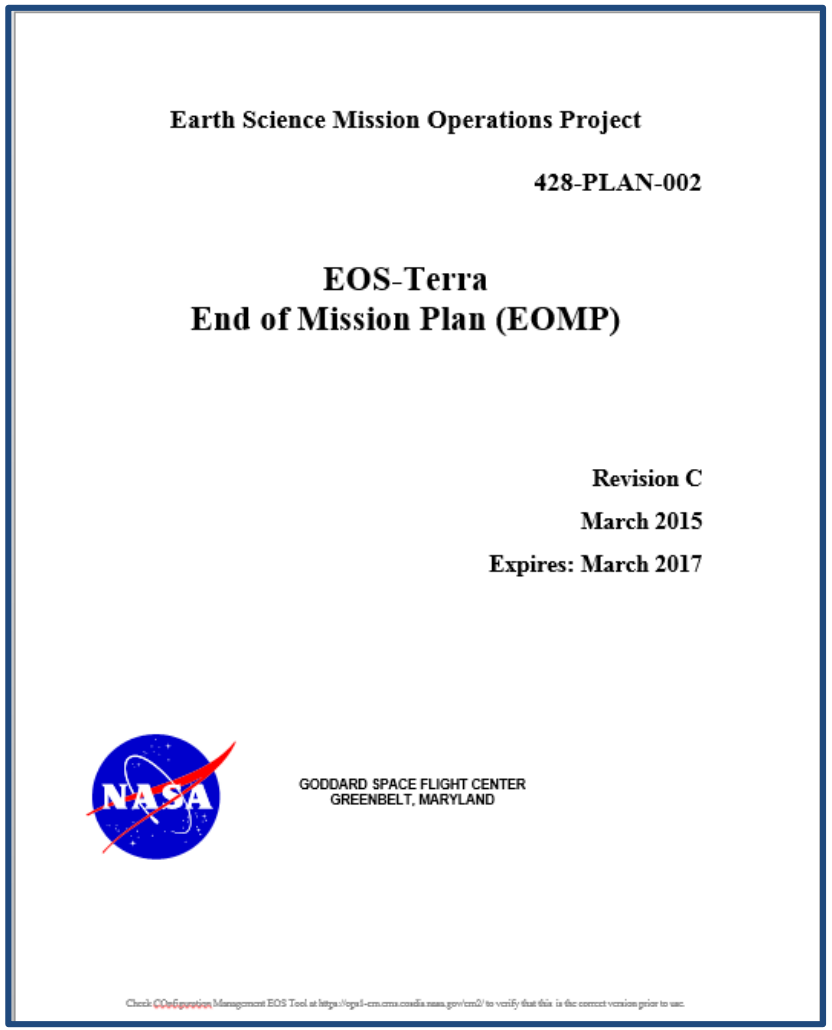
Terra End-of-Mission Plan

Document Status

- Rev D - End-of-Mission Plan Document has been revised and under review cycle
- Hope is to have signed version in CM prior to October inclination maneuvers

Content

- Terra will continue normal operations through October 2020
- Once all non-reserved fuel has been used, MLT will be drifted to 10:15 AM
- Jan 2022, Terra exits constellation
- Remain fuel used to lower perigee prior to spacecraft passivation
- Plan is consistent with the revised Afternoon Constellation (A-Train) Operations Coordination Plan



Earth Science Mission Operations Project

428-PLAN-002

EOS-Terra
End of Mission Plan (EOMP)

Revision C

March 2015

Expires: March 2017

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

Check COnfiguration Management EOS Tool at https://cpa1-cm.cms.eosdis.nasa.gov/cm2/ to verify that this is the correct version prior to use.

Future Plans

Upcoming Activities	
NASA Review of Lunar Deep Space Cal	**05/03/17 @ 9:30 AM**
Terra FSSE CCB	**06/01/17 @ 11 AM**
ASTER Interface Meeting @ Tokyo	**06/05/17 – 06/09/17**
Constellation MOWG @ GSFC	**06/13/17 – 06/15/17**
Update to SSR Auto-LUR Patch	**2Q2017**
Lunar Deep Space Calibration	**08/05/17**
SA adjusts TMON patch	**3Q2017**
Update Drag Scale Factor	**4Q2017**

Summary

- **Terra remains very healthy 17+ years into the mission**
  - Electrical Power Subsystem performance has been stabilized following 2009 anomaly
  - Fuel Remaining to continue operations to 2020 and beyond
- **Data Capture percentages continue at ~100%**
- **Collision Avoidance events continue to be part of routine ops**
- **End of Mission Plan (Rev D) currently under review**
  - **Updated dates and analysis based on latest drag predicts**
  - **Review edits will be incorporated then doc resent through signature cycle**
  - **Target completion date is Sept/Oct 2017**

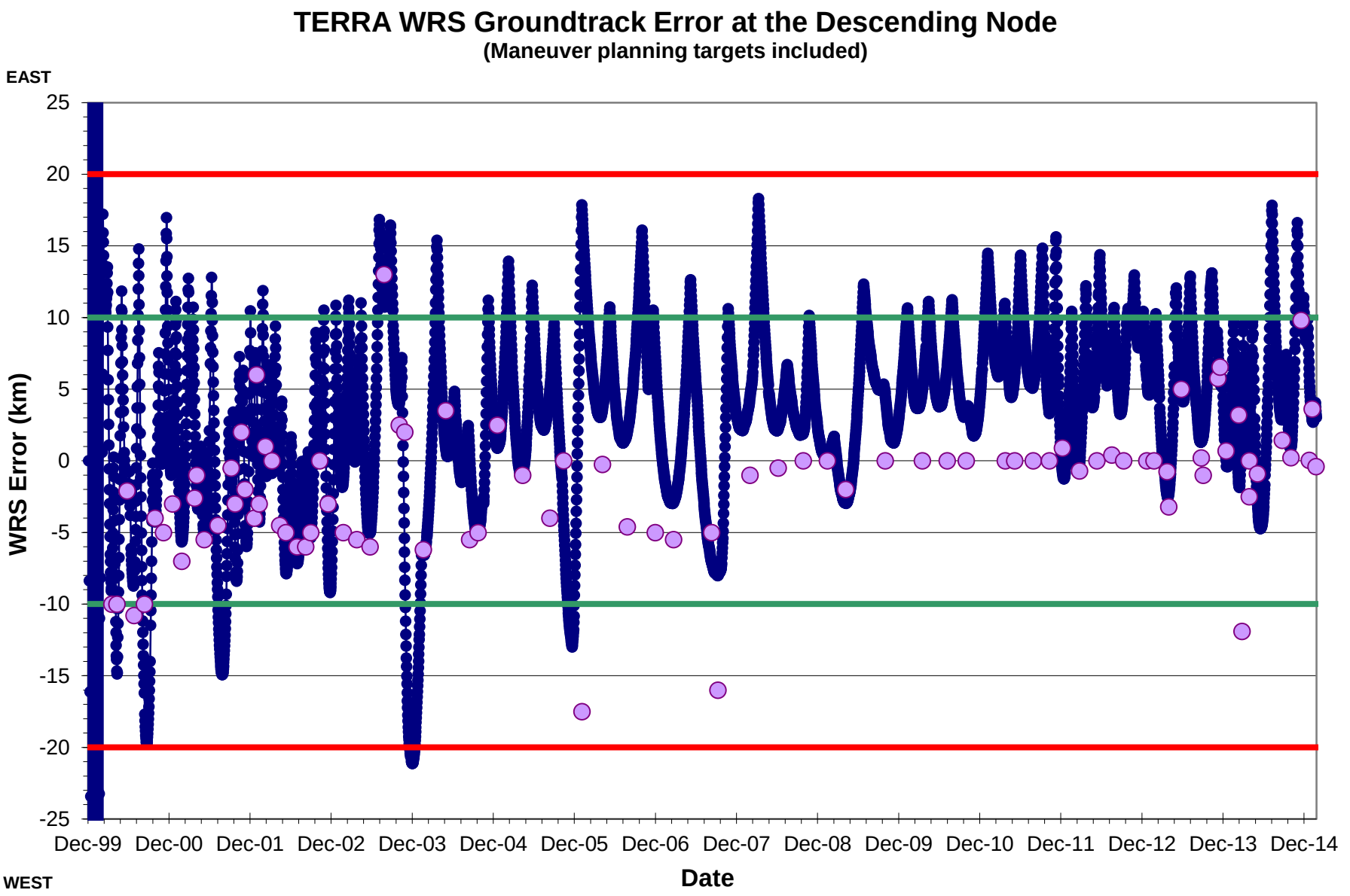
Additional Slides

- Orbit / Inclination / MLT Maintenance
- WRS Ground Track Error
- EPS Performance
- Terra Safehold

Orbit/Inclination/MLT Maintenance

- **Requirement**: Mean Local Time (MLT) maintained between 10:15 and 10:45 measured at the Descending Node.
- **Goal**: Maintain Terra mean local time of the descending node (MLTDN) below 10:31.
- **Constraint**: OCO-2 has requested Terra maintain a MLT less than 10:31 for the duration of its lifetime to maintain a safe separation at the poles.
- **Requirement**: Maintain WRS-2 ground track error, 0 +/-20 km.
- **Requirement**: Maintain Frozen orbit with Argument of Perigee at 90 degrees +/-20 and Eccentricity of 0.0012 +/- 0.0004.
- **Constraint**: Maximum burn duration limited to 320 seconds by spacecraft manufacturer. Complete yaw slews and inclination maneuvers during spacecraft orbital night. Maneuver close to spring and fall equinox to maximize efficiency.

WRS Ground Track Error (GTE)



EPS Subsystem Performance

- **Bus Load: Nominal**
  - Average bus load: 2311 Watts
  - Average housekeeping current: 11.93 A
  - Total instrument current: 7.135 A
- **Battery Performance**: **Nominal with exception of anomalous BBAT condition**
  - BBAT cell # 50 failed following IAM #24 on October 13 (DOY 286) 2009
    - BBAT Voltage Temperature curve changed to better reflect a failed cell
  - BBAT heater control electronics (HCE) anomaly occurred following IAM #24 on October 13 (DOY 286) 2009
    - Performed soft reset, power cycle, switching to redundant side and re-enabling one of the nonfunctioning heater groups to recover HCE functionality without success
    - At least 4 of 9 BBAT heater groups are no longer being controlled
    - Heater control setpoints to changed for controllable heater groups to reduce the thermal gradient
  - PBAT Charge/Discharge Ratio was reduced from 105% to 104% on April 25, 2013 in an effort to extend PBAT life
  - PBAT BPC Channel A Disabled January 14, 2014; increases BBAT cold temperatures due to increased discharge
  - PBAT Charge/Discharge Ratio was reduced from 104% to 103% on August 20, 2015 in an effort to extend PBAT life
- **Battery Temperatures**: **Nominal with exception of anomalous BBAT data**
  - PBAT and half of BBAT Battery temperatures are regulated by flight software to ≈ -1°C to -5°C
  - Almost half of BBAT cell temperatures are below normal (but stable) in the -5°C to -13°C range
- **Battery Voltages** (BBAT)
  - Minimum battery voltages at 66.15 Volts
- **Solar Array**
  - Last offset adjustment performed on December 20th 2016
  - Average drift rate for the month, -0.065 deg/day
  - Present offset drift rate is decreasing
- **BBAT Cell with Lowest Temperature** (excluding Cell #50)
  - Cell # 20 : -10.69°C
  - Thermal Gradient(avg): 7.26°C

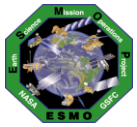
Terra Earth Point Safe Mode (DOY 049)

Process Improvement

- **Root Cause and Corrective Action (RCCA) process was performed to document what happened and capture preventative actions to prevent a similar safe event in the future**
  - The FOT generated the RCCA document and conducted a review board on 04/07/16 identifying 4 Preventative Actions to be completed prior to the next IAM series in October 2016

Action #	Preventative Action	Status
1	**Update and CM IAM SOP** • Planning, Verification, Execution, and Waive-Off • Update and Document timing constraints, including Inhibit IDs • Document Contingencies, including new "incorrect slew" contingency	**COMPLETED:** Initial version of SOP in CM. Updated version Delivered to CM
2	**Add constraints to Script and check tool**	**COMPLETED:** Script expanded to more clearly show sequence of ATC and GND commands and constraint for IAM #44 and #45
3	**Generate pre-planned contingency response for incorrect slew event** • Test on simulator to ensure it works as designed • Document in CAM and Script	**COMPLETED:** Developed and simulated generic and specific contingency responses prior to executing IAM #44 & #45
4	**Lock down all IAM maneuver parameters** • If change occurs then additional simulation is needed (time permitting) or waive-off & reschedule for another day	**COMPLETED:** Established new lock-down schedule with FDS group (Integrated into documentation)

- **External NASA review was held on 4/28/16 to review the event and corrective actions**
  - **FOT integrated RFAs into IAM and Safe hold working groups**
- **IAM Redesign and actions completed prior to October 20th, 2016 IAM**
- **Only three remaining Safehold improvements to be completed in 2017**


Mission Operations
Science
Earth
Applications
Space
NASA
GSFC
ESMO

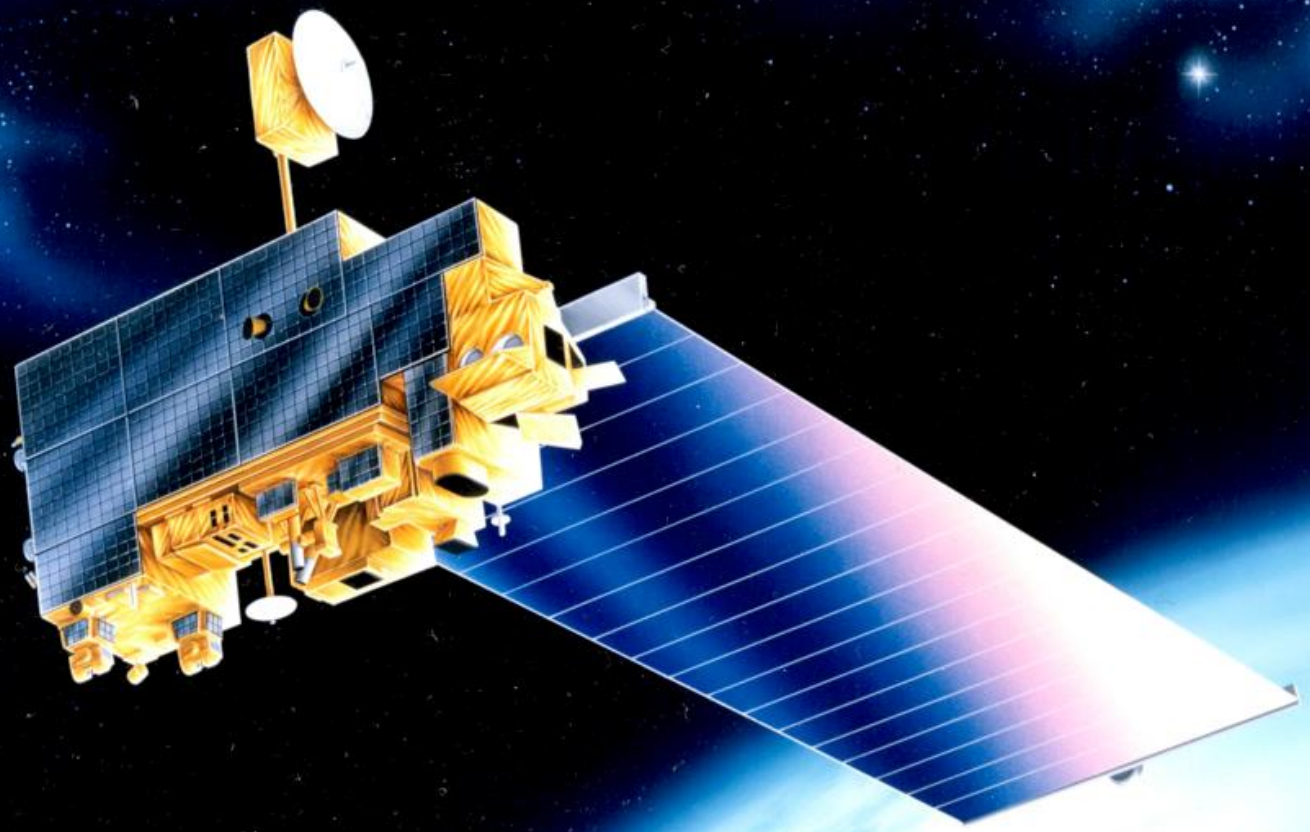

NASA

Questions

EOS Terra

Terra Future Plan Update

June 13th-15th, 2017



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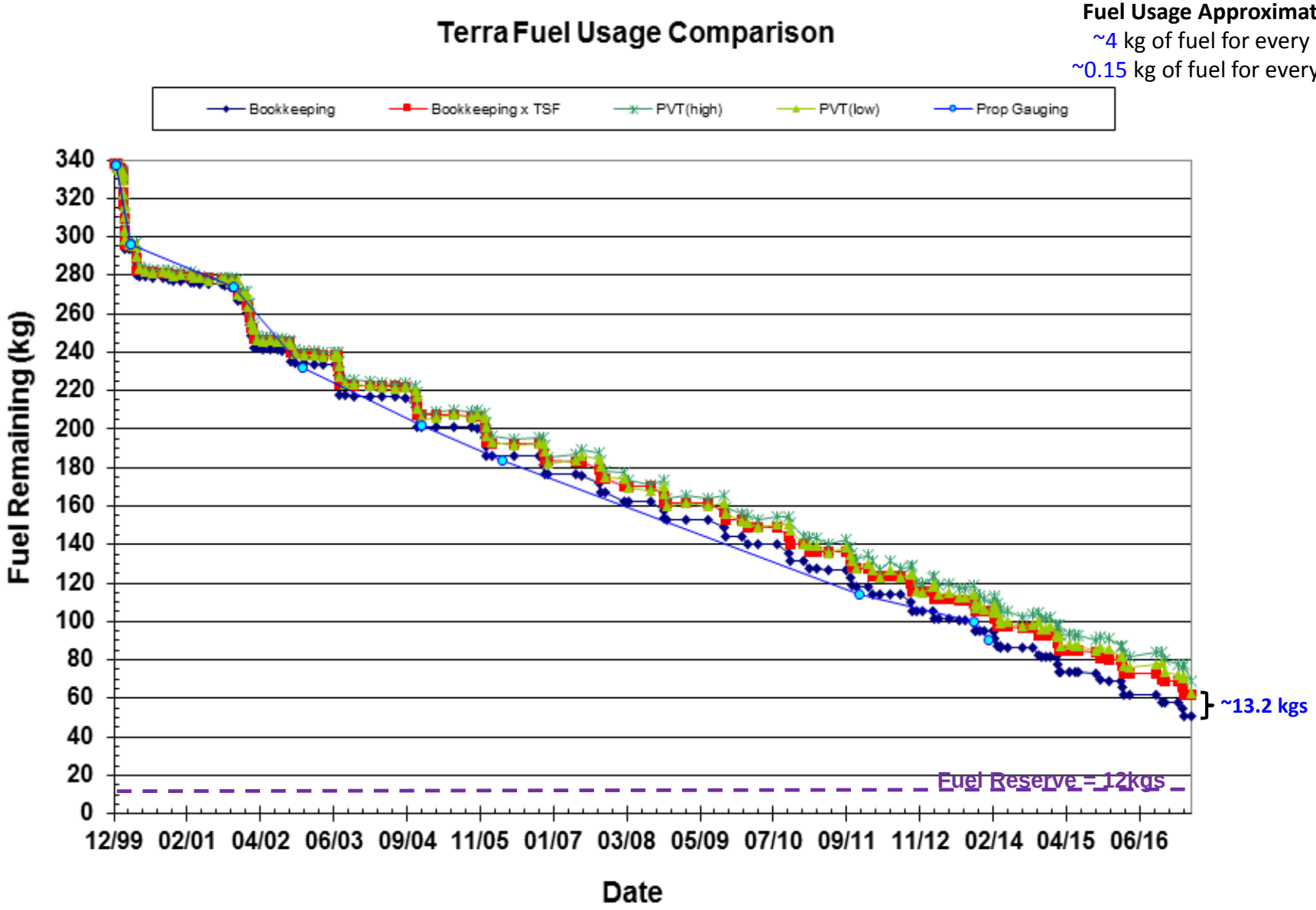
Agenda

- **Background/Historical Plans**
  - Brief History of Terra EOM Work
  - Options Summary Table (Sept 2016 MOWG)
- **Updated Status on Options & Waiver**
- **Updated Future Maneuver Plans**
  - Option 1
- **Conclusion/Summary**

Lifetime Fuel Estimates

Fuel Usage Approximations:
~4 kg of fuel for every IAM
~0.15 kg of fuel for every DMU



Brief History of Terra EOM Work

Sept 2016 MOWG

- Fuel ~ 100kg trigging maneuver option analysis – Summer/Fall 2013
- Options sent to IOTs for their feedback – April 2014
- EOM Engineering Peer Review – July 2014
- Science Team Meeting – Aug 2014
- IOT feedback received – Sept 2014 (Proposed plan selected)
- Constellation MOWG – Oct 2014
- Briefing to NASA Program Exec – Jan/Feb 2015
- Waivers generated and sent for Goddard Signatures – Feb 2015
- Terra Senior Review Proposal Submitted – March 2015
- Waiver signatures received for Goddard – June 2015
- Constellation MOWG – June 2015
  - Aerospace presented their debris risk analysis
- Science Team Meeting – March 2016
- Constellation MOWG – April 2016
- Removed "Baseline" Plan and Created new "fallback" options – May->Aug 2016
- Constellation MOWG – September 2016

- Present Future Maneuver Options to NASA HQ – October 2016
- Update Waivers, Get Goddard Signatures & Deliver to NASA HQ – Sept->Nov 2016
- Final Decision Deadline – Prior to February 2017 IAM(s)
- Terra Senior Review Proposal Submission – March 2017

Option Summary

Time-on-Orbit Comparisons

Decommissioning Plan	Exit Year	De-orbit Year	# of de-orbit burns	Final Apogee (km)	Final Perigee (km)	End of Mission (EOM)	EOM to Reentry (yrs)	Reentry date
Baseline	2020	N/A	0	689.08	672.05	2025	39	2064
Option 1	**2022**	**2026**	**6**	**702.31**	**671.43**	**2026**	**50**	**2076**
Option 2	2017	2017	18	705.08	609.23	2017	32	2049
Fallback Option 1	2018	2024	14	701.45	630.55	2024	36	2060
Fallback Option 2	2018	2022	18	701.00	608.50	2022	31	2053
Fallback Option 3	2021	2022	18	700.26	613.76	2022	31	2053

Reference Only
Planned Option
Fallback Options

- These Options were presented in detail to NASA HQ (Earth Science Director)
- NASA HQ was onboard with Option 1 and eliminated all Fallback Options except Fallback Option #3
- Earth Science Director requested independent panel review plus begin discussions with OSMA on waivers for Terra

Revised Path Forward

- Update Terra Waivers – September/October 2016
- Briefing to Code 400 and NASA HQ – October 2016

Decommissioning Plan	Exit Year	End of Mission (EOM)	EOM to Reentry (yrs)	Reentry date
Option 1	**2022**	**2026**	**50**	**2076**
Fallback Option 3	2021	2022	31	2053

- Submit Waivers for Goddard Signatures – October 2016
- Deliver Waivers to NASA Headquarters (including Orbital Debris Office) – Nov 2016
  - Received written direction from Orbital Debris Office that Terra does not require waivers
- Final Decision Deadline – Prior to February 2017 IAM(s)
  - Received written approval from NASA HQ to proceed with Terra IAMs in February 2017
- Terra Senior Review Proposal Submission – March 2017
- Constellation MOWG – June 2017
- Submit End of Mission Plan (Rev D) to NASA HQ for signatures – July/Aug 2017
- **NEW** Final Decision Deadline – Prior to October 2017 IAM(s)

Senior Review, Independent Panel and Signed EOMP will serve as approval to proceed with Option 1

FUTURE PLAN

Option 1

Lifetime and Orbit Lowering Maneuvers

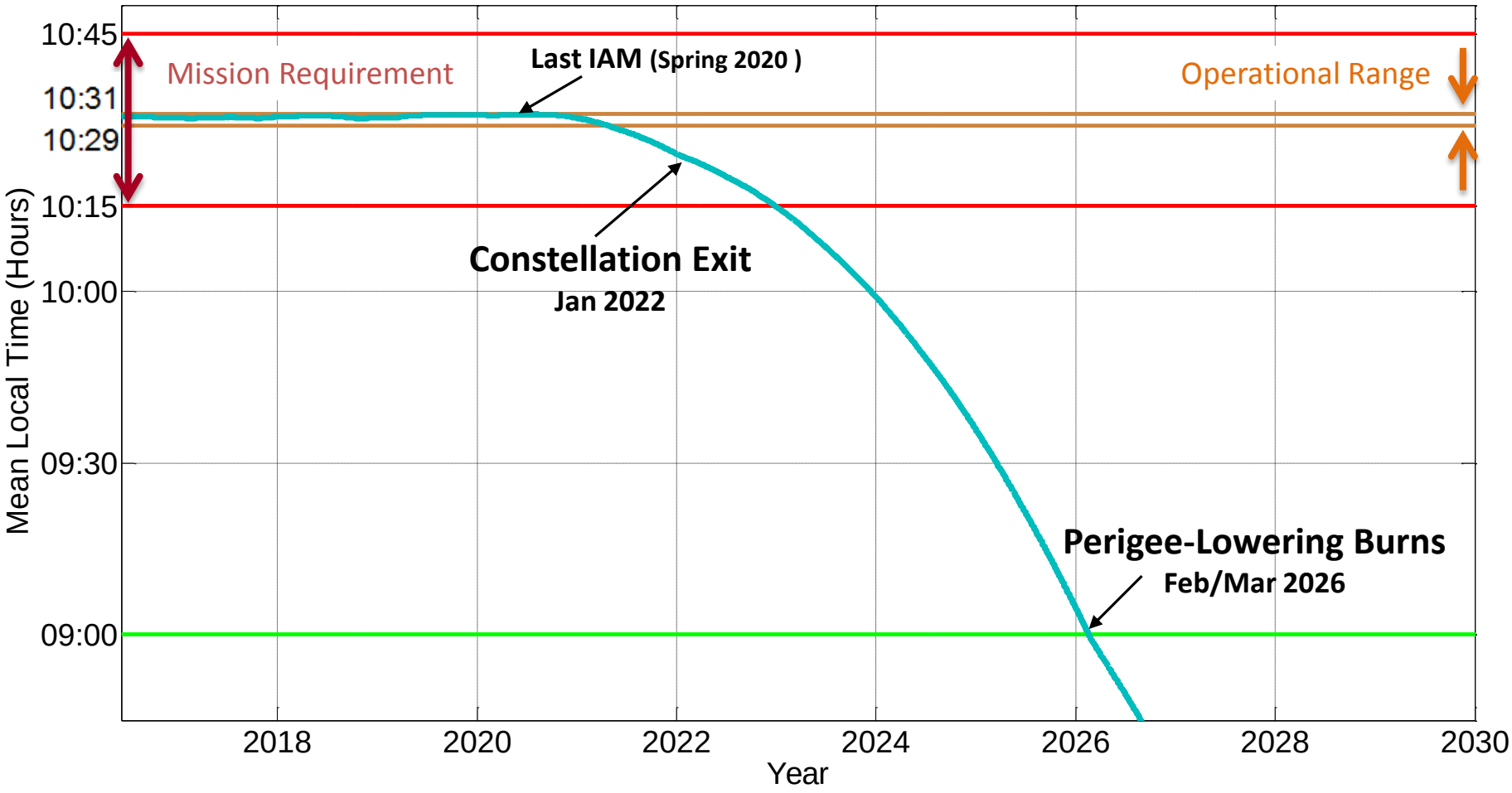
- **Terra Lifetime (in constellation):**

Mission Year (-)	Inclination Maneuvers (-)	DMU Maneuvers (-)	Fuel Used (kg)	Fuel Remaining (kg)
2016	0 Spring, 1 Fall	1	3.92	73.43
2017	2 Spring, 2 Fall	3	15.05	58.39
2018	1 Spring, 2 Fall	1	10.79	47.59
2019	2 Spring, 1 Fall	3	10.77	36.82
2020	2 Spring, 0 Fall	2	7.11	29.72
2021	0 Spring. 0 Fall	2	0.23	29.48

- **Terra Constellation Exit and Orbit Lowering:**

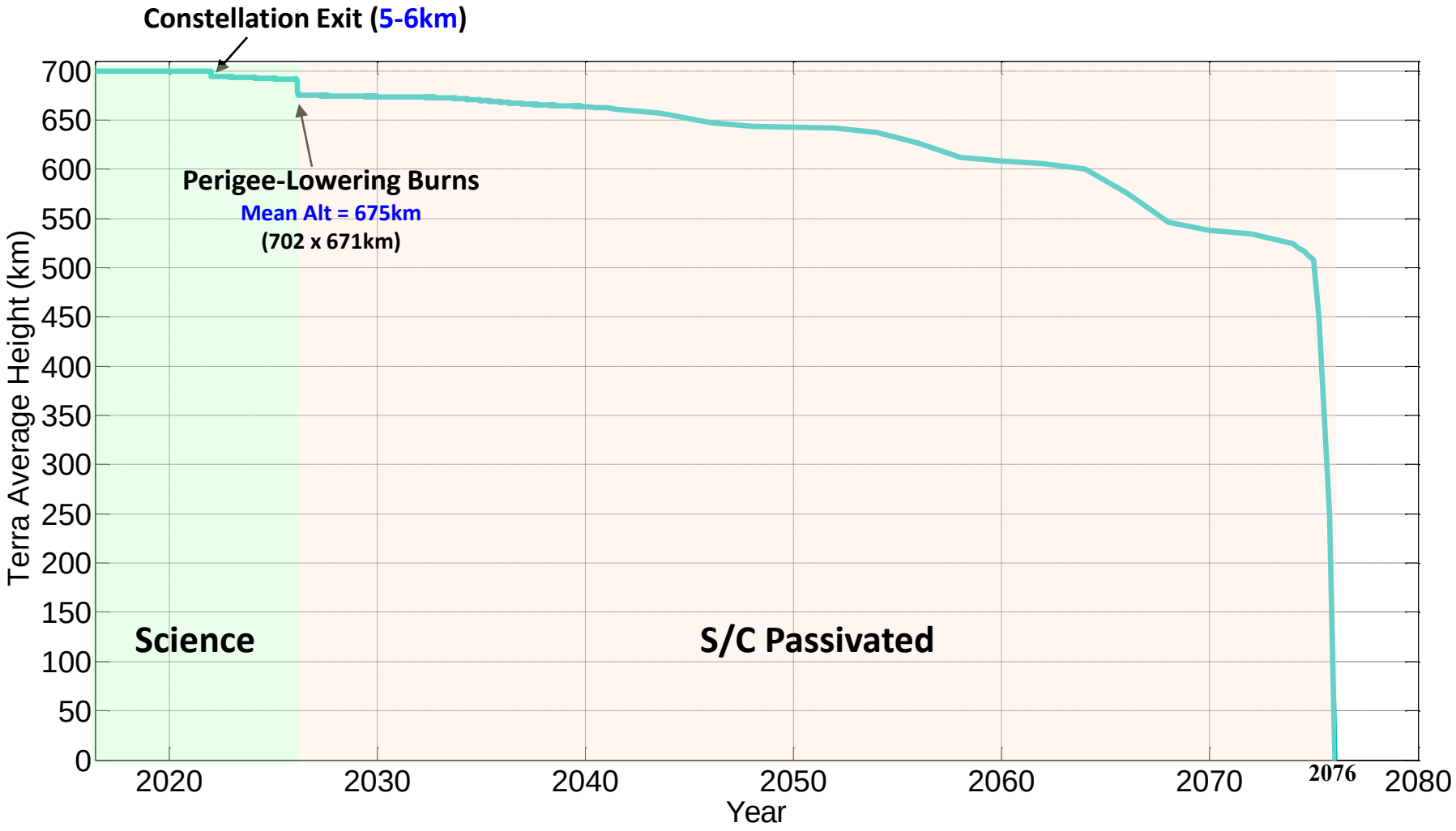
Mission Year (-)	Maneuver Type (-)	Fuel Used (kg)	Fuel Remaining (kg)
1/11/2022	Envelope Exit #1	3.44	26.04
1/11/2022	Envelope Exit #2	3.42	22.62
2/19/2026	De-orbit #1	3.40	19.21
2/24/2026	De-orbit #2	3.39	15.83
2/26/2026	De-orbit #3	3.37	12.46
3/3/2026	De-orbit #4	3.35	9.11
3/5/2026	De-orbit #5	3.33	5.78
3/10/2026	De-orbit #6	3.31	2.47

Option 1
Mean Local Time



Option 1

Lifetime Average Height



Conclusion/Summary

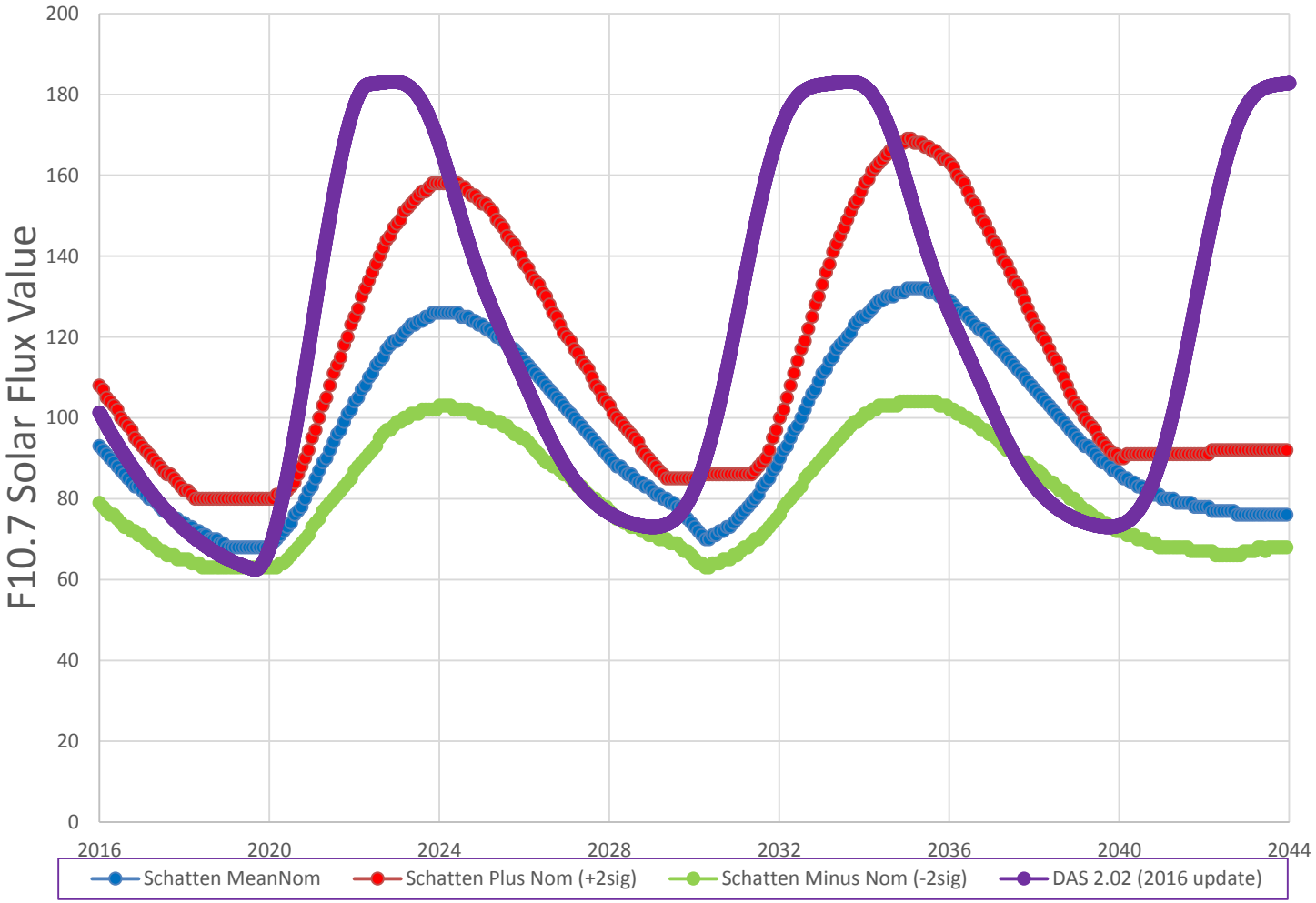
- It was determined officially that Terra does not require waivers
- Based on that fact, decision for Terra's future lies with Earth Science Division @ NASA HQ
- Senior Review, Independent Science Panel and a signed EOMP will serve as authorization to proceed
- If Science Panel not conducted and/or EOMP not signed prior to next inclination series, then ESMO will request written authorization from NASA HQ to execute inclination maneuvers until they are both completed
- Plan is for Terra to Exit Constellation in early 2022 and end mission in early 2026

Questions

Backup Material

- Solar Flux Used in Analysis
- DAS Assessment Software
- Constellation Envelope Definition
- Aerospace Risk Assessment Study Results
- Terra Science Team Meeting Summary
- Terra Key Facts
- Option Slides from Sept 2016 MOWG

Predicted Solar Flux Data
April 2016 Schatten and March 2016 DAS



Debris Assessment Software

- ***The Debris Assessment Software (DAS) was created by the Orbital Debris Office in Johnson Space Center and is currently on version 2.0.2***
- ***DAS utilizes predicted F10.7 values for solar flux based on sine and cosine curve fits to definitive data***
- ***The DAS contains a separate utility to estimate time-on-orbit, given the following inputs:***
  - The operational orbit parameters
  - The "Start" date (ex. Decommissioning date)
- ***In turn, DAS outputs:***
  - Calculated Orbit Lifetime from the "Start" date
  - The last year of propagation
- ***This tool was used to find the reentry dates for the different plans.***
- ***The Area to Mass ratio used in this analysis used a tumbling area (43.95 m^2) based on NASA-STD-8719.14A compared to Terra's operational area (40.5 m^2). A higher area decreases the time on orbit therefore Terra reenters earlier.***

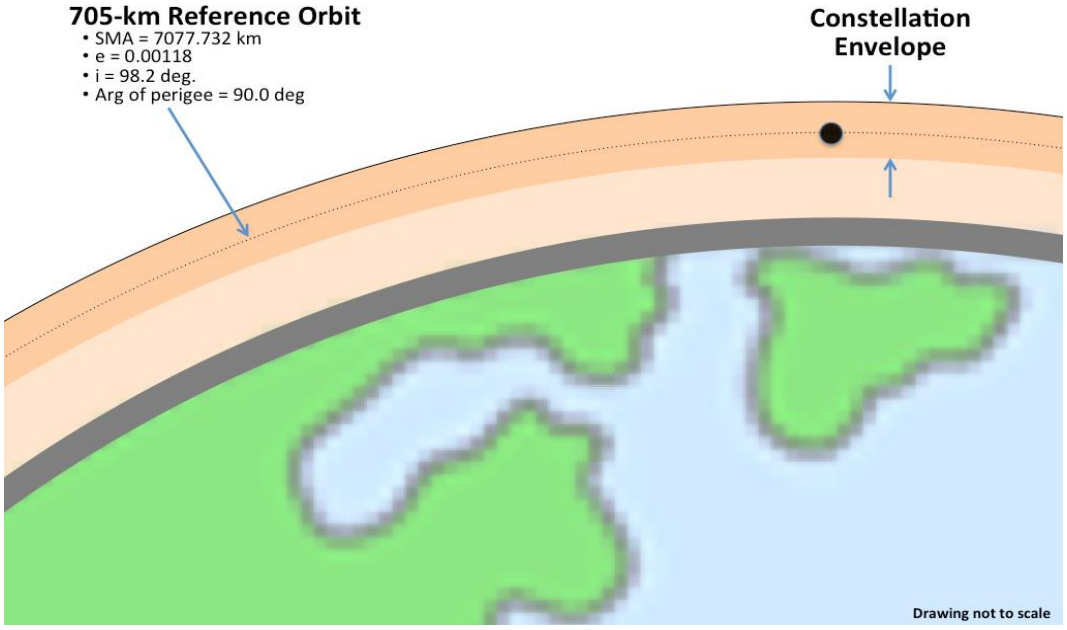
Constellation Envelope
Definition

- All additional options are based on being completely **outside** the Constellation "envelope" and are represented by the following equation*:

$$\left|sma_R - sma_B\right| - \left|sma_R * e_R - sma_B * e_{BMax}\right| > \text{Margin} + \text{Frozen Orbit Tolerance}$$

Where:

- sma_R = Mean semi-major axis of the 705km Reference Orbit
- e_R = Mean eccentricity of the 705km Reference Orbit
- Margin = 2.5 km
- Frozen Orbit Tolerance = 1.5 km and is based on a maximum eccentricity deviation of 0.0002
- B subscript references the satellite in question (e.g. Terra)



*Source: 2014 Operations Coordination Plan for the Morning and Afternoon Constellations

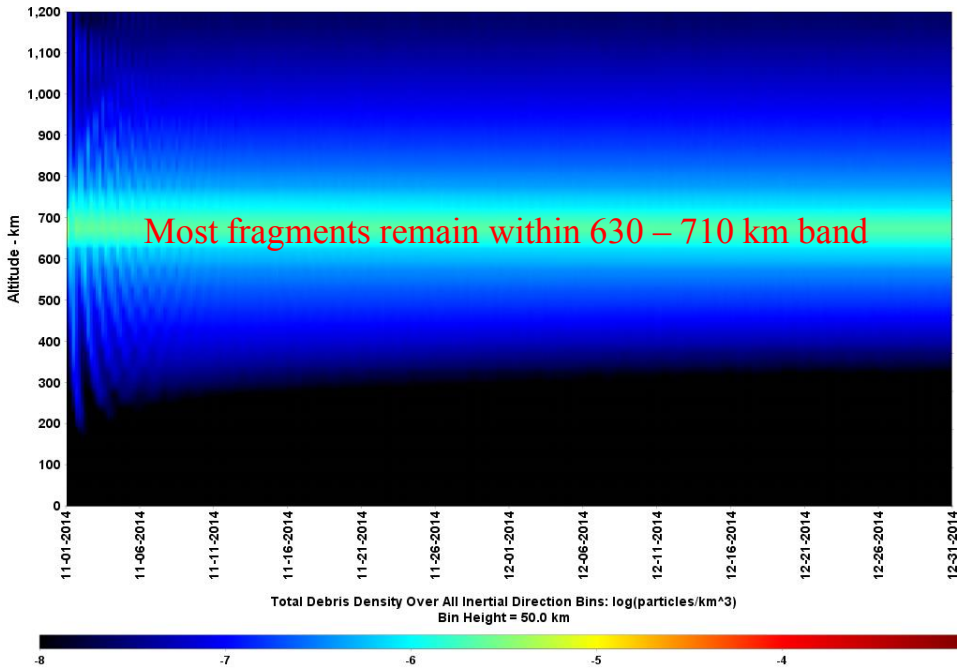
Debris Risk Study Results

- **Aerospace Corp tasked to review risk to Constellation if proposal approved**

Aerospace Corp. Debris Risk Assessment Results

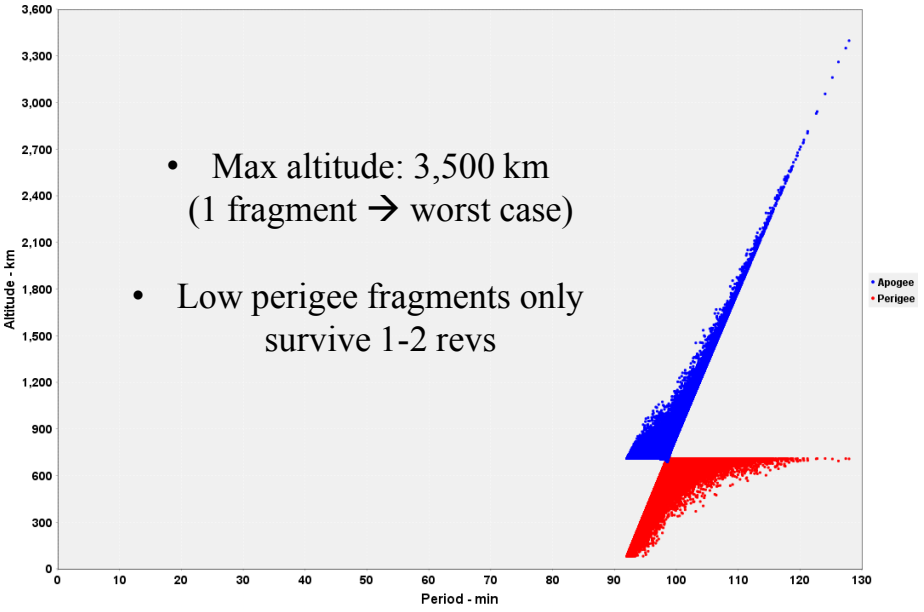
Debris Distribution by Altitude (60-Day)

100% Terra Breakup



log(particles/km^3)

Gabbard Plot of Fragment Distribution



- Max altitude: 3,500 km (1 fragment → worst case)
- Low perigee fragments only survive 1-2 revs

Debris field is spread over thousands of kilometers

- Debris field is concentrated over **80km** band
- Debris spreads over **3000km** of orbit altitude = **No "Safe" Disposal Orbit** (other than the ocean)

Debris Risk Study Results (cont)

- **Difference in Risk is SMALL**: The Aerospace Corporation found for a 100% breakup of Terra

Worst-Case Risk	Probability	Delta	Odds
Current	9.20E-06		1 in 108,700
Terra break-up @ 19km	9.70E-06	5.4%	1 in 103,100
Terra break-up @ 4km	1.00E-05	8.7%	1 in 100,000

Perspective

- From NOAA website (US only) -> Odds of being struck by lightening in your lifetime (80 years) = **1 in 12,000**
- Odd of **dying** in a car accident (US only) = **1 in 4,000-8,000**/year ; **1 in 50-100**/lifetime
- Odds of hitting Powerball jackpot = **1 in 175,223,510**

- **Other LARGE objects close by**: Based on a review of SATCAT at JSpOC, there are currently **772 other objects** with a cross sectional area greater than **12.6 square meters** or a radius larger than 2 meters that cross through altitudes of **685 to 725 km**.
  - Approximately 103 of these objects are in near circular orbits such that they remain within the altitude band for most if not all of their orbit. For comparison then, there are **already 103 Terra-sized objects** near enough to the 705 km constellation to **create a risk similar** to the results reported in this study.

- **Risk to Constellation between exit at 19km vs. 4km is very SMALL (Δ=3.3%)**
- **Risk exists today and in the future, regardless of what Terra does**

Terra Science Team Meeting Results

- **Attendees**: NASA Program Exec, Project Scientist, Mission Director, Instrument Team Leads, Instrument Scientist, Instrument Data Processing experts, JPL Management & Flight Dynamics expert

- **Topics covered**
  - Future Lunar Deep Space Calibration Maneuver (LDSC)
  - Future maneuver plans (Baseline & Proposed or Other Options)
  - Impacts to each instruments science data due to an MLT or Altitude change
  - Content of report & recommendation from the team to NASA HQ and Science Panel

- **Meeting Summary**
  - As stated by 2015 Senior Review Panel, Terra will continue to collect high quality data of sufficient value to warrant mission continuation regardless of if waiver is approved
  - Longer science record (closer to 20 years) increases probability that secular climate trends can be distinguished from inter-annual variability
  - A change in MLT of 15 mins equates to a 1% change in cloud fraction for boundary layer stratocumulus clouds
  - A change in MLT of 15 mins equates to a 1^{o}C change in mean land surface temperature or 0.025 ^{o}C in sea surface temperature
  - Change to Altitude & Inclination (MLT) will change WRS-2 ground track & 16 day repeat cycle
  - Change to Altitude will require changes to Level 1 processing for both ASTER and MISR
    - Changes will take approximately 1 year for ASTER and 2 years for MISR

- **Decisions Made**
  1. Lunar Deep Space Calibration Maneuver will take place in July 2017 regardless of waiver approval
     - May perform Deep Space Calibration without the moon for CERES at some future data as well
  2. Recommendation from instrument teams and project scientist will be to request the 3 additional years at the current MLT and altitude

- **Next Steps**
  - Present summary of findings from meeting to Science Panel and NASA HQ (4/6) **– COMPLETE**
    - Feedback from panel is that there is a science case to justify requesting the proposed 3 years of tight MLT and current altitude
  - Perform analysis on potential other options (listed above) to be ready if waiver is denied **– COMPLETE**
  - Provide analysis to decision makers and await final decision – **November 1st, 2016@ NASA HQ**

Terra Key Facts

- **Terra launched in Dec 1999 before NASA 25 & 30 year requirements**
  - Terra is therefore "grandfathered" in and is **not required to meet these**
  - Terra no longer has sufficient fuel to meet 25 year requirement (late 2012)
- **Terra is part of the Morning Constellation**
  - Orbit = 705km altitude, sun-synchronous polar, 98.2° incl -> 16 day repeat cycle
- **Terra's MLT requirement is 10:15 to 10:45am**
  - Terra has flown at a much tighter MLT range of 10:29-10:31am since 2002
- **Terra currently has ~75kg of fuel**
- **There is no planned replacement for Terra**
  - NASA Class-A Mission; Rated #2 Earth Science Mission in NASA's mission set
- **Greatest science benefit is gained by Terra maintaining tight MLT and current altitude for as long as possible**
  - Continues current science record; allows for climate change information
- **Change to MLT or Altitude requires science processing algorithm changes**
  - Greatest impact is to MISR and ASTER
    - MISR needs $2M and 2 years to make their updates
    - ASTER needs ~1 year to make their updates
- **Future science benefit must be weighed against time to reentry/debris risk**

Concerns Raised by MOWG

1. Dwelling at Exit Altitude of 4km

- Concern addressed:
  - Terra plans (and has planned) to perform 2 exit burns to lower approximately **5-6 km** below the constellation envelope

2. Possible Debris Source after Constellation Exit

- Concern addressed:
  - Updated proposed plan and all new options include orbit lowering burns prior to passivation
    - Reduction of mean altitude to at least 675km (30km below constellation)
  - Reserve RMM fuel up until passivation
    - No additional debris risk until after Terra mission has ended
  - Aerospace Corp performed risk analysis
    - Worst case is low risk (worst case EXTREMELY unlikely)
      - » Risk = 1.0E-05 (1 in 100,000) with 100% breakup right after exit

REVISED LIFETIME PROPOSAL AND FALLBACK OPTION OVERVIEW

Updates for Sept 2016 MOWG

- **Removed Baseline Option**
  - Based on old constellation requirement that no longer exists, therefore no longer a reason to execute this specific plan
  - All plans show constellation exit of **5-6km**
  - New Fallback Options re-enter sooner and provide additional science
- **Used Most Accurate Fuel Estimate based on AETD and LM analysis**
  - Bookkeeping was historically used (overly conservative)
    - This assumes the worst case efficiency and lowest pressure for every maneuver
  - PVT and Bookkeeping x TSF were determined to be most accurate
    - Analyses took average of both methods as correct assumption (13.2kg over bookkeeping)
  - Changed unusable fuel estimate to 2.7kg instead of historic 5kg (2.3kg more fuel)
    - Spacecraft Vendor expects 1.5kg unusable fuel with worst case of 3.9kg (avg = 2.7kg)
  - Proposed Plan holds additional 15.5kg strictly for orbit lowering
- **Updated charts to show orbit lowering burns prior to passivation**
  - Show altitude through re-entry for all options
  - Reduction of mean altitude to at least 675km (30km below constellation)
- **Created new Fallback options if Proposed Plan is not approved**
  - Attempts to provide compromise between science and debris/time on orbit goals
  - All new plans show constellation exit of 5-6km and orbit lowering burns prior to passivation
  - Further reduction in mean altitude and earlier re-entry are achieved with all fallback options

Future Maneuver Plans

- **Option 1: Updated Proposed Plan – BEST for SCIENCE (continues current science record)** Slides 13-17
  - Terra performs nominal IAM thru Spring 2020 and DMUs thru Fall 2021
  - Constellation Exit is performed in Jan 2022
  - Terra performs perigee-lowering burns with all remaining fuel at ~ MLT of 9:00 AM prior to spacecraft passivation

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- **Option 2: Exit & Lower Orbit ASAP – USED as LOWER BOUND ONLY** Slide 19
  - Terra will discontinue all Inclination & Drag Make Up maneuvers after the Fall 2016 series
  - Constellation Exit performed in March 2017
  - Terra performs perigee-lowering burns with all remaining fuel immediately after constellation exit & passivates

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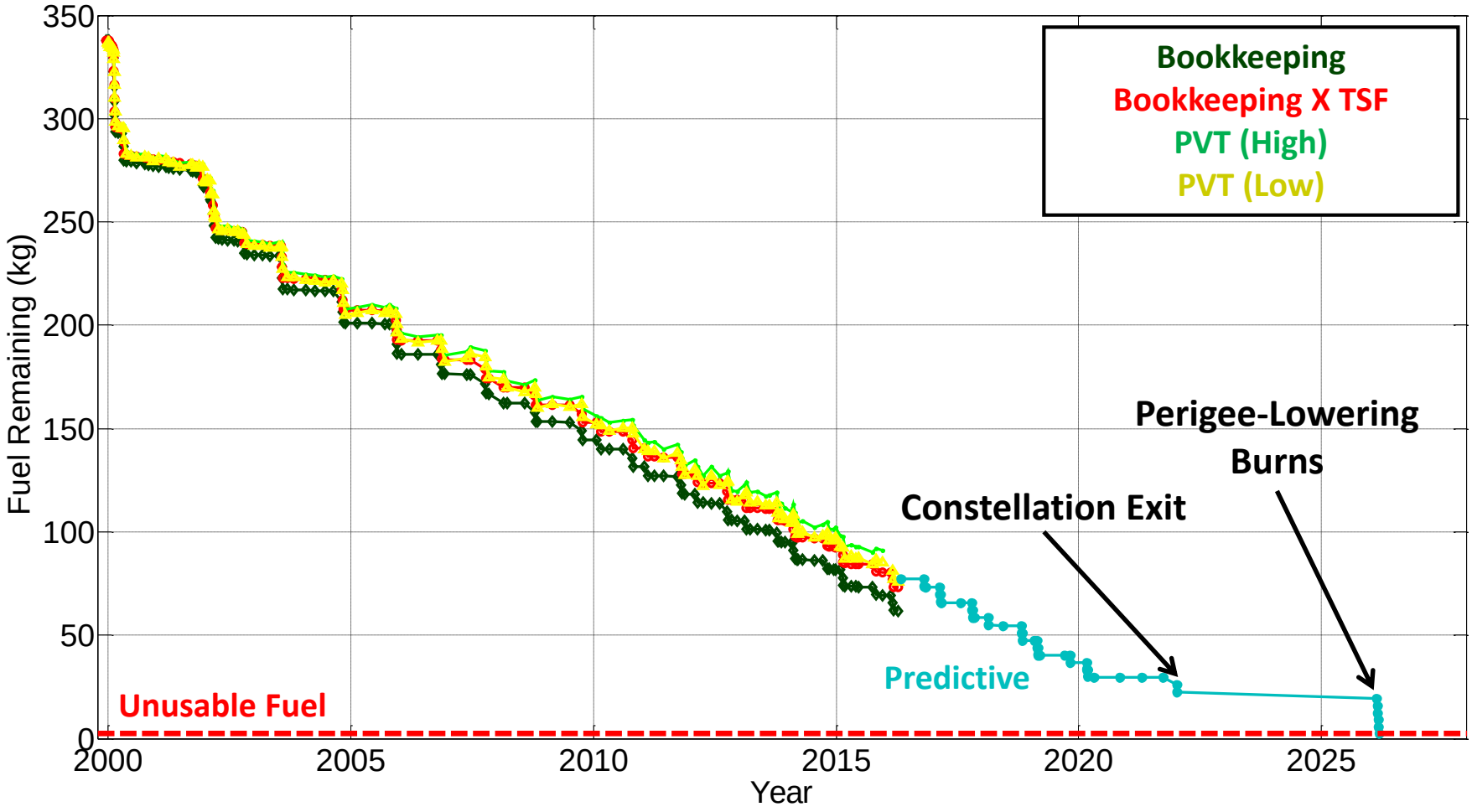
- **Fallback Option 1: Maintain Current Orbit (MLT & Altitude) until after LDSC** Slide 21
  - Terra will perform nominal IAM and DMU planning until after **Lunar Deep Space Calibration** (Aug 2017)
  - Constellation Exit performed in January 2018
  - Terra takes science while drifting both MLT and Altitude until decision to end mission
  - Terra performs perigee-lowering burns with all remaining fuel at ~ MLT of 9:00 AM prior to spacecraft passivation
- **Fallback Option 2: Maintain Orbit Altitude until after LDSC** Slide 22
  - Terra will discontinue all Inclination series after the Fall 2016 series
  - Will still perform DMUs until constellation exit in January 2018
  - Terra takes science while drifting both MLT and Altitude until decision to end mission
  - Terra performs perigee-lowering burns with all remaining fuel at ~ MLT of 9:00 AM prior to spacecraft passivation
- **Fallback Option 3: Maintain Orbit Altitude for as long as possible (beyond LDSC)** Slide 23
  - Terra will discontinue all Inclination series after the Fall 2016 series
  - Will still perform DMUs until required to lower due to proximity to other mission or other reason (est @ MLT of 9AM)
  - Terra immediately performs perigee-lowering burns with all remaining fuel prior to spacecraft passivation
  - Provides additional time for MISR to perform their science data processing algorithm updates

Updated Proposed Plan (Option 1)

Lifetime Fuel Estimates



EXIT AND LOWER ASAP & FALLBACK OPTIONS

Exit and Lower ASAP (Option 2)

Lifetime and Orbit Lowering Maneuvers

- **Terra Lifetime (in constellation):**

Mission Year (-)	Inclination Maneuvers (-)	DMU Maneuvers (-)	Fuel Used (kg)	Fuel Remaining (kg)
2016	0 Spring, 1 Fall	0	3.72	73.63

- **Terra Constellation Exit & Orbit Lowering:**

For Comparison Only – No Plan to Execute

Mission Year (-)	Maneuver Type (-)	Fuel Used (kg)	Fuel Remaining (kg)
3/2/2017	Envelope Exit #1	3.72	69.91
3/2/2017	Envelope Exit #2	3.70	66.22
3/7/2017	De-orbit #1	3.67	62.54
3/9/2017	De-orbit #2	3.65	58.90
3/14/2017	De-orbit #3	3.62	55.28
3/16/2017	De-orbit #4	3.60	51.68
3/21/2017	De-orbit #5	3.58	48.10
3/23/2017	De-orbit #6	3.55	44.54
3/28/2017	De-orbit #7	3.53	41.01
3/30/2017	De-orbit #8	3.51	37.50
4/4/2017	De-orbit #9	3.49	34.01
4/6/2017	De-orbit #10	3.47	30.54
4/11/2017	De-orbit #11	3.45	27.09
4/13/2017	De-orbit #12	3.43	23.66
4/18/2017	De-orbit #13	3.41	20.25
4/20/2017	De-orbit #14	3.39	16.86
4/25/2017	De-orbit #15	3.37	13.49
4/27/2017	De-orbit #16	3.35	10.13
5/2/2017	De-orbit #17	3.34	6.80
5/4/2017	De-orbit #18	3.32	3.48

For Comparison Only – No Plan to Execute

Fallback Option Overview

- **All Fallback Options were developed in case the Proposed Plan (Option 1) is not approved by NASA HQ**
  - Attempts to balance science vs. debris/time on orbit goals
- **Fallback 1 - Maintains both MLT & altitude until after the Lunar Deep Space Calibration (LDSC) scheduled for August 2017**
  - LDSC is attempting to replicate the 2003 maneuver to greatest extent possible
  - Results will be compared to validate ASTER science mission data
- **Fallback 2 - Maintains altitude until after the Lunar Deep Space Calibration scheduled for August 2017**
  - Holds altitude for LDSC in August 2017
- **Fallback 3 - Maintains altitude for as long as possible before we get close to another mission**
  - Holds altitude for LDSC in August 2017 and beyond
  - Allots MISR until 2021 to get their science processing updated to account for lower altitude

Fallback Option 1

Lifetime and Orbit Lowering Maneuvers

- **Terra Lifetime (in constellation):**

Mission Year (-)	Inclination Maneuvers (-)	DMU Maneuvers (-)	Fuel Used (kg)	Fuel Remaining (kg)
2016	1 Fall	1	3.92	73.43
2017	2 Spring. 2 Fall	3	15.04	58.39

- **Terra Constellation Exit & Orbit Lowering :**

Mission Date (-)	Maneuver Type (-)	Fuel Used (kg)	Fuel Remaining (kg)
1/11/2018	Envelope Exit #1	3.62	54.77
1/11/2018	Envelope Exit #2	3.60	51.17
12/19/2023	De-orbit #1	3.57	47.60
12/21/2023	De-orbit #2	3.55	44.05
12/26/2023	De-orbit #3	3.53	40.52
12/28/2023	De-orbit #4	3.51	37.01
1/2/2024	De-orbit #5	3.49	33.52
1/4/2024	De-orbit #6	3.47	30.06
1/9/2024	De-orbit #7	3.45	26.61
1/11/2024	De-orbit #8	3.43	23.18
1/16/2024	De-orbit #9	3.41	19.77
1/18/2024	De-orbit #10	3.39	16.38
1/23/2024	De-orbit #11	3.37	13.01
1/25/2024	De-orbit #12	3.35	9.66
1/30/2024	De-orbit #13	3.33	6.33
2/1/2024	De-orbit #14	3.32	3.01

Fallback Option 2

Lifetime and Orbit Lowering Maneuvers

- **Terra Lifetime (in constellation):**

Mission Year	Inclination Maneuvers	DMU Maneuvers	Fuel Used (kg)	Fuel Remaining (kg)
2016	0 Spring, 1 Fall	1	3.92	73.43
2017	0 Spring, 0 Fall	2	0.21	73.22

- **Terra Constellation Exit & Orbit Lowering:**

Mission Year	Maneuver Type	Fuel Used (kg)	Fuel Remaining (kg)
1/11/2018	Envelope Exit #1	3.72	69.51
1/11/2018	Envelope Exit #2	3.69	65.81
6/21/2022	De-orbit #1	3.67	62.14
6/23/2022	De-orbit #2	3.64	58.50
6/28/2022	De-orbit #3	3.62	54.88
6/30/2022	De-orbit #4	3.60	51.28
7/5/2022	De-orbit #5	3.57	47.71
7/7/2022	De-orbit #6	3.55	44.16
7/12/2022	De-orbit #7	3.53	40.63
7/14/2022	De-orbit #8	3.51	37.12
7/19/2022	De-orbit #9	3.49	33.63
7/21/2022	De-orbit #10	3.47	30.16
7/26/2022	De-orbit #11	3.45	26.71
7/28/2022	De-orbit #12	3.43	23.29
8/2/2022	De-orbit #13	3.41	19.88
8/4/2022	De-orbit #14	3.39	16.49
8/9/2022	De-orbit #15	3.37	13.12
8/11/2022	De-orbit #16	3.35	9.77
8/16/2022	De-orbit #17	3.33	6.43
8/18/2022	De-orbit #18	3.32	3.11

Fallback Option 3

Lifetime and Orbit Lowering Maneuvers

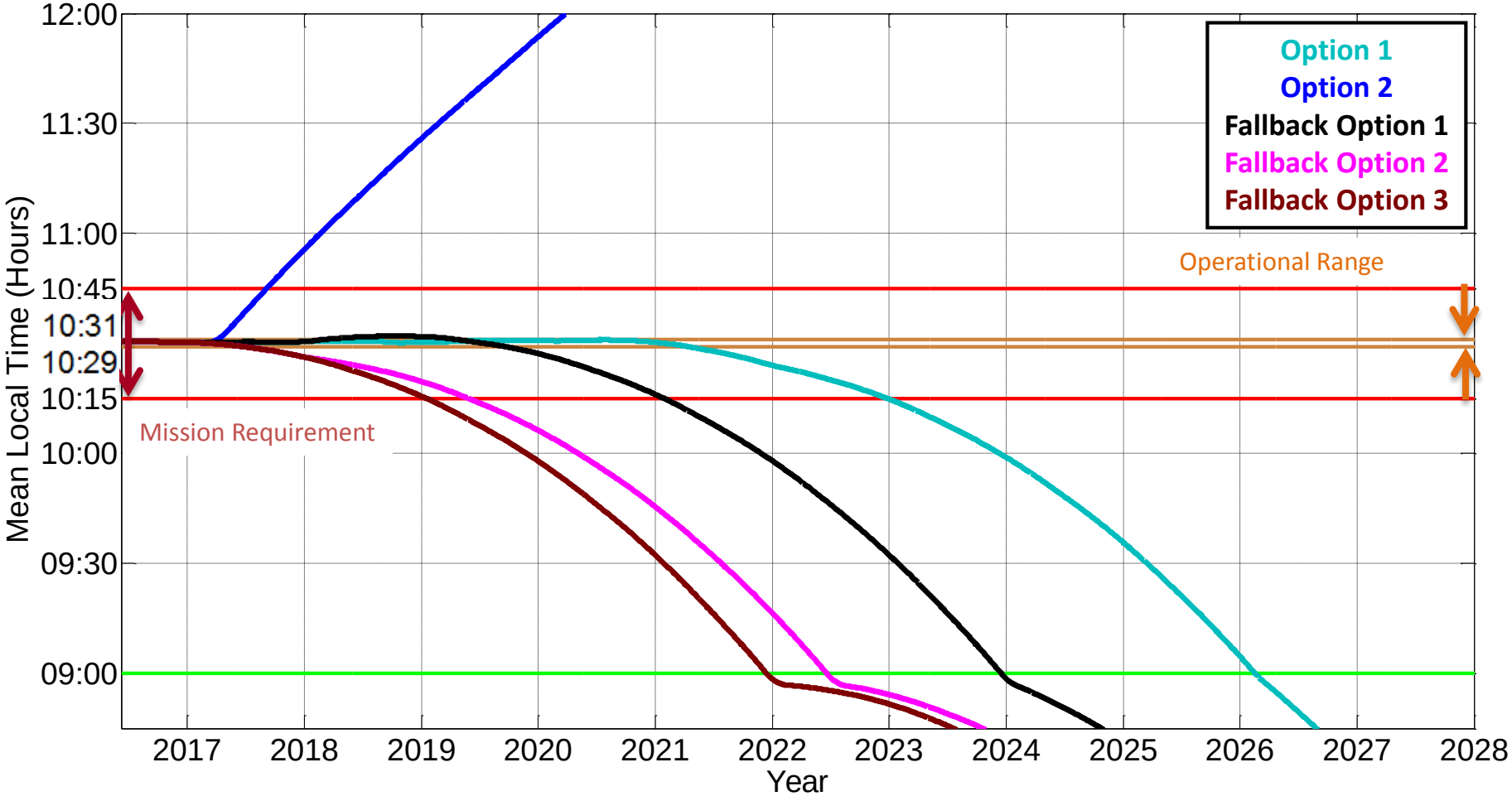
- **Terra Lifetime:**

Mission Year	Inclination Maneuvers	DMU Maneuvers	Fuel Used (kg)	Fuel Remaining (kg)
2016	0 Spring, 1 Fall	1	3.92	73.43
2017	0 Spring, 0 Fall	2	0.21	73.22
2018	0 Spring, 0 Fall	3	0.27	72.96
2019	0 Spring, 0 Fall	1	0.08	72.88
2020	0 Spring, 0 Fall	2	0.15	72.73
2021	0 Spring. 0 Fall	3	0.33	72.39

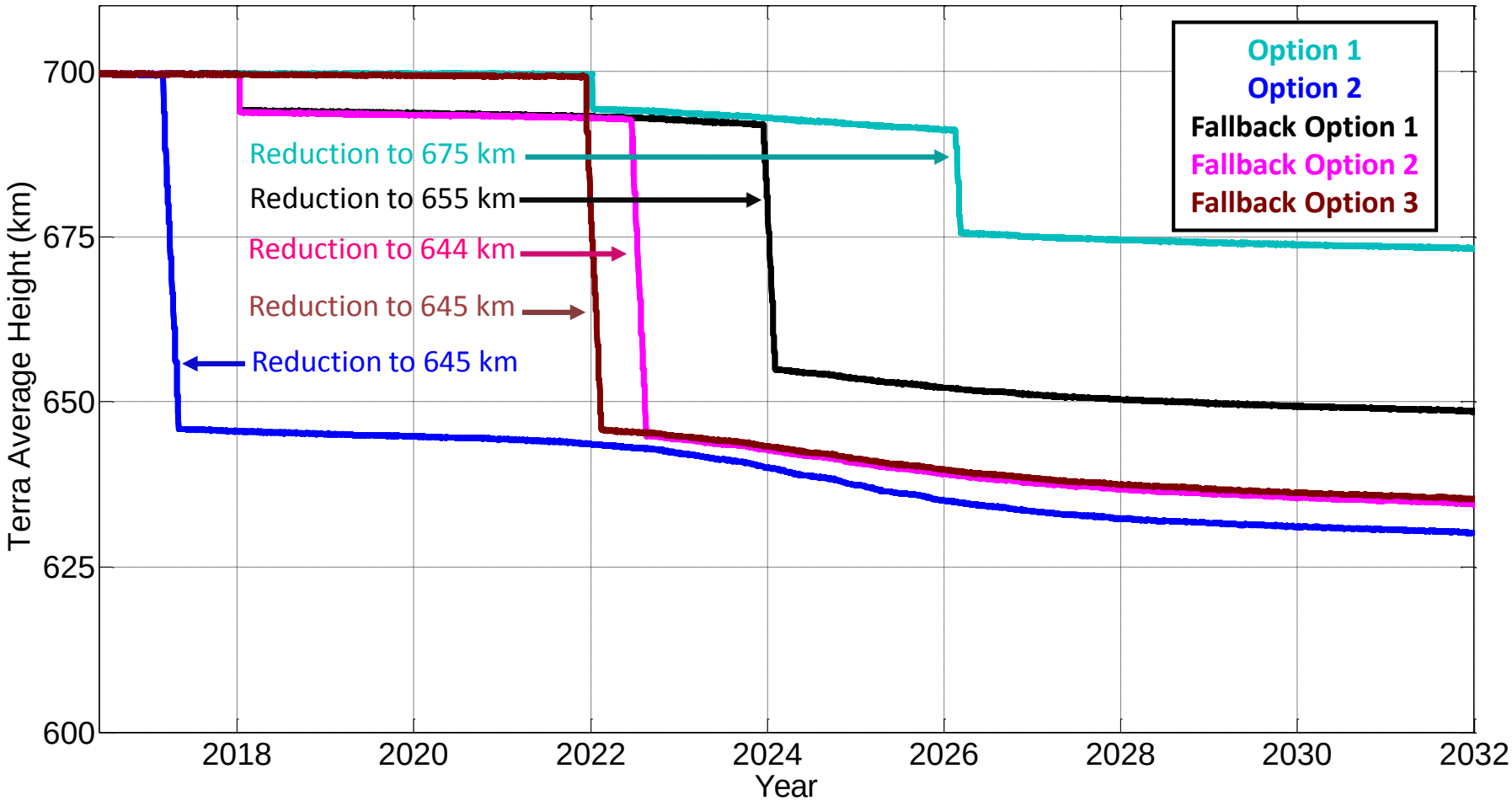
- **Terra Constellation Exit & Orbit Lowering :**

Mission Year	Maneuver Type	Fuel Used (kg)	Fuel Remaining (kg)
12/14/2021	Envelope Exit #1	3.71	68.68
12/14/2021	Envelope Exit #2	3.69	64.99
12/16/2021	De-orbit #1	3.66	61.33
12/21/2021	De-orbit #2	3.64	57.69
12/23/2021	De-orbit #3	3.61	54.08
12/28/2021	De-orbit #4	3.59	50.49
12/30/2021	De-orbit #5	3.57	46.92
1/4/2022	De-orbit #6	3.55	43.37
1/6/2022	De-orbit #7	3.53	39.84
1/11/2022	De-orbit #8	3.50	36.34
1/13/2022	De-orbit #9	3.48	32.86
1/18/2022	De-orbit #10	3.46	29.39
1/20/2022	De-orbit #11	3.44	25.95
1/25/2022	De-orbit #12	3.42	22.53
1/27/2022	De-orbit #13	3.40	19.12
2/1/2022	De-orbit #14	3.39	15.74
2/3/2022	De-orbit #15	3.37	12.37
2/8/2022	De-orbit #16	3.35	9.02
2/10/2022	De-orbit #17	3.33	5.69
2/15/2022	De-orbit #18	3.31	2.38

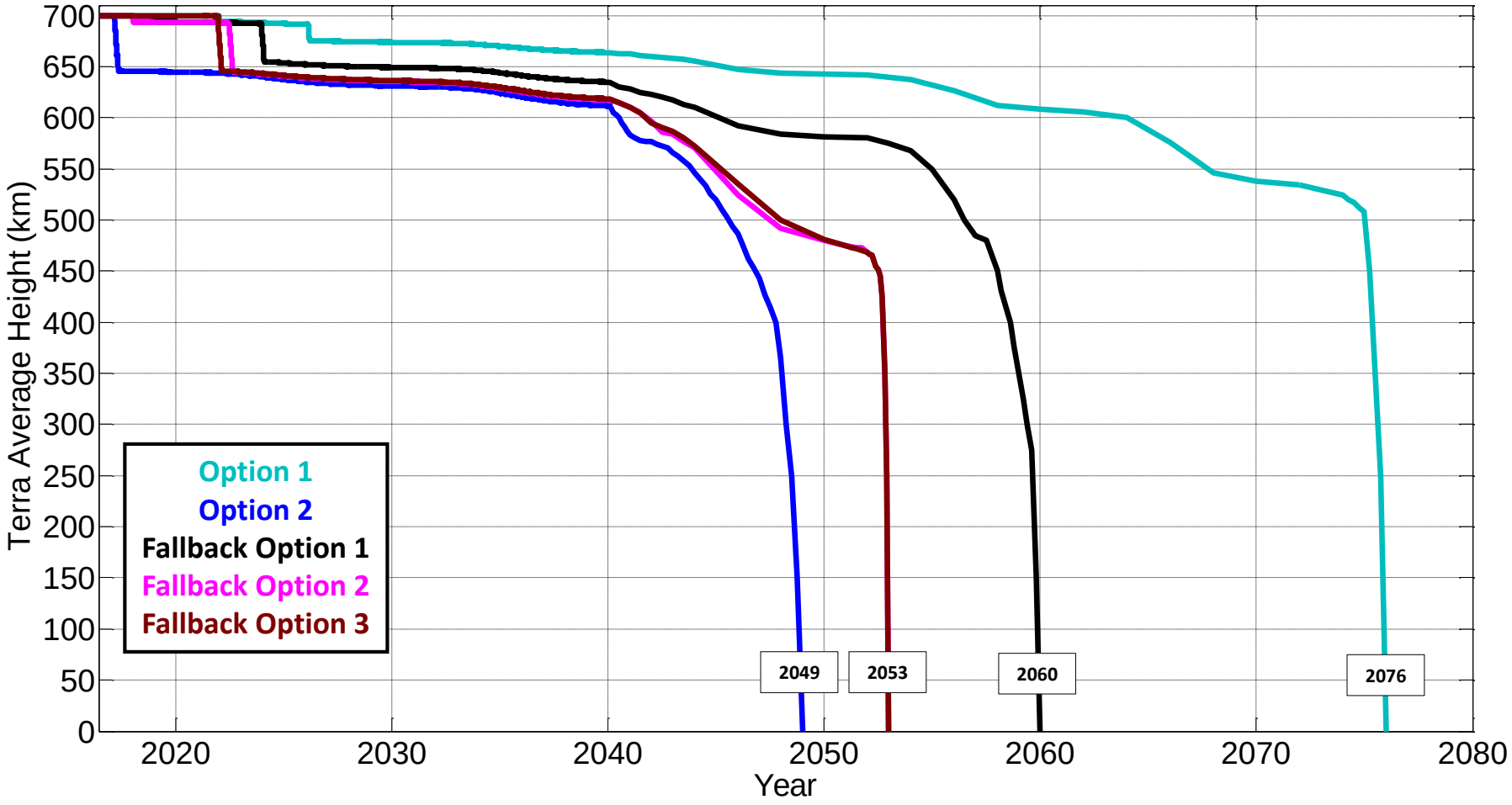
Mean Local Time



Final Average Height



Lifetime Average Height



Lifetime Fuel Estimates