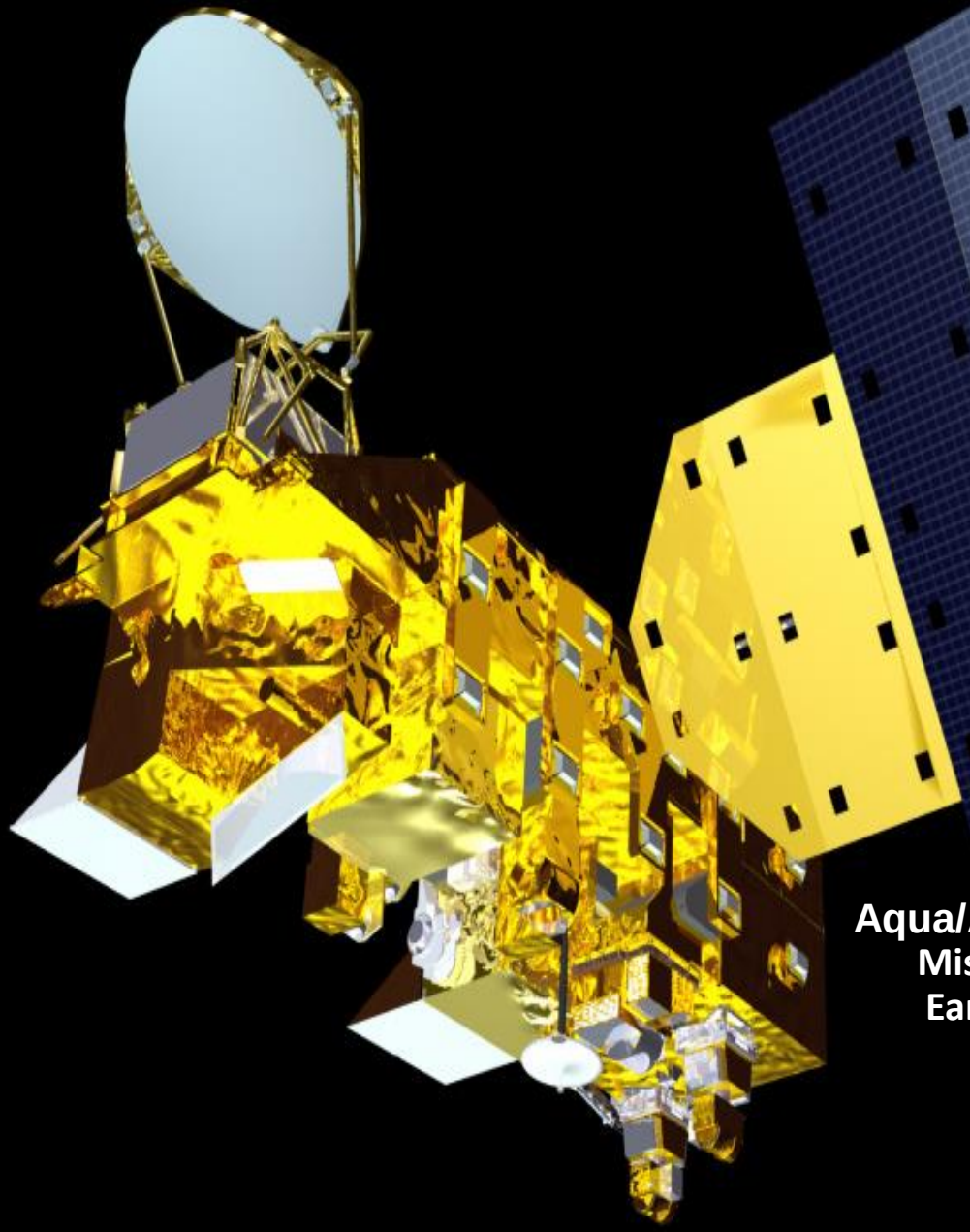
EOS Aqua



Extended Mission Options at Earth Science Constellation MOWG Meeting Albuquerque, NM

September 28, 2016

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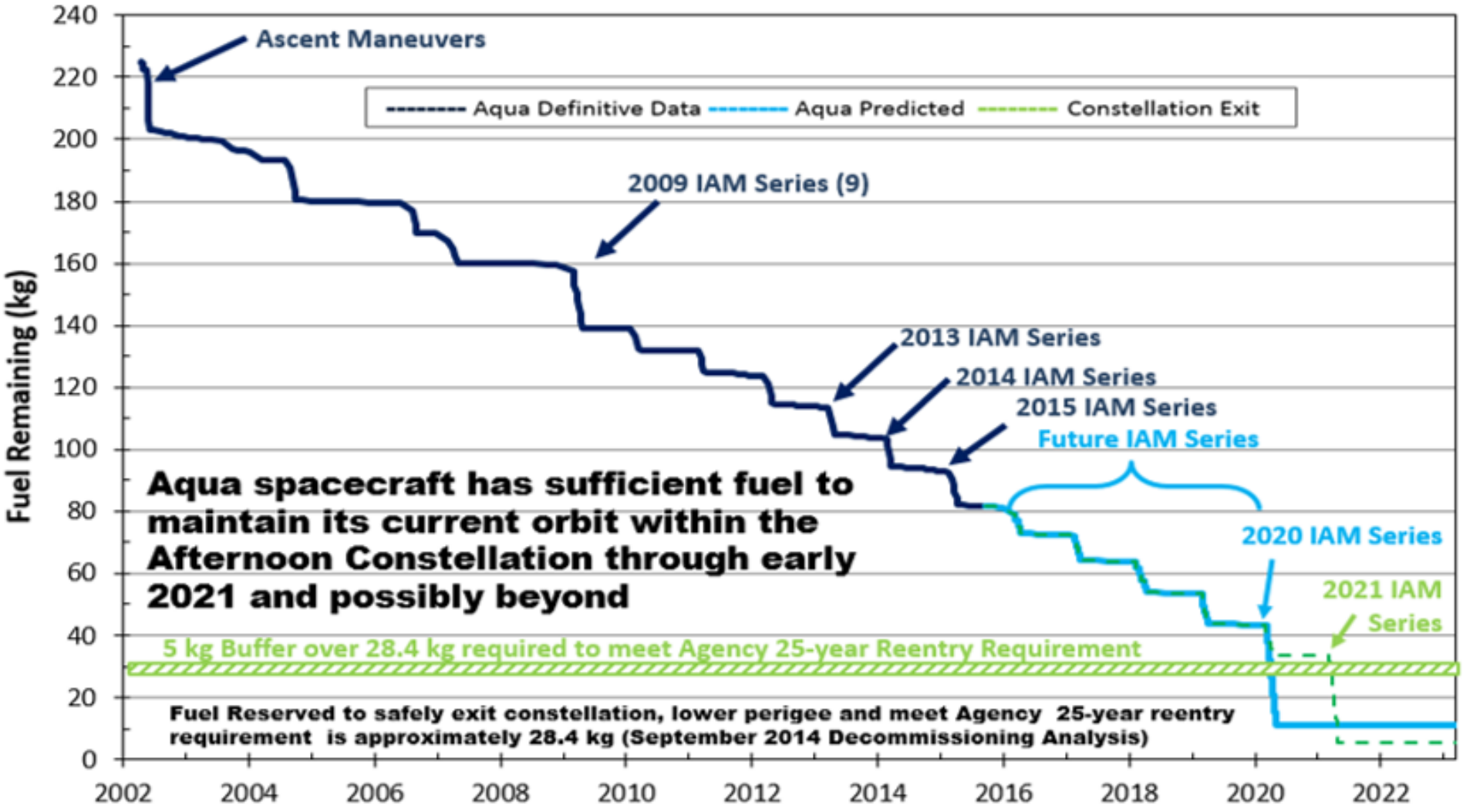
Topics

- **Aqua Fuel Usage and Predictions**
  - April 2016 MOWG Meeting (historical)
  - Changes incorporated since last MOWG Meeting
  - Fuel Usage – Life of Mission (Book-keeping vs PVT)
  - Aqua Key Facts
  - End of Fuel Life Predicts (based on NASA's Debris Assessment Software)
- **Aqua Extended Mission Options**
  - Option 1: Continue MLT maintenance at 705km for as long as possible
  - Option 2: Allow MLT to drift slowly by conducting fractional (smaller) IAMs
  - Option 3: Stop IAMs early, exit constellation and continue science for extended duration (work in progress – limited analysis presented)
- **Aqua and A-Train Possible Path Forward**
  - Aqua seeking inputs from other member missions for 2018 and beyond

Fuel Usage: Actual & Predicted

(February 2016)

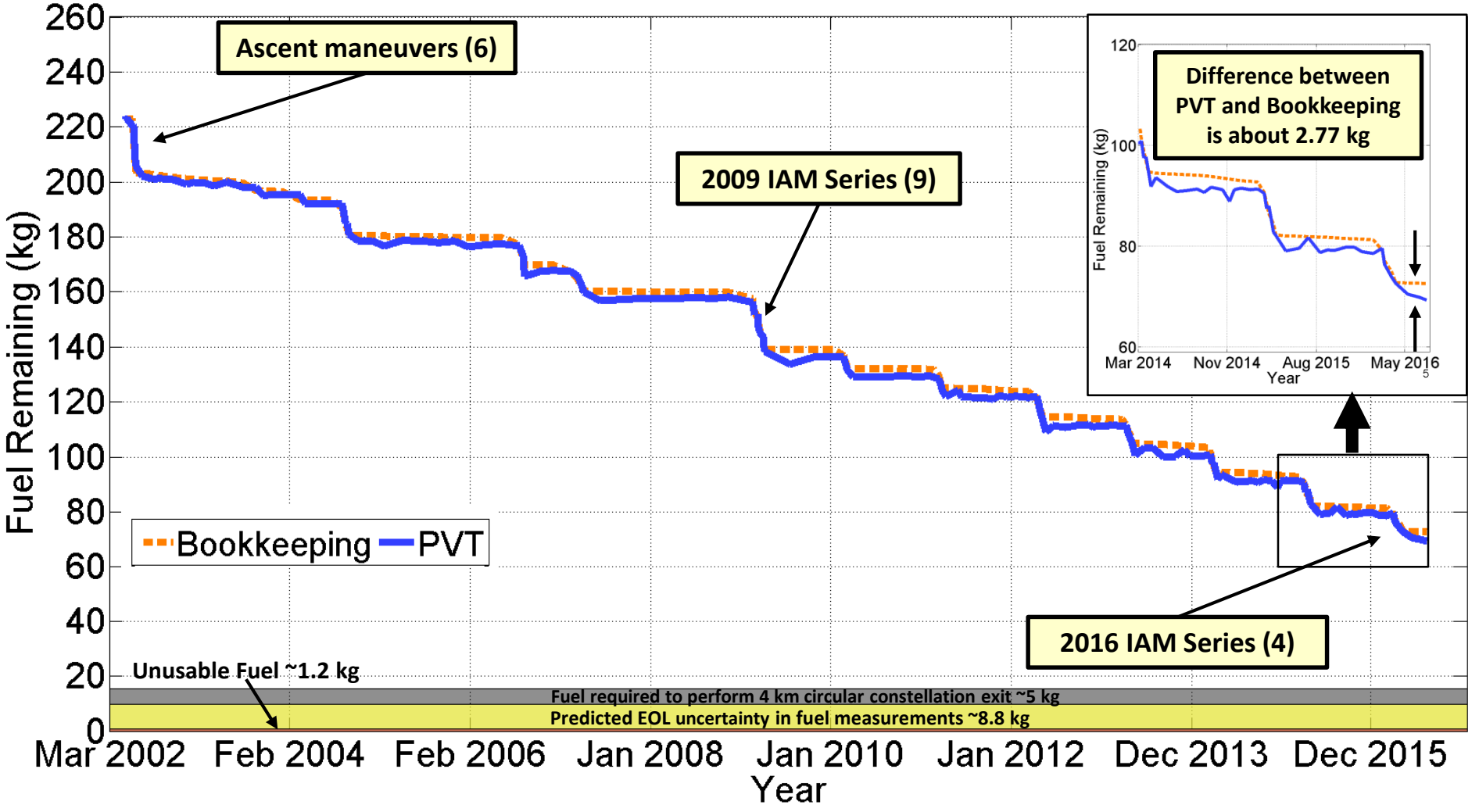


Reference: Aqua Mission Status as presented at April 2016 ESC/A-Train MOWG

Summary of changes for this MOWG Meeting

- **Constellation Exit:**
  - **Aqua adopted the 4 km exit as its new baseline exit (requires about 5 kg)**
    - Based on approval of the 2015 Operations Coordination Plan
    - Based on lessons learned from Terra and Landsat-8 (and also PARASOL)
- **Fuel Analysis:**
  - **Expanded fuel usage plots to include multiple measuring methods**
    - Bookkeeping (B-K) - what's been shown in the past
    - Pressure, Volume and Temperature (PVT) – most conservative
  - **Now including estimated uncertainty in the fuel measurements (8.8 kg)**
  - **Now including unusable fuel trapped in lines and tank (1.2 kg)**
- **Extended Mission Analysis:**
  - **Currently investigating more fuel efficient methods of performing retrograde maneuvers and inclination adjust maneuvers**
  - **Currently investigating various methods for extending the Aqua operational science mission lifetime with sufficient fuel to exit constellation and meet the 25 year re-entry requirement**

Aqua Fuel Usage: Life of the Mission
(September 2016)



Source: Lifetime Results, Draft Aqua Decommissioning Analysis, September 1,2016, Juan Ojeda Romero and Waqar Zaidi

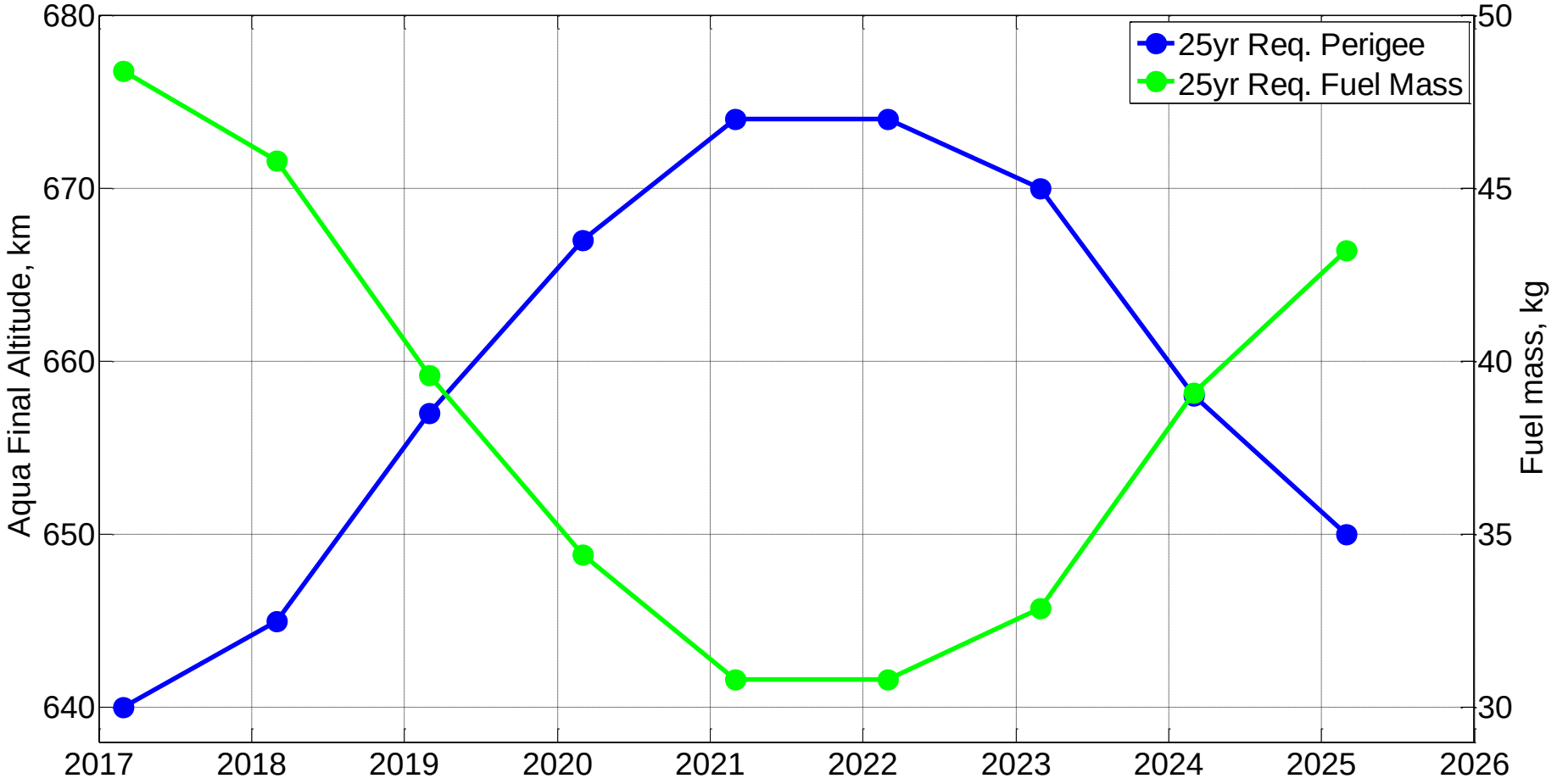
Aqua Key Facts

- **Aqua has been the anchor for the Afternoon Constellation**
- **Required to hold sufficient fuel in reserve to:**
  - Safely exit the constellation
  - Lower perigee to meet the NASA 25-year reentry requirement
- **Required to use the NASA's Debris Assessment Software (DAS) for end of mission life analysis**
  - Created by NASA's Orbital Debris Office at Johnson Space Center.
  - DAS is the Agency standard for end of mission life analyses and lifetime estimations (Current Version 2.0.2)
  - DAS Solar Flux model is updated twice per year
- **Maximize mission and constellation science objectives with remaining fuel while still meeting the Constellation Exit and 25 year re-entry requirements**
  - Current plan is to perform full Inclination adjustments in 2017 and 2018

Aqua DAS End of Fuel Life Predictions

(September 2016)

DAS required perigee to meet 25-year reentry after 4 km circular exit.
Fuel Required includes 5kg for exit constellation, 1.2 kg unusable, 8.8 kg uncertainty.



Shows Solar Cycle effects on perigee required to meet 25 year reentry requirement.

Aqua DAS End of Fuel Life Predictions

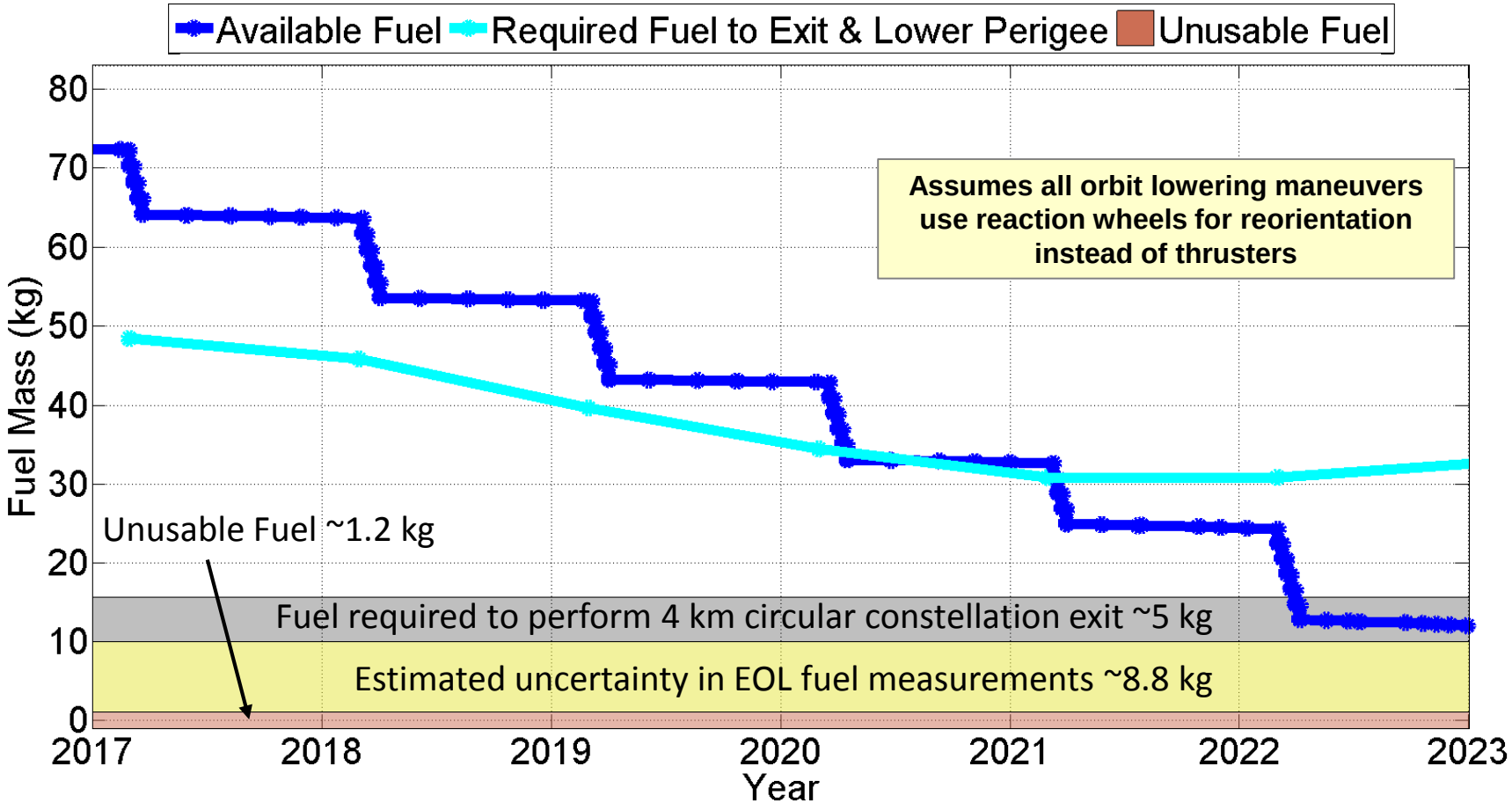
(Based on August 2016 DAS Flux Update)

Decommissioning Date (March 1st)	Decom. Perigee to meet 25-yr Req (km)	Fuel Required to reach Decom. Perigee (kg)	Pre-IAM Estimated Fuel Remaining (kg)	Predicted 10.7 cm Flux on Decom. Date (Aug 2016)
2017	640	**48.4**	72.3	87.0
2018	645	**45.8**	63.7	74.1
2019	657	**39.6**	53.2	66.1
2020	667	**34.4**	42.9	63.8
2021	674	**30.8**	32.8	109.9
2022	674	**30.8**	24.5	169.7
2023	670	**32.9**	12.0	183.1
2024	658	**39.1**	N/A	172.4
2025	650	**43.2**	N/A	138.4

- Estimated Fuel Remaining assumes full IAMs are performed every year to maintain Mean Local Time (MLT).
- The Fuel Remaining is not related to the fuel required to meet the 25yr requirement.
- Fuel Required includes constellation exit (~5 kg) plus fuel uncertainty (~8.8 kg) and unusable fuel (~1.2 kg)

Insufficient fuel to perform 2021 IAM and meet constellation exit and 25 year re-entry requirements. Operational changes will likely have to occur sometime between March 2019 and March 2021.

Aqua Predicted Fuel Usage: 2017 - 2023
(September 2016)



Fuel required to exit constellation & lower perigee to meet 25-year reentry requirement.

Insufficient Fuel to continue performing Full Inclination Maneuvers beyond 2020.

May Exit Constellation sooner (No earlier than March 2019) to maximize mission science and reserve additional fuel to meet 25 year requirement in the 2025 timeframe.

Aqua Extended Mission (EM) Options

1	**Maintain current MLT (IAM series) for as long as possible then perform 4 km exit**
	New Aqua Baseline **Benefit**: Provides consistent science and constellation MLT though 2020. **Drawback**: Aqua will likely need to exit in 2020 and decommission in 2025.
2	**Allow MLT to slowly drift by conducting less than full IAMs starting as early as 2019**
	Perform fewer IAM burns per year starting in 2019. Causes MLT to drift toward 13:45. **Benefit**: Extends the mission life within the operational MLT requirement and maintains nominal ground track and altitude. **Drawback**: Will result in passing/crossing situation between the afternoon and morning constellations. Aura crossing/passing Landsat-8 followed by other Afternoon constellation members. **Currently considered too risky**. Further analysis required to determine if this can be done safely.
3	**Stop IAMs early (No earlier than March 2019), exit the constellation, drift the MLT and continue science operations**
	Exit Constellation. No drag make-up maneuvers will be performed. (allow orbit to decay naturally) Fuel will be reserved to execute debris avoidance maneuvers and meet 25 year reentry. Mean Local Time (MLT) of the node crossing will be allowed to drift. **Benefit**: Aqua will continue its science mission for an extended period of time up to and through 2025 and potentially beyond. **Drawback**: Science algorithm development and calibration at the lower orbit.

Option 1: Maintain MLT at 705km for as long as possible, Constellation exit in 2020, lower perigee in 2025

- Aqua performs Inclination Adjust Maneuvers (IAMs) each Spring near the equinox (March to April) in 2017, 2018 and 2019.
- Aqua performs mirror pole Drag Make Up Maneuvers (DMUMs) to maintain ground track constraints, frozen orbit maneuvers are performed to maintain frozen orbit parameters before each IAM series.
- Essentially business as usual for the next few years. (2017 – March 2020)
- Constellation exit in early 2020 before the 2020 IAMs, orbit decays naturally, no DMUMs but will perform DAMs as necessary.
- Continue Science Mission in lower orbit with drifting MLT. (no IAMs)
- Lower perigee in spring 2025 and continue operations or decommission.
- Reentry around 2047.

Mission Year	Inclination Maneuvers	DMU Maneuvers	Fuel Used (kg)**	Fuel Remaining (kg)**
2016 (Jun - Dec)	0	5	0.38	72.32
2017	4	5	8.60	63.72
2018	5	5	10.50	53.21
2019	5	5	10.30	42.91
2020	0	1	0.05	42.87*

*Fuel Remaining is end-of-year fuel mass except for March 1st 2020

** Post maneuver

Option 2 – Fractional IAMs starting in 2019 (to save fuel) Exit in 2020, Lower perigee and decommission in 2025

- Aqua performs full IAMs each Spring near the equinox (March/April) until Spring 2019.
- Aqua performs mirror pole DMUs to maintain ground track constraints, frozen orbit maneuvers are performed to maintain frozen orbit parameters before each IAM series.
- Starting in Spring 2019, Aqua performs fractional IAMs based on nominal IAM planning.
- Does not guarantee that Aqua will stay within its science or mission MLT constraints.
- **Potential orbital safety issue between Aura and Landsat-8.**
- Aqua exits the constellation in 2020. Maybe 2021 if sufficient fuel to lower perigee in 2025 and meet 25-year reentry requirement.
- Aqua continues its Science Mission in lower orbit with drifting MLT. (no IAMs)
- Lower perigee in spring 2025 (or later) and continue operations or decommission.
- Reentry will occur within 25-years of the end of the science mission.

Mission Year	Inclination Maneuvers	DMU Maneuvers	End-of-Year MLT (HH:mm)	Fuel Used (kg)+	End-of-Year Fuel Remaining (kg)+
2016 (Jun - Dec)	0	5	13:35	0.38	72.32
2017**	4	5	13:35	8.60	63.72
2018**	5 (maybe less)	5	13:35	10.50	53.21
2019	2 of 5	5	13:37	6.64	46.57
2020	2 of 5	5	13:41	6.58	39.99

*High Solar flux requires more DMUs to maintain ground track. Solar Flux F10.7 values are nominal mean Schatten predictions (March 2016 update).
** Nominal IAM series performed in these years.
+ Post maneuver

Option 3 – Stop IAMs early, exit constellation in 2019 and continue science for extended duration in a lower orbit

- Aqua performs full IAMs each Spring near the equinox (March to April).
- Aqua performs mirror pole DMUs to maintain ground track constraints, frozen orbit maneuvers are performed to maintain frozen orbit parameters before each IAM series.
- Constellation exit in 2019. (to save fuel)
- Continue operations in a lower orbit with drifting MLT. (no IAMs or DMUMs)
- Allow orbit to decay naturally.
- Retain sufficient fuel to perform debris avoidance maneuvers (DAMs) and eventually lower perigee so the reentry occurs within 25-years.
- Final perigee lowering and decommissioning/passivation date is 2025+
- Reentry within 25-years of decommissioning and passivation.

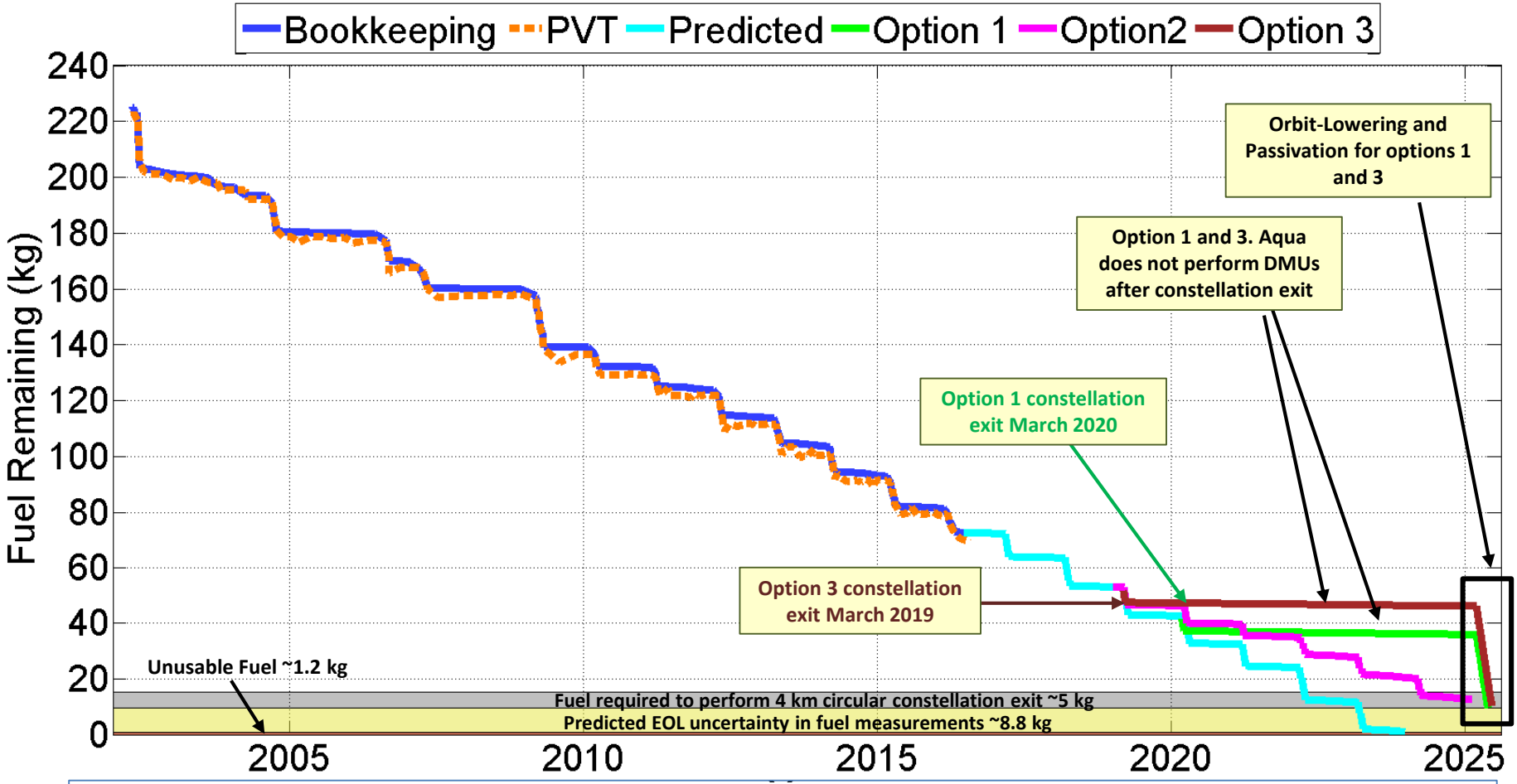
Mission Year	Inclination Maneuvers (#)	DMU Maneuvers (#)	Fuel Used (kg)**	Fuel Remaining (kg)**
2016	0	5	0.38	72.32
2017	4	5	8.60	63.72
2018	5	5	10.50	53.21
2019	0	5	0.04	53.17*

*Fuel Remaining is end-of-year fuel mass except for March 1st 2019

**Post maneuver

Aqua Proposed Options

Fuel Usage: Actual & Predicted



Predicted fuel is based on full IAM series each year thru fuel depletion

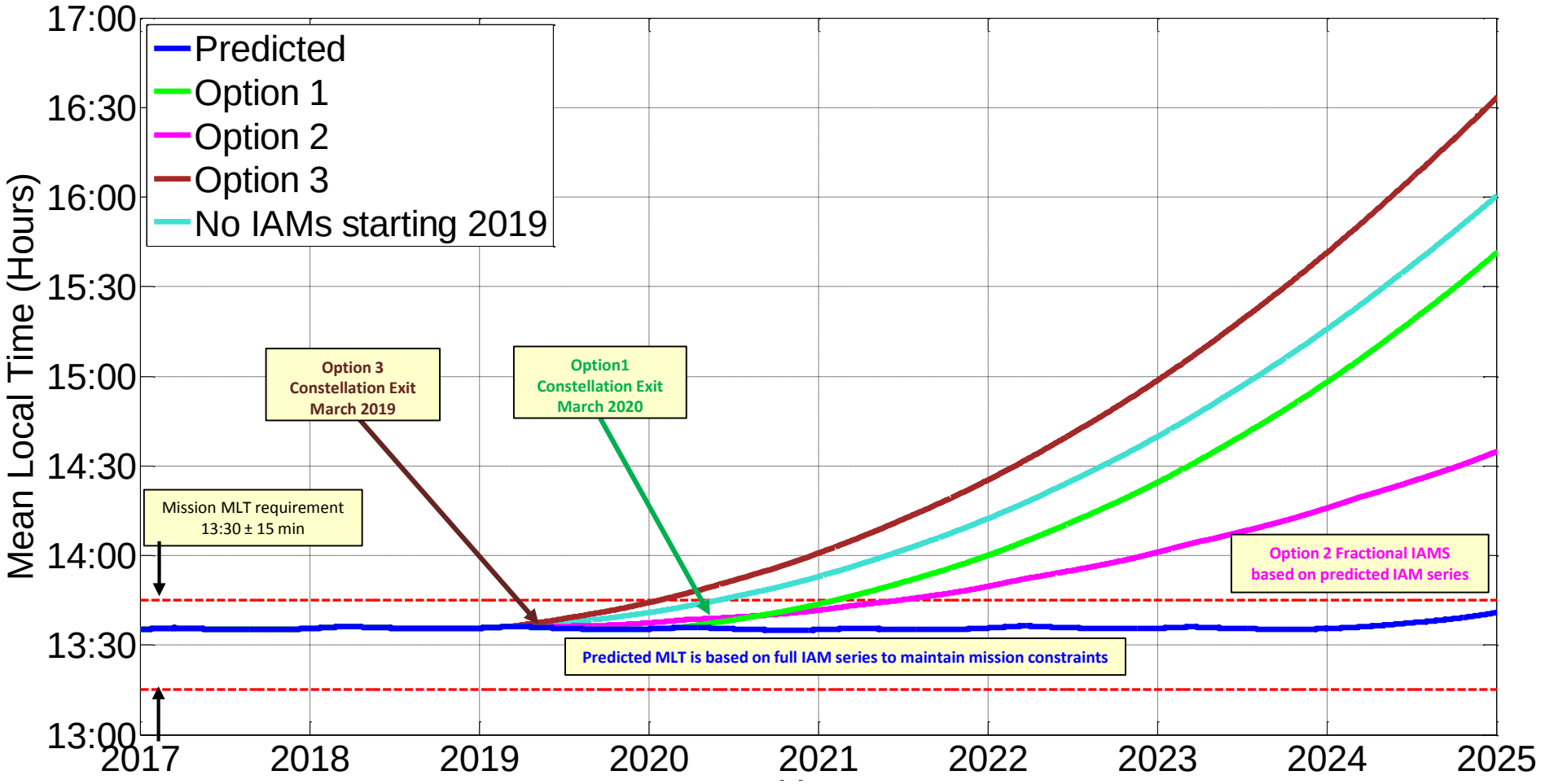
Option 1: Maintain MLT at 705km for as long as possible, exit in 2020

Option 2: Fractional IAM series starting in 2019 (to save fuel), exit in 2020+

Option 3: Stop IAMs and exit in 2019, continue science as long as possible

Aqua Proposed Options

Mean Local Time (MLT) of node crossing

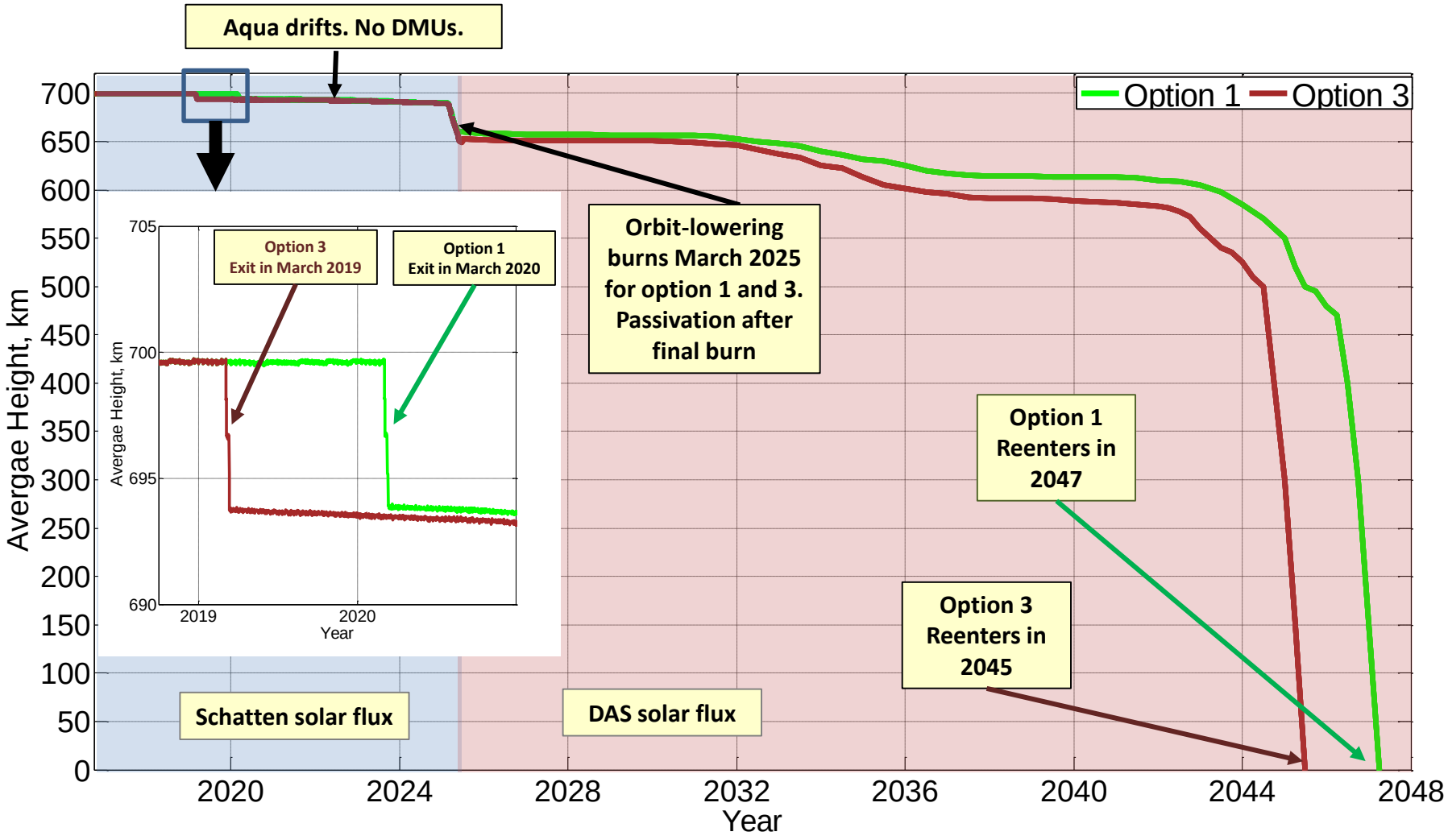


Options 2 and 3 are proposed to save fuel in the 2019 to 2020 time frame to provide sufficient fuel in the 2024 to 2025+ time frame to meet 25-year reentry

Option 2 will create crossing conjunctions between Aura and Landsat-8

Aqua Proposed Options Long-Term Orbit Decay

Lifetime Average Height



Schatten nominal mean F10.7 solar flux values were used in the analysis through early 2025
DAS 2.0.2 solar flux values were used in the reentry analysis. (comparison in back-up slides)

Aqua Extended Mission (EM) Status and Plans

- 2016 Lifetime analysis indicates fewer than 5 years left – June 2016
- Briefed Aqua Project Scientist – July/August/September 2016
- Briefed NASA Program Executive – September 2016
- ----------
- Constellation MOWG Meeting – September 2016
- Develop & Perform Analysis on viable mission extension options – October 2016
- Send options to Aqua Instrument Teams for their feedback – November 2016
- Aqua Instrument Team feedback due – December 2016
- Send options to Constellation for feedback – December 2016
- Extended Mission Engineering Peer Review – TBD
- Constellation Feedback – February 2017
- Aqua Science Team Meeting Opportunity – December 2016 (at AGU)
- Aqua Extended Mission Senior Review Proposal due – March 3, 2017
- Spring 2017 Inclination Adjustment – March 2017
- Science Team Meeting at A-Train Science Symposium – April 2017
- Constellation MOWG Meeting (at GSFC) – June 2017
- Constellation MOWG Meeting – October 2017
- Final Decision Deadline – Prior to 2018 Inclination Adjust (Nov/Dec 2017)

Backup Slides

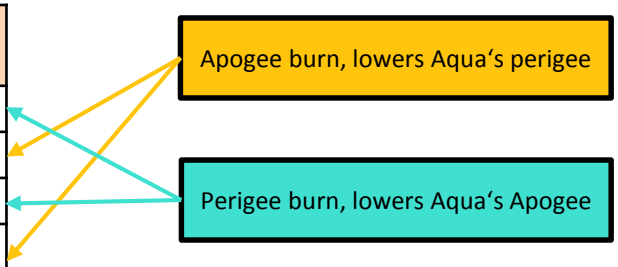
Aqua Remaining Fuel Estimations
Options 1 & 3 Additional Information

Aqua Remaining Fuel Estimate Simulations
(September 2016)

- **Long-term orbit simulations were run for Aqua through 2023**
  - Used mean nominal Schatten solar flux predictions (August 2016)
  - Estimated the frequency of drag make-up maneuvers (DMUMs) to maintain Aqua's WRS-2 ground track requirements
  - Estimated the required number of annual inclination maneuvers (IAMs) for Aqua to maintain it's mean local time (MLT) requirement
  - Did not include potential debris avoidance maneuvers
  - Utilized FreeFlyer 6.7.2 which incorporated the solid earth tide model allowing greater accuracy for long term predictions of inclination, beta angle, and mean local time

Option 1 – Constellation exit in 2020
Lower perigee and decommission in 2025

Mission Date (-)	Maneuver Type (-)	Fuel Used (kg)*	Fuel Remaining (kg)**	Perigee (km)**	Apogee (km)**
3/3/2020	Constellation Exit	1.35	41.51	694.74	707.47
3/4/2020	Constellation Exit	1.35	40.16	692.06	707.42
3/10/2020	Constellation Exit	1.35	38.82	692.11	704.27
3/11/2020	Constellation Exit	1.34	37.48	689.32	704.12
3/4/2025	Orbit-Lowering #1	1.34	36.14	680.76	701.52
3/6/2025	Orbit-Lowering #2	1.34	34.80	678.45	701.07
3/11/2025	Orbit-Lowering #3	1.33	33.47	676.82	700.55
3/13/2025	Orbit-Lowering #4	1.33	32.14	674.97	700.22
3/18/2025	Orbit-Lowering #5	1.33	30.82	674.15	699.25
3/20/2025	Orbit-Lowering #6	1.32	29.49	672.57	698.40
3/25/2025	Orbit-Lowering #7	1.32	28.17	672.45	696.92
3/27/2025	Orbit-Lowering #8	1.32	26.86	671.37	696.09
4/1/2025	Orbit-Lowering #9	1.31	25.55	671.51	693.62
4/3/2025	Orbit-Lowering #10	1.31	24.24	669.68	692.68
4/8/2025	Orbit-Lowering #11	1.31	22.93	668.31	689.99
4/10/2025	Orbit-Lowering #12	1.30	21.63	665.79	688.43
4/15/2025	Orbit-Lowering #13	1.30	20.33	663.40	685.70
4/17/2025	Orbit-Lowering #14	1.30	19.04	660.81	684.70
4/22/2025	Orbit-Lowering #15	1.29	17.74	658.57	684.60
4/24/2025	Orbit-Lowering #16	1.29	16.45	656.29	685.15
4/29/2025	Orbit-Lowering #17	1.29	15.17	653.35	687.45
5/1/2025	Orbit-Lowering #18	1.28	13.88	650.69	688.50
5/6/2025	Orbit-Lowering #19	1.28	12.60	646.65	690.70
5/8/2025	Orbit-Lowering #20	1.28	11.33	643.25	691.35
5/13/2025	Orbit-Lowering #21	1.27	10.05	637.69	693.23

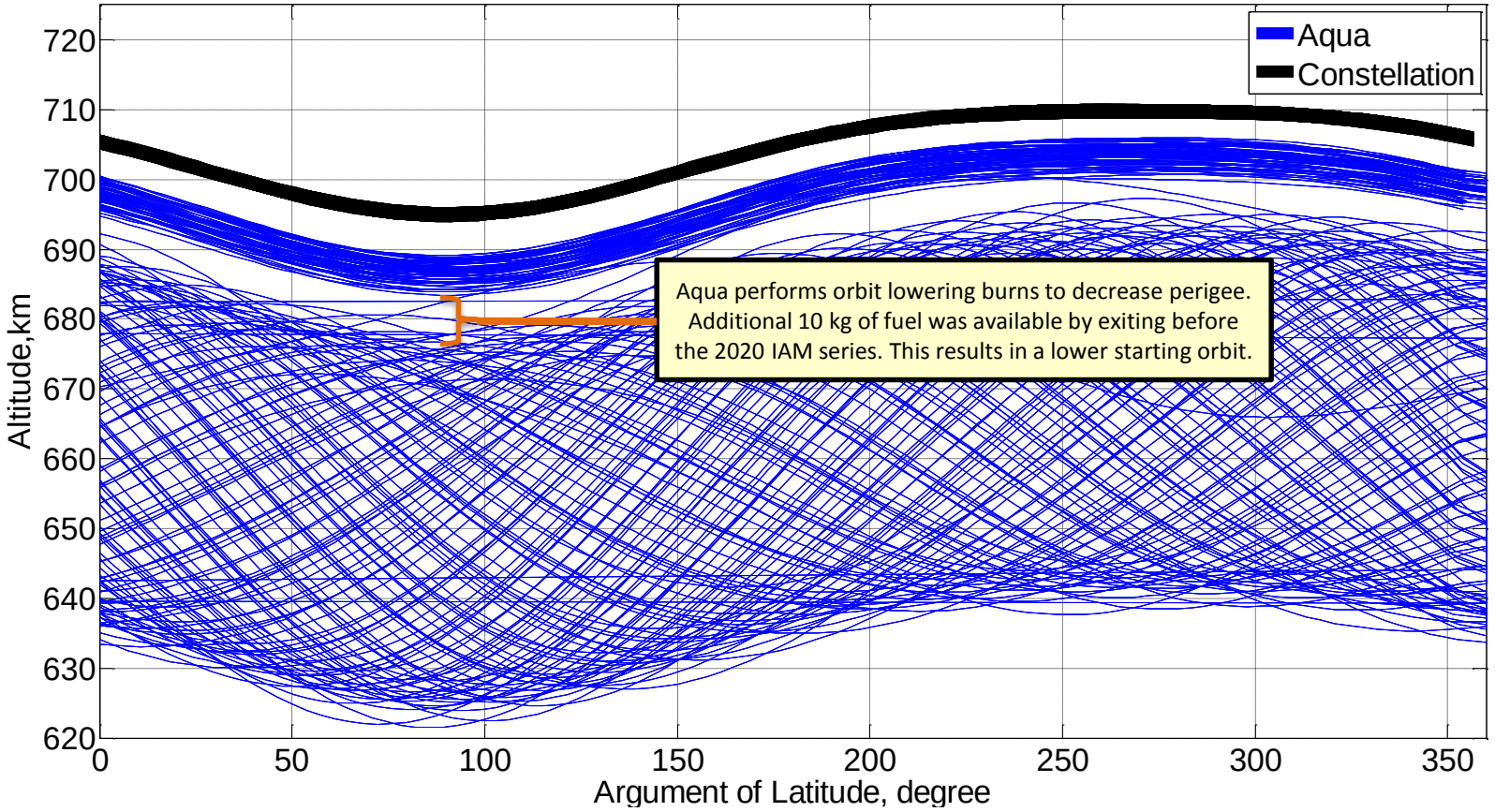


- Exit the constellation in March 2020
- Aqua will rotate to an anti-velocity orientation with its reaction wheels and perform 2 burn pairs of orbit-lowering retrograde maneuvers (4 total maneuvers) to exit at least 4 km below the constellation.
- Aqua will continue its Science Mission after constellation exit in 2020 and will not perform any DMUs or IAMs but will retain fuel for debris avoidance maneuvers (DAMs).
- Further orbit-lowering maneuvers start on March 1st 2025. These are centered at apogee to decrease Aqua's perigee altitude.

*Decreasing fuel used is a result of decreasing pressure in the tank with each retrograde maneuver performed. Aqua is performing a 550 sec retrograde maneuver and assuming fixed duty cycle values obtained from ETSF simulation.
** Post maneuver.

Aqua Proposed Option 1 Altitude

(10 years after exit and passivation with starting orbit of 645 by 697 km)



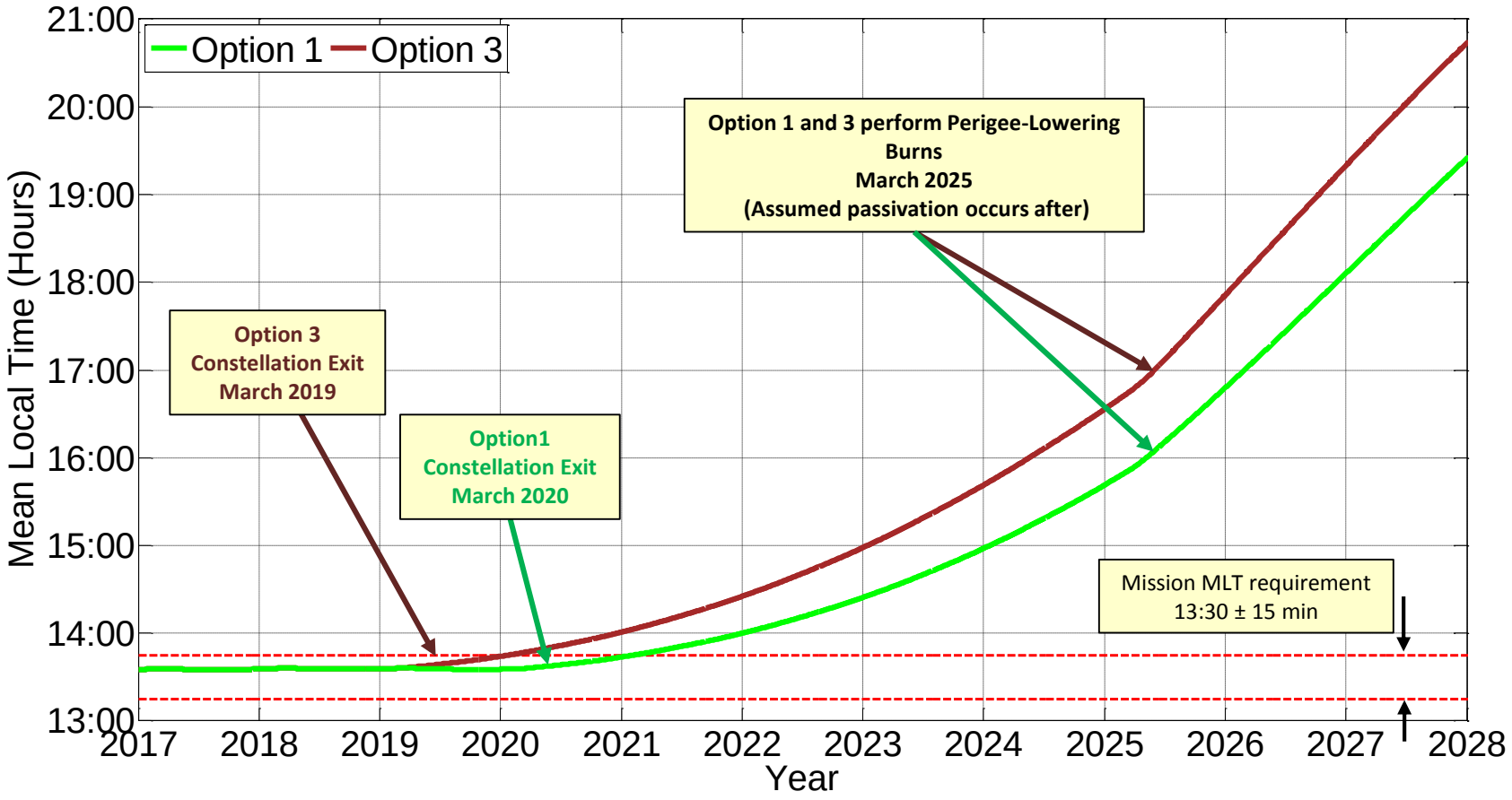
- Aqua exists the constellation in Mar 2020.
- Aqua's orbit propagated 10 years after passivation (~2025).

Analysis indicates 10 years after passivation:

- **Aqua does not re-enter the Constellation**
- **Aqua's Apogee is below the Constellation Envelope, no further analysis required**

Aqua Options 1 and 3 Long-Term Plan

Mean Local Time (MLT) of node crossing

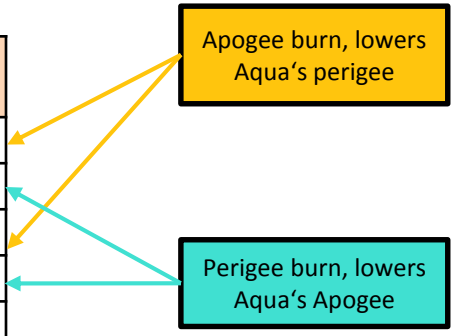


Working with Aqua Project Scientist to determine maximum MLT acceptable for science

Option 3 – Constellation exit in 2019
Predicted Decommissioning

- Aqua exits the constellation in March 1st 2019 using retrograde maneuver pairs centered at apogee and perigee.
- Option 3 use an "Active Pitch" retrograde maneuver to exit 4 km below the constellation and perform orbit-lowering maneuvers. Aqua slews into an anti-velocity orientation using reaction wheels.
- Aqua will drift after constellation exit in 2019 and will not perform any DMUs.
- Orbit-Lowering maneuvers start on March 1st 2025. These are centered at apogee to decrease Aqua's perigee.

Mission Date (-)	Maneuver Type (-)	Fuel Used (kg)*	Fuel Remaining (kg)**	Perigee (km)**	Apogee (km)**
3/5/2019	Constellation Exit	1.38	51.79	694.11	708.16
3/6/2019	Constellation Exit	1.38	50.41	691.36	707.96
3/12/2019	Constellation Exit	1.37	49.04	691.49	704.67
3/13/2019	Constellation Exit	1.37	47.67	688.86	704.57
3/4/2025	Orbit-Lowering #1	1.37	46.30	680.27	701.53
3/6/2025	Orbit-Lowering #2	1.36	44.94	677.90	701.11
3/11/2025	Orbit-Lowering #3	1.36	43.58	676.27	700.58
3/13/2025	Orbit-Lowering #4	1.36	42.23	674.38	700.22
3/18/2025	Orbit-Lowering #5	1.35	40.88	673.62	698.89
3/20/2025	Orbit-Lowering #6	1.35	39.53	672.25	698.33
3/25/2025	Orbit-Lowering #7	1.34	38.18	672.15	696.71
3/27/2025	Orbit-Lowering #8	1.34	36.84	670.78	695.57



*Decreasing fuel used is a result of decreasing pressure in the tank with each retrograde maneuver performed. Aqua is performing a 550 sec retrograde maneuver and assuming fixed duty cycle values obtained from ETSF simulation.
** Post maneuver.

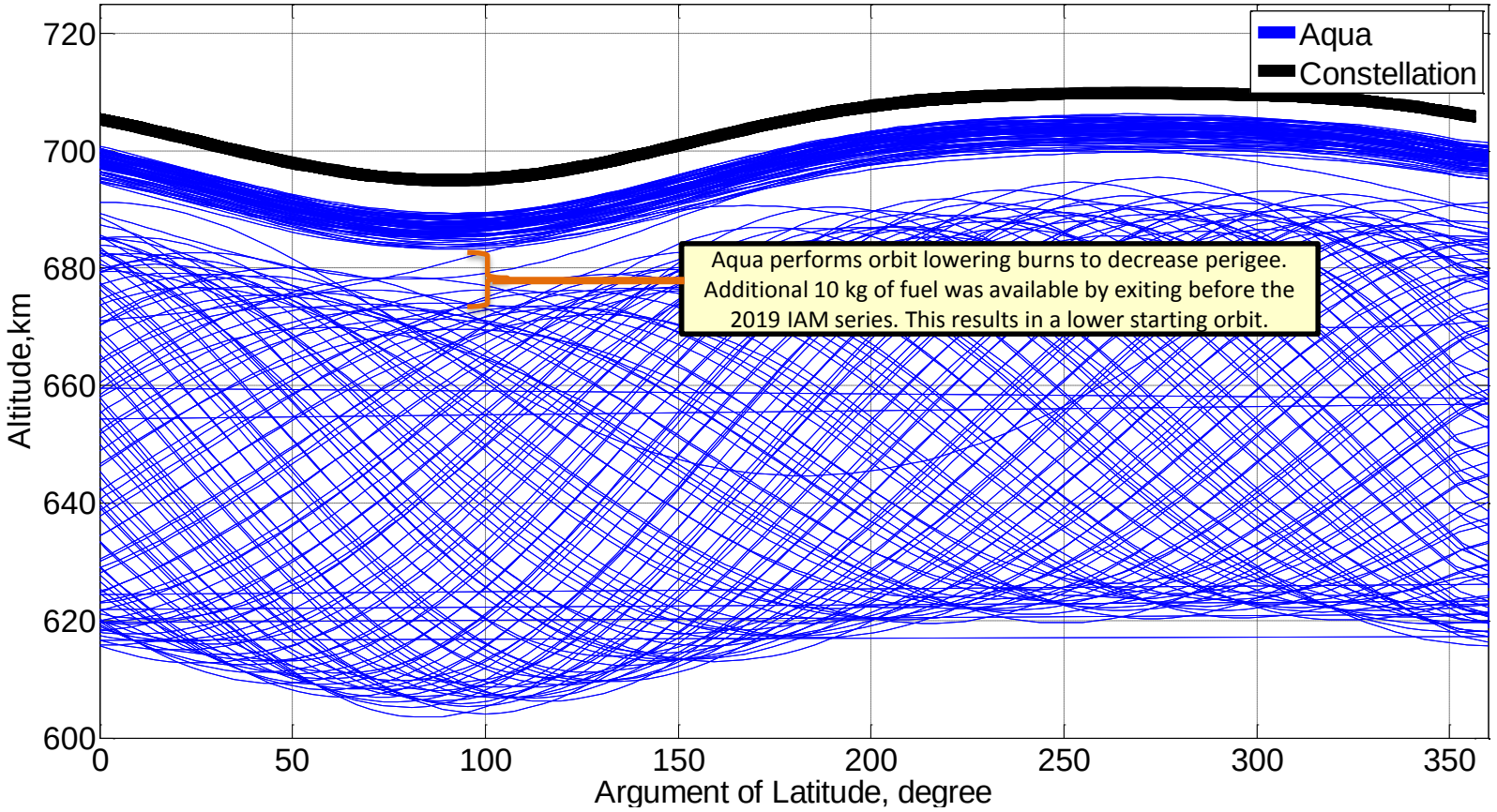
Option 3 – Constellation exit in 2019
Predicted Decommissioning

Mission Date (-)	Maneuver Type (-)	Fuel Used (kg)*	Fuel Remaining (kg)**	Perigee (km)**	Apogee (km)**
4/1/2025	Orbit-Lowering #9	1.34	35.51	670.90	693.43
4/3/2025	Orbit-Lowering #10	1.33	34.17	669.01	692.32
4/8/2025	Orbit-Lowering #11	1.33	32.84	667.30	689.46
4/10/2025	Orbit-Lowering #12	1.33	31.52	664.75	688.14
4/15/2025	Orbit-Lowering #13	1.32	30.19	662.36	685.35
4/17/2025	Orbit-Lowering #14	1.32	28.87	659.53	684.41
4/22/2025	Orbit-Lowering #15	1.32	27.55	657.26	684.86
4/24/2025	Orbit-Lowering #16	1.31	26.24	654.90	685.47
4/29/2025	Orbit-Lowering #17	1.31	24.93	652.12	688.07
5/1/2025	Orbit-Lowering #18	1.31	23.62	649.22	688.81
5/6/2025	Orbit-Lowering #19	1.30	22.32	644.85	691.03
5/8/2025	Orbit-Lowering #20	1.30	21.02	641.33	691.85
5/13/2025	Orbit-Lowering #21	1.30	19.72	636.01	693.45
5/15/2025	Orbit-Lowering #22	1.29	18.43	632.12	693.91
5/20/2025	Orbit-Lowering #23	1.29	17.14	626.95	694.91
5/22/2025	Orbit-Lowering #24	1.29	15.85	623.41	695.08
5/27/2025	Orbit-Lowering #25	1.29	14.56	618.87	695.66
5/29/2025	Orbit-Lowering #26	1.28	13.28	615.69	695.45
6/3/2025	Orbit-Lowering #27	1.28	12.00	612.23	695.60
6/5/2025	Orbit-Lowering #28	1.28	10.73	609.54	695.51

*Decreasing fuel used is a result of decreasing pressure in the tank with each retrograde maneuver performed. Aqua is performing a 550 sec retrograde maneuver and assuming fixed duty cycle values obtained from ETSF simulation.
** Post maneuver.

Aqua Proposed Option 3 Altitude

(10 years after exit and passivation with starting orbit of 626 by 696 km)



- Aqua exists the constellation in Mar 2019.
- Aqua's orbit propagated 10 years after passivation (~2025).
- Monthly snapshots (one orbit every 4 weeks)

Analysis indicates 10 years after passivation:

- **Aqua does not re-enter the Constellation**
- **Aqua's Apogee is below the Constellation Envelope, no further analysis required**