Differential Evolution Optimization for Targeting Spacecraft Maneuver Plans

Daniel Mattern

NASA GSFC || Omitron, Inc.

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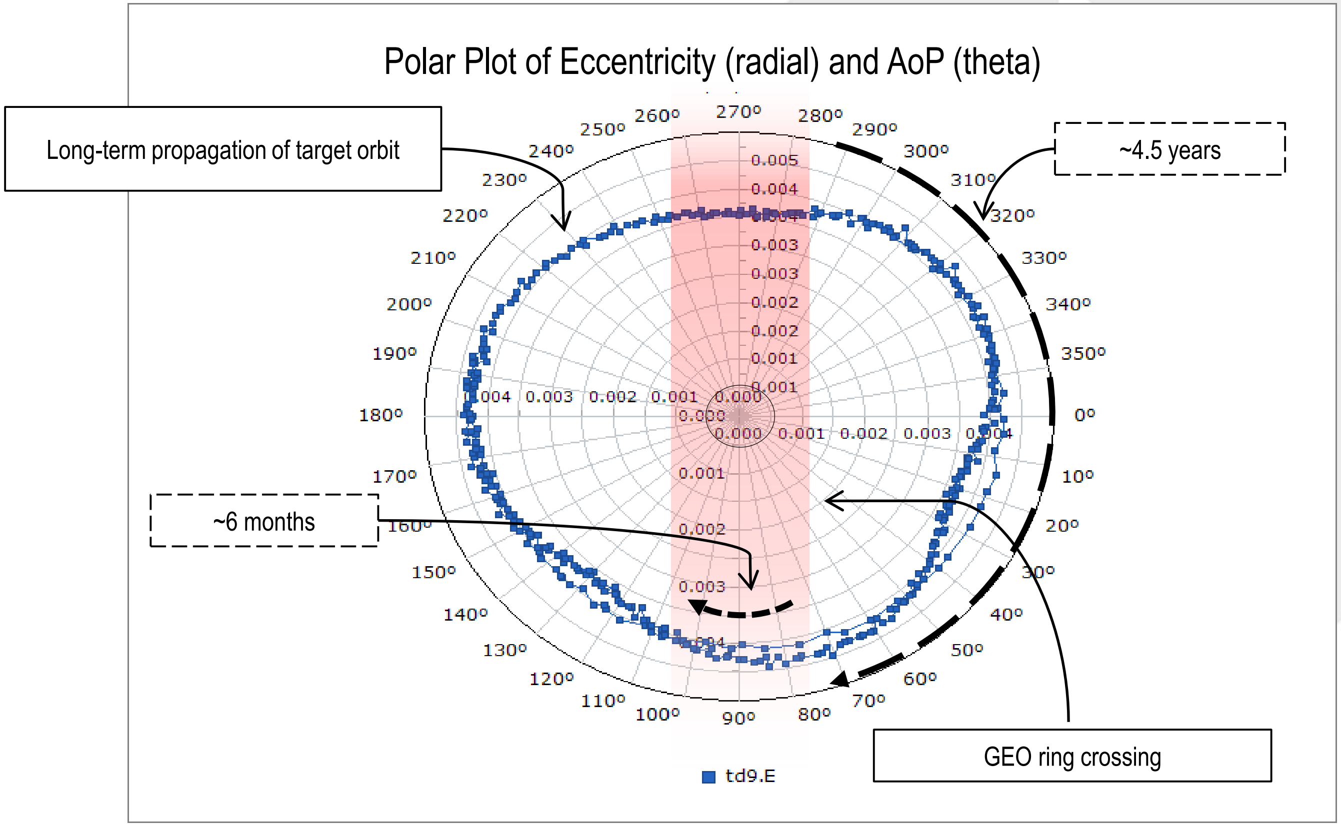
BACKGROUND

- Analysis performed for the Tracking and Data Relay Satellite (TDRS)
- Previous analysis examined the long-term impact to operational geosynchronous (GSO) region occupants if a TDRS at-risk spacecraft were to fail while on orbit
  - ***Required at least 50 km "keep out zone" of GSO ring***
  - ***Found that "ideal" TDRS orbits had eccentricity of 0.004 and argument of perigee (AoP) of 300˚***
    - ***Only violation at perigee when AoP is aligned equatorially***
    - ***Lowest "allowable" eccentricity of 0.0012***
  - See references on last slide
- In 2015, TDRS-9 changed longitudes from 41˚ W to 12˚ W
  - ***This analysis examined if the "ideal" orbit parameters could be achieved with the drift termination (DT) maneuvers alone***

Previous Analysis

TARGET



CONSTRAINTS

- Constraints
  - ***Physical limits of the spacecraft thrusters based on tank and thruster temperatures***
  - All maneuver burn durations must be ≤ 10 sec
  - Any 2 maneuvers must be ≥ 30 minutes apart
  - Final maneuver(s) must be on 10 June
  - All maneuvers must be executed between 03:00 and 14:00Z on a given day

Assumptions and Simplifications

- Assumptions
  - Only 18 DT maneuvers
  - Each maneuver can be approximated by an impulsive maneuver
    - Radial: -3.136 (10-5) km/s
    - In-track: 5.716 (10-5) km/s
    - Cross-track: -5.242 (10-5) km/s

    Provided by White Sands Complex (WSC)

- Simplifications
  - Maneuvers executed on the half hour (03:00, 03:30, etc.)
  - The first DT maneuver occurs no sooner than 1 June with maneuvers evenly distributed over the days leading to 10 June
    - 9 maneuvers/day for 2 days, 6 maneuvers/day for 3 days, etc.

APPROACH

- Single maneuver effects
  - Looking at maneuvers executed across the window and on different days
    - Examined 18 May, 2 June, 4 June, 6 June, 8 June, and 10 June
- Differential Evolution Optimization
  - A target ephemeris created using the "ideal" orbit parameters
  - Maneuver schedule is the control parameter
  - 7-day summed difference between target and resultant position is the cost function
  - 4 maneuver scenarios examined
    1. DT-0 days: All maneuvers executed on 10 June
    2. DT-1 days: 9 maneuvers per day occurring on 9 and 10 June
    3. DT-2 days: 6 maneuvers per day occurring on 8, 9, and 10 June
    4. DT-5 days: 3 maneuvers per day occurring on 5, 6, 7, 8, 9, and 10 June

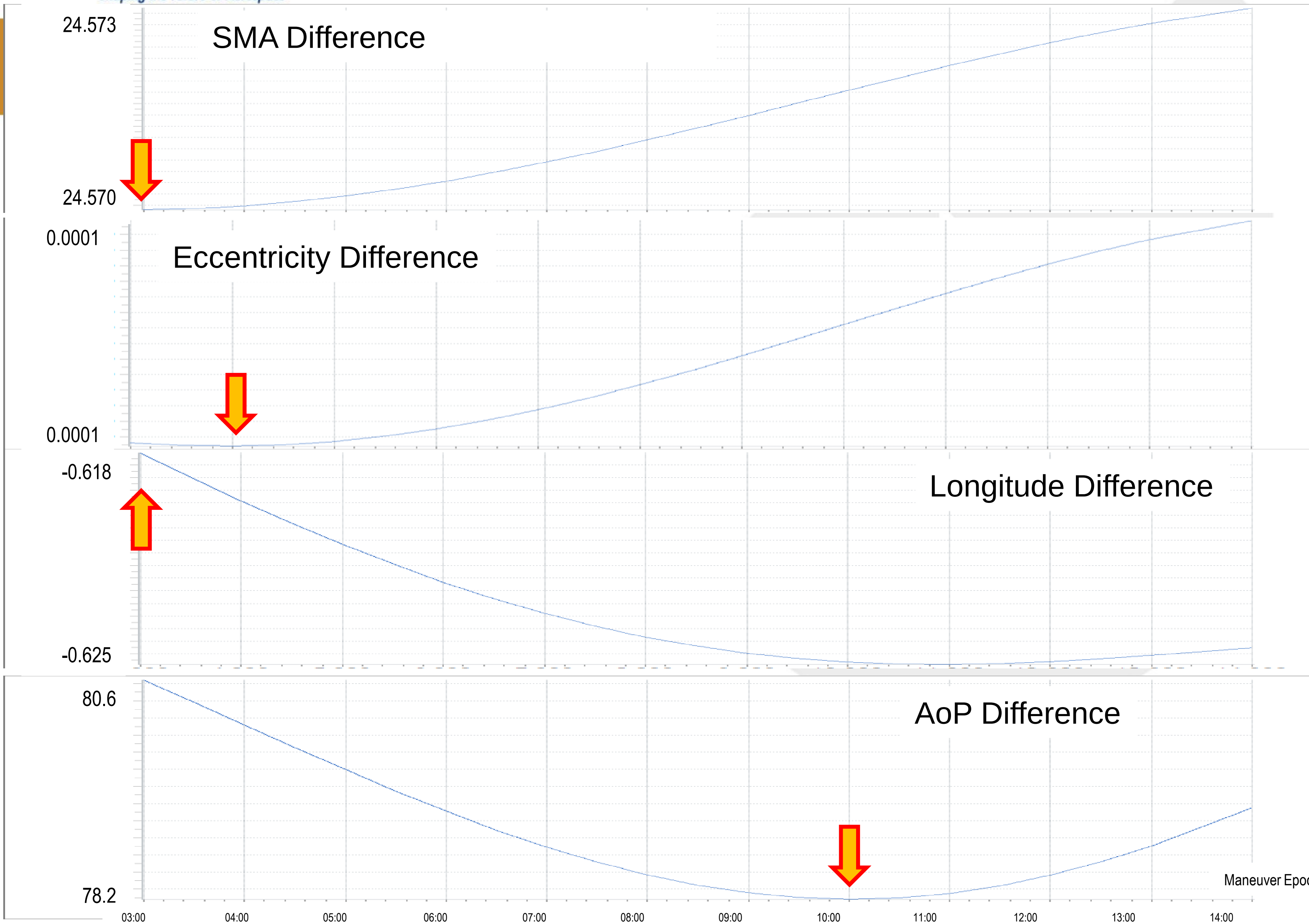
Single Maneuver Effects

SINGLE MANEUVER EFFECTS

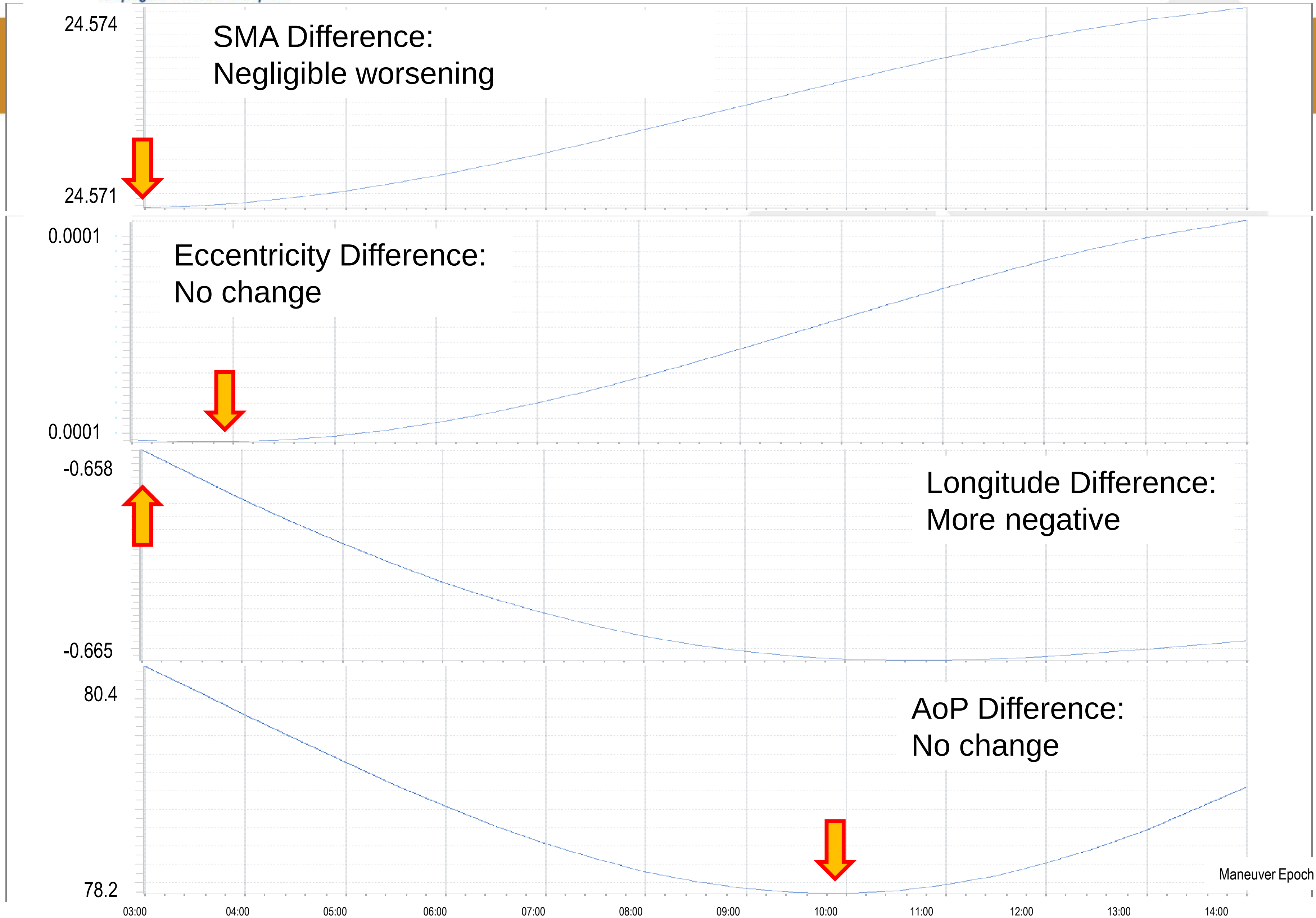
- Needed to qualitatively assess how different maneuver epochs would effect the target orbital parameters
  - Maneuver epochs could be varied across days and across the daily maneuver window

- Specifically looking for
  - Maneuver window effects
    - Competing target constraints
  - Maneuver day effects
    - Possible changes in end-state proximity to target state

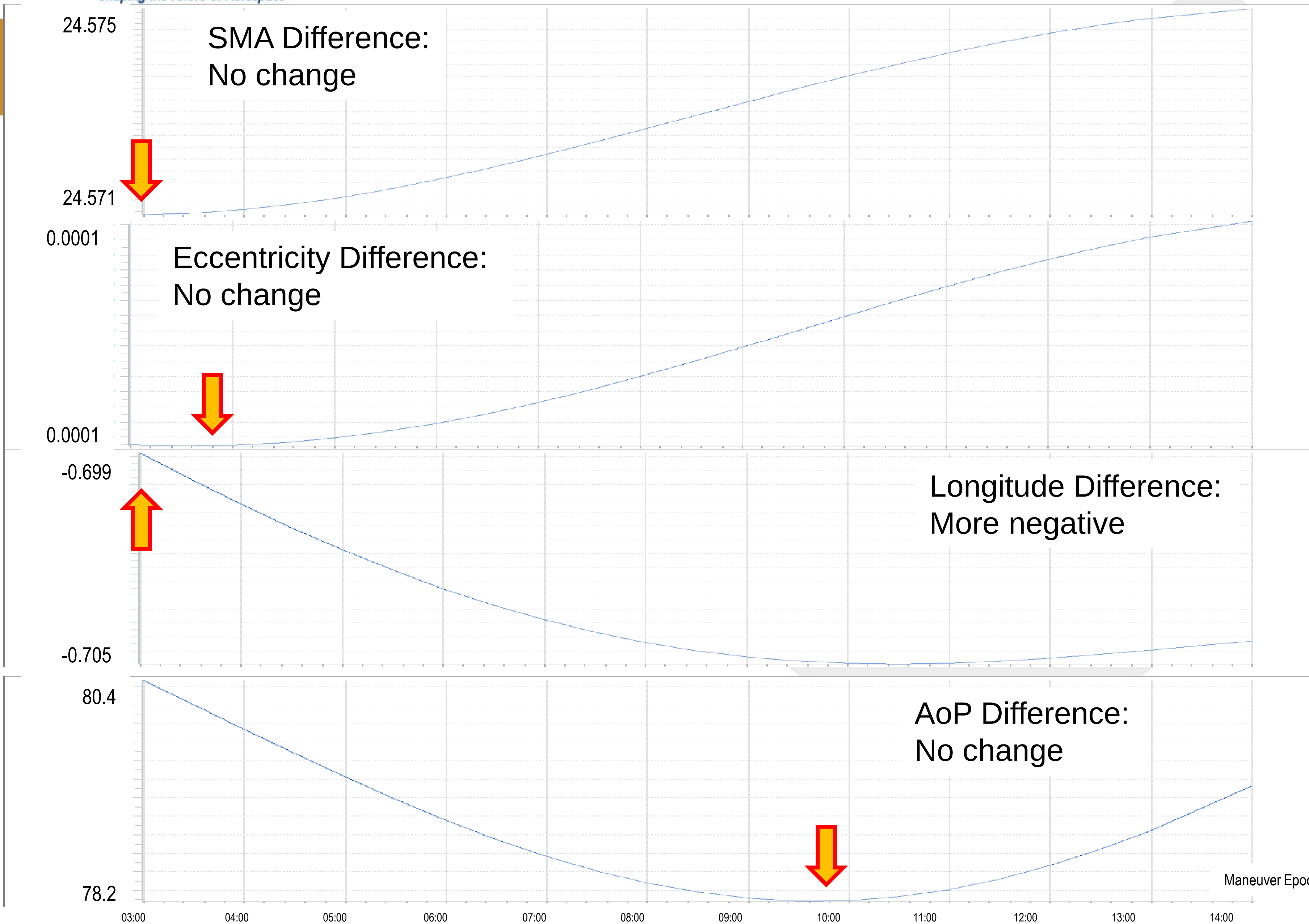
End State Effects: Maneuver on 2 June



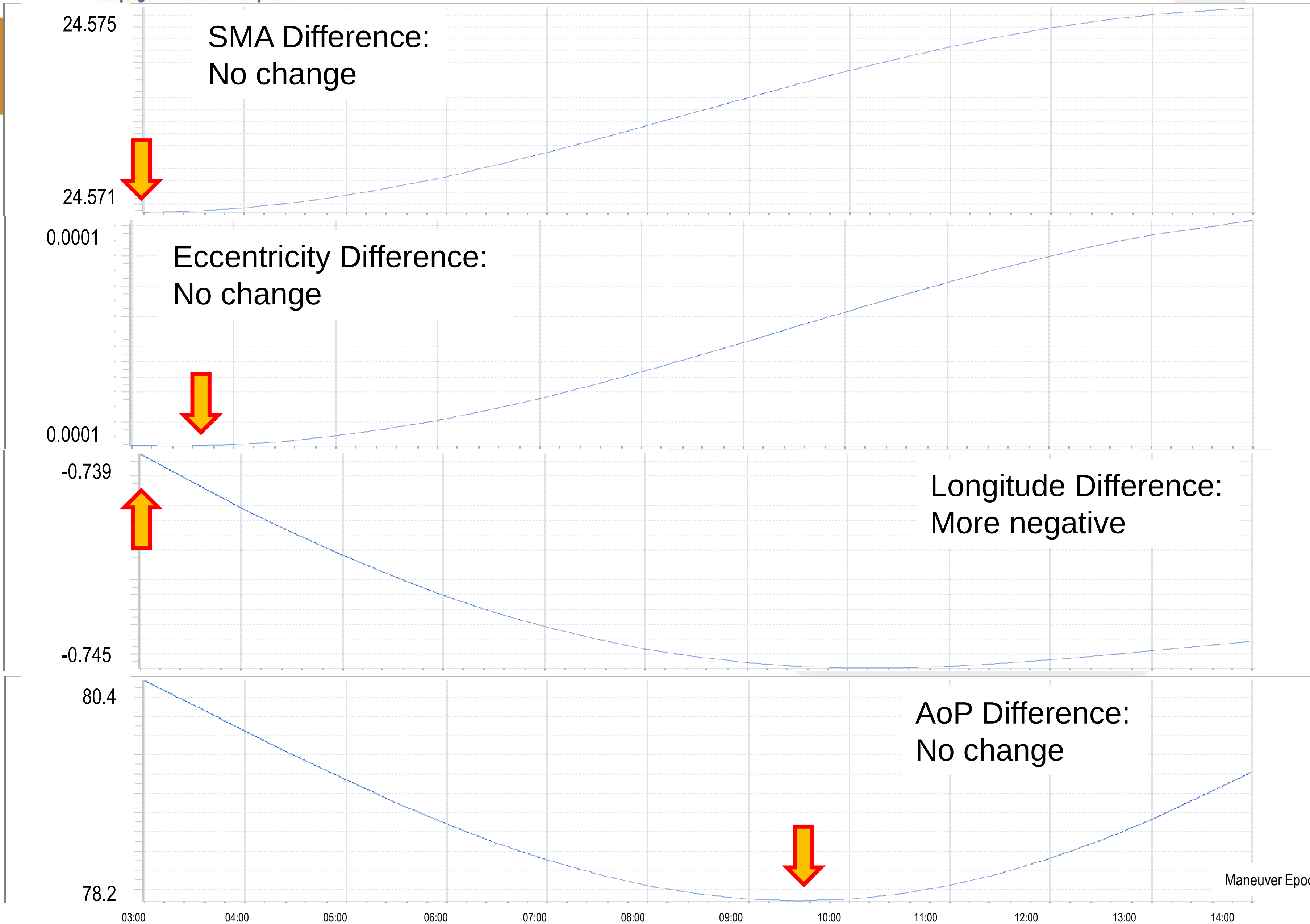
END STATE EFFECTS: MANEUVER ON 4 JUNE



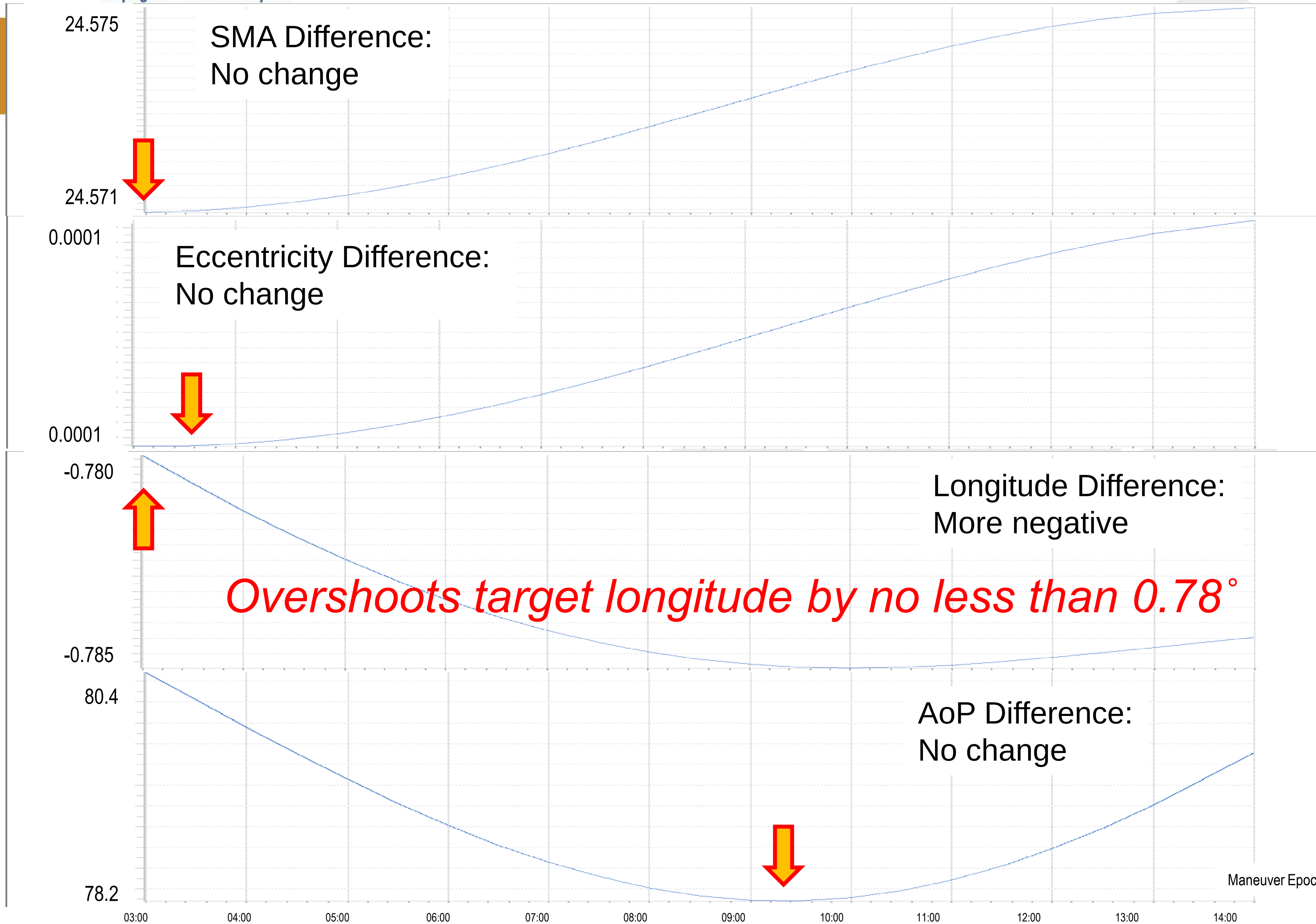
End State Effects: Maneuver on 6 June



End State Effects: Maneuver on 8 June



End State Effects: Maneuver on 10 June



Single Maneuver Analysis

- Maneuver Day Effects
  - Waiting to maneuver closer to 10 June increases the likelihood of overshooting the target longitude.
    - SMA, eccentricity, and AoP are marginally effected by changes in maneuver day
- Maneuver Window Effects
  - There are competing constraints
    - Maneuvering early in the window improves targeting SMA and eccentricity, but is bad for targeting AoP (and vice versa)

Optimized Maneuver Scenarios

Optimized Scenarios

- Starting with a target state, created a 7-day ephem
- Varied maneuver schedule to minimize target-to-resultant ephem difference
  - Assumptions, constraints, and simplifications resulted in 10^{10} possible maneuver schedule combinations
- Also looked at end-states which met the on-station longitude requirements
  - Mean daily official edges: 12° W $\pm$ 0.3°
  - Daily East-most drift tolerance: 11.5° W (*expected*)

DT-0 DAYS

TARGET

Maneuver Window DT - 0 days (June 10)																		
Burn Time	mnvr 1	mnvr 2	mnvr 3	mnvr 4	mnvr 5	mnvr 6	mnvr 7	mnvr 8	mnvr 9	mnvr 10	mnvr 11	mnvr 12	mnvr 13	mnvr 14	mnvr 15	mnvr 16	mnvr 17	mnvr 18
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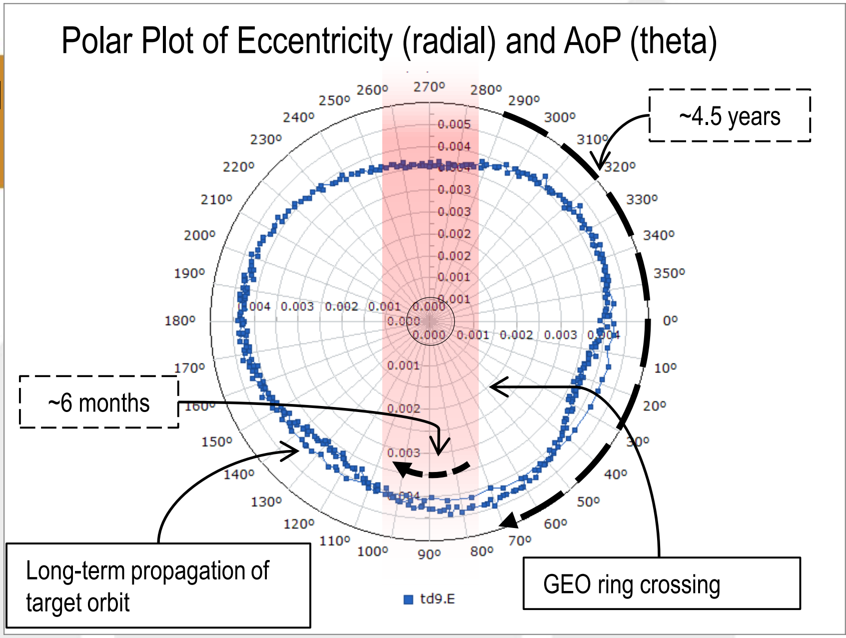

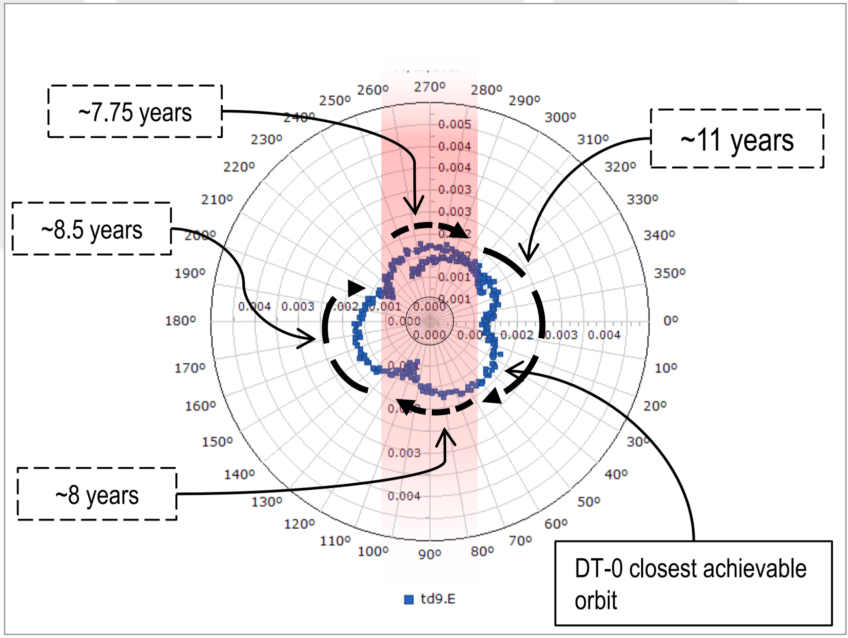

- Optimized maneuver plan
  - 10 Jun 2015
    - Every half hour from 05:30 to 14:00

- At 14:00Z on 10 June
  - Longitude: 11.2˚W
  - Eccentricity: 0.0011
  - Arg. of Perigee: 248.6˚

DT-1 Days

TARGET

Maneuver Window DT - 1 days (June 9, 10)									
Burn Time	mnvr 1	mnvr 2	mnvr 3	mnvr 4	mnvr 5	mnvr 6	mnvr 7	mnvr 8	mnvr 9
03:00									
03:30									
04:00									
04:30									
05:00									
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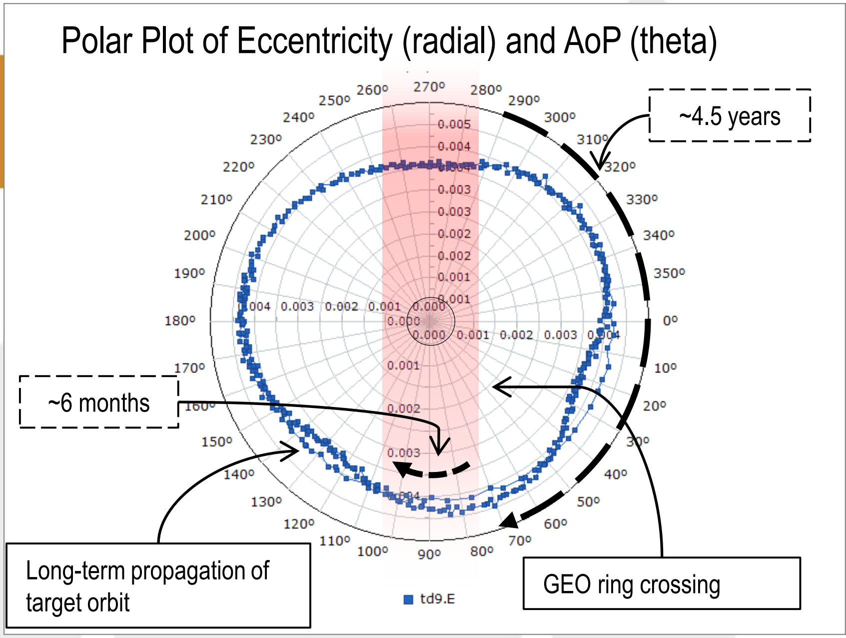
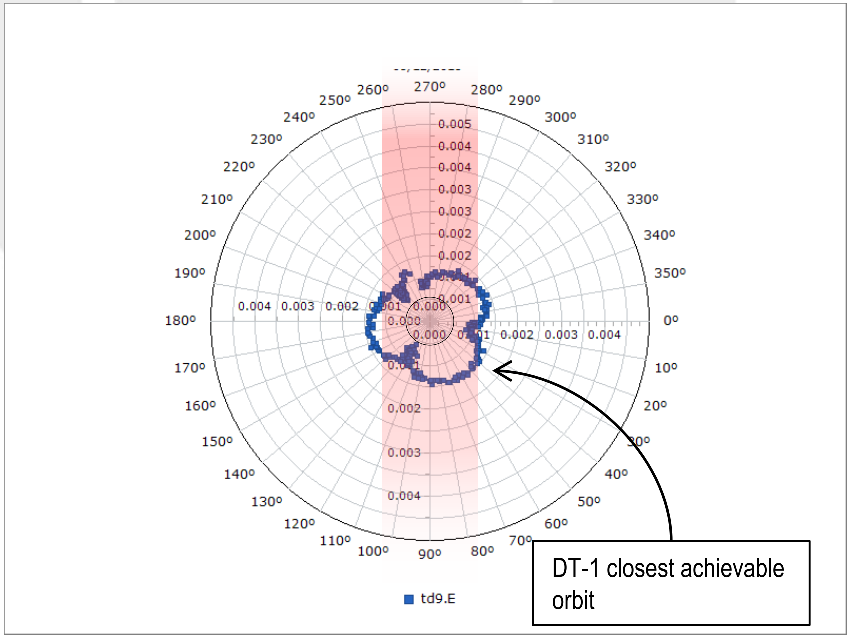
13:30									
14:00									



- Optimized maneuver plan
  - 9, and 10 Jun 2015
    - Every half hour from 10:00 to 14:00

- At 14:00Z on 10 June
  - Longitude: **11.4˚W**
  - Eccentricity: **0.0008**
  - Arg. of Perigee: **258.0˚**



DT-2 DAYS

TARGET

Maneuver Window DT - 2 days (June 8, 9, 10)						
Burn Time	mnvr 1	mnvr 2	mnvr 3	mnvr 4	mnvr 5	mnvr 6
03:00						
03:30						
04:00						
04:30						
05:00						
05:30						
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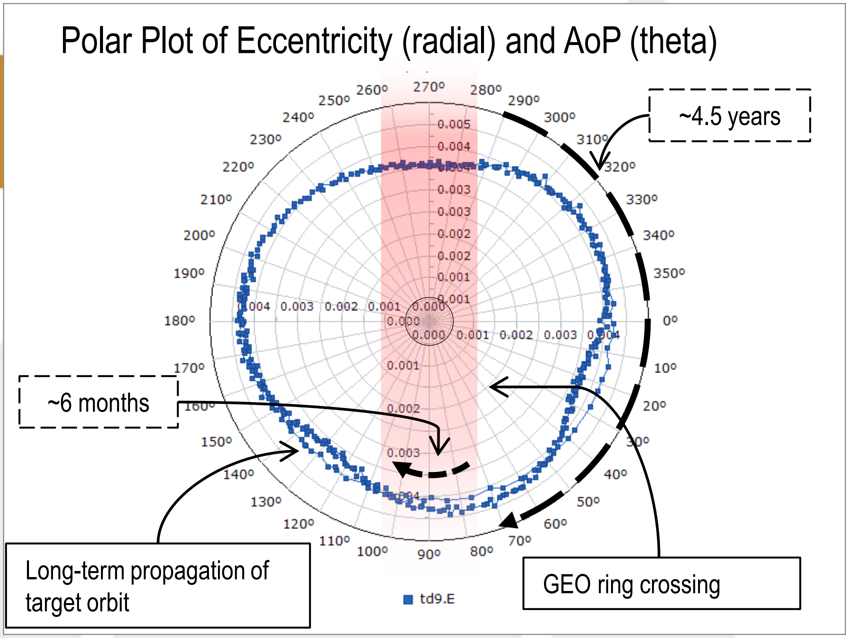
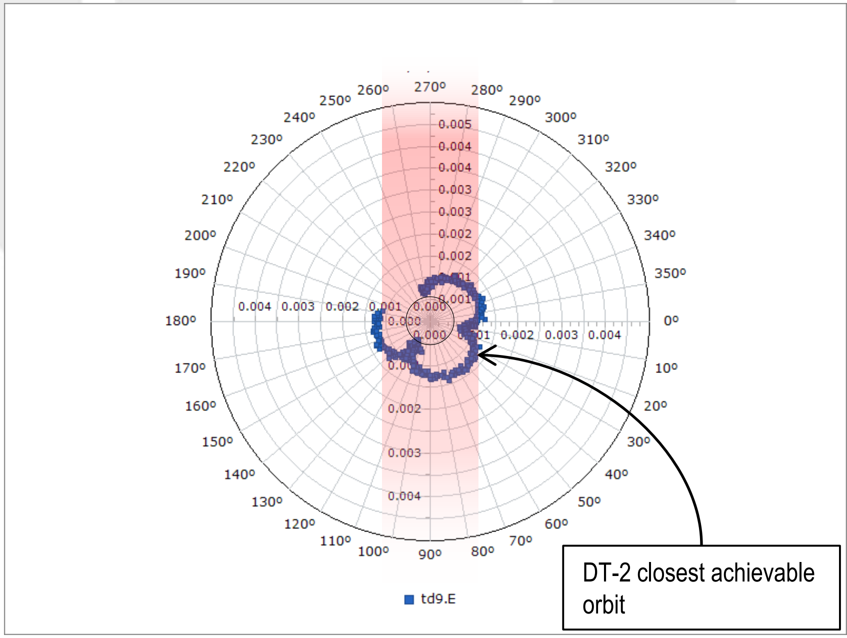
14:00						



- Optimized maneuver plan
  - 8 , 9, and 10 Jun 2015
    - Every half hour from 11:30 to 14:00

- At 14:00Z on 10 June
  - Longitude: **11.6˚W**
  - Eccentricity: **0.0007**
  - Arg. of Perigee: **258.3˚**



DT-5 DAYS

Maneuver Window DT - 5 days (June 5, 6, 7, 8, 9, 10)			
Burn Time	mnvr 1	mnvr 2	mnvr 3
03:00			
03:30			
04:00			
04:30			
05:00			
05:30			
06:00			
06:30			
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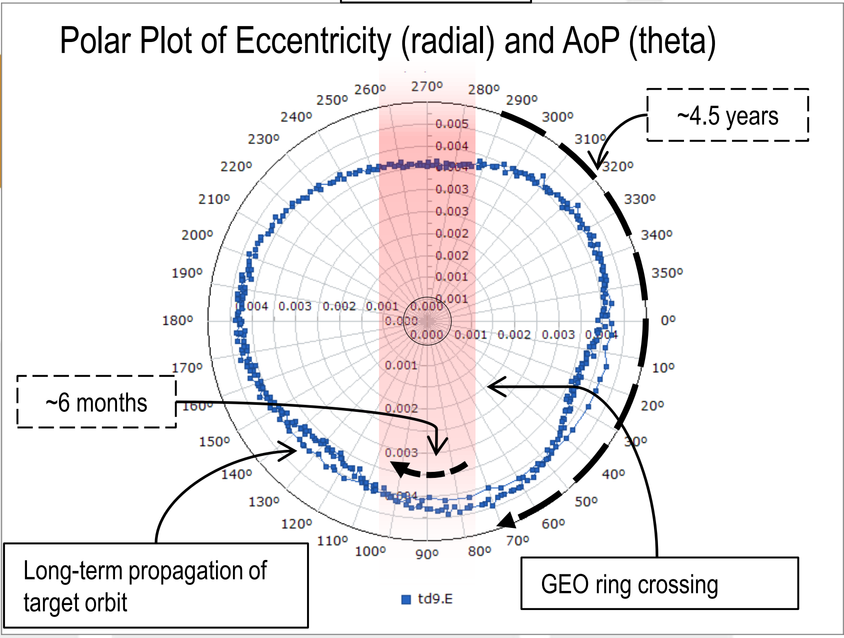
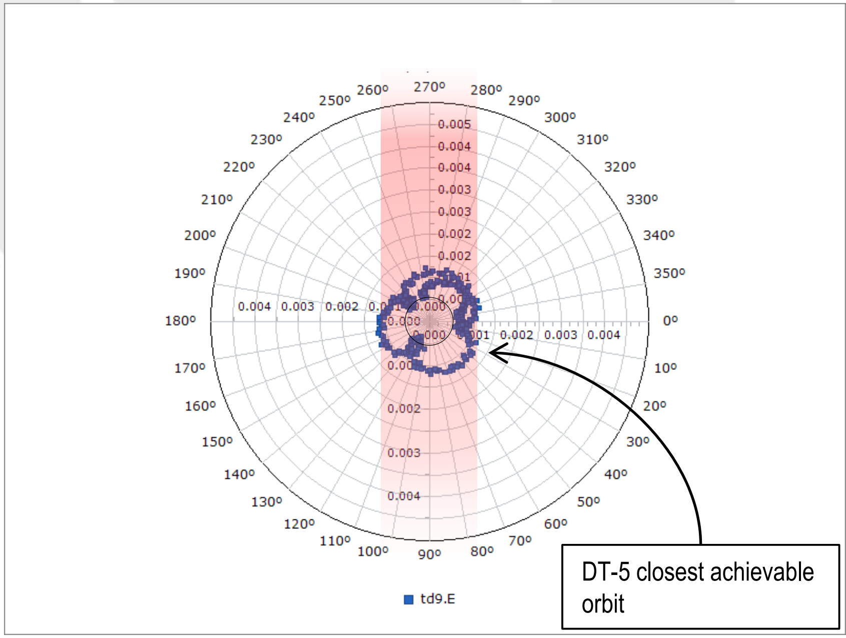
14:00			

- Optimized maneuver plan
  - 5, 6, 7, 8, 9, and 10 Jun 2015
    - Every half hour from 13:00 to 14:00

- At 14:00Z on 10 June
  - Longitude: **12.1˚W**
  - Eccentricity: **0.0006**
  - Arg. of Perigee: **256.1˚**

TARGET





RELAXED CONSTRAINTS

Relaxed Constraints

- Previous analyses suggested that the AoP constraint may be weighting the optimizer to target a greater change in AoP

- As a result, wanted to remove the AoP constraints to see if the optimizer would target a greater change in eccentricity
  - Tested hypothesis using the DT-0 day, DT-2 day, and DT-5 day maneuver cadences

- Results
  - Resultant optimizations targeted early window maneuver plans with better results
  - Agreed with single-maneuver analysis

DT-0 Early Window Maneuvers

Maneuver Window DT - 0 days (June 10)												
Burn Time	mnvr 1	mnvr 2	mnvr 3	mnvr 4	mnvr 5	mnvr 6	→	mnvr 14	mnvr 15	mnvr 16	mnvr 17	mnvr 18
03:00							→					
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04:30							→					
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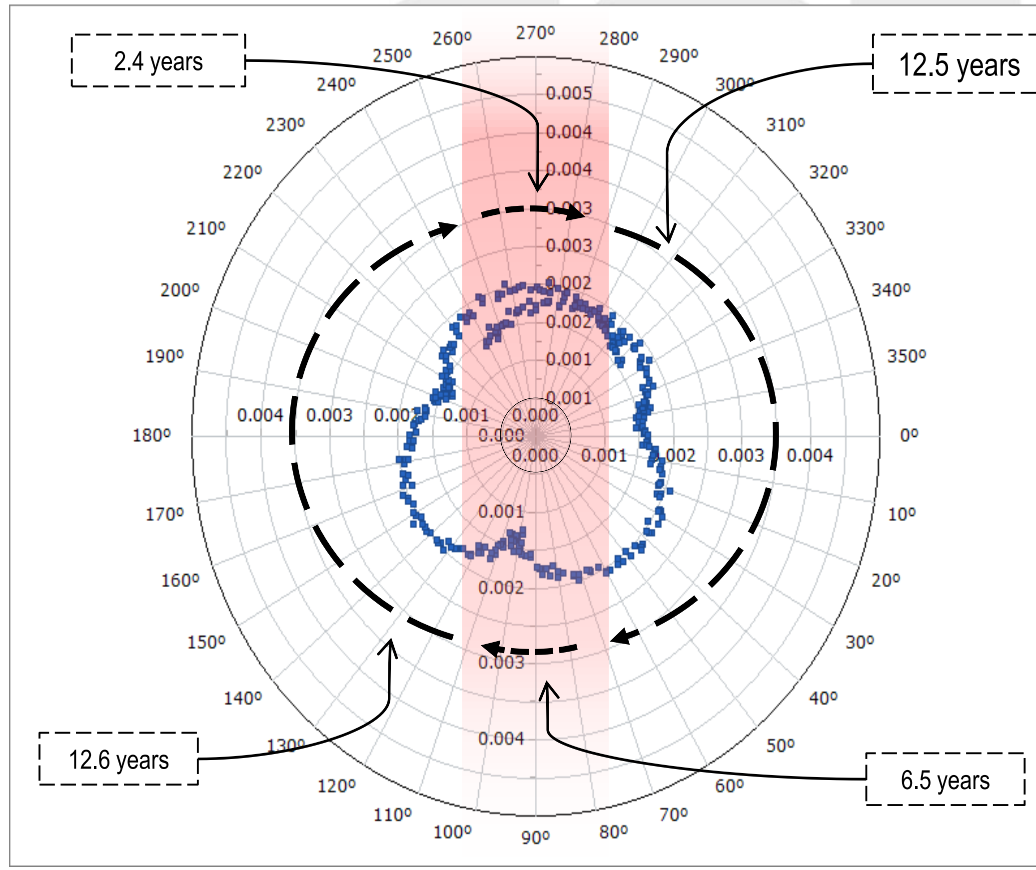
14:00							→					

- At 14:00Z on 10 June
  - Longitude: 11.2˚W
  - Eccentricity: 0.0014



DT-2 Early Window Maneuvers

Maneuver Window DT - 2 days (June 8, 9, 10)						
Burn Time	mnvr 1	mnvr 2	mnvr 3	mnvr 4	mnvr 5	mnvr 6
03:00						
03:30						
04:00						
04:30						
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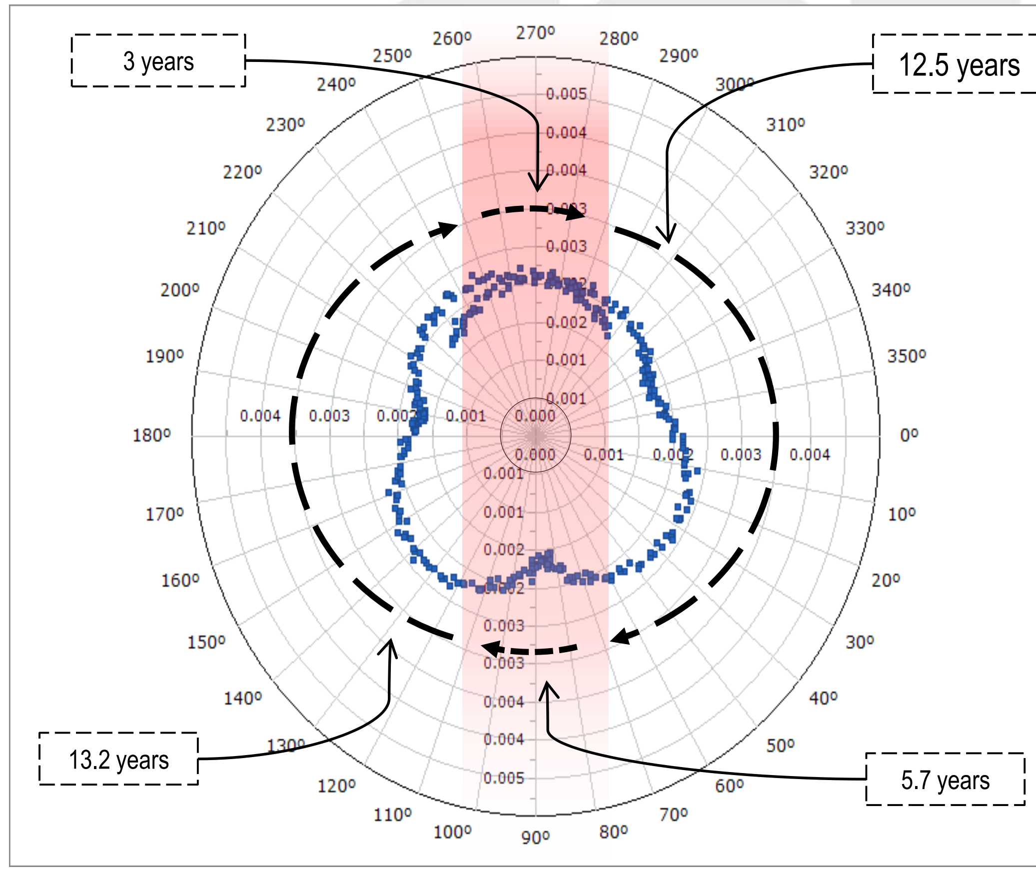
- At 14:00Z on 10 June
  - Longitude: **11.65˚W**
  - Eccentricity: **0.0017**



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DT-5 EARLY WINDOW MANEUVERS

Maneuver Window DT - 5 days (June 5, 6, 7, 8, 9, 10)			
Burn Time	mnvr 1	mnvr 2	mnvr 3
03:00			
03:30			
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04:30			
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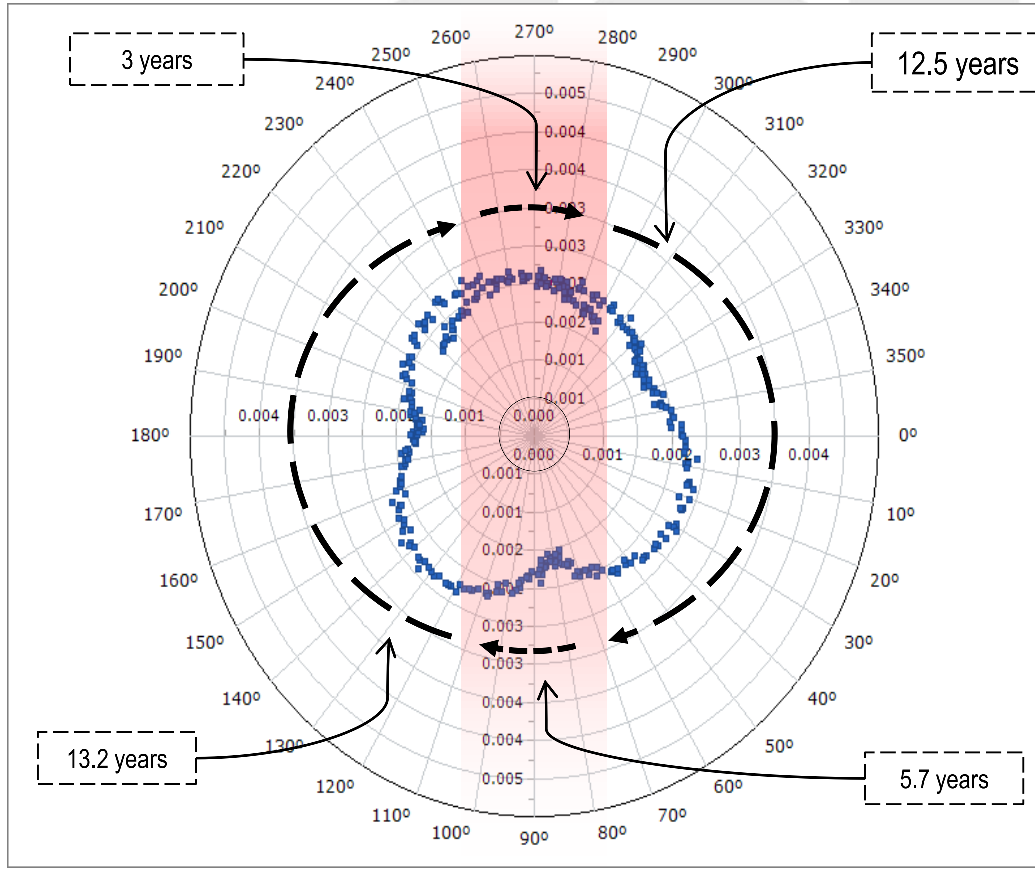
14:00			

- At 14:00Z on 10 June
  - Longitude: **12.2˚W**
  - Eccentricity: **0.0017**



CONCLUSIONS

- To meet the original constraints (AoP = 300˚, ecc = 0.004), the largest state change came from the AoP
  - Optimizer originally targeted late window maneuver plans to accommodate
- By removing the AoP constraints, the optimizer began targeting maneuvers earlier in the window, thus producing larger changes in eccentricity
  - AoP drifts continually clockwise, so this constraint is somewhat superfluous
  - ***Optimization's best achieved eccentricity ≈ 0.0017***
- WSC eventual maneuver plan
  - 10 DT maneuvers on 9 June
  - 8 DT maneuvers and 1 small correction burn on 10 June
  - All maneuver sequences began at the start of window and were executed every 30 minutes
  - ***Resultant eccentricity ≈ 0.0015***

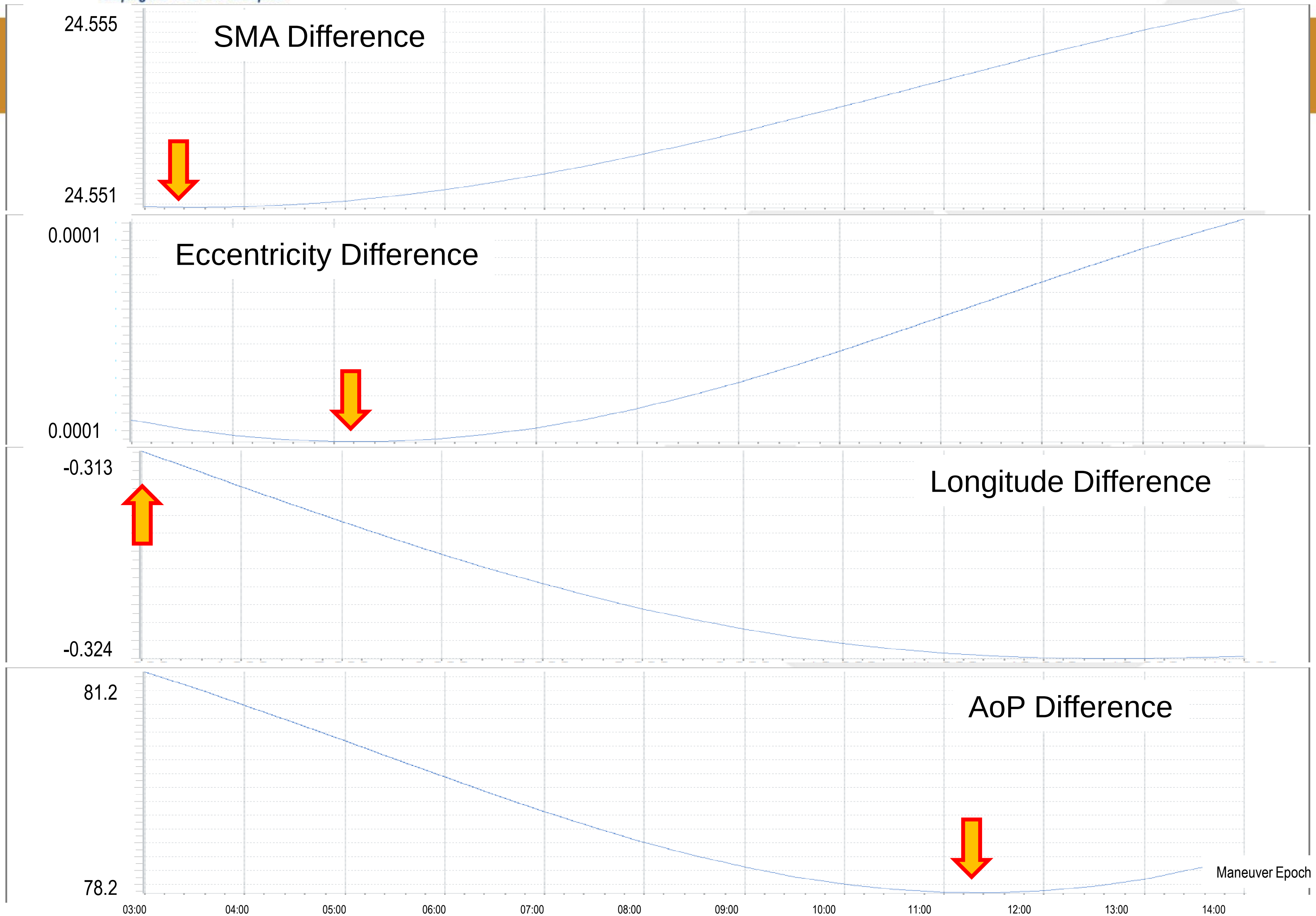
References

- Dykes, A., *Considering Orbit Changes for the Tracking and Data Relay Satellite System*, NASA Orbital Debris Colloquium at GSFC, March 2002

- Cherney, R., et al., *Eccentricity Management for TDRS Fleet*, Presentation to Jon Walker (Code 452), 2005

Back-up Slides

END STATE EFFECTS: MANEUVER ON 18 MAY



Additional Notes

- Things to note:
  - Waiting to execute maneuvers closer to or on 10 June caused the spacecraft to pass the target longitude (with current drift rate, should reach 12˚W around 8 or 9 June)
  - All maneuver plans resulted in an SMA at 14:00Z on 10 June of about 42166 km (2 km greater than GSO radius)
    - Changes in SMA between "Early window" and "Late Window" maneuver plans were less than 1 km
  - Larger eccentricities will require larger East-most and West-most daily tolerances

- Recommendation delivered to WSC
  - Reaching the target longitude on the target date needs to be the highest priority. Therefore, this analysis would suggest beginning the DT maneuvers before 10 June
  - Executing burns earlier in the window should result in achieving a more desirable eccentricity
    - Remaining ΔV provides a best achievable eccentricity of about 0.0017
  - If desired, future station-keeping maneuvers may be used to further increase the eccentricity

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