DIFFERENTIAL EVOLUTION OPTIMIZATION FOR TARGETING SPACECRAFT MANEUVER PLANS

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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
Polar Plot of Eccentricity (radial) and AoP (theta)

Long-term propagation of target orbit

~4.5 years

~6 months

GEO ring crossing
 CONSTRAINTS

• Constraints
  ▪ **Physical limits of the spacecraft thrusters based on tank and thruster temperatures**
  ▪ All maneuver burn durations must be \( \leq 10 \) sec
  ▪ Any 2 maneuvers must be \( \geq 30 \) 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

• 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
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

SMA Difference

Eccentricity Difference

Longitude Difference

AoP Difference

03:00 04:00 05:00 06:00 07:00 08:00 09:00 10:00 11:00 12:00 13:00 14:00

Maneuver Epoch
END STATE EFFECTS: MANEUVER ON 4 JUNE

SMA Difference: Negligible worsening

Eccentricity Difference: No change

Longitude Difference: More negative

AoP Difference: No change
**END STATE EFFECTS: MANEUVER ON 6 JUNE**

- SMA Difference: No change
- Eccentricity Difference: No change
- Longitude Difference: More negative
- AoP Difference: No change
**End State Effects: Maneuver on 8 June**

**SMA Difference:**
No change

**Eccentricity Difference:**
No change

**Longitude Difference:**
More negative

**AoP Difference:**
No change
END STATE EFFECTS: MANEUVER ON 10 JUNE

- SMA Difference: No change
- Eccentricity Difference: No change
- Longitude Difference: More negative
- Overshoots target longitude by no less than 0.78°
- AoP Difference: No change
**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: $12^\circ \ W \pm 0.3^\circ$
  - Daily East-most drift tolerance: $11.5^\circ \ W$ (expected)
**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

Maneuver Window DT - 1 days (June 9, 10)

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- 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**

- **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

- 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°**
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

- At 14:00Z on 10 June
  - Longitude: 11.2°W
  - Eccentricity: 0.0014
DT-2 Early Window Maneuvers

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<th>Maneuver Window</th>
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- At 14:00Z on 10 June
  - Longitude: 11.65°W
  - Eccentricity: 0.0017
DT-5 Early Window Maneuvers

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<th>Maneuver Window DT - 5 days (June 5, 6, 7, 8, 9, 10)</th>
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- 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**

### SMA Difference

- **Values:**
  - 24.555
  - 24.551

### Eccentricity Difference

- **Values:**
  - 0.0001
  - 0.0001

### Longitude Difference

- **Values:**
  - -0.313
  - -0.324

### AoP Difference

- **Values:**
  - 81.2
  - 78.2
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