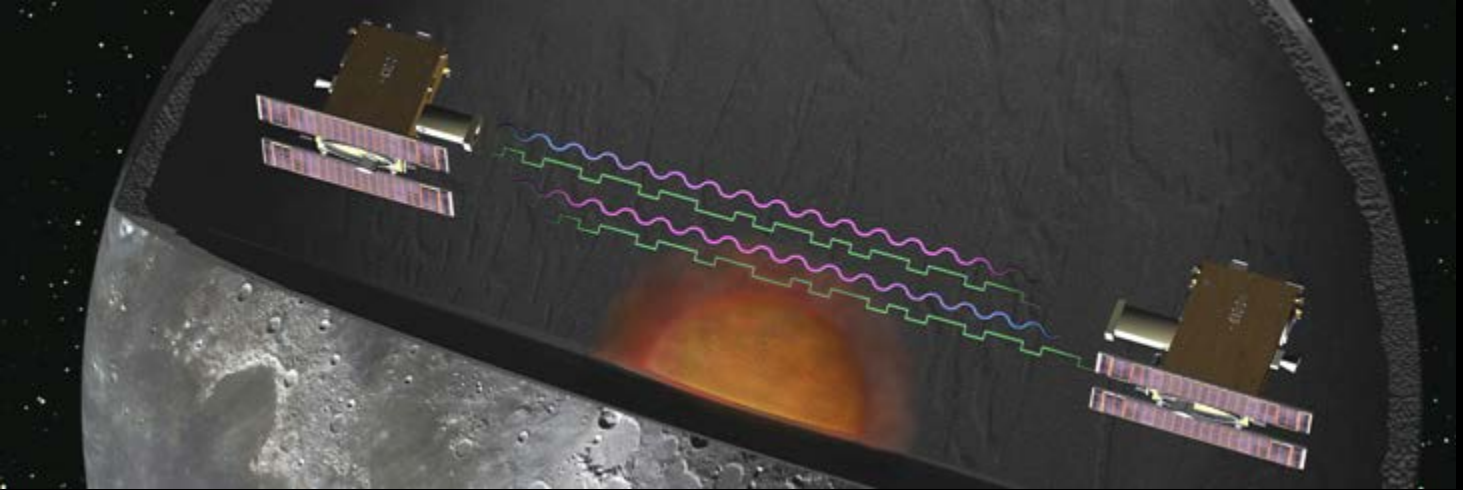

GRAIL

Gravity Recovery and Interior Laboratory

GRAIL TCM-5 Go/No-Go: Developing Lunar Orbit Insertion (LOI) Criteria

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(c) 2013 California Institute of Technology. Government sponsorship acknowledged.

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Acknowledgments

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- The work was supported by the GRAIL project at JPL.
- Roby S. Wilson and Ralph B. Roncoli (JPL) for review.
- GRAIL navigation team members for their support and for the successful navigation of the mission, including: Peter Antreasian, Ram Bhat, Kevin Criddle, Sara Hatch, Troy Goodson, David Jefferson, Julie Kangas, Eunice Lau, Ralph Roncoli, Mark Ryne, Ted Sweetser, Tung-Han You, Brian Young, Hui Ying Wen, & Mau Wong.

Abstract

- The Gravity Recovery and Interior Laboratory (GRAIL) mission successfully completed mapping the Moon's gravity field to an unprecedented level for a better understanding of the internal structure and thermal evolution of the Moon.
- The mission success was critically dependent on the success of the Lunar Orbit Insertion (LOI).
- In this paper we **establish a set of LOI criteria** to meet all the requirements and we use these criteria to establish Go/No-Go boundaries of the last, statistical Trajectory Correction Maneuvers (TCM-5s) for operations.

Background

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- GRAIL Prime Mission Phases and Maneuvers:
  1. Launch Phase & Injection
  2. **TLC (Trans-Lunar Cruise) Phase & TCMs (Trajectory Correction Maneuvers)**
  3. **LOI (Lunar Orbit Insertion) Phase & LOIs**
  4. **OPR (Orbit Period Reduction) Phase & PRMs (Period Reduction Maneuvers)**
  5. **TSF (Transition to Science Formation) Phase & TSMs (TSF Maneuvers)**
  6. Science Phase
- GRAIL Low-energy TLC Trajectory
  - Accurate Injection led the cancelation of TCM-1.
  - LOI design before TCM-3 forced TCM-4 to be deterministic.
  - TCM-5, the only statistical maneuver.

GRAIL TLC Trajectories & TCMs

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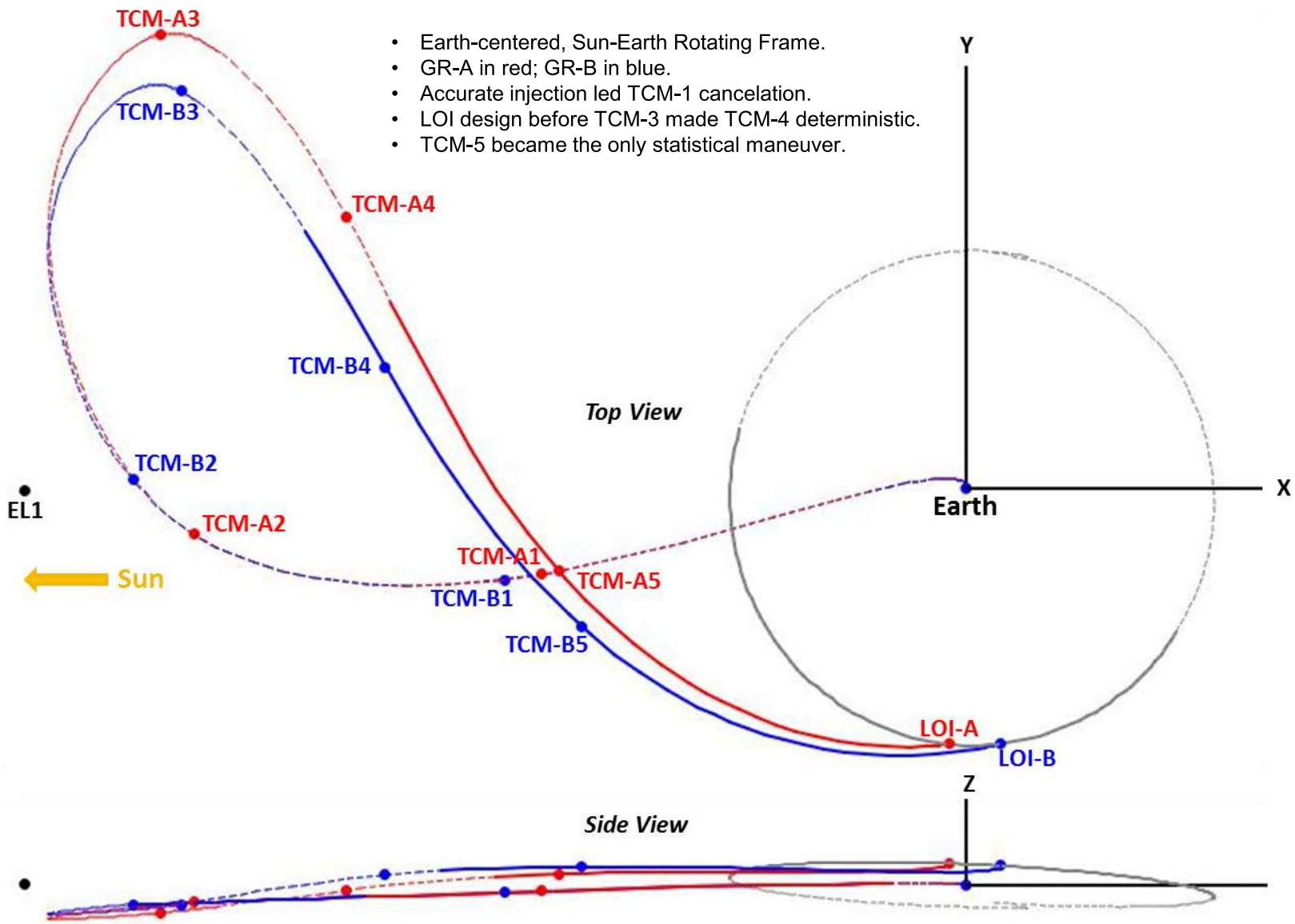
- Earth-centered, Sun-Earth Rotating Frame.
- GR-A in red; GR-B in blue.
- Accurate injection led TCM-1 cancelation.
- LOI design before TCM-3 made TCM-4 deterministic.
- TCM-5 became the only statistical maneuver.



Introduction

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- GRAIL LOI Somewhat Unfamiliar:
  - Elliptical approach from low-energy TLC trajectory.
  - How LOI delivery dispersion affected **the science formation phase and its maneuvers** was not well understood.
- Operations required a set of TCM-5 Go/No-Go criteria.
- JPL s/w LAMBIC (Linear Analysis of Maneuvers with Bounds and Inequality Constraints) used effectively for the statistical analysis of TCMs; however, not for the orbital maneuvers due to non-linear dynamics in low lunar orbits.
- An alternate, simpler approach was sought for as the time of TCM-5 was approaching fast.

Preliminary Considerations

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- LAMBIC LOI Delivery Dispersion Statistics:
  - 6 LOI delivery parameters: SMA, RCA, INC, LAN, AOP, TTP.
  - LOI Delivery dispersion 3-sigma (3σ) from TCM-4 & 5:

LOI delivery Parameters	TCM-4 (3σ)		TCM-5 (3σ)	
	GR-A	GR-B	GR-A	GR-B
SMA (km)	293.9	800.7	286.3	791.6
RCA (km)	2.590	1.929	1.091	1.060
INC (deg)	0.095	0.091	0.028	0.032
LAN (deg)	0.048	0.060	0.041	0.058
AOP (deg)	0.074	0.074	0.072	0.074
TTP (sec)	170.5	112.6	27.5	26.5

» To ensure all the science requirements <u>with TCM-5</u>, must show **±3σ TCM-5** values can be handled adequately.

» To be able to <u>cancel TCM-5</u>, must show **±3σ TCM-4** dispersions can be handled adequately. Or, if some ±3σ TCM-4 dispersions are too large, must establish some boundaries on those parameters.

Derived Requirements

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- Derived from the Science Requirements to ensure no orbital crossing or COLA (Collision Avoidance) >= 10 km while placing GR-A & B into the science formation.
  - LOI Phase: LOIs to capture s/c into 11.5-hr orbits separated by 25 hr.
  - OPR Phase: Two sets of PRMs (PRM-1 thru 3 and PRM-4 thru 7) to reduce periods to the near science periods.
  - TSF Phase: TSMs to set GR-A&B in science formation:
    - 5 TSMs: TSM-A1, TSM-B1, TSM-A2, TSM-B2, & TSM-B5 in the order of execution.
    - Period targets derived to avoid COLA.
    - <u>Max ΔV</u> of each TSMs derived such that the execution error propagation does not exceed the expected limit for the formation.
    - TSMs are best visualized in *e*-ω space/plot.

E-ω Plot for Reference Orbits during TSF

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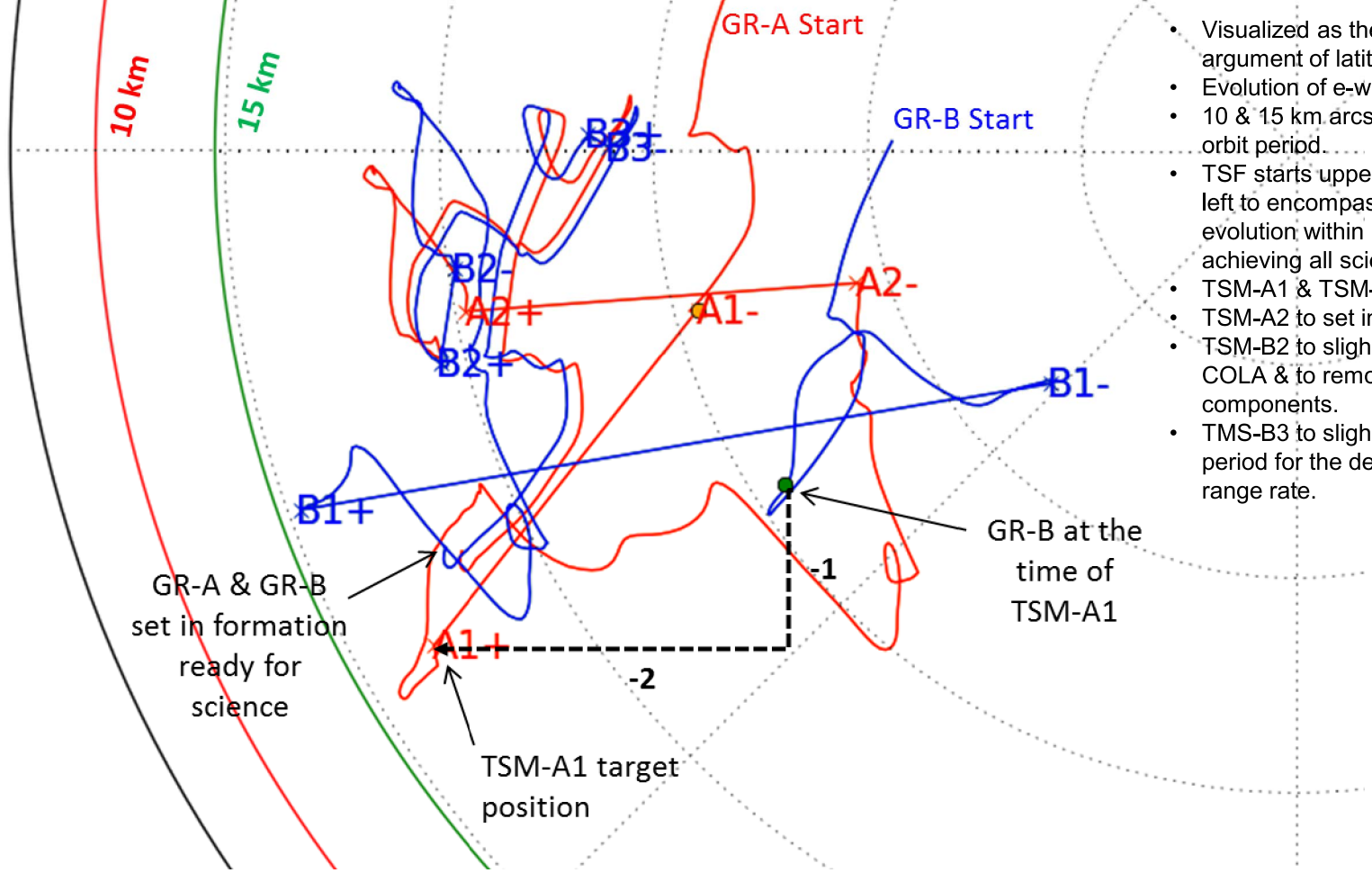
A_SMA+0.000 RCA+0.000 INC+0.000 LAN+0.000 AOP+0.000 TTP+0.0 B_SMA+0.000 RCA+0.000 INC+0.000
07-FEB-2012 16:44:31.71303I695 UTC A0 A1- dv=16.2165 m/s (dt=3.16701 min, pitch=260.56

SMA(km)	T(min)	AveT(min)	PA(km)	AA(km)	ECC	INC(deg)	NOD(deg)	AOP(deg)	TRU(deg)	T
1800.200	114.2320	114.0007	36.764	88.837	0.014463	89.6476	115.0566	194.9589	-65.9589	
1829.764	117.0575	117.0004	66.279	118.449	0.014256	89.5832	115.1481	213.1317	-42.3892	
1800.200	114.2320	114.0007	36.764	88.837	0.014463	89.6476	115.0566	194.9589	-65.9589	
1829.764	117.0575	117.0004	66.279	118.449	0.014256	89.5832	115.1481	213.1317	-42.3892	



- Visualized as the movement of the argument of latitude of a polar orbit.
- Evolution of e-w plot: left to right.
- 10 & 15 km arcs derived from 1.9-hr orbit period.
- TSF starts upper right & ends lower left to encompass all 3 months evolution within the 10-km arc, while achieving all science requirements.
- TSM-A1 & TSM-B1 to 1.9-hr period.
- TSM-A2 to set into science orbit.
- TSM-B2 to slightly higher period for COLA & to remove out-of-plane components.
- TMS-B3 to slightly below the science period for the desired separation range rate.

Initial Pilot Runs

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- To assess mission success while reducing the number of runs, the following two sets of runs were made initially:
  - (1) TCM-5 $\pm 3\sigma$ combination (to assess with TCM-5).
  - (2) TCM-4 $\pm 3\sigma$ combination (to assess w/o TCM-5).
    - With opposite 3σ between GR-A & B. For example, GR-A (SMA, RCA, INC, NOD, AOP, TTP) = ($+3\sigma$, -3σ, $+3\sigma$, -3σ, $+3\sigma$, $+3\sigma$) is combined with GR-B (-3σ, $+3\sigma$, -3σ, $+3\sigma$, -3σ, -3σ) to compose one case, resulting total 2^6=64 cases.
- Result (1) : All 64 cases completed; some by hand. Some with TSM-B5 over 5 m/s (fixable by hand). So, <u>with the execution of TCM-5</u> we could make the mission.
- Result (2) : More challenging; some did not complete. Some violated TSM-B1 & B3 max ΔV limits. So, we expected there would be <u>some cases we could not cancel TCM-5</u>.

Considering GR-A Dispersions Individually

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- Examine the behavior of $\pm 3\sigma$ TCM-A4 LOI delivery dispersion of each parameter individually against the nominal GR-B. For example, for SMA, GR-A ($\pm 3\sigma$, 0, 0, 0, 0, 0) with GR-B (0, 0, 0, 0, 0, 0), and, for RCA, GR-A (0, $\pm 3\sigma$, 0, 0, 0, 0) with GR-B (0, 0, 0, 0, 0, 0), etc.
- We found that
  - Any individual TCM-A4 $\pm 3\sigma$ were handled adequately by subsequent orbital maneuvers.
  - The two most critical LOI delivery parameters were **TTP** and **RCA**. Most apparent in *e*-ω plots. TTP also caused COLA.
  - The dispersions for the rest of the parameters were rather insignificant.
  - Refer to the paper for *e*-ω plots.

E-ω Plots for ±3σ GR-A SMA Dispersion

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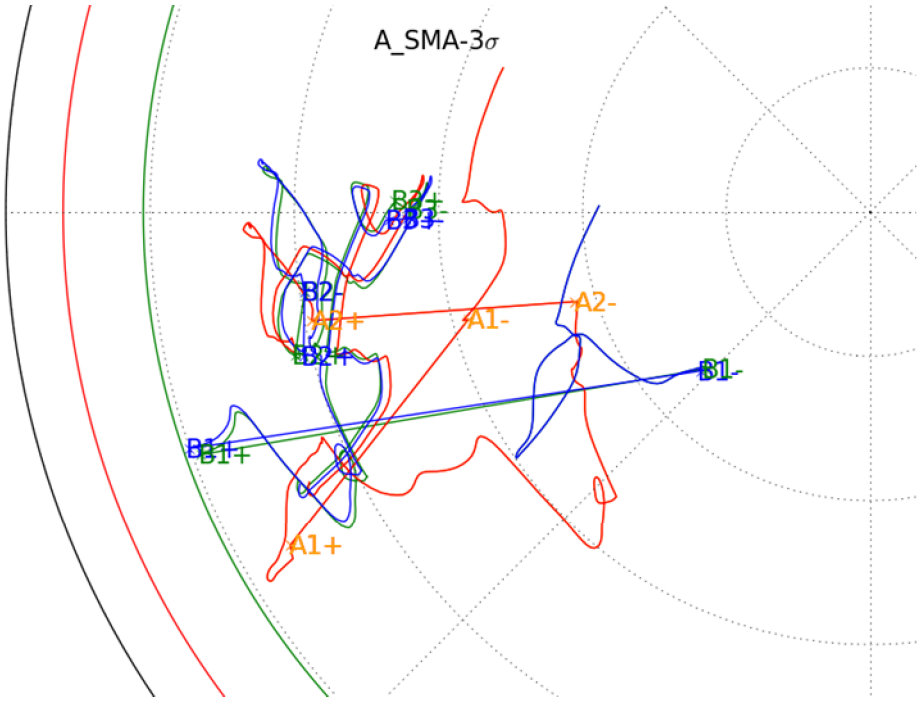
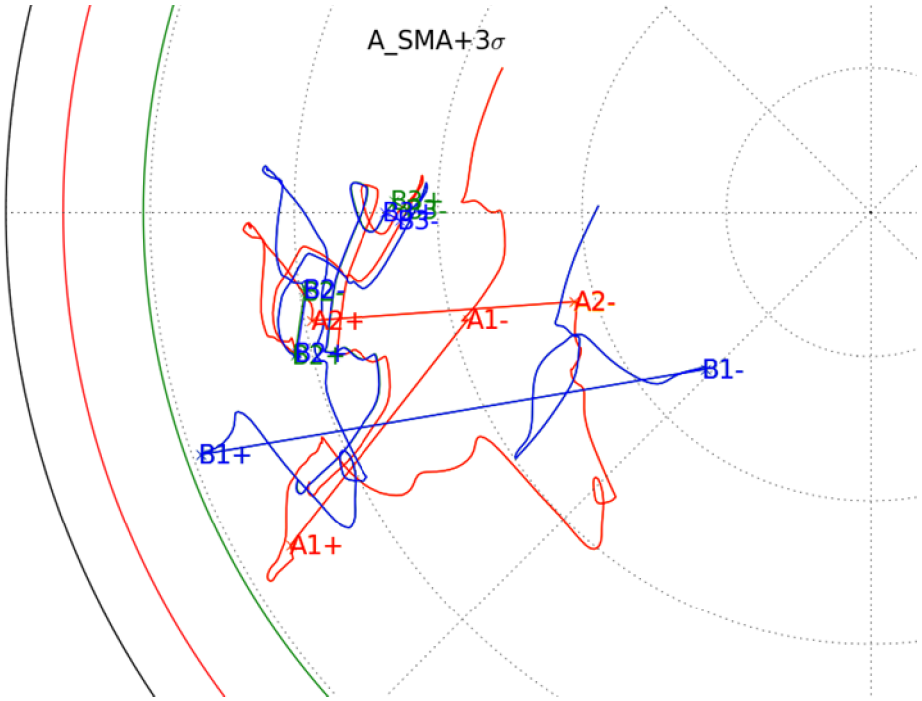
- Orange & green are the reference orbits for GR-A & B.
- Red & blue are the dispersed orbits.
- For example, ±3σ SMA dispersions are insignificant. TSMs for the dispersed cases do similar to TSMs for the nominal.





E-ω Plots for ±3σ GR-A TTP Dispersion

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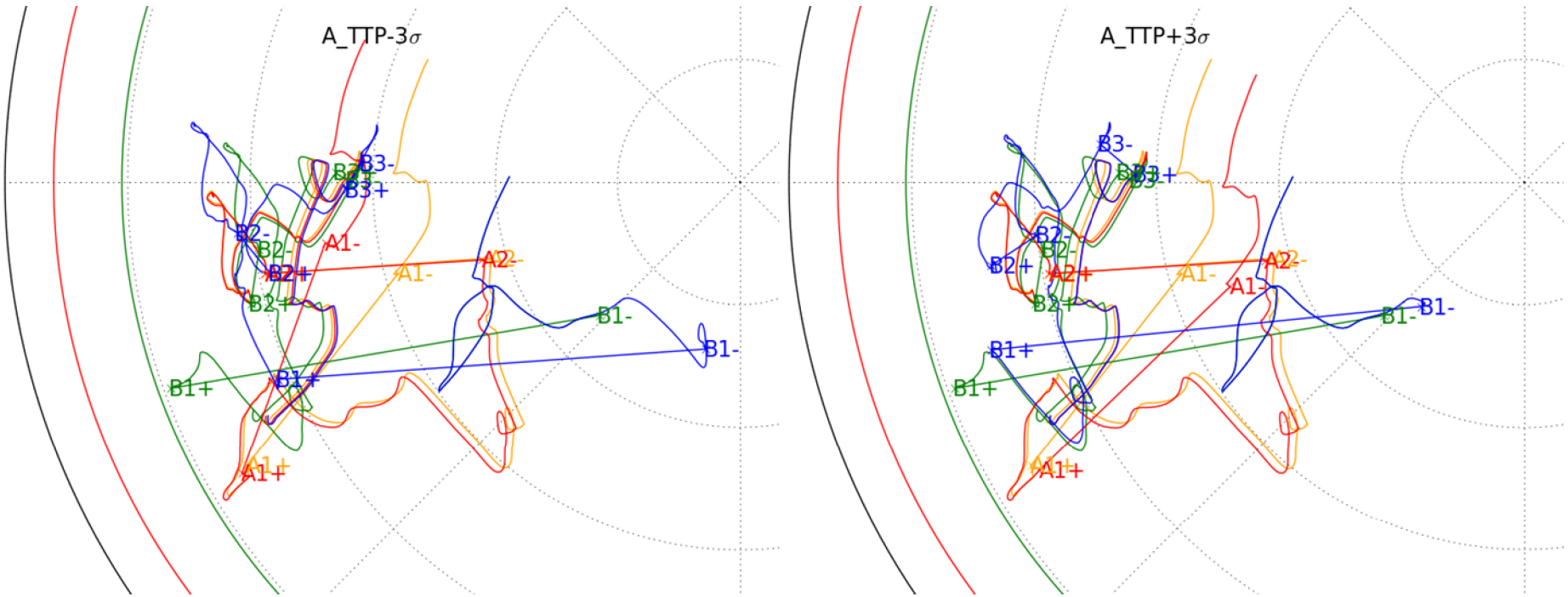
- Although TTP dispersions are the most apparent, they are handled effectively by the TSMs.



Considering GR-B Dispersion Individually

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Discovery

- Examine the behavior of $\pm 3\sigma$ TCM-B4 LOI delivery dispersion of each parameter individually against the nominal GR-A.
- We found that
  - -3σ TTP dispersion case violated 10-km altitude constraint after TSM-A1.
  - The two most critical LOI delivery parameters were **TTP** and **RCA**. Most apparent in *e*-ω plots. TTP also caused COLA.
  - The dispersions for the rest of the parameters were rather insignificant.

E-ω Plots for ±3σ GR-B TTP Dispersion

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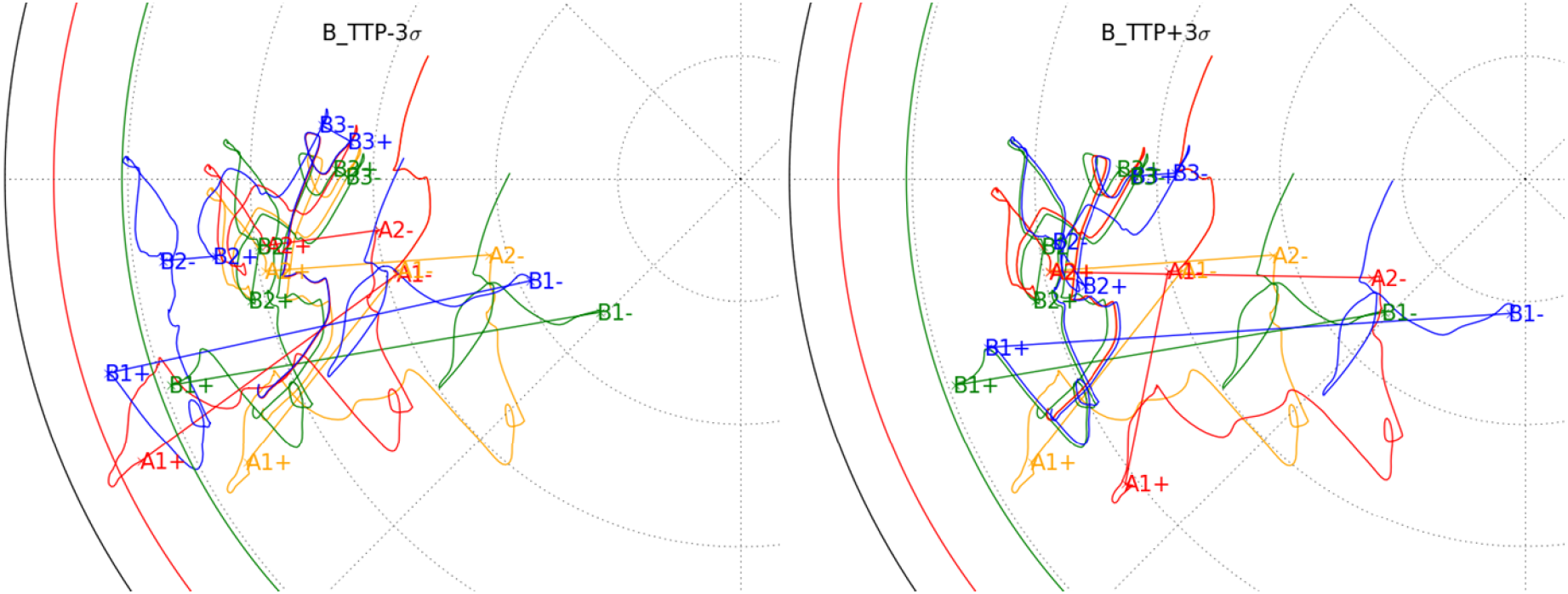
- TTP dispersions are the most apparent in TSF.
- Note that the 10-km altitude arc is crossed after TSM-A1 for the -3σ TTP dispersion case.



GR-A LOI Boundary w/o COLA

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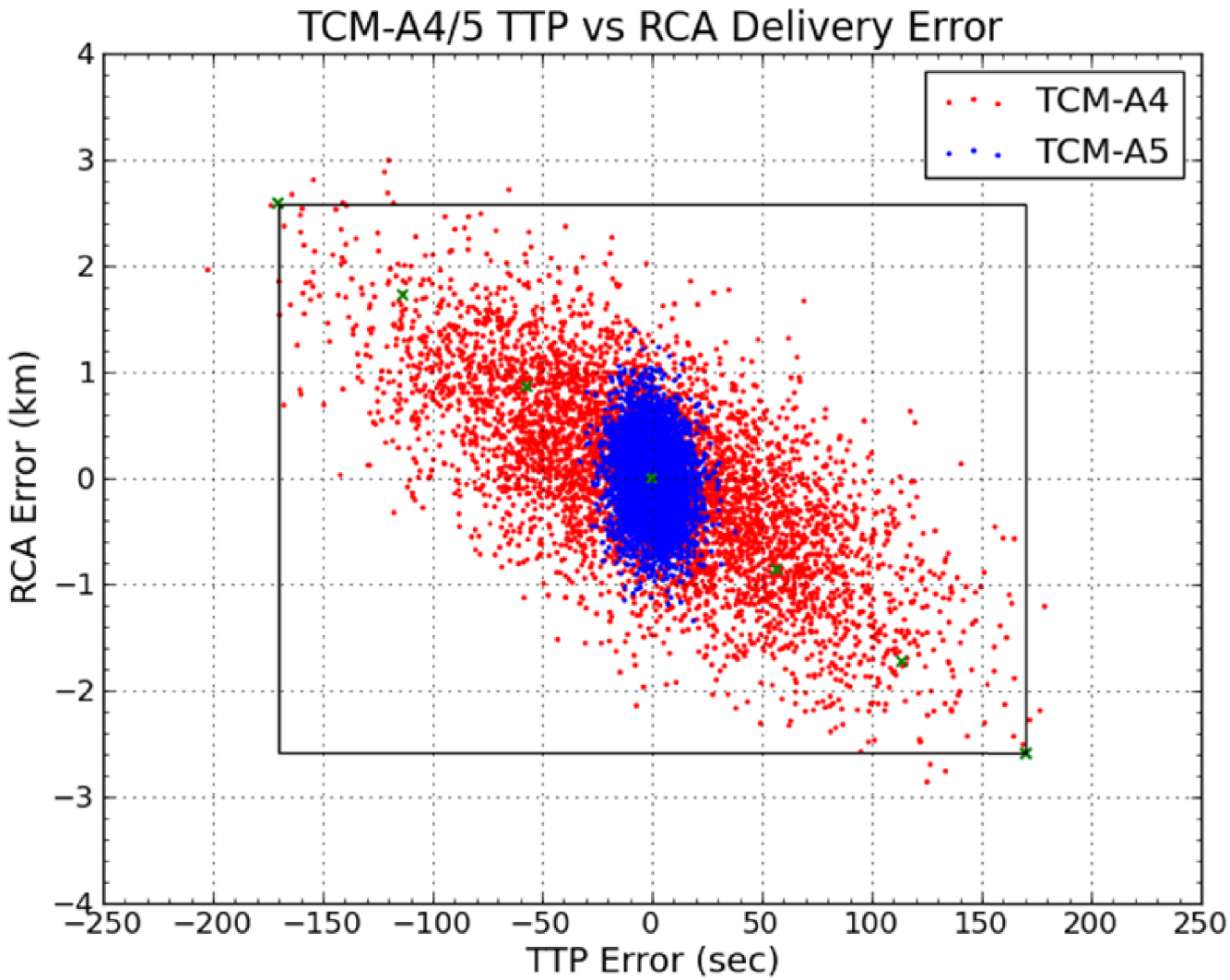
Discovery

- To determine GR-A boundary,
  - Ran 64 cases involving $\pm 3\sigma$ TCM-A4 dispersions in GR-A with $\pm 3\sigma$ TCM-B4 dispersions in all but TTP & RCA parameters. For example, GR-A ($+3\sigma$, -3σ, $+3\sigma$, -3σ, $+3\sigma$, $+3\sigma$) + GR-B($+3\sigma$, 0, $+3\sigma$, -3σ, $+3\sigma$, 0).
  - All runs completed successfully, confirming any combination of GR-A $\pm 3\sigma$ TSM-A4 LOI delivery dispersion is fine as long as GR-B dispersions in TTP and RCA remain nominal.
  - In other words, if it fails, it fails not due to GR-A dispersion but due to GR-B TTP & RCA dispersion being off nominal.
  - Next plot shows the boundary with TCM-A4 and TCM-A5 LAMBIC samples at LOI in the background.

GR-A Boundary w/o COLA



GR-B Boundary w/o COLA (1)

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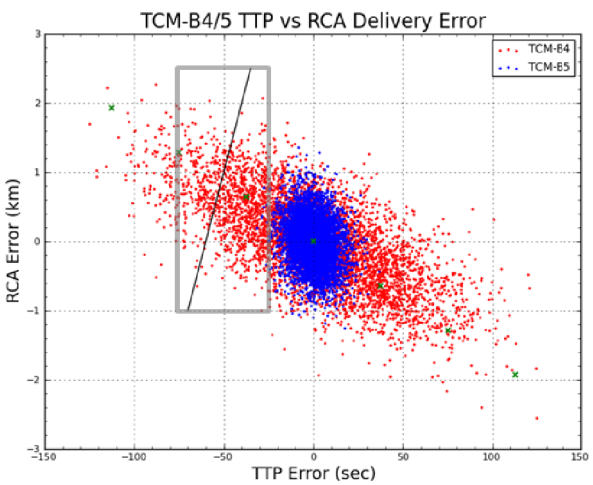
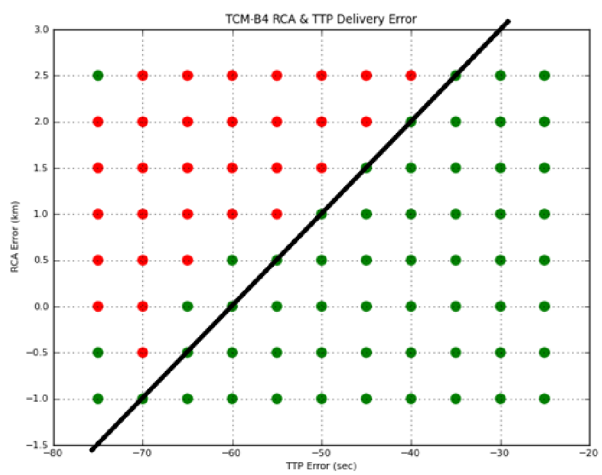
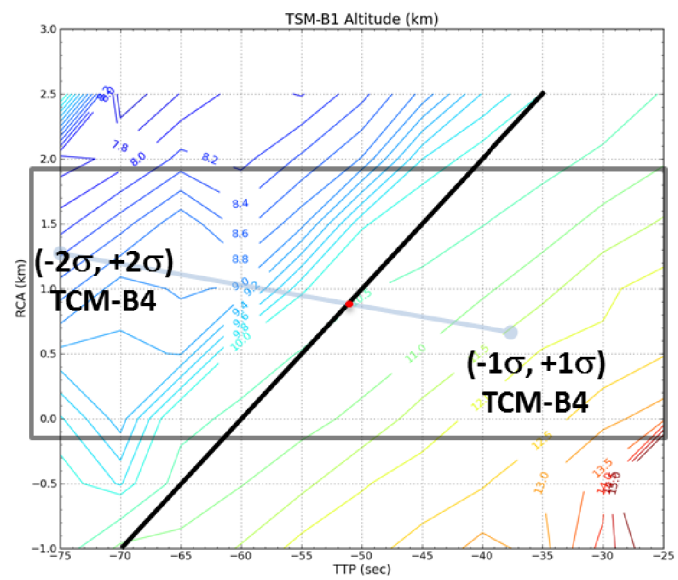
- Left Boundary
  - Caused by violating 10-km altitude constraint after TSM-A1 for a highly negative TTP dispersion.
  - Ran 11x8 cases to determine the boundary.







GR-B Boundary w/o COLA (2)

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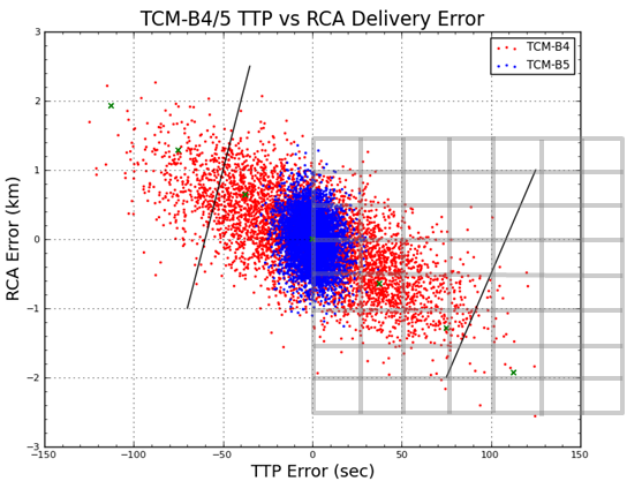
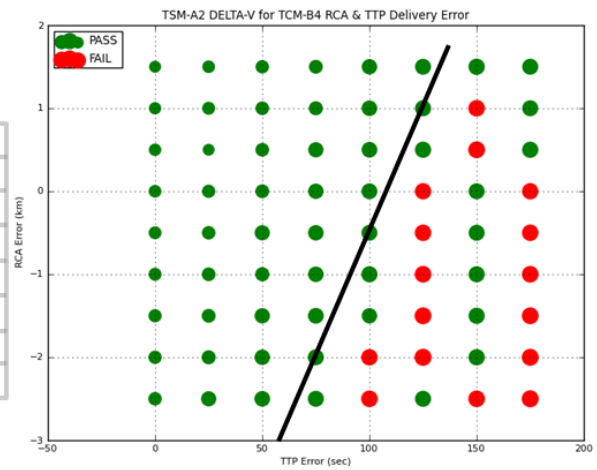
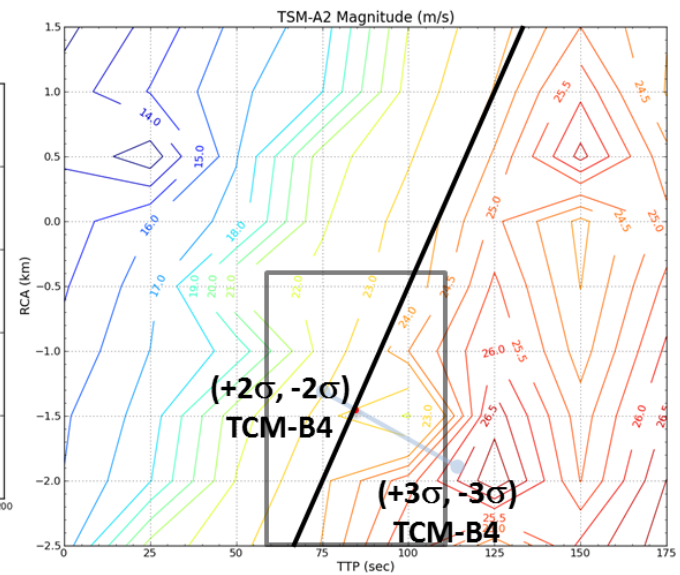
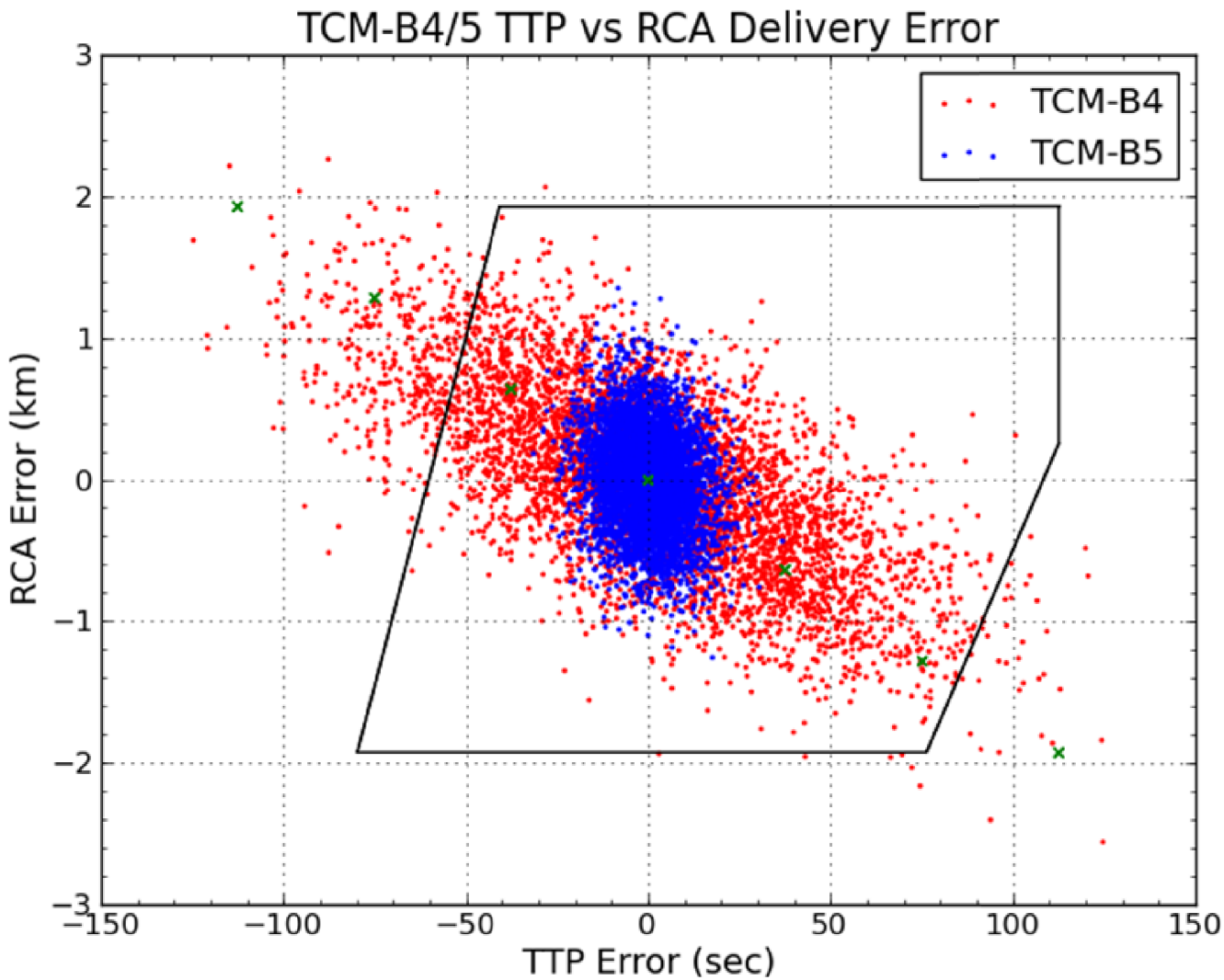
- Right Boundary:
  - Cased by violating 25-m/s maximum ΔV for TSM-A2 for a highly positive TTP dispersion.
  - Ran 8x9 cases to determine the right boundary.







GR-B LOI Boundary w/o COLA



- The boundary includes 4,578 TCM-B4 samples (91.6%) and 5,000 TCM-B5 samples (100%).
- It predicts 91.6% chance of canceling TCM-B5 without considering COLA.

COLA Boundaries

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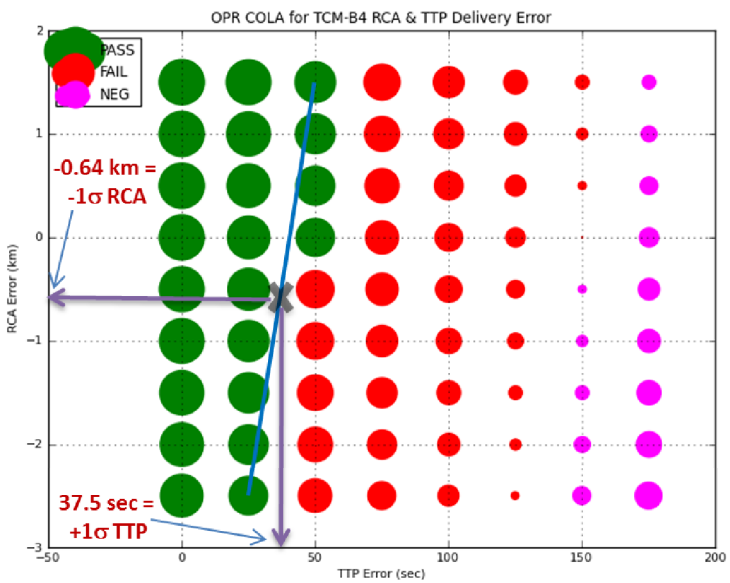
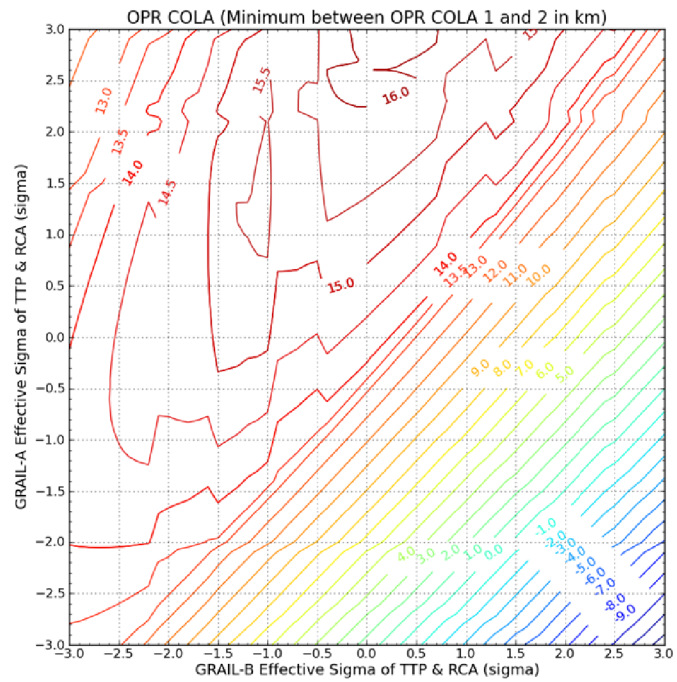
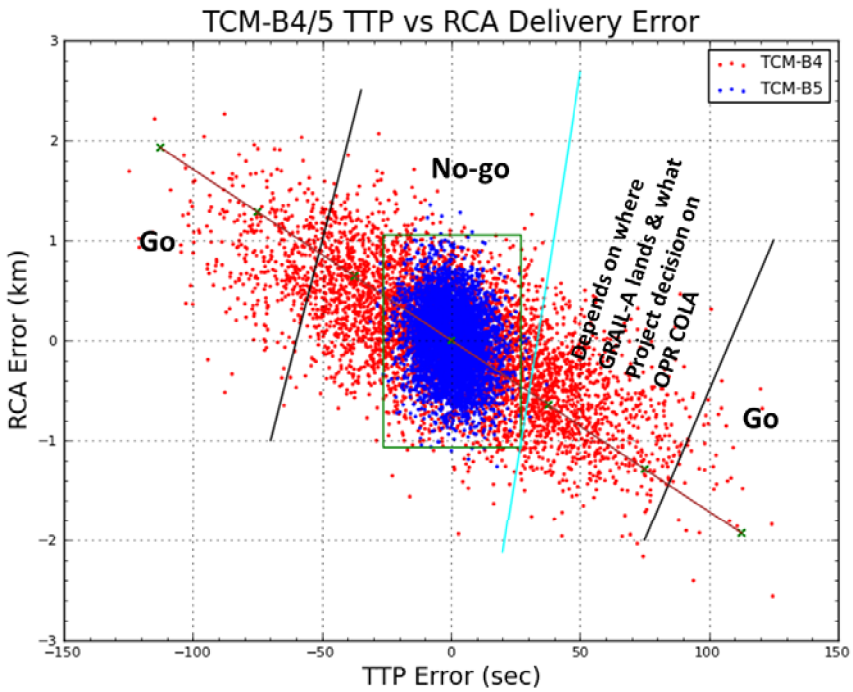
- Simplification for Computation & Visualization
  - Assume COLA occurs with slope RCA / TTP = 4 km / 25 sec.
  - We compute only (TTP, RCA) = (-x, x) cases where we shall call x “effective sigma” and infer all other points in (TTP, RCA) with the above empirical slope.

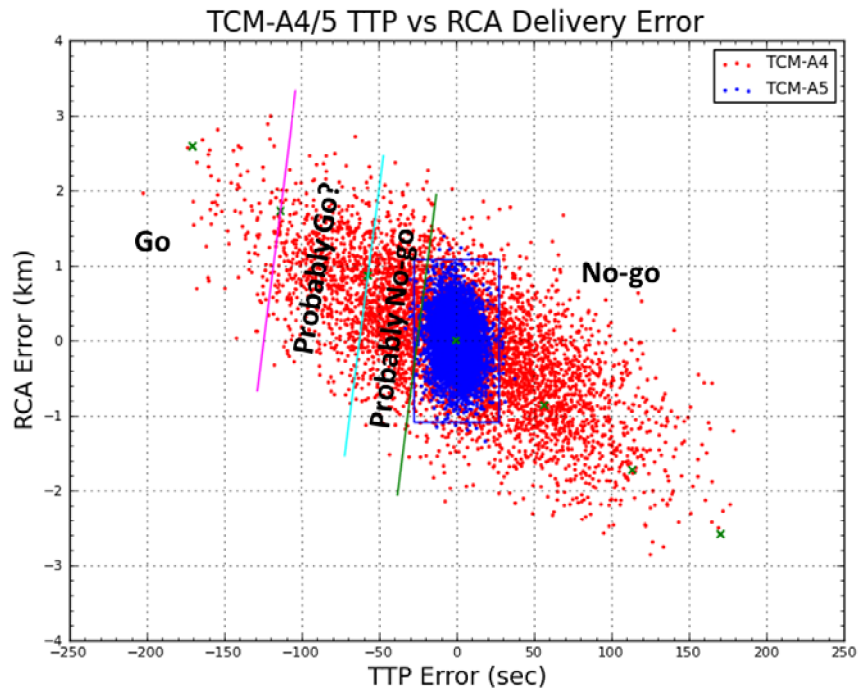




Options for COLA

- From the contour plot, we chose the following option:
  - GR-B: Chose the least GR-B at +0.8σ(effective) for GR-A (71.5% TCM-B4 samples & 99.96% TCM-B5 samples).
  - GR-A: -1σ(effective) for 7.5 km COLA (cyan), which corresponds to 85% without and 100% with TCM-A5.





Final TCM-5 Go/No-Go Boundary w/ COLA

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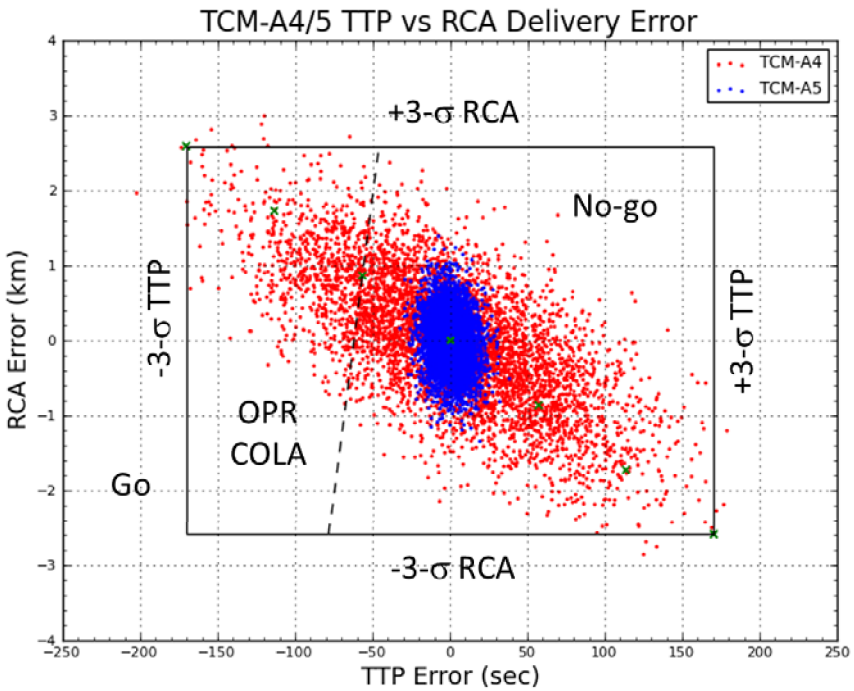

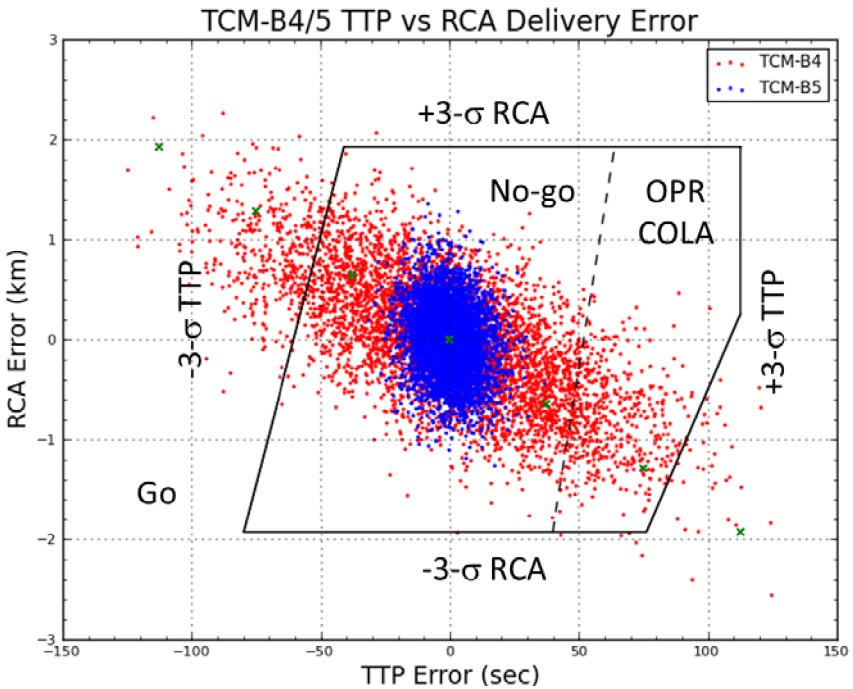

Conclusion

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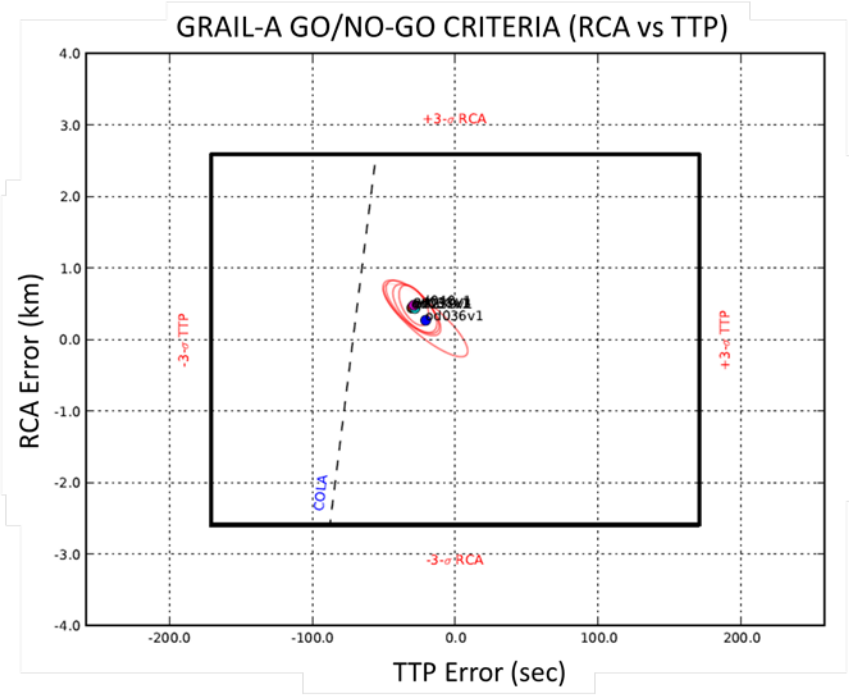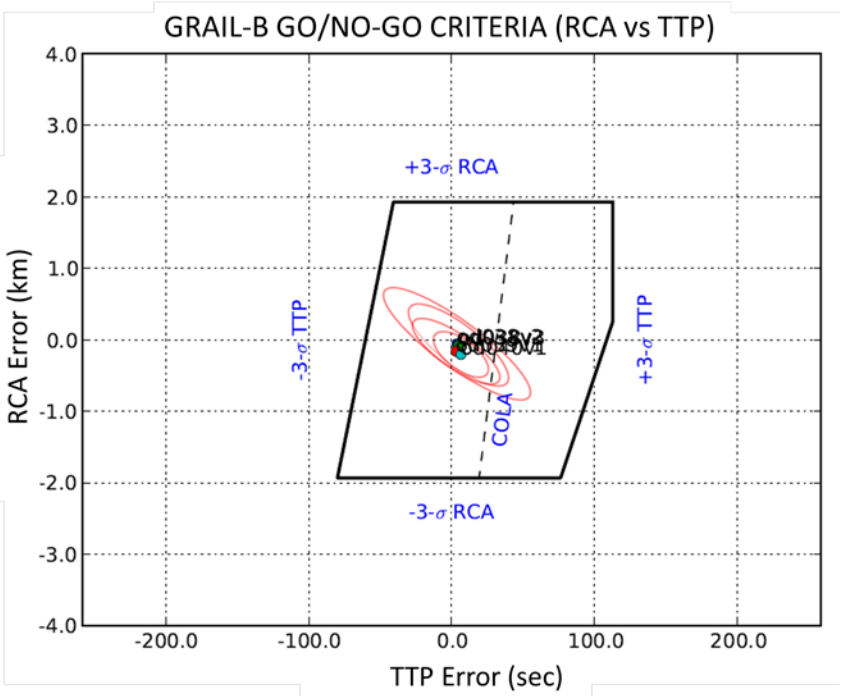
- Both TCM-4s had to be executed (outside the boundaries).
- GR-A found within the TCM-A5 No-Go boundary even after hitting maximum cutoff timer. TCM-A5 was canceled.
- GR-B also within the boundary. TCM-B5 also canceled.