



Maneuver Design Overview of the 2018 InSight Mars Lander Mission



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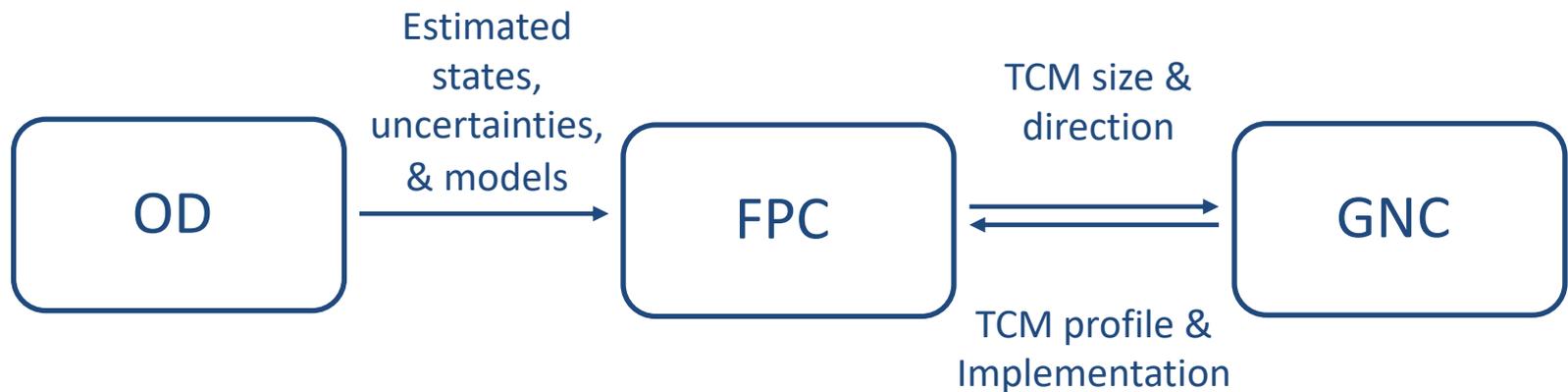
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- Introduction
 - TCMs, Targets and Requirements
- Maneuver Design Cycles
 - Interface with OD, Interface Cycles with GNC
- Maneuver Design Tools
 - Interface to EDL, TCM Search, Statistical Analysis, Presentation
- Maneuver Performance during Operations
 - TCM-1, TCM-2, TCM-3, TCM-4, TCM-5/5X, TCM-6/6X, Reconstruction Comparison
- TCM-6XM Menu Design

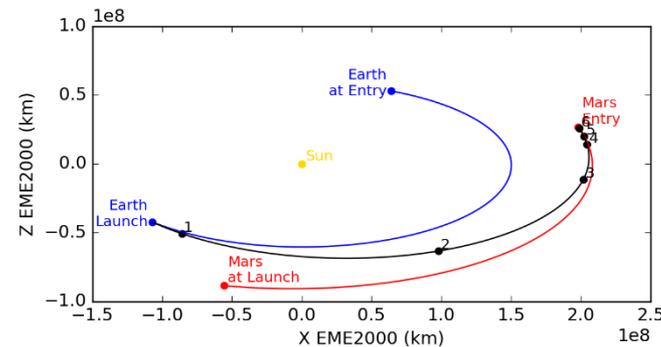
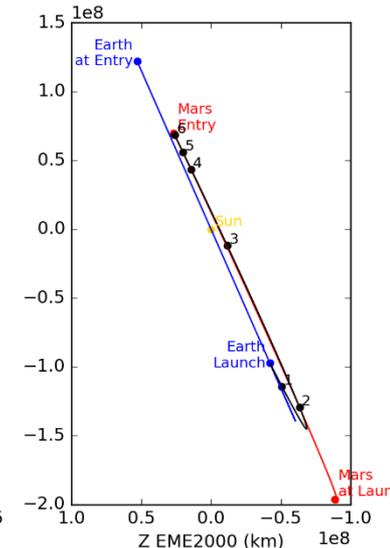
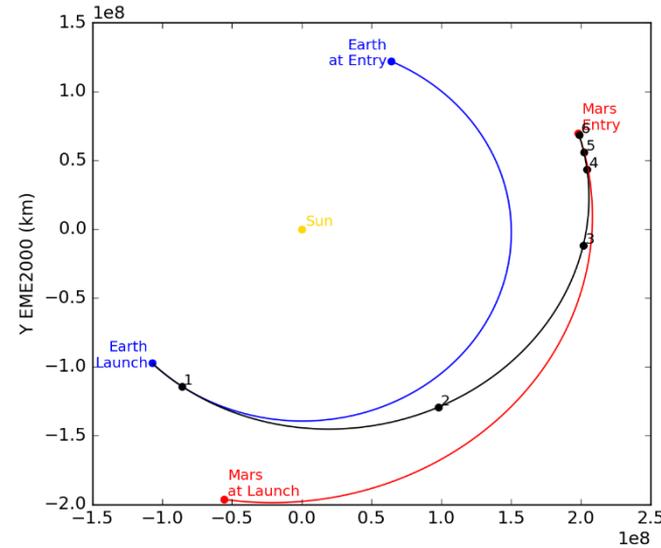
TCM = Trajectory correction maneuver; EDL = Entry descent landing

- Navigation objective:
 - To deliver the lander to a relatively flat target landing site (4.51°N , 135.99°E) in the Elysium Planitia region on Mars.
- Given the atmosphere & wind models, the landing site translates into the entry targets: $R = 3,522.2\text{ km}$; $\text{EFPA} = -12.0^\circ \pm 0.21^\circ$ ($3\text{-}\sigma$); B-plane theta angle.
- FPC designs TCMs to place the spacecraft back on its course to meet the entry targets.



EFPA = Entry flight path angle; FPC = Flight path control; OD = Orbit determination; GNC = Guidance and Control

- Six Nominal TCMs:
 - TCM-1 deterministic & TCM-2 to 6 planned statistical
 - TCAL between TCM-1 & 2
 - TCM-2 became deterministic due to TCM-1/2 re-optimization.
 - TCM-4 was cancelled.
- Contingency TCMs planned:
 - TCM-5X for TCM-5 missed
 - TCM-6X for TCM-6 missed
 - TCM-6XM (a menu of 20 pre-designed & pre-verified TCMs) at TCM-6X

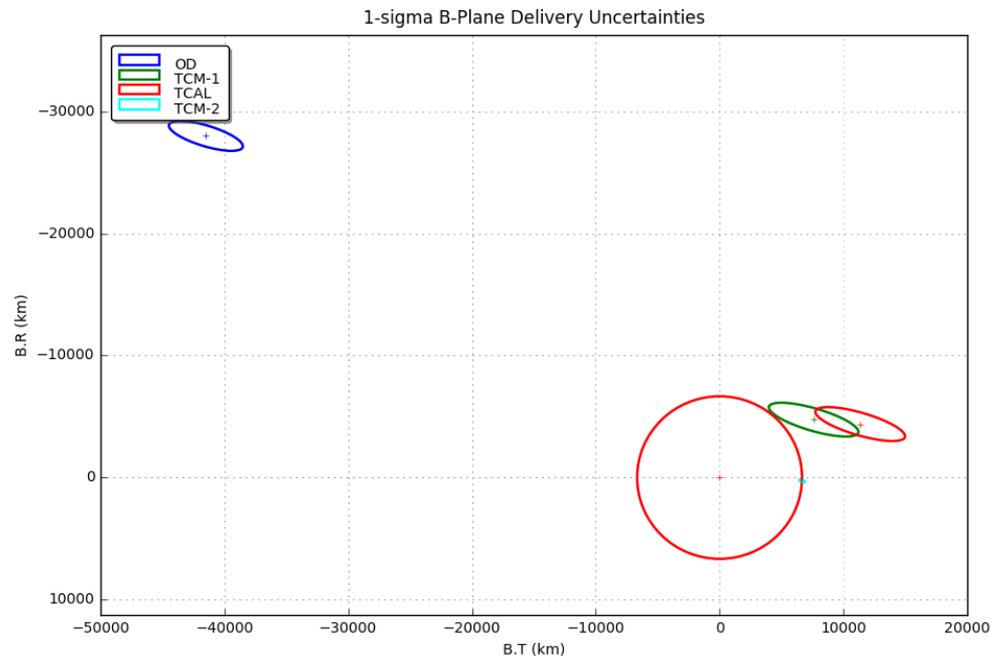


- The primary purpose of TCM-1: to remove the injection bias and clean up the injection errors.
- TCM-1 delayed by one week to L+17d due to
 - OD was not as stable as expected at the nominal date at L+10d due to higher-than-expected out-gassing during the beginning of the cruise.
 - ΔV vs TCM-1 date plot remained relatively flat for the first couple of weeks.
- TCM-1/2 re-optimization strategy was adopted:
 - TCM-1/2 ΔV (3.777 m/s & 0.939 m/s) < a single TCM-1 ΔV (4.845 m/s < prelaunch mean of 7.101 m/s because of good injection).
 - The cumulative impact probability ($0.744e-03$) < the requirement ($1.e-02$). The single TCM-1 case was $1.044e-02$.
 - The uncertainty in the TCAL between TCM-1 and TCM-2 made the case stronger to perform the two-maneuver optimization.

- Statistics:

TCM	Epoch (UTC)	DV Mean (m/s)	DV Sigma (m/s)	DV01 (m/s)	DV50 (m/s)	DV99 (m/s)
OD	15-MAY-2018 15:29:46	0.000	0.000	0.000	0.000	0.000
TCM-1	22-MAY-2018 18:00:00	3.779	0.027	3.715	3.779	3.843
TCAL	26-JUN-2018 20:10:00	0.473	0.030	0.401	0.473	0.542
TCM-2	28-JUL-2018 18:00:00	1.033	0.164	0.713	1.018	1.522
TCM-3	12-OCT-2018 18:00:00	0.071	0.036	0.016	0.064	0.177
TCM-4	11-NOV-2018 18:00:00	0.062	0.025	0.015	0.059	0.129
TCM-5	18-NOV-2018 18:00:00	0.042	0.017	0.009	0.040	0.089
TCM-6	25-NOV-2018 21:40:00	0.173	0.076	0.039	0.162	0.382
Total		5.632	0.200	5.214	5.615	6.211

- Delivery ellipses:



- TCM-5 execution fairly accurate:
 - ~7 km short on the B-plane
 - ~20 km NE on the surface
 - EFPA was -11.9° , ok to EDL.
- Thus, from NAV perspective, no need to perform TCM-6
 - All landing site criteria met by a post-DCO OD right before TCM-6 execution
- Project elected to proceed with TCM-6 execution:
 - The landing site error on the surface was in the downtrack direction towards a ridged terrain in the North-East.
 - The history of previous Mars missions “Landing Long on Mars” (not always the case in the past and InSight was on the opposite side).



DCO = Data cutoff

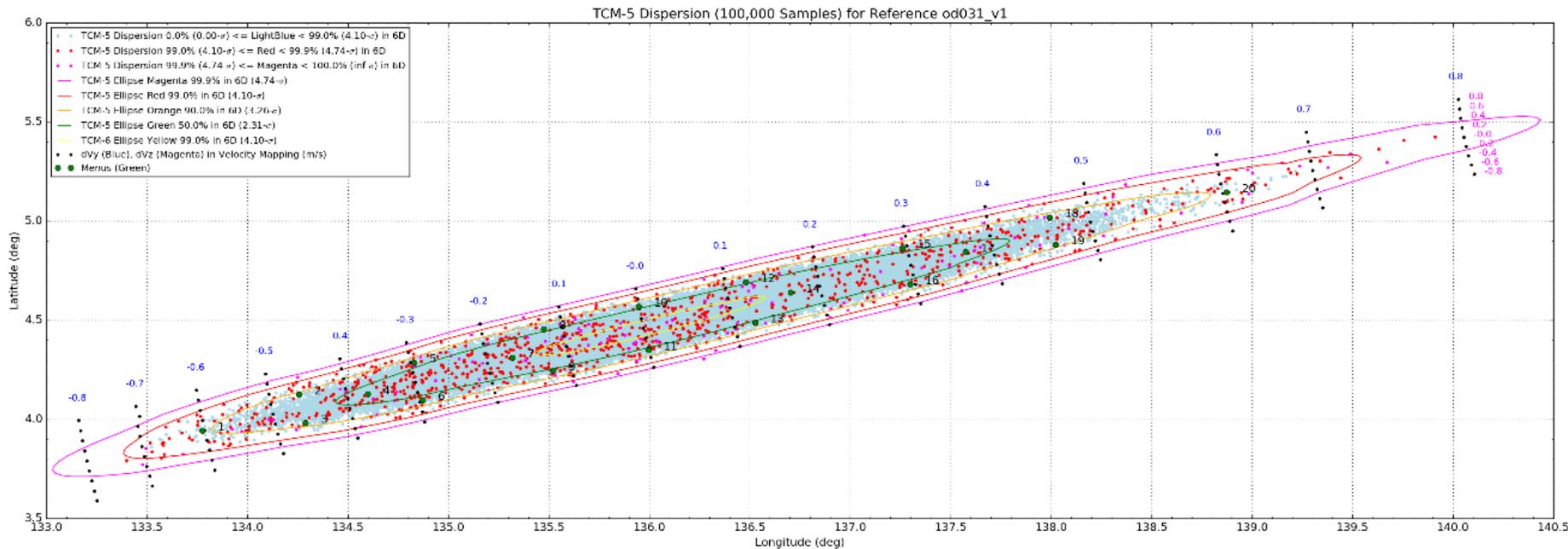
- Comparison between the TCMs in EME2000 as designed by FPC and as reconstruction by OD and GNC:

TCM	Epoch (UTC)	FPC Design			OD Reconstruction			GNC/IMU Reconstruction		
		Mag (m/s)	RA (°)	Dec (°)	Mag (m/s)	RA (°)	Dec (°)	Mag (m/s)	RA (°)	Dec (°)
TCM-1	22-MAY-2018 18:00:00	3.7772	92.0606	-7.8236	3.7612	92.1575	-7.9703	3.7561	91.9105	-8.4321
TCM-2	28-JUL-2018 18:00:00	1.4977	102.2828	-25.8663	1.5030	102.6210	-26.4804	1.4963	102.2720	-26.4348
TCM-3	12-OCT-2018 18:00:00	0.1673	336.3295	61.6730	0.1604	333.4344	61.1926	0.1663	333.4850	60.0395
TCM-4										
TCM-5	18-NOV-2018 18:00:00	0.0571	160.6484	28.2760	0.0634	164.1026	36.1741	0.0616	165.1178	29.3023
TCM-6	25-NOV-2018 21:39:00	0.0850	69.9090	-79.8082	0.0907	92.2825	-78.6892	0.0924	71.6259	-78.0032

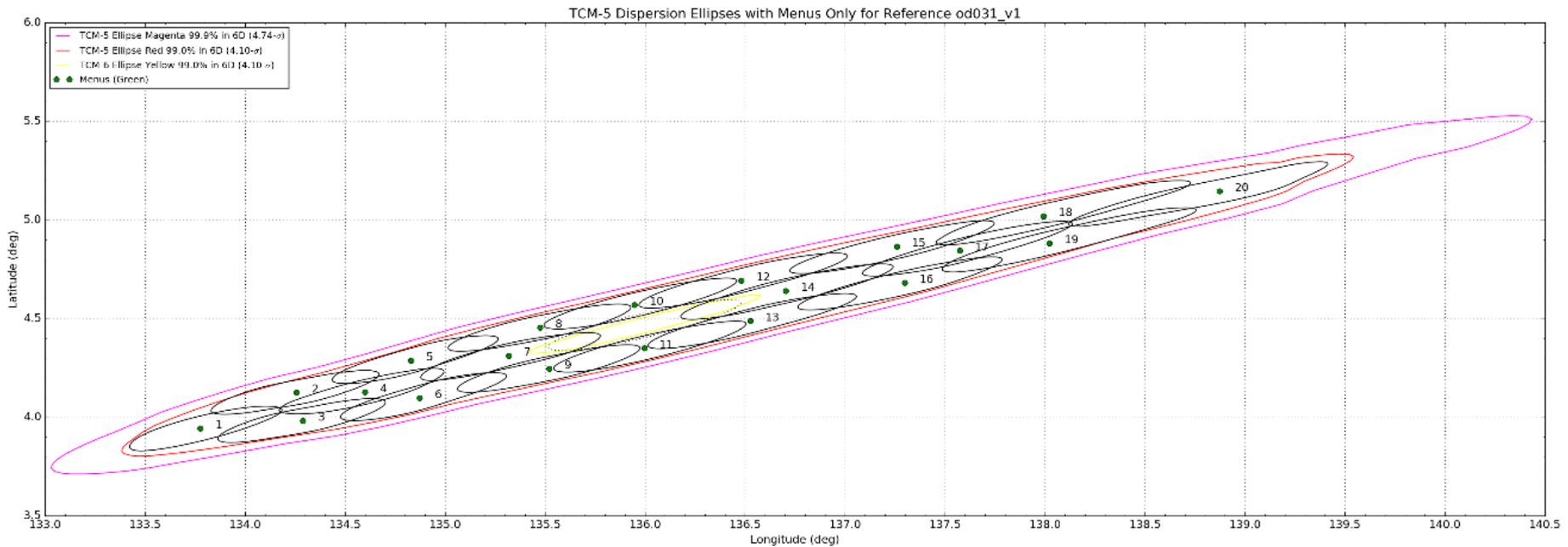
- In particular, TCM-6 was about 2.3- σ off in execution. This TCM-6 execution error as well as the atmospheric uncertainties contributed in InSight coming to rest about 20 km West of the target landing site.

- Objective:
 - Twenty pre-designed (by FPC) and pre-verified (by GNC) menu TCMs available for execution in case TCM-6 failed to execute, and TCM-6X could not satisfy the requirements (Note that TCM-6X is designed at the same time as TCM-6 to be executed only in case TCM-6 fails).
 - Accordingly, TCM-6XM had to be distributed in such way that the 99% TCM-5 landing dispersion ellipse was reduced to the about size of the 99% TCM-6 landing dispersion ellipse.
- To accomplish this objective, two rotations could strategically reduce the problem simply into a geometric one:
 - The first rotation is one that rotates a randomly sampled Gaussian sigma state dispersion from the TCM-5 OD covariance into the “**Sigma Frame**,” in which the velocity dispersion (δV) components at TCM-5 DCO are mapped to the landing dispersion ellipse as follows: δV_x very close to the center, δV_y along the semi-major axis, and δV_z along the semi-minor axis. Note that the 3- σ position dispersion at TCM-5 DCO maps insignificantly smaller from the center.

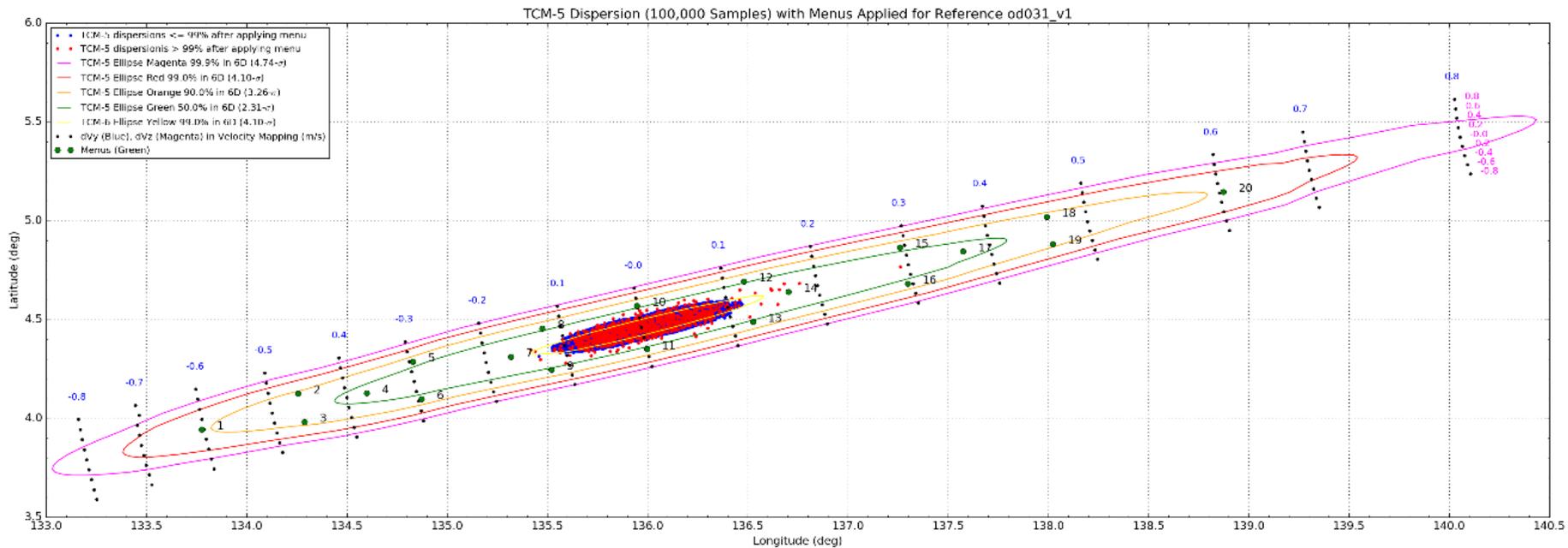
- The second rotation is one that rotates the nominal state at TCM-6XM into the “**Velocity Frame**,” in which the ΔV components at TCM-6XM map the nominal state to the landing dispersion ellipse as follows: ΔV_x very close to the center, ΔV_y along the semi-major axis, and ΔV_z along the semi-minor axis.



- Thus, selecting twenty menu TCMs becomes a matter of distributing a dispersion ellipse of ΔV_y by ΔV_z size in the Velocity Frame within the 99% TCM-5 dispersion ellipse.
 - The size of each dispersion ellipse was 0.118 m/s by 0.24 m/s in the Velocity Frame. The ΔV “locations” in the Velocity Frame can be converted into EME2000 components for implementation



- Figure below shows 100,000 randomly sampled TCM-5 dispersions corrected by one of the twenty TCM-6XM menu maneuvers.



- Thankfully, the spacecraft performed well and TCM-6XM did not have to be used in operations.



Conclusion



- Through several Operational Readiness Tests (ORTs) the navigation and maneuver design tools were honed into final forms and the analysts were trained and prepared for the pace and expectations of operations.
- For the several months from Earth launch to Mars landing each TCM was dealt with one at a time, sometimes working on weekends, holidays, and nights.
- In the end, the InSight team encountered no major issues and was able to see InSight landed safely on Mars.



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