Ground-Based Navigation and Dispersion Analysis for the Orion Exploration Mission 1

Christopher D'Souza

Johnson Space Center,
Houston, TX

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Outline

- **The First Exploration Mission (EM-1)**
  - The TLI and Maneuver Execution Model
- **The On-board Navigation System**
- **The Navigation and Dispersion Analysis**
- **The Sensitivity Analysis**
- **Conclusions**

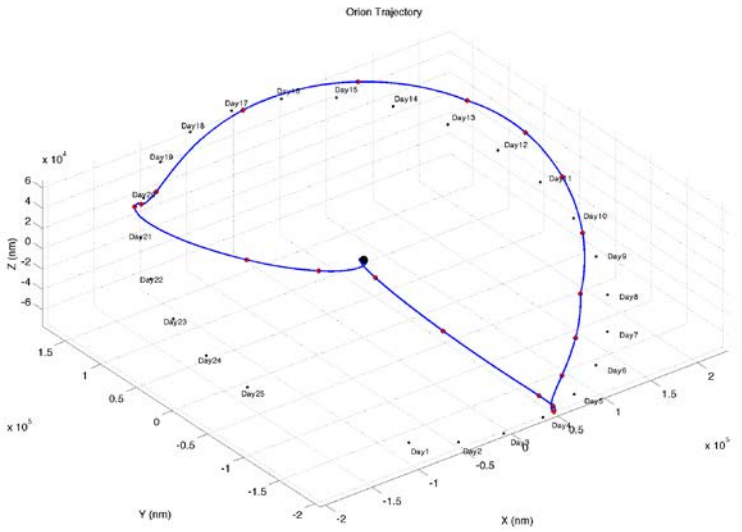
Assumptions -- Trajectory

- **The EM-1 Trajectory is planned to be a Distant Retrograde Orbit (DRO)**
  - Two powered lunar flybys
  - 25 day trajectory
    - 4 day stay at the DRO
  - Various Correction Maneuvers
    - 4 on translunar leg
    - 3 on Moon-to-DRO leg
    - 3 in the DRO
    - 3 on DRO-to-Moon leg
    - 3 on the trans-Earth leg
- **Began after upper stage (ICPS) sep and ullage maneuvers**
- **Included Sun, Moon, Earth gravity**

Maneuver #	Type	t_{ig} (hrs)	$\|\Delta V_{nom}\|$ (ft/s)
1	OTC-1	6.81	0.000
2	OTC-2	25.81	0.000
3	OTC-3	81.60	0.000
4	OTC-4	97.60	0.000
5	OPF	103.60	572.627
6	OTC-5	122.41	0.000
7	OTC-6	144.00	0.000
8	DRI	169.21	797.479
9	OM-1	204.00	0.000
10	OM-2	240.00	0.000
11	OM-3	276.00	0.000
12	DRD	316.80	278.567
13	RTC-1	372.01	0.000
14	RTC-2	426.01	0.000
15	RTC-3	477.62	0.000
16	RPF	483.62	827.866
17	RTC-4	501.61	0.000
18	RTC-5	591.04	0.000
19	RTC-6	607.04	0.000
Total			**2476.539**

Assumptions – Injection Accuracy and Maneuver Execution Errors

- **TLI has the following accuracy**
  - Position (3σ)
    - Radial: 30,984 ft
    - Tangential: 196,002 ft
    - Normal: 10,981 ft
  - Velocity (3σ)
    - Radial: 171 ft/s
    - Tangential: 29 ft/s
    - Normal: 43 ft/s
  - These were represented in a full 6x6 covariance matrix in the UVW coordinate frame
- **The Maneuver Execution Errors are modeled as follows:**
  - Noise: 0.09 ft/s (3σ)
  - Bias: 0.03 ft/s (3σ)
  - Scale Factor: 450 ppm (3σ)
  - Misalignment: 0.03 deg (3σ)



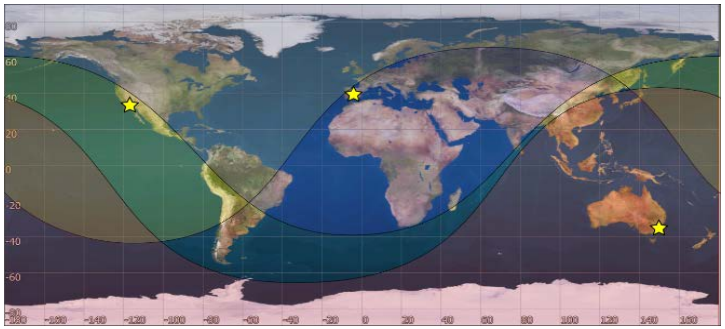
Vehicle Noise

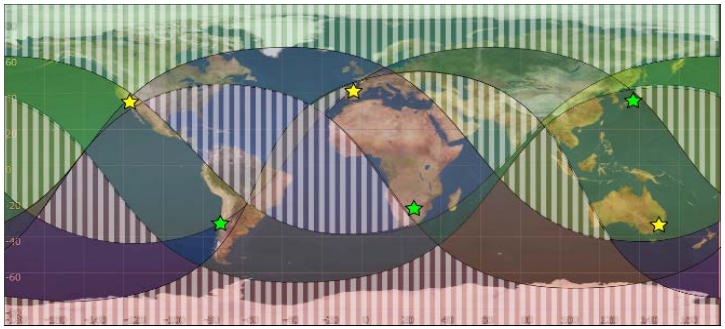
- **Thrusting Sources of Process Noise**
  - Thrusters
    - Attitude Deadbanding
    - Attitude Slewing Maneuvers
      - 50 slews for non-pan/tilt camera
      - 24 slews for pan/tilt camera
  - ECLSS
    - PSA
    - Ammonia Sublimator Venting
    - Urine (Neglected for this analysis)
- **Other Sources of Process Noise**
  - Gravitational (Neglected for this analysis)
    - Lunar Mascons
    - Higher-Order Lunar and Earth Gravity Fields
  - Solar Radiation Pressure (Neglected for this analysis)

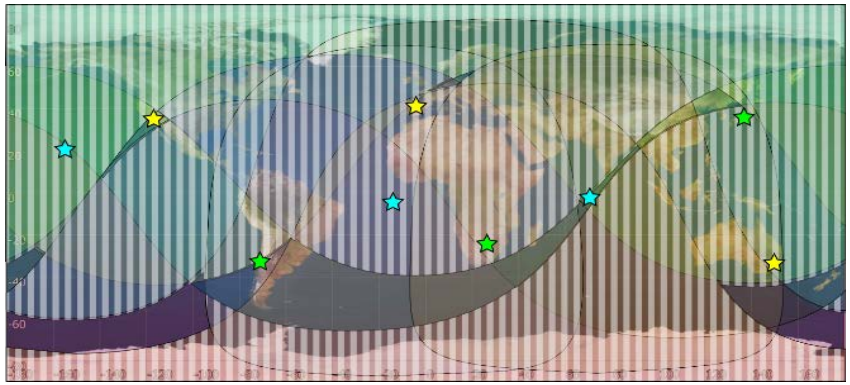
Type of Noise	Assumptions	Noise (ft^2/s^3)
Attitude Dead-banding	Jet firing every 30 minutes	2.644×10^{-10}
Attitude Slewing	50 attitude events	3.541×10^{-8}
Attitude Slewing	25 attitude events	1.830×10^{-8}
PSA Vents	Every 6-10 minutes (up to 40 minutes with complete desaturation)	4.681×10^{-9}
Ammonia Sublimator	Operates in close lunar environment and before EI (for 0.5 hour)	CM/SM: 1.497×10^{-4} CM-only: 9.003×10^{-4}

A Word About the Ground Navigation Model

- **The Nominal Ground Navigation Network comprises 6 stations**
  - Goldstone, Madrid, Canberra, Hartebeestoek, Santiago, Usuda
  - Range and Doppler
  - State uploaded 1 hour prior to maneuver
  - Allow time for turn to burn attitude
- **A Sensitivity Analysis was performed as to the number of Ground Stations**
  - 3 DSN Stations (Goldstone, Madrid, Canberra)
  - 9 Station Network (6 stations + Diego Garcia, Hawaii, Ascencion Island)
- **Apollo used 10-12 sites**



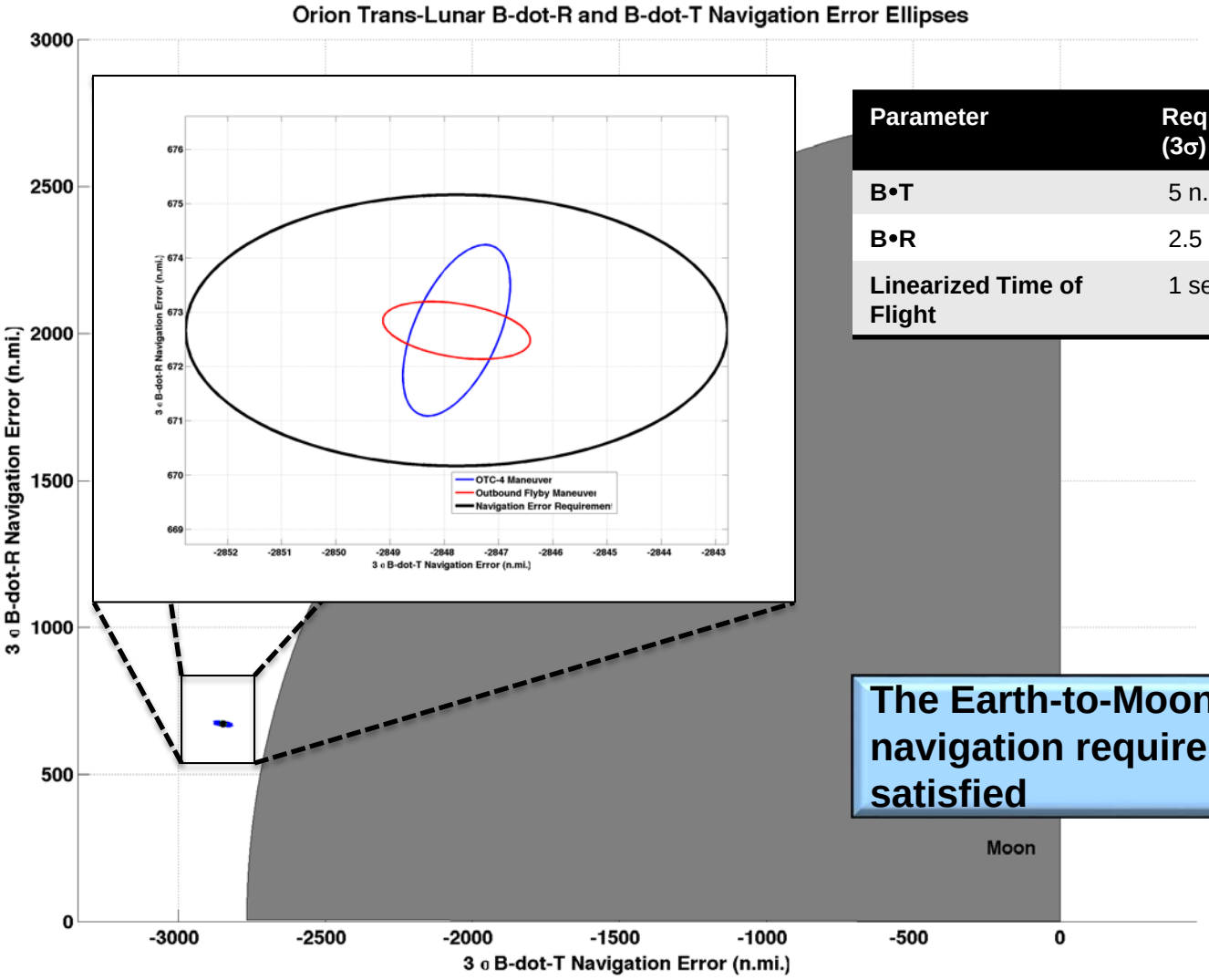




A Few Comments About the Linear Covariance Results

- **The results are broken up into navigation errors and trajectory dispersions**
  - Navigation errors: estimated state – true state
  - Trajectory dispersions: true state – nominal state
- **These navigation errors and trajectory dispersions are mapped to the Entry Flight Path Angle via a state transition matrix and partials**
  - Note that the future state noise is NOT included in this mapping forward
    - This should be interpreted as representing the errors at EI if there was no more state noise from that point forward in time
- **The maneuver partials were found via central difference**
  - State was perturbed in the + and – direction
  - Linearity was analyzed by changing the perturbation size

First Lunar Encounter (OPF) Navigation Performance



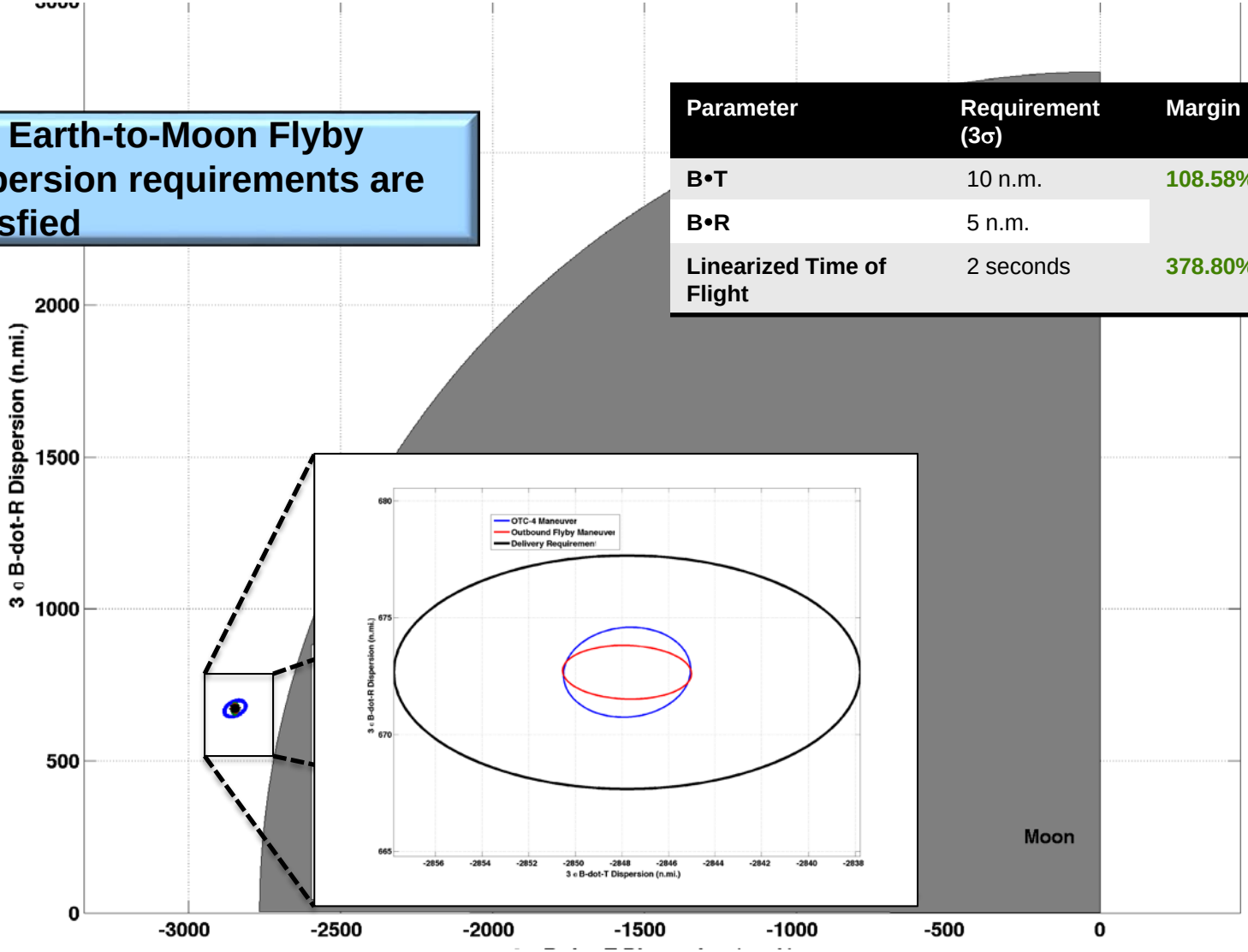
Parameter	Requirement (3σ)	Margin
B•T	5 n.m.	99.54%
B•R	2.5 n.m.	
Linearized Time of Flight	1 seconds	1478.14%

The Earth-to-Moon Flyby navigation requirements are satisfied

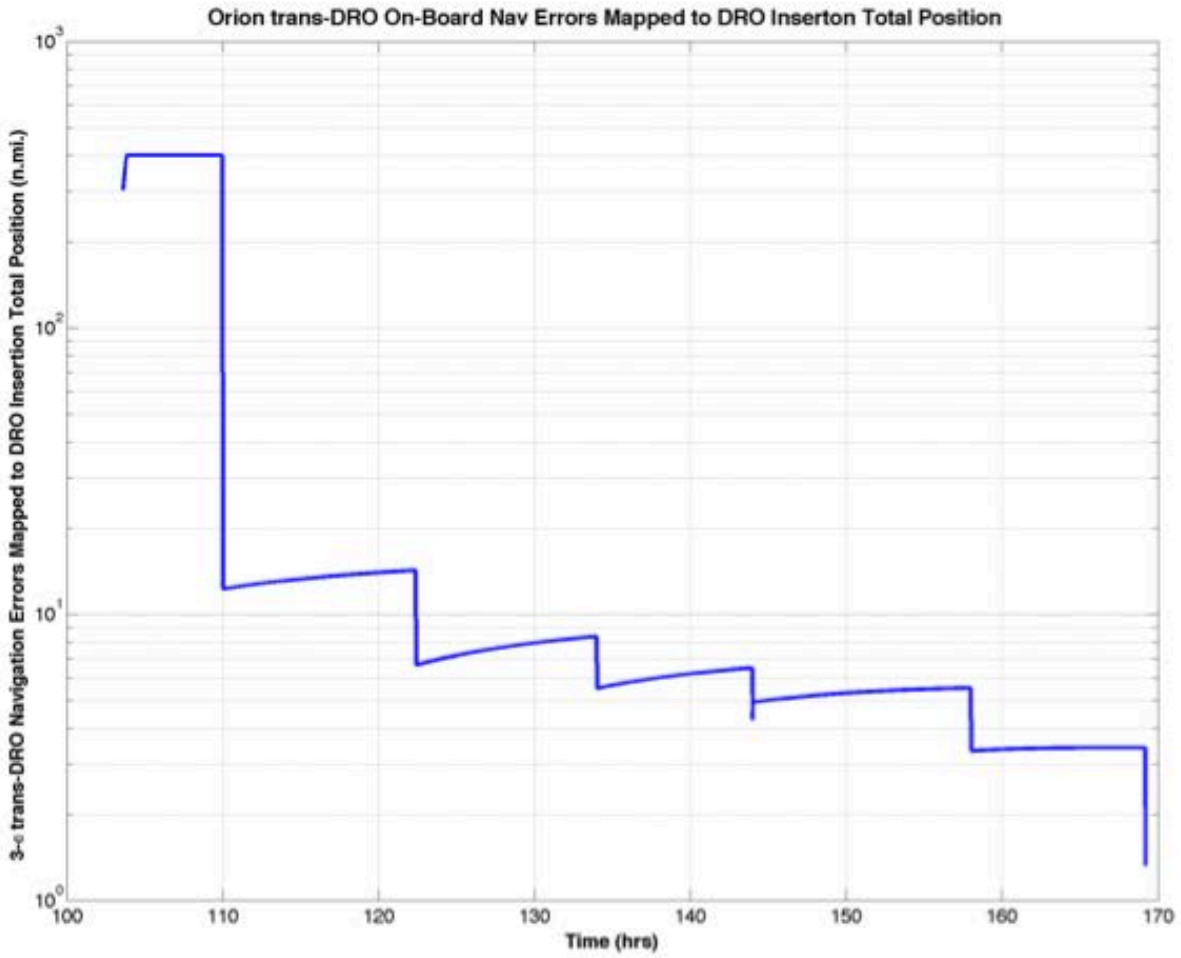
First Lunar Encounter (OPF) Trajectory Dispersions

The Earth-to-Moon Flyby dispersion requirements are satisfied

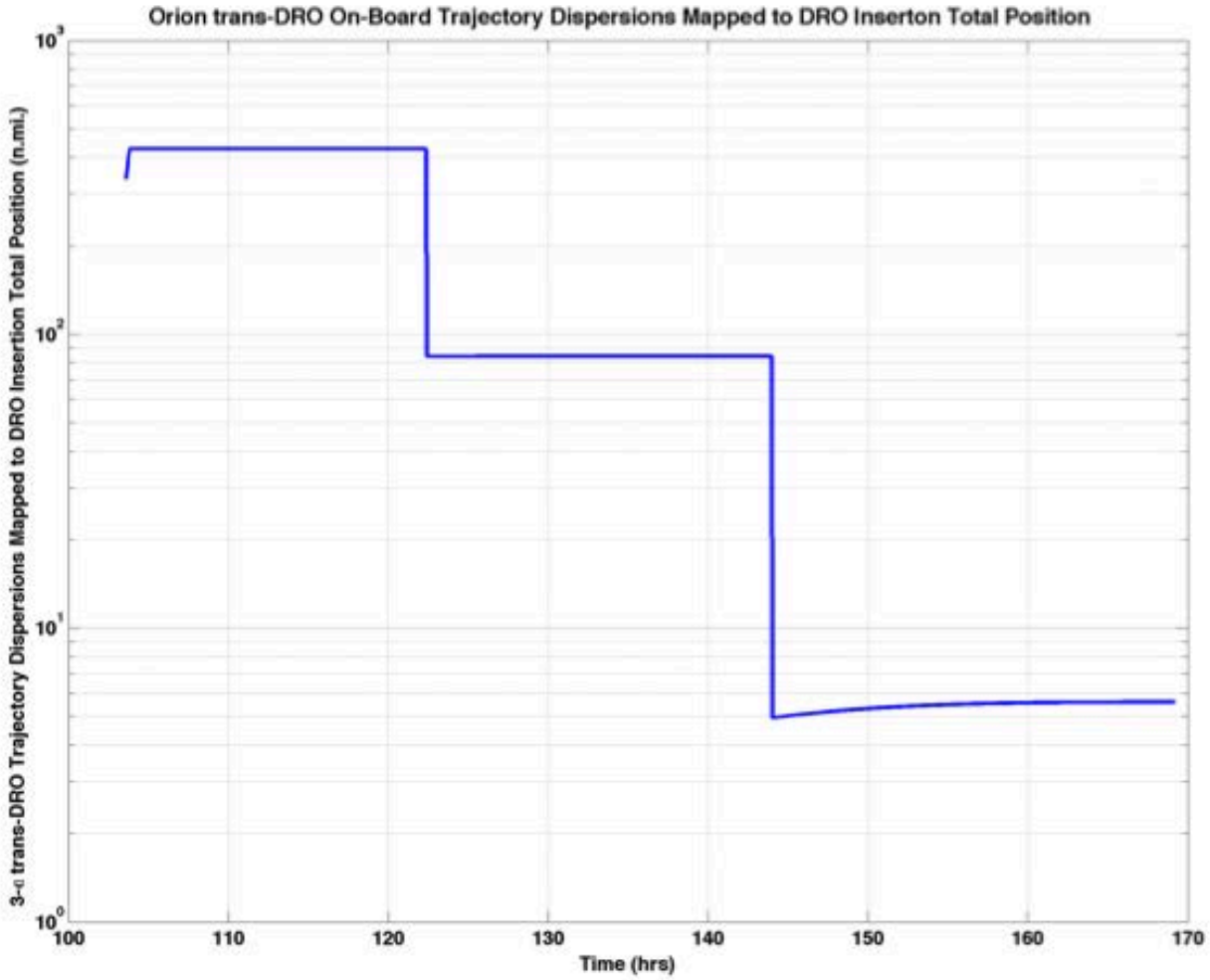
Parameter	Requirement (3σ)	Margin
B•T	10 n.m.	108.58%
B•R	5 n.m.	
Linearized Time of Flight	2 seconds	378.80%



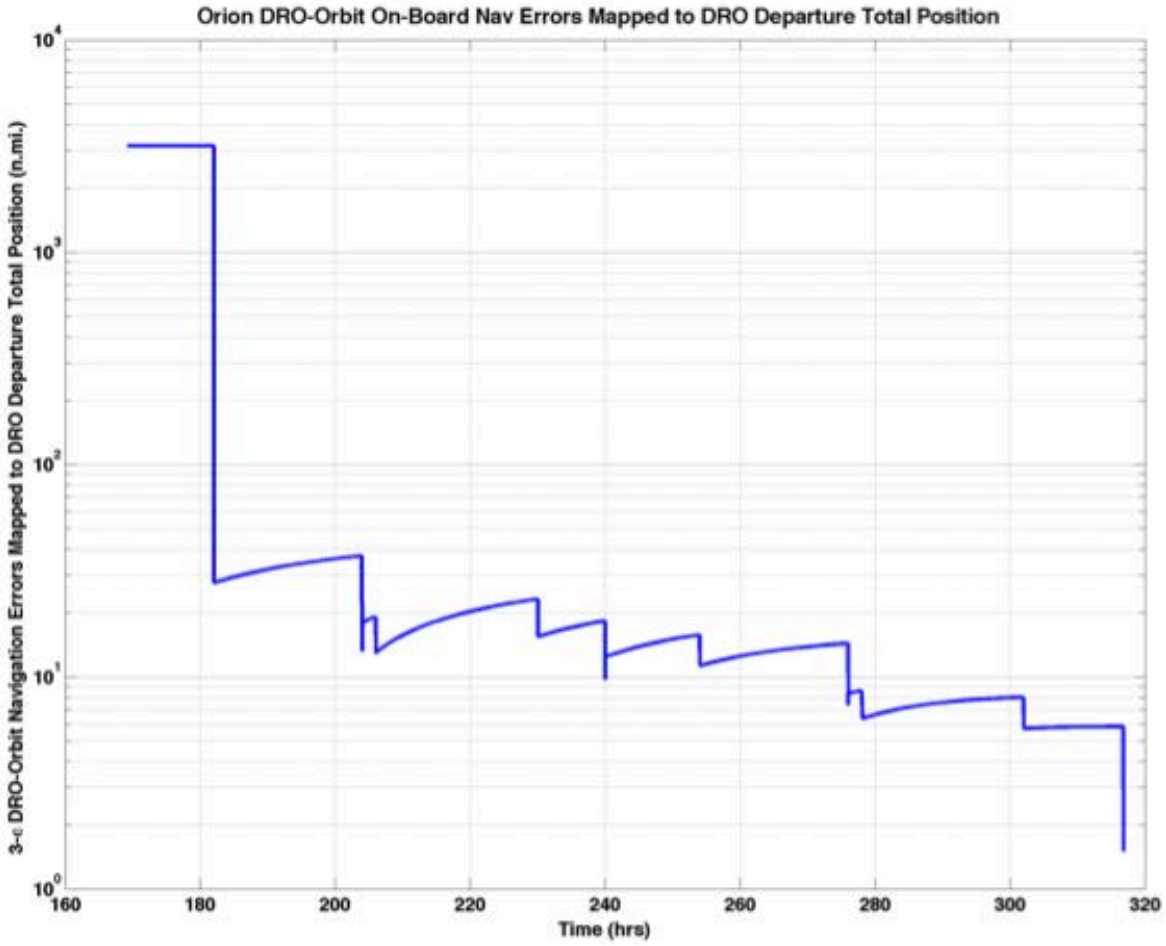
Trans-DRO Navigation Errors Mapped to DRO Insertion Position



Trans-DRO Dispersions Mapped to DRO Insertion Position



DRO Orbit Navigation Errors Mapped to DRO Departure Position



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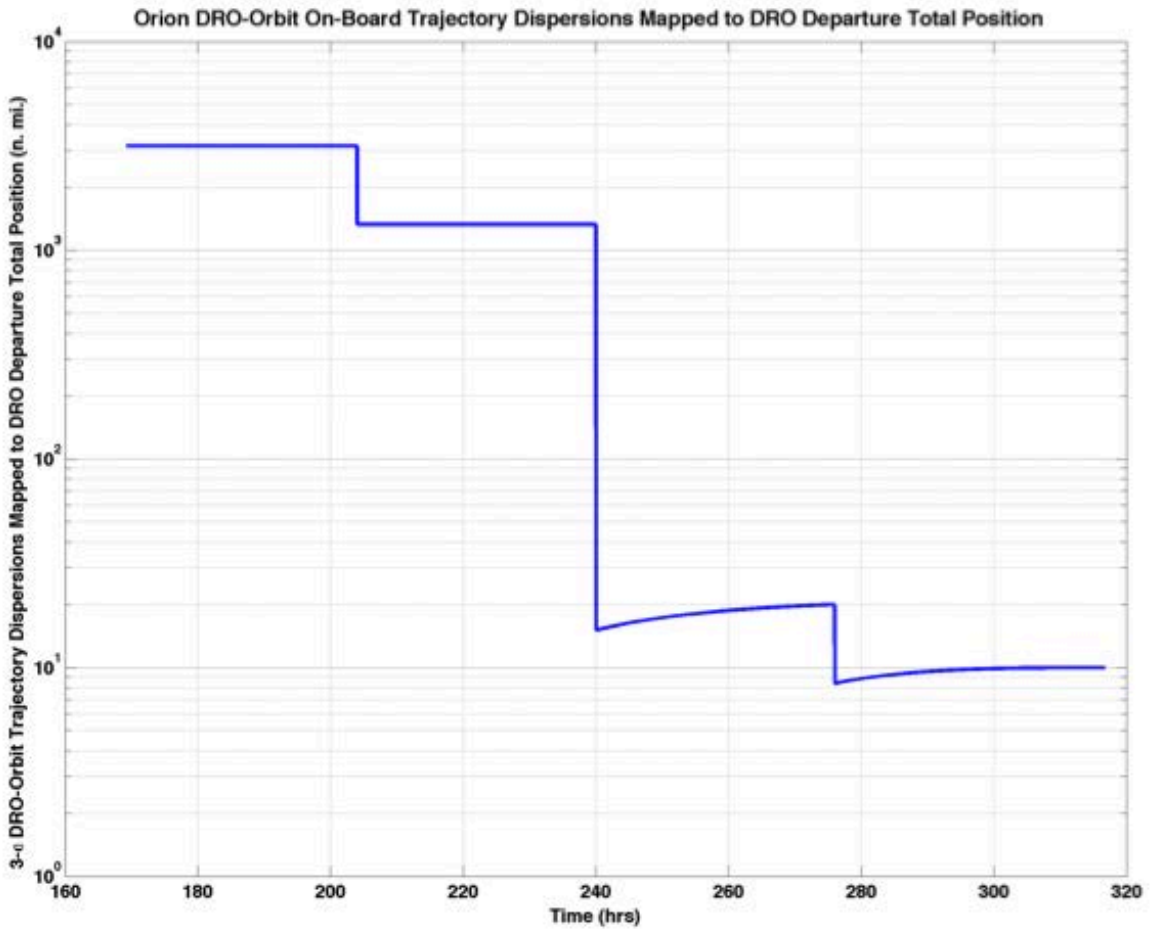
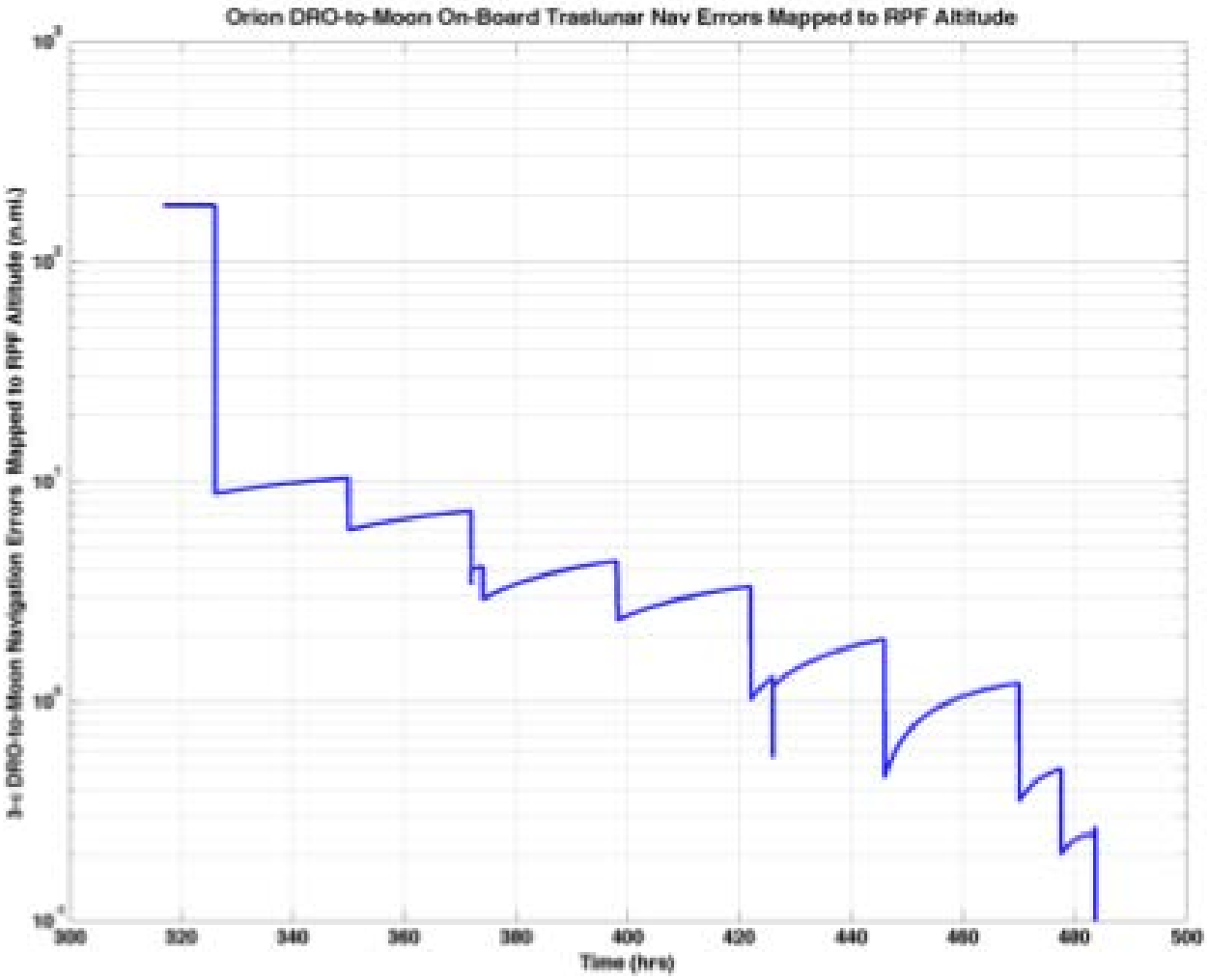
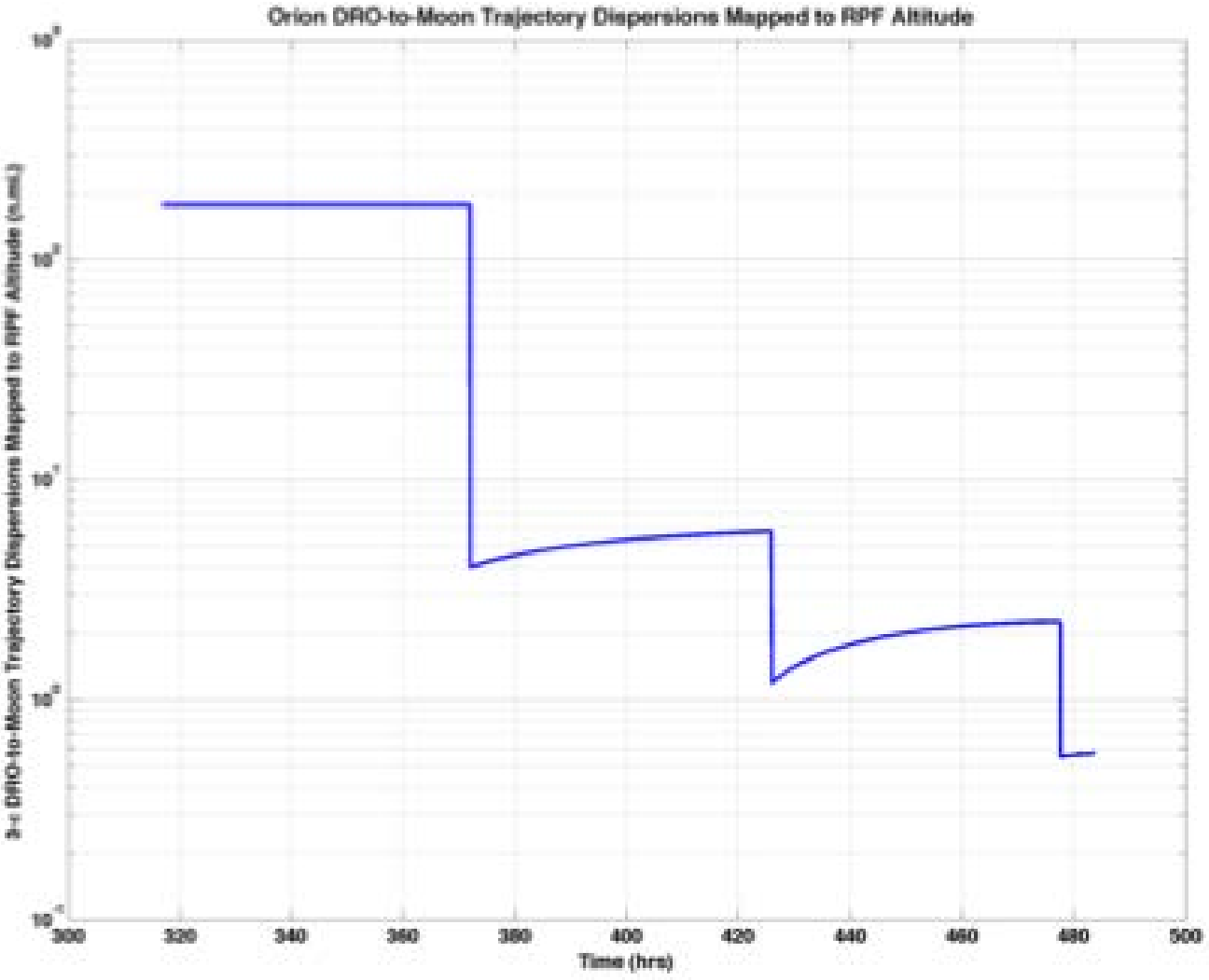


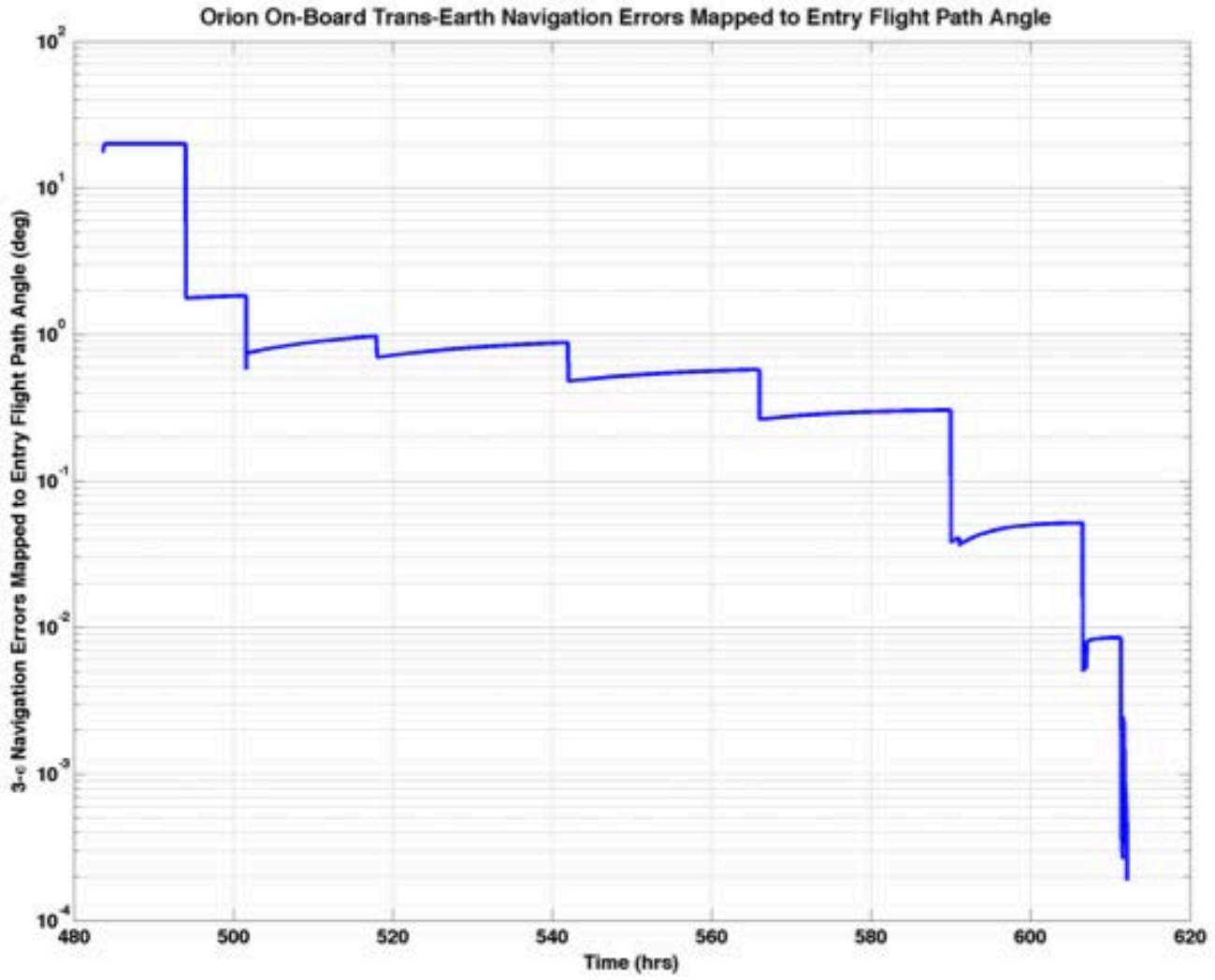
DRO-to-Moon Navigation Errors – Pericynthion Radius



DRO-to-Moon Trajectory Dispersions– Pericynthion Altitude



Trans-Earth Navigation Errors mapped EI Flight Path Angle Errors



Trans-Earth Dispersions mapped EI Flight Path Angle Errors

ΔV Usage -- Nominal Case (6 Ground Stations)

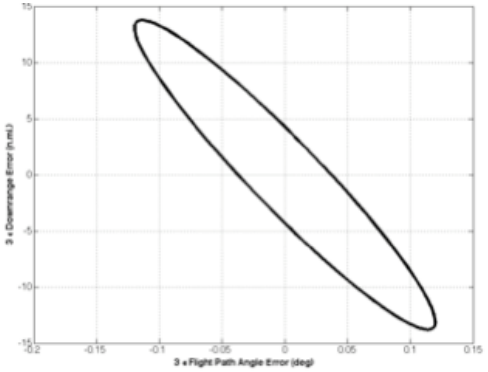
Maneuver #	Type	t_{ig} (hrs)	$\|\Delta\mathbf{V}\|_{nom}$ (ft/s)	$\mu_{\|\Delta\mathbf{V}\|}$ (ft/s)	$\sigma_{\|\Delta\mathbf{V}\|}$ (m/s)	$\|\Delta\mathbf{V}\|_{99.73}$ (ft/s)
1	OTC-1	6.81	0.000	13.357	8.811	46.666
2	OTC-2	25.81	0.000	0.208	0.107	0.574
3	OTC-3	81.60	0.000	0.463	0.207	1.170
4	OTC-4	97.60	0.000	0.791	0.376	2.133
5	OPF	103.60	572.627	572.714	1.888	578.728
6	OTC-5	122.41	0.000	4.214	3.084	15.377
7	OTC-6	144.00	0.000	1.680	1.070	5.533
8	DRI	169.21	797.479	797.478	0.122	797.805
9	OM-1	204.00	0.000	1.312	0.660	3.616
10	OM-2	240.00	0.000	0.688	0.332	1.870
11	OM-3	276.00	0.000	0.222	0.094	0.551
12	DRD	316.80	278.567	278.567	0.106	278.849
13	RTC-1	372.01	0.000	0.446	0.233	1.333
14	RTC-2	426.01	0.000	0.259	0.112	0.647
15	RTC-3	477.62	0.000	1.209	0.814	4.302
16	RPF	483.62	827.866	827.869	0.471	829.190
17	RTC-4	501.61	0.000	1.741	1.078	5.938
18	RTC-5	591.04	0.000	0.862	0.492	2.634
19	RTC-6	607.04	0.000	0.523	0.252	1.382
Total			**2476.539**	**2504.604**		**2578.300**

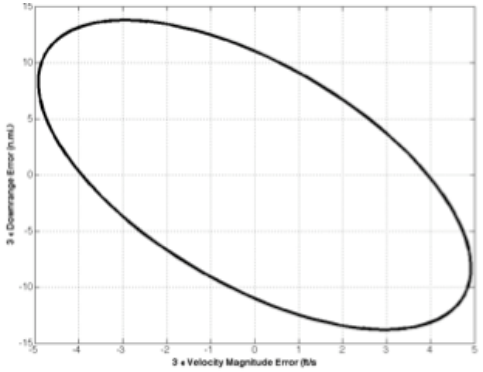
Entry Requirements

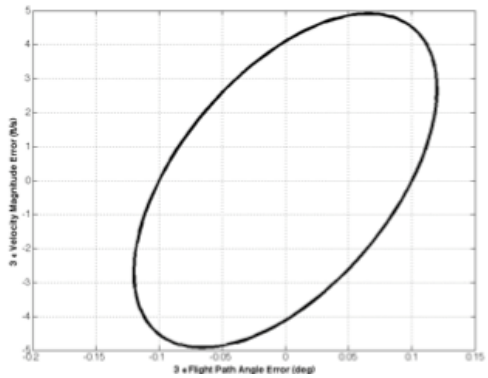
Allocated Requirement

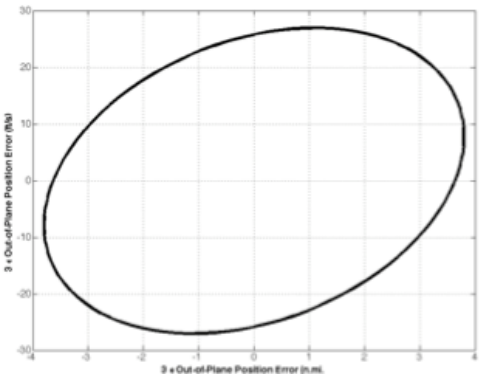
GNC.0463 EI Accuracy Nominal Return

GNC shall meet all requirements related to lunar return with the correlated dispersions at Entry Interface as given below





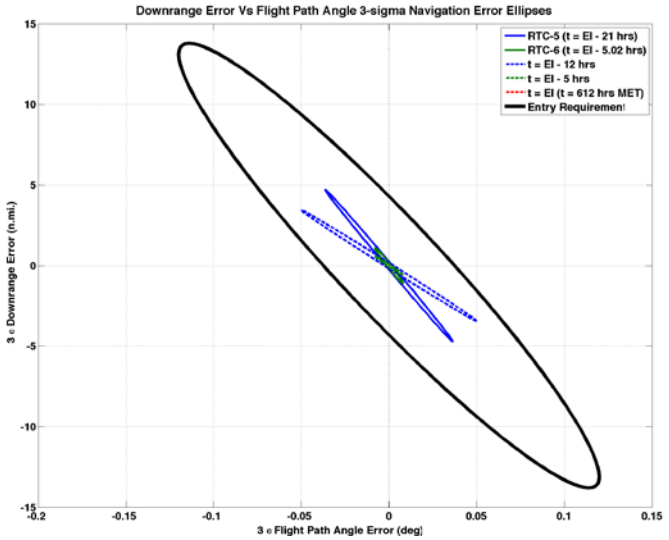


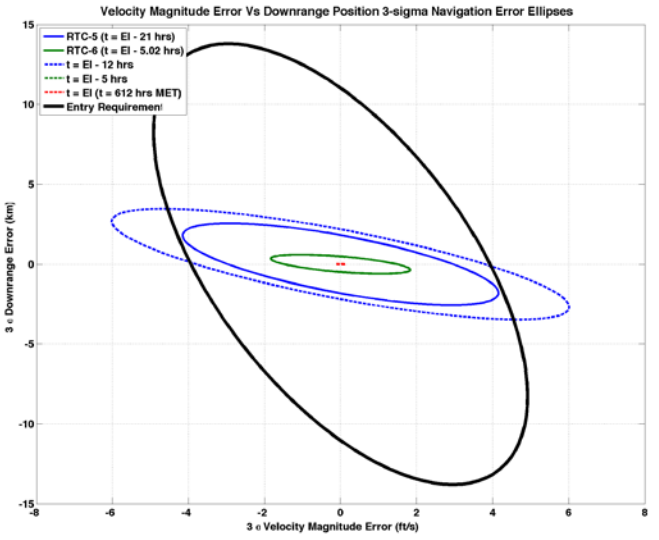


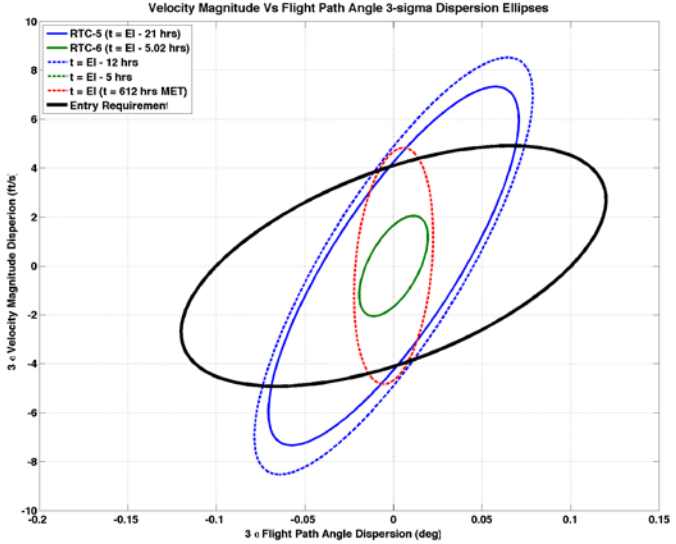
EI Parameter	Requirement (3σ)
Downrange Position	13.82 n.m.
Crosstrack Position	3.8 n.m.
Inertial Velocity Magnitude	4.92 ft/s
Flight Path Angle	0.12 deg
Crosstrack Velocity	27.0 ft/s

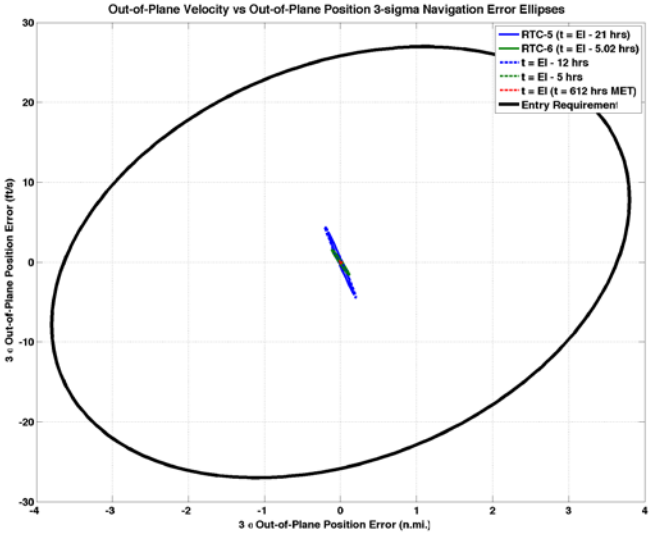
EI Parameters	Correlation Coefficient
Downrange Position / Flight Path Angle	-0.60
Downrange Position / Velocity Magnitude	-0.95
Velocity Magnitude / Flight Path Angle	0.55
Crosstrack Position / Crosstrack Velocity	0.29

Entry Interface Navigation Performance

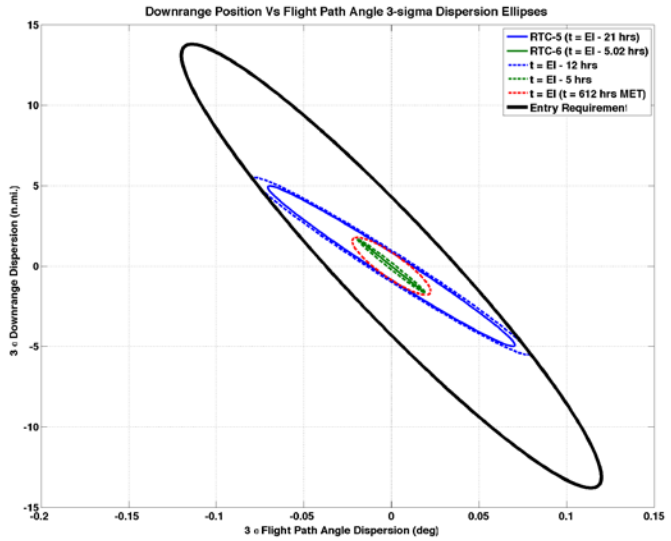


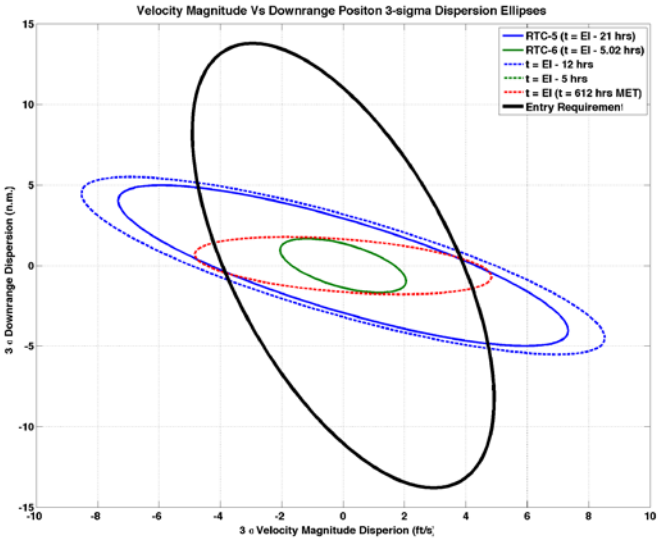


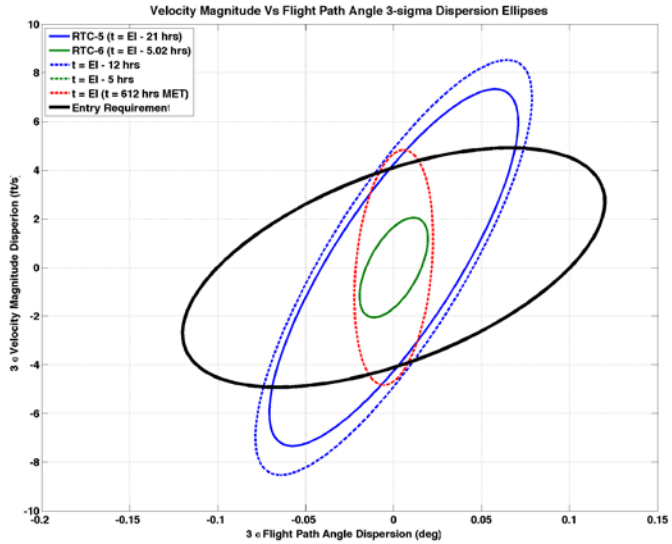


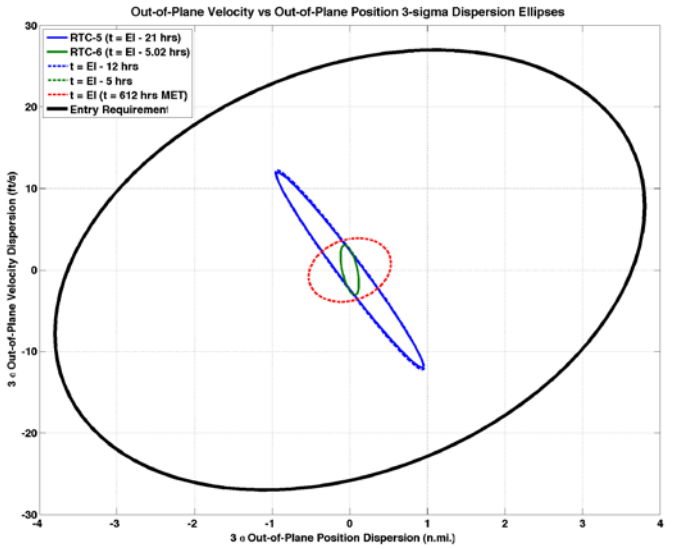


Entry Interface Trajectory Dispersions

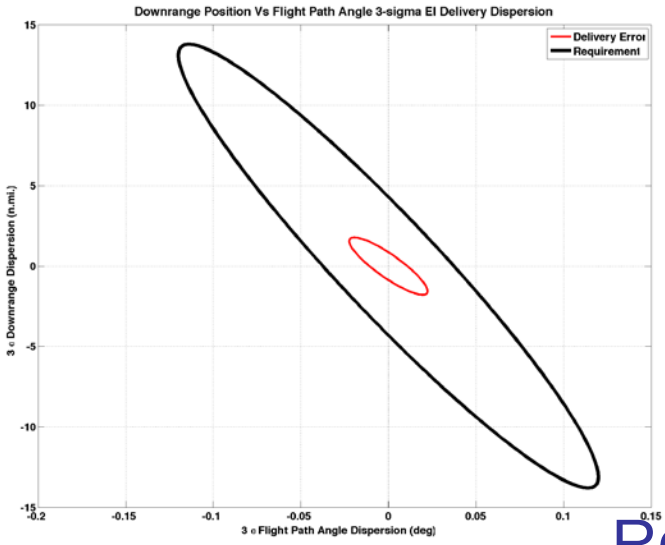


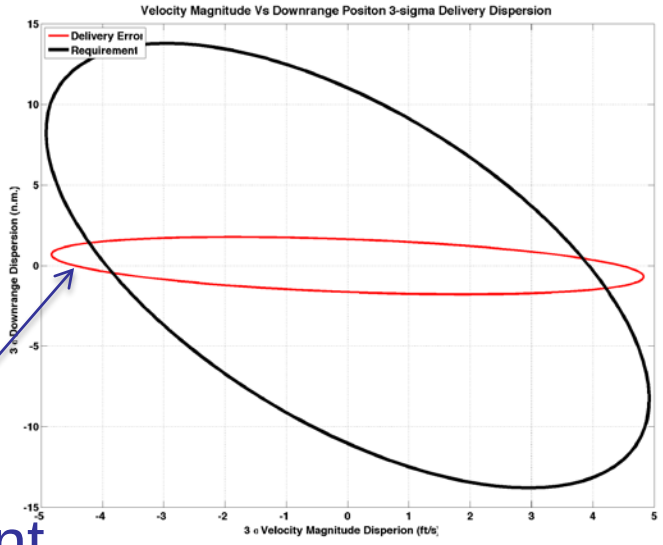




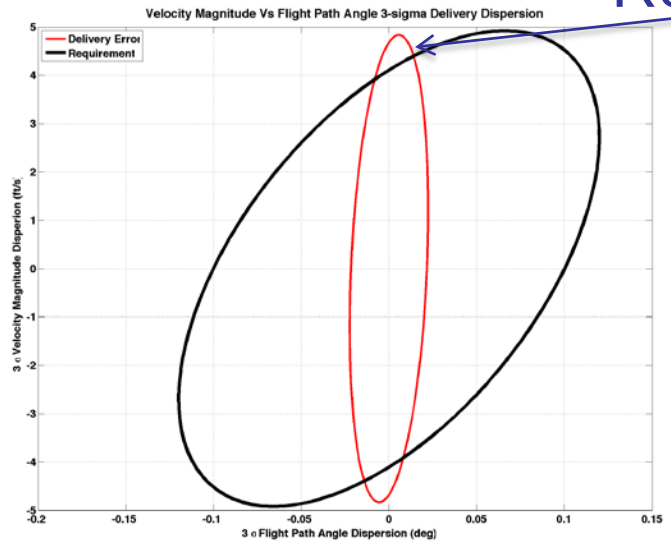


Entry Interface Requirement Compliance





Requirement Violation



Entry Interface Delivery Statistics

Type	Entry Interface 3σ Value
Latitude	0.0444 deg
Longitude	0.0097 deg
Flight Path Angle	0.0199 deg
Heading Angle	0.0286 deg

Type	PASS / FAIL	Margin
Downrange Position Vs Flight Path Angle	PASS	220.8044
Velocity Magnitude Vs Flight Path Angle	FAIL	-15.5571
Velocity Magnitude Vs Downrange Position	FAIL	-20.0120
Velocity Magnitude Vs Flight Path Angle	PASS	621.5096

Variation in the Number of Ground Navigation Stations

				6 Ground Stations	3 Ground Stations	9 Ground Stations
Man #	Type	t_{ig} (hrs)	$\|\Delta\mathbf{V}\|_{nom}$ (ft/s)	$\|\Delta\mathbf{V}\|_{99.73}$ (ft/s)	$\|\Delta\mathbf{V}\|_{99.73}$ (ft/s)	$\|\Delta\mathbf{V}\|_{99.73}$ (ft/s)
1	OTC-1	6.81	0.000	46.666	46.666	46.666
2	OTC-2	25.81	0.000	0.574	0.574	0.574
3	OTC-3	81.60	0.000	1.170	1.171	1.169
4	OTC-4	97.60	0.000	2.133	2.128	2.128
5	OPF	103.60	572.627	578.728	578.638	578.361
6	OTC-5	122.41	0.000	15.377	15.804	15.089
7	OTC-6	144.00	0.000	5.533	5.723	5.400
8	DRI	169.21	797.479	797.805	797.811	797.804
9	OM-1	204.00	0.000	3.616	3.618	3.616
10	OM-2	240.00	0.000	1.870	1.875	1.870
11	OM-3	276.00	0.000	0.551	0.553	0.544
12	DRD	316.80	278.567	278.849	278.850	278.848
13	RTC-1	372.01	0.000	1.333	1.332	1.334
14	RTC-2	426.01	0.000	0.647	0.666	0.639
15	RTC-3	477.62	0.000	4.302	4.322	4.291
16	RPF	483.62	827.866	829.190	829.189	829.190
17	RTC-4	501.61	0.000	5.938	5.938	5.939
18	RTC-5	591.04	0.000	2.634	2.638	2.633
19	RTC-6	607.04	0.000	1.382	1.393	1.378
Total			**2476.539**	**2578.300**	**2578.889**	**2577.472**

Variation in the Number of Ground Navigation Stations

EI Delivery Error	6 Ground Stations	3 Ground Stations	6 Ground Stations
Latitude (3σ)	0.044°	0.047°	0.044°
Longitude (3σ)	0.010°	0.010°	0.010°
Flight Path Angle (3σ)	0.020°	0.021°	0.020°
Heading Angle (3σ)	0.029°	0.030°	0.028°

Type	Nominal Case	3 Ground Stations	9 Ground Stations
Downrange Position Vs Flight Path Angle	220.804	209.520	222.977
Velocity Magnitude Vs Flight Path Angle	-15.557	-23.512	-14.523
Velocity Magnitude Vs Downrange Position	-20.012	-28.823	-18.849
Crossrange Positon Vs Crossrange Velocity	621.510	598.443	625.797

Variation in the Vehicle Noise

EI Delivery Error	Nominal	SM/CM Sublimator Noise	Quiescent Sublimator Noise
Latitude (3σ)	0.044°	0.043°	0.042°
Longitude (3σ)	0.010°	0.004°	0.002°
Flight Path Angle (3σ)	0.020°	0.017°	0.016°
Heading Angle (3σ)	0.029°	0.026°	0.026°

Type	Nominal Case	SM/CM Noise	Quiescent Noise
Downrange Position Vs Flight Path Angle	220.804	419.469	499.159
Velocity Magnitude Vs Flight Path Angle	-15.557	59.293	116.517
Velocity Magnitude Vs Downrange Position	-20.012	51.533	103.562
Crossrange Positon Vs Crossrange Velocity	621.510	910.442	949.406

Conclusions

- **The Orion EM-1 DRO Mission poses challenges on just about every front of GNC**
- **The Entry Interface Delivery Requirements are particularly stressful**
  - Flight Path Angle
  - Velocity Magnitude
- **The mission, as currently planned, is violating the Entry Interface Delivery Requirements**
  - The delivery requirement for velocity magnitude is 1.5 m/s (3σ)
  - This is particularly significant in light of the fact that the entry velocity is 11 km/s
- **Ammonia Sublimator Vent is critical to meeting Flight Path Angle Constraints**
  - Particularly for optical navigation (contingency)
- **We're sharpening our pencils**