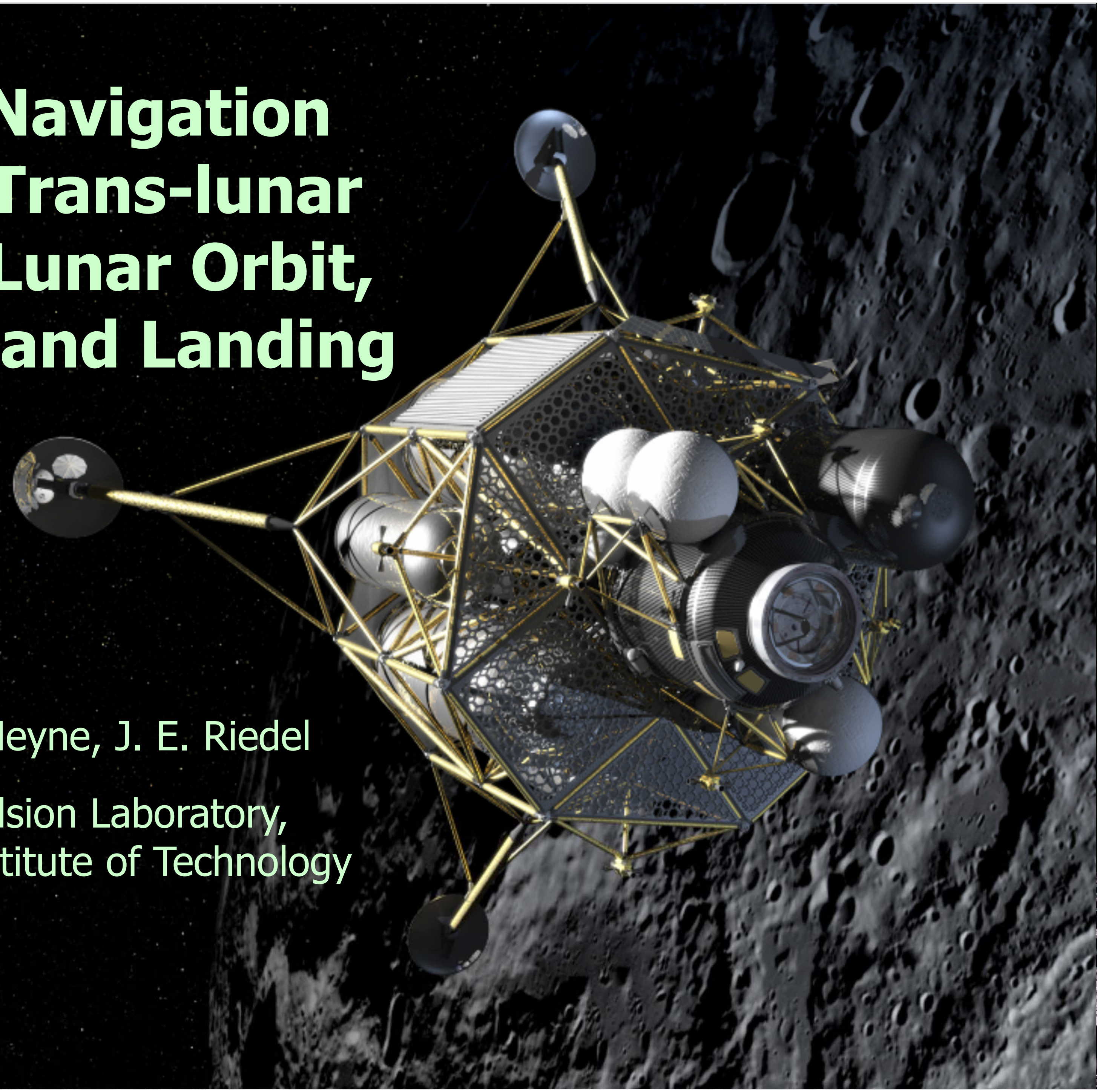
Altair Navigation during Trans-lunar Cruise, Lunar Orbit, Descent and Landing



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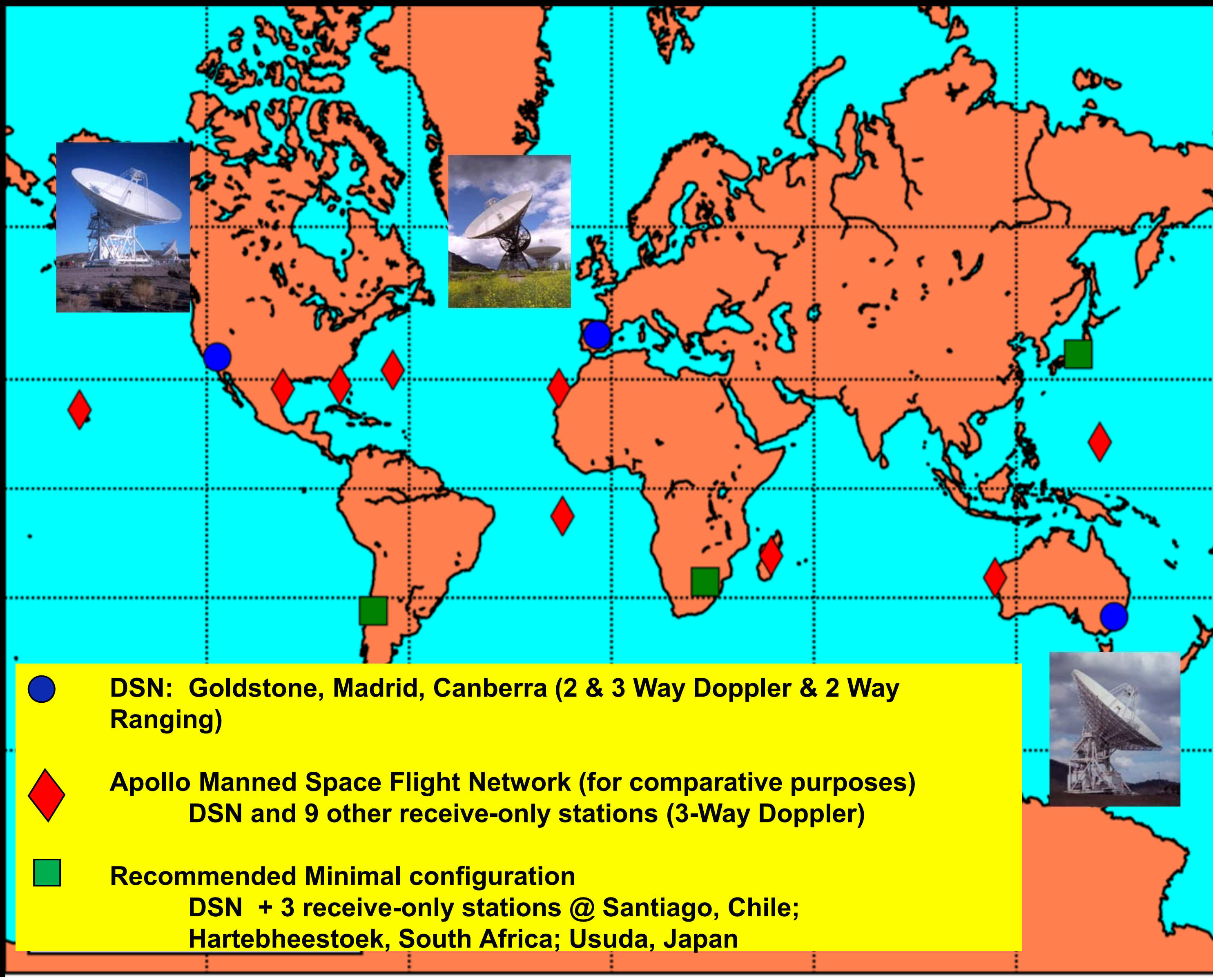
Altair Key Navigation Requirements

- Perform navigation and attitude determination beginning with Earth orbital operations through Altair disposal.
- Land < 100 (TBR) m of a designated landing point on the lunar surface for Lunar Outpost Missions.
- Land < 1 (TBR) km of a designated landing point on the lunar surface for Lunar Sortie Missions.
- Return the crew to Orion independent of communications with Mission Systems.
  - Related parent requirement: Return the crew to the Earth surface independent of communications with Mission Systems during all mission phases.
- *Results in both capable ground-based and on-board navigation systems*

Altair Navigation Plan

- **Ground based navigation includes orbit determination (OD) using the Earth-Based Ground System (EBGS) radiometric tracking data (S-band 2-Way range and 2/3-Way Doppler) and nominal maneuver design.**
  - **State vector updates will be uplinked frequently (frequency is TBD but could be every few minutes up to an hour) and prior to critical events**
  - **Maneuver information (burn times, magnitudes, and quaternions) will be computed on the ground and uplinked to Altair**
- **On-board navigation will include**
  - **OD using:**
    - Uplinked ground state vectors during all flight phases
    - Passive optical tracking of lunar landmarks (a.k.a. TRN) during all flight phases and, potentially, artificial Earth satellites during Trans Lunar Cruise
    - IMU during maneuvers, descent, and ascent
    - Radar altimetry and velocimetry during descent
    - Terrain Hazard Detection and Avoidance (i.e., ALHAT) during descent – *not discussed in this presentation*
    - Lidar and docking camera during rendezvous, proximity operations, and docking (RPOD)
  - **A trajectory and maneuver design function for use in an abort or more serious loss of comm with the subsequent need to return 'home' safe (which includes both return to Earth or dock with Orion).**

Earth Based Ground System

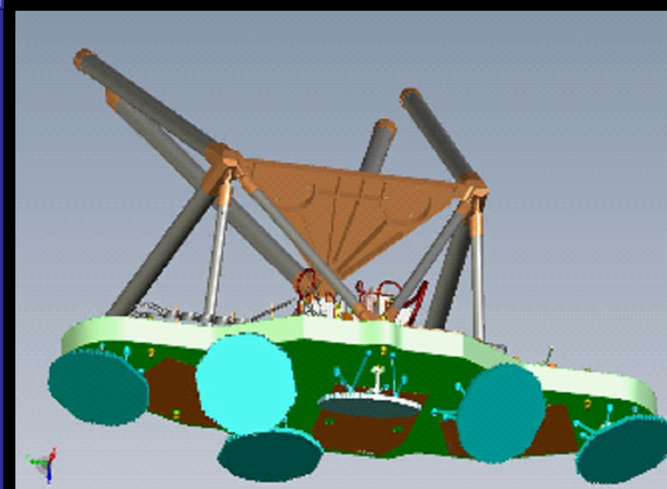


Accelerometer & Radar Altimeter Velocimeter

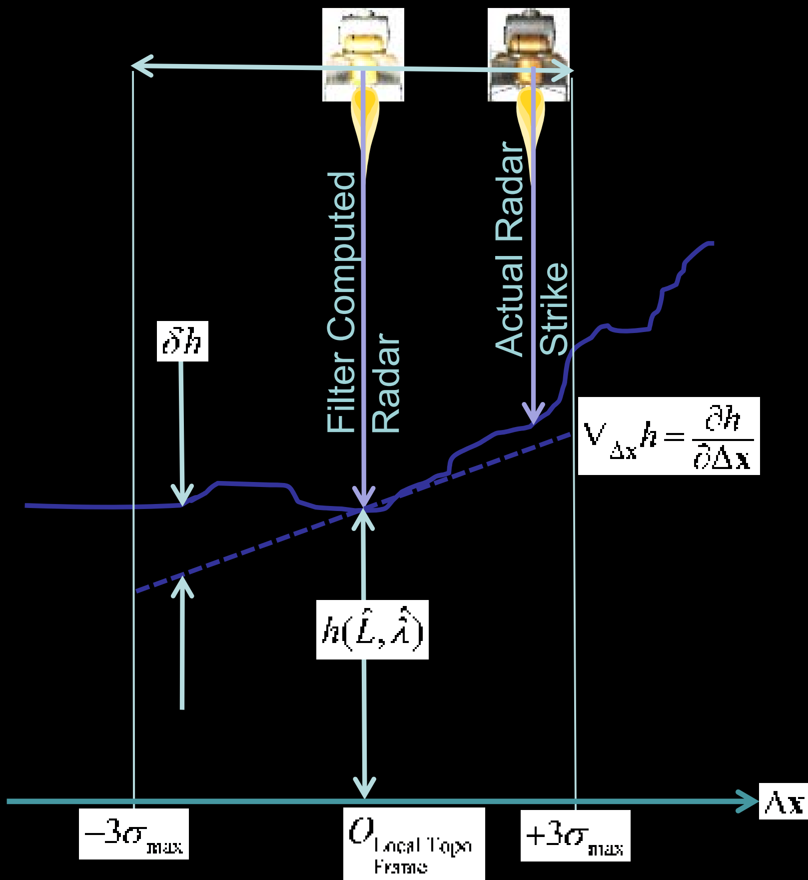
Accelerometer Component	Error Levels (1σ)	Model
Initial Alignment	50 arcsec	Random Bias
Scale Factor	150 ppm	ECRV τ = 2 hr
Bias Error	28 μg	ECRV τ = 2 hr
Attitude Error*	1.3 mrad (attitude	ECRV τ = 5 sec
Velocity Random Walk	1.3E-5 m/s/sqrt(s)	Random Walk

* Navigation Simulation is 3 DOF + prescriptive attitude with attitude error modeling at prescribed levels

Component	Altimeter (1σ) Operates < 20 km Altitude	Velocimeter (1σ) Operates < 210 m/s	Model
Scale Factor	0.1 m	0.01 m/s	ECRV τ = 100 s
Bias Error	0.001	0.0013	ECRV τ = 100 s
Noise	2% of range	0.16 m/s	
Terrain Error	See next chart	Not Req	

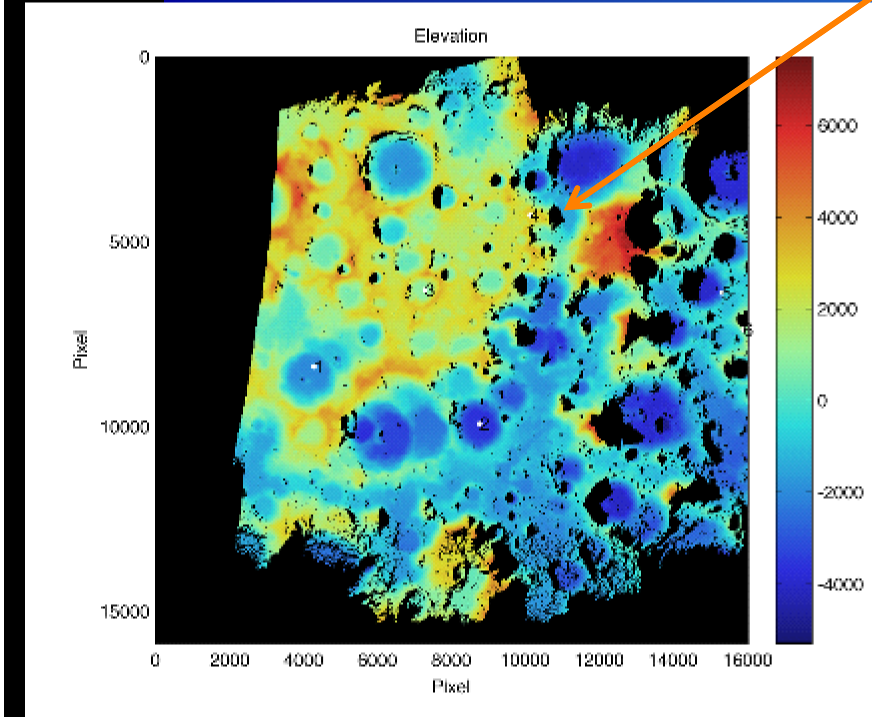


Terrain Stochastic Error Modeling in the Filter
1-D Illustration

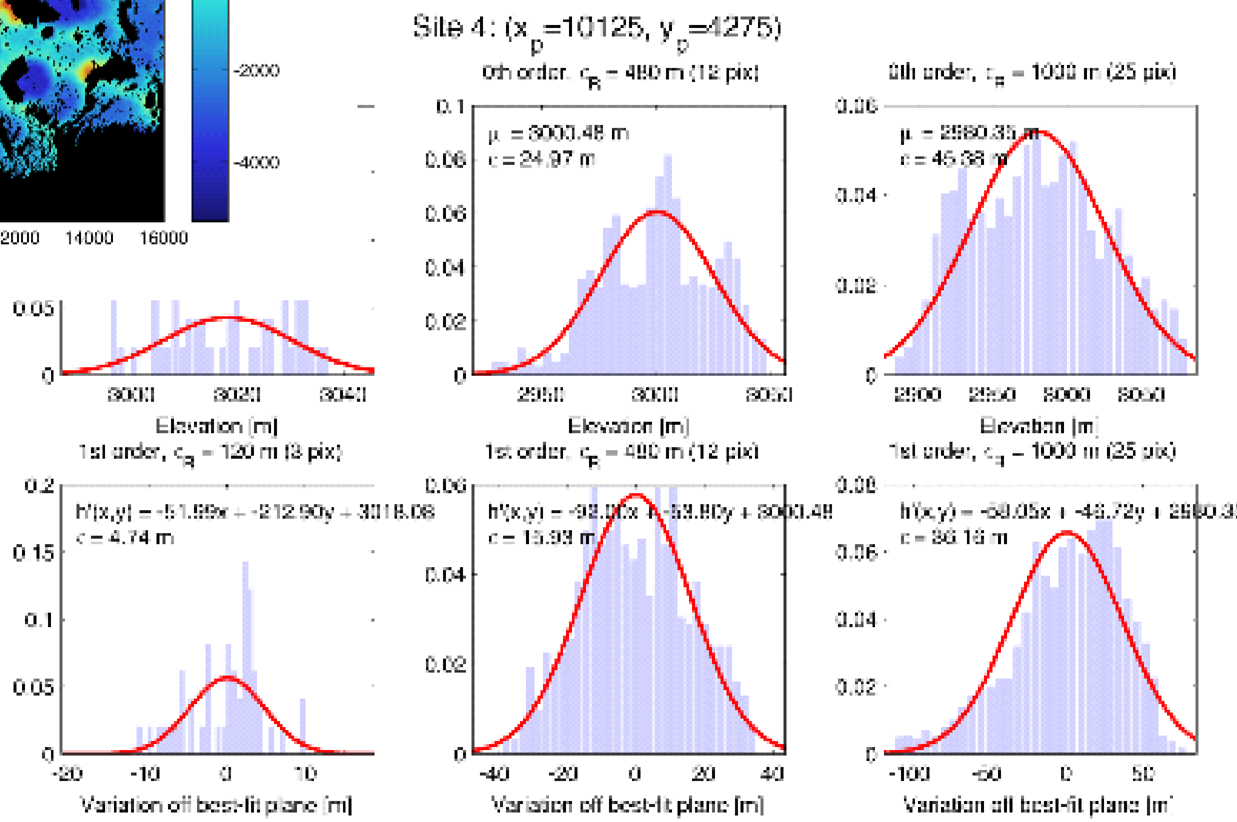


- The actual radar strike hits the ground at a spot that is different then where the filter thinks it hit
  - Since we are not terrain matching with the altimetry data (we are with the OpNav data) need to deweight altimeter measurement with stochastic altitude variations within the current Altair position uncertainty
  - Flight software needs to interrogate the DEM to form these statistics as a function of current position

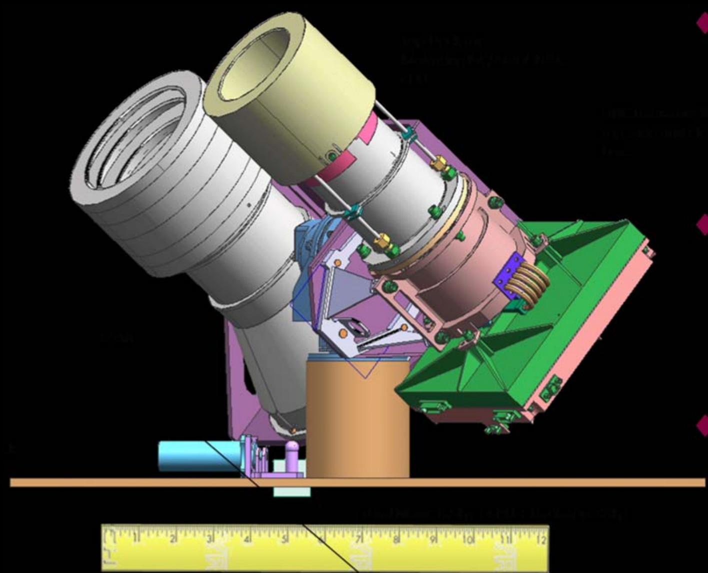
Example Terrain Statistics – A Rough Spot



- For results shown later *static* statistic selected to drive the terrain stochastic model with a 36 m (1s) noise uncertainty and a 40 m correlation distance (a measure of surface roughness). Real time terrain statistic calculation currently being integrated into simulation.



Optical Navigation



- Gimbaled passive optical cameras image the surface using the Optical Navigation Sub-system (ONSS).
  - Landmarks are identified and compared to a pre-loaded digital elevation map (DEM).
  - 10 – 15 landmarks identified in each picture form (line/pixel) measurements that are processed by the navigation filter

- Trans Lunar Cruise (TLC) Picture Schedule:
  - Narrow Angle Camera (NAC) images every 10 minutes.
  - Wide Angle Camera (WAC) images every 10 minutes beginning at 1 day prior to LOI
- Low Lunar Orbit (LLO) Picture Schedule
  - NAC images every 10 minutes until 20 km altitude
  - WAC images every 10 minutes until DOI, 20 seconds until 5 min - PDI, every 5 seconds until landing
- Nadir pointed until 2 km away from landing target, then point to target
  - TLC: Point error at 2.5 μrad (1σ) using background stars
  - LLO: Standard attitude error at 1.3 mrad (1σ)
- Camera Image Noise
  - 0.1 pixels (1-sigma) for both the NAC and WAC
- Landing Target Estimation
  - When imaged estimate landing site and 4 other landmarks around site with an initial uncertainty of 100 m
  - Other landmarks are in error due to map tie and DEM resolution errors
- Map Tie Error
  - 2 km away from landing: 150 m (1 sigma) with a 5 km correlation
  - Within 2 km of landing: 2.5 m white noise
- DEM resolution
  - 25 m (1 sigma) globally, 2.5 m within 5 km of landing site

Key Trajectory Error Sources

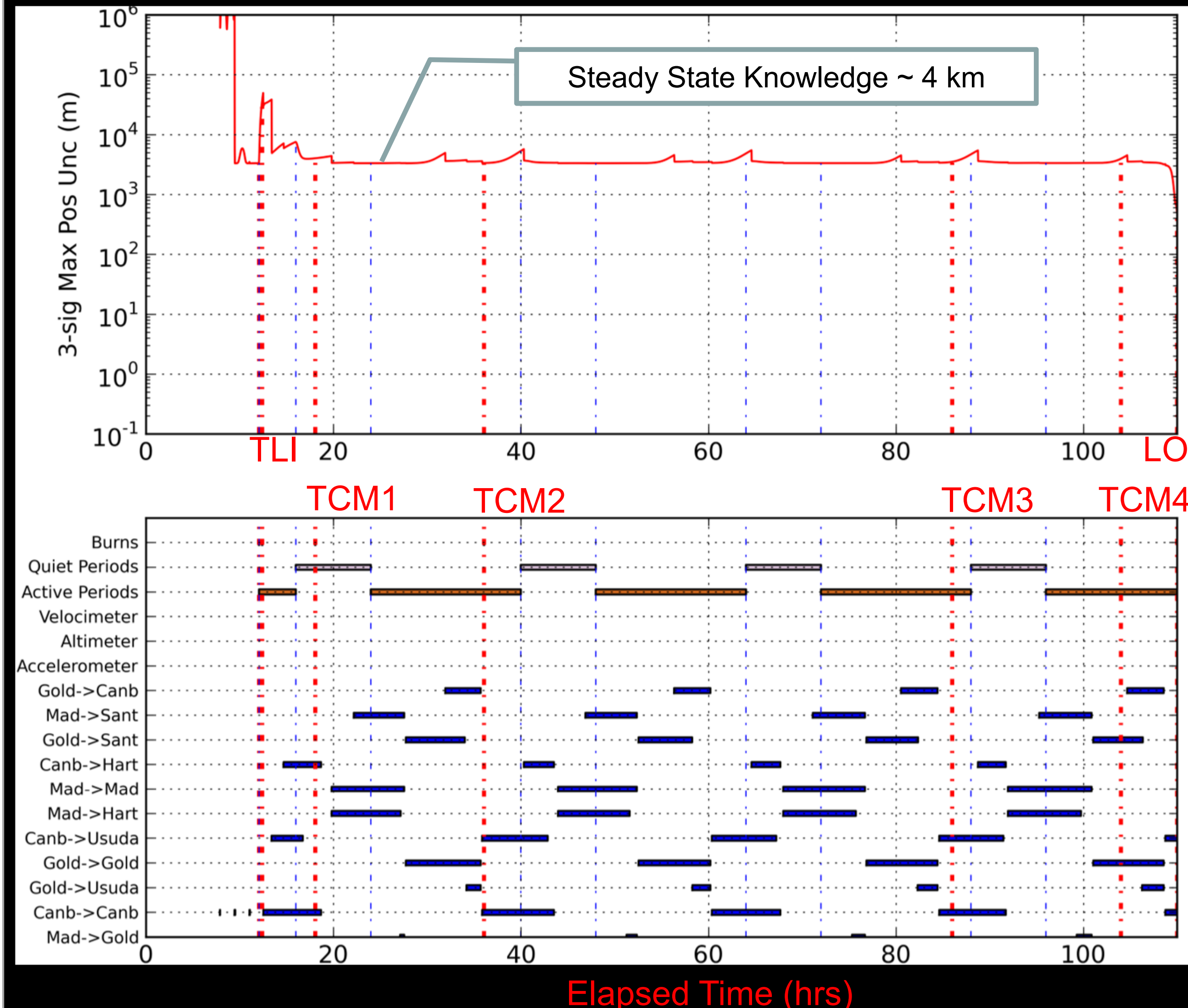
- **FLAK = un-Fortunate Lack of Acceleration Knowledge**
  - **Non-gravitational "environment" accelerations, examples include**
    - RCS firings (even 'coupled' jets contribute)
    - PSA vents (6 times / hour) to actively condition the cabin atmosphere
    - Wastewater vents (max 8 per day)
    - Sublimator (as needed for active thermal control)
  - **FLAK is a driving contributor to navigation performance – yields about an order of magnitude error over other error sources**
  - **During Apollo this error contributed 500 m dispersions per every ½ orbital rev**
    - During any given day active levels (500 m) scheduled for 16 hrs, and quiet levels during the remaining crew-sleep periods
    - Current vehicle models being investigated
  - **Currently modeled as a 1st-order Gauss-Markov process, however more likely a shaped Poisson process (accounts for random, discrete execution times).**
- **Maneuver execution errors**
  - **Along with FLAK, contribute directly to trajectory dispersions**
  - **During operations, observable via Doppler tracking and confirmed using IMU tracking**

Other Navigation Error Sources

- **Dynamic modeling errors**
  - **Earth/Moon spherical gravity**
  - **Earth/Moon non-spherical gravity error during TLC and LLO**
    - Anticipated GRAIL simulated gravity field knowledge diminishes current error of hundreds of meters of to 10 m or less. With this result, gravity errors in are not modeled in these phases.
  - **Earth/Moon non-spherical gravity field truncation error during Powered Descent**
    - Initial studies using an onboard 25x25 field add several hundred meters to the landing dispersion when using only the IMU/Altimeter, use of a 100x100 field reduced this to a few 10's of meters. The 100 x 100 field is assumed and truncation errors are modeled as a 1st order Gauss-Markov process.
  - **Earth/Moon ephemeris errors consistent with the current DE421 uncertainties**
- **Other modeling errors including**
  - **Atmospheric delays (ionosphere and troposphere)**
  - **Earth orientation errors and prime meridian location (i.e., UT1 timing)**
  - **EBGS station location errors**

TLC EBGS Radiometrics-Only Results

TLI – 12 hrs to LOI

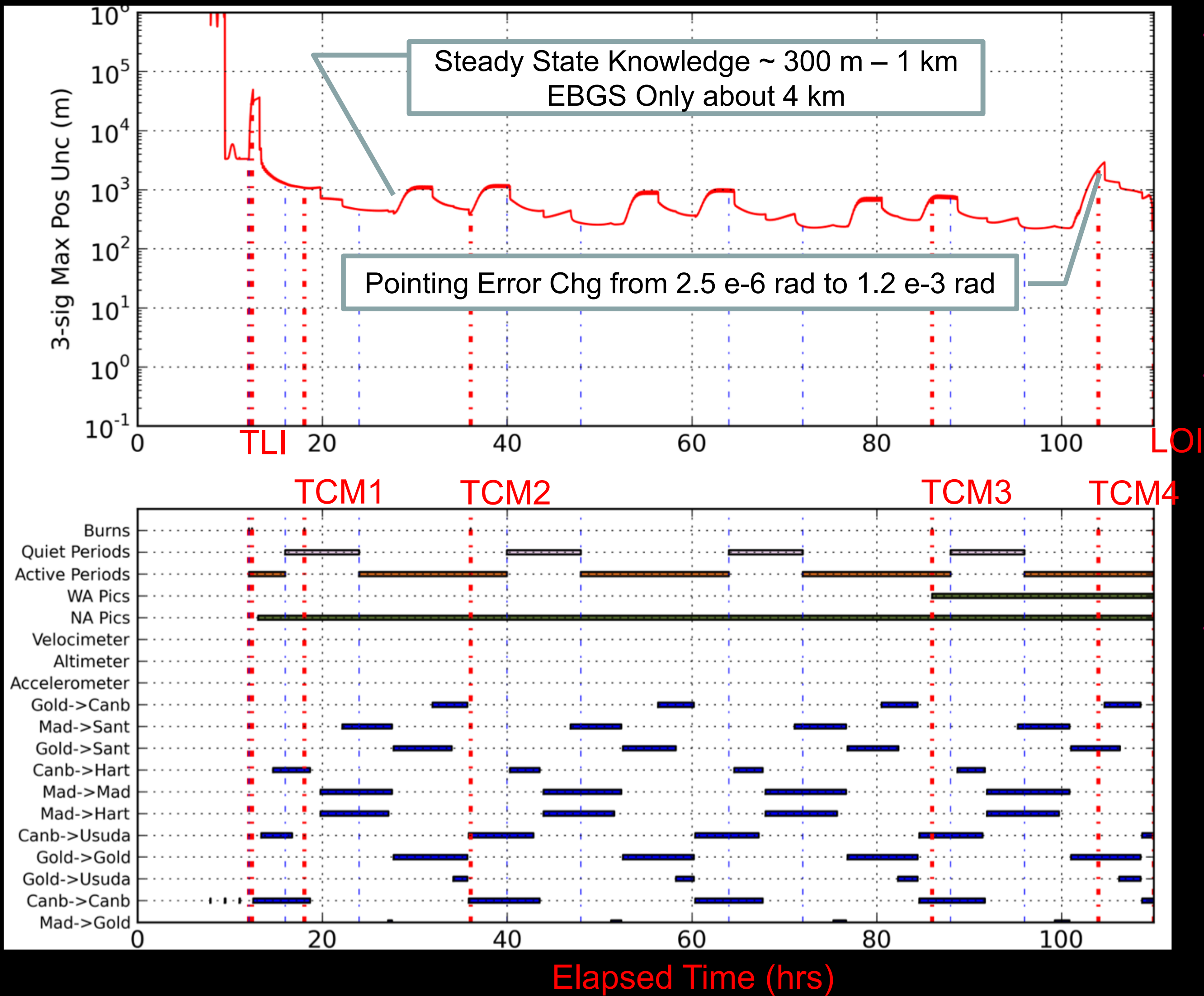


TCMs	Mean + 3σ (m/sec)
TCM 1	21.6
TCM 2	2.0
TCM 3	3.6
TCM 4	2.7
LOI-Clean Up	6.9
Total (Sum of Means + RSS of 3σ)	29.0

Nominal LOI *Perilune Altitude = 100 km*	**3σ (km)**
LOI Perilune Altitude Delivery Error	12.2

TLC EBGS Radiometrics + OpNav Results

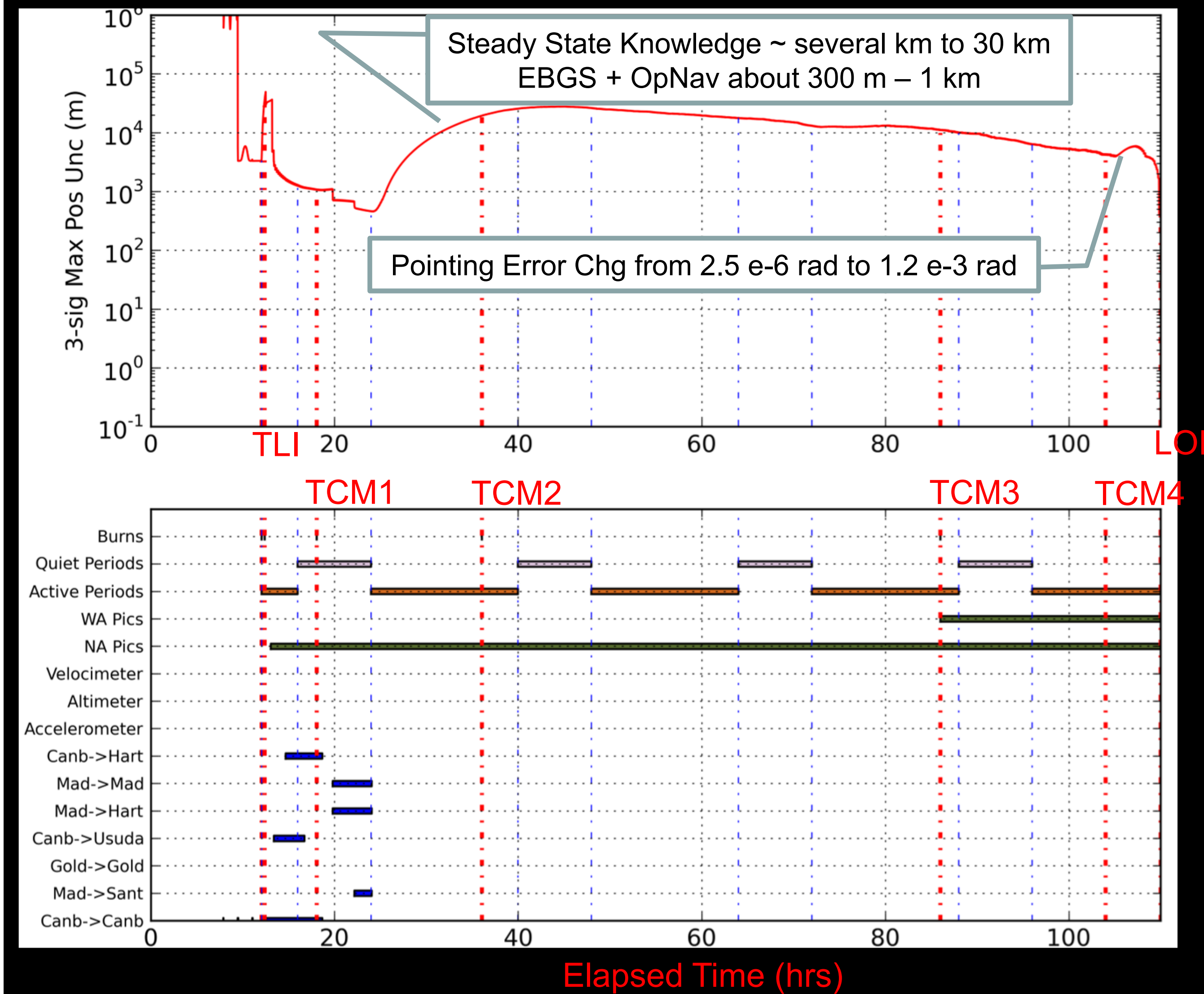
TLI – 12 hrs to LOI



- TCM total delta v requirement largely unaffected by addition of OpNav – goes from 29.0 m/s to 28.96 m/sec
- LOI perilune altitude delivery error improves a little from 12.2 km to 11.7 km
- Primary impact is improvement of trajectory knowledge throughout most of TLC – from about 4 km to better than 1 km

Loss of Comm Scenario

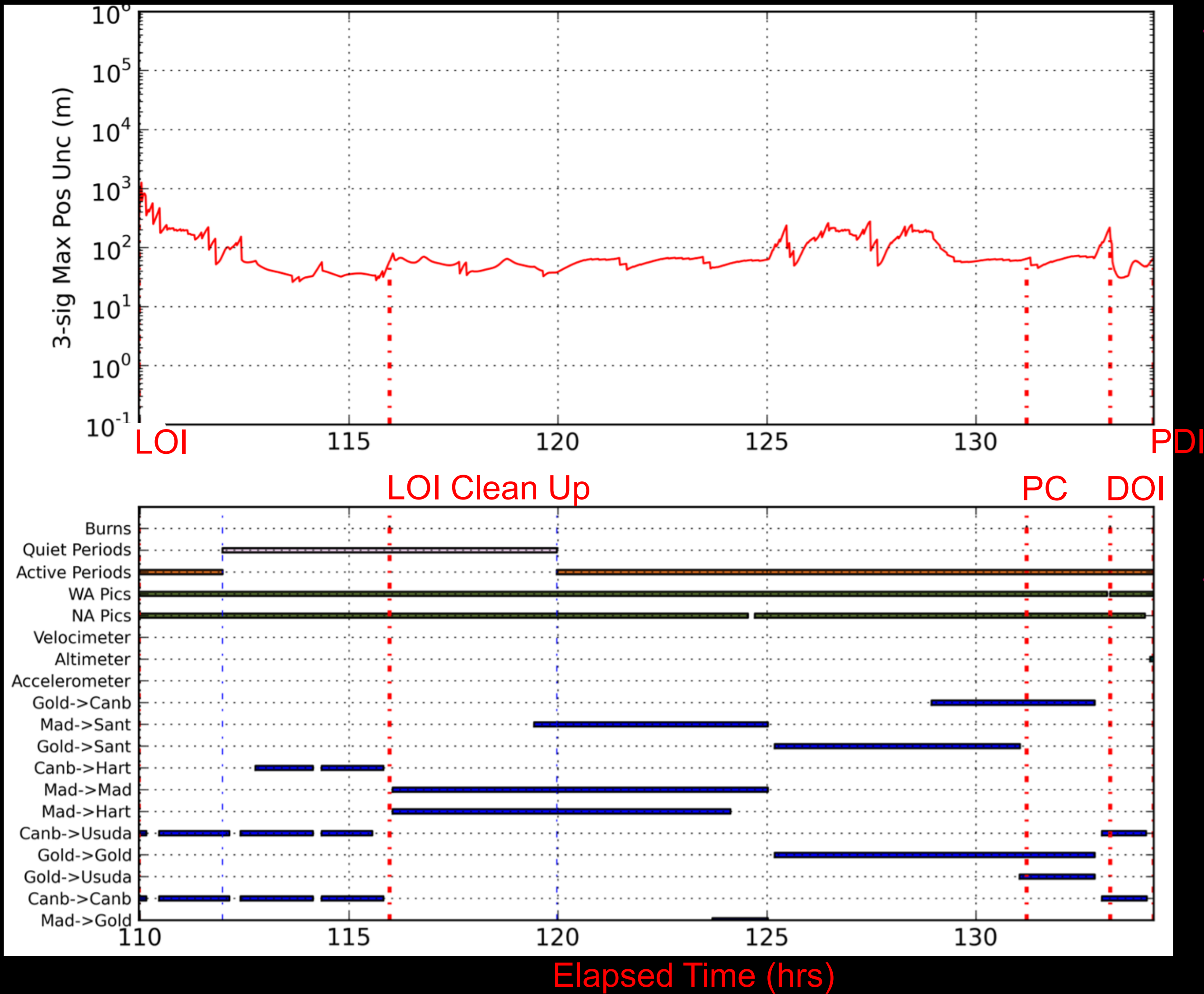
TLI – 12 hrs to LOI



- Sample loss of mission support scenario where the tracking outage occurs 12 hrs after TLI.
- Loss of trajectory knowledge due to imaging distant lunar landmarks
  - Possible mitigation strategy is to image Earth orbiting satellites in 1st half of TLC
- Even with loss of trajectory knowledge LOI altitude dispersion degrades only marginally from 12.2 km to 12.3 km
- TCM budget increases significantly from 29 m/s to ~ 79 m/s

LLO and De-Orbit Nominal Results

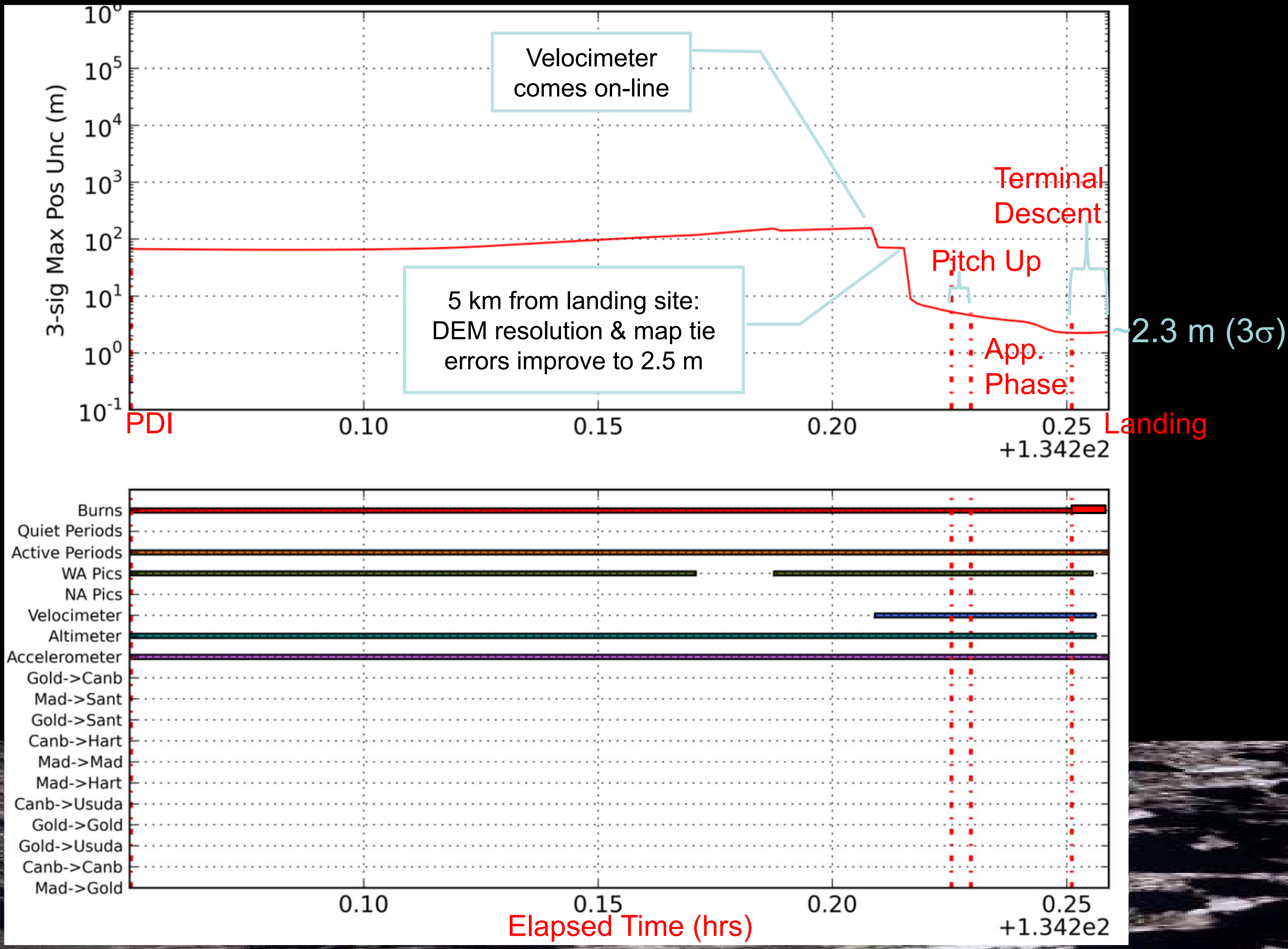
LOI to PDI



- Position and velocity knowledge range between 50 m to 400 m (3 sig) and 0.05 m/s to 0.7 m/s
  - Larger uncertainties occur when Earth-based tracking is sparse (c.f. period with only a 2-Way station and a single 3-Way station).
- Delivery altitude error to PDI is 1.05 km (3 sig) – FLAK is the key factor contributing to this error. Sensitivity to FLAK and tracking architecture shown next

Landing Nominal Results (Nav-Only)

PDI to Landing



Preliminary Landing Dispersions (Nav-Only)

Nominal, Minimal, and Failure Cases

Configurations	3 Position Uncertainty (m)		3 Velocity Uncertainty (m/s)	
	Horizontal	Vertical*	Horizontal	Vertical
Nominal Configuration (IMU, Altimeter, Velocimeter, OpNav)	2.9	2.0	0.07	0.05
Minimal Configuration (Nominal without OpNav)	124.3	8.7	0.07	0.05
Failure Cases (from the Nominal Configuration)				
State Update Fails at DOI	2.9	2.0	0.07	0.05
Velocimeter Fails at Terminal Descent	3.9	2.8	0.12	0.11
Altimeter & Velocimeter Fail at Pitch-Up	12.3	9.3	0.24	0.25
Velocimeter Fails at Pitch-Up	13.0	9.6	0.25	0.27
Altimeter & Velocimeter Fail	13.5	9.1	0.27	0.26
OpNav Fails at Pitch-Up	91.4	6.3	0.07	0.05
OpNav, Altimeter, Velocimeter Fail at Pitch-Up (IMU-only during approach and terminal descent)	95.5	33.0	0.45	0.54
OpNav, Altimeter, Velocimeter Fail at PDI (IMU-only during entire descent phase)	848.7	1068.0	1.34	2.04

* Changing altimeter terrain stochastic error model to real time calculation (versus current static model) will yield significant improvements in altitude uncertainties when altimetry is present.

Conclusions

- Sufficient performance is achieved with a navigation architecture that is more robust than provided by the current DSN-alone
  - The recommended 6 station EBGS configuration coupled with a capable gimbaled OpNav system on board Altair is needed to meet acceptable TCM allocations and lunar orbit insertion delivery bounds
  - OpNav necessary for safe return to Orion/Earth in the event of loss of Earth ground support
- OpNav enables precision landing (< 100 m) and ensures that the on-board nav system is robust/fault tolerant
  - Combination of OpNav and velocimetry necessary to meet contemplated precision landing requirement for outpost – may reduce to ~ 18 m (from 100 m) to accommodate 50 m diameter landing berms
- Minimal configuration with altimetry and 3-axis velocimetry sufficient to meet the coarse landing requirement (<1 km), however
  - Sensitive to delay's/failures with ground state updates unless OpNav is available
  - Less robust to other system failures. For instance the loss of the velocimeter degrades a 138 m/0.05 m/s landing dispersion using the minimal configuration to 422 m/1.11 m/s (the altimetry/IMU only solution).
- The preceding results are preliminary - on-going performance studies needed as design matures, modeling fidelity improves, and alternative scenarios are considered

Backup

Delivery and Knowledge Error