

Linking Lunar Orbital Dynamics to Planetary Protection Policy

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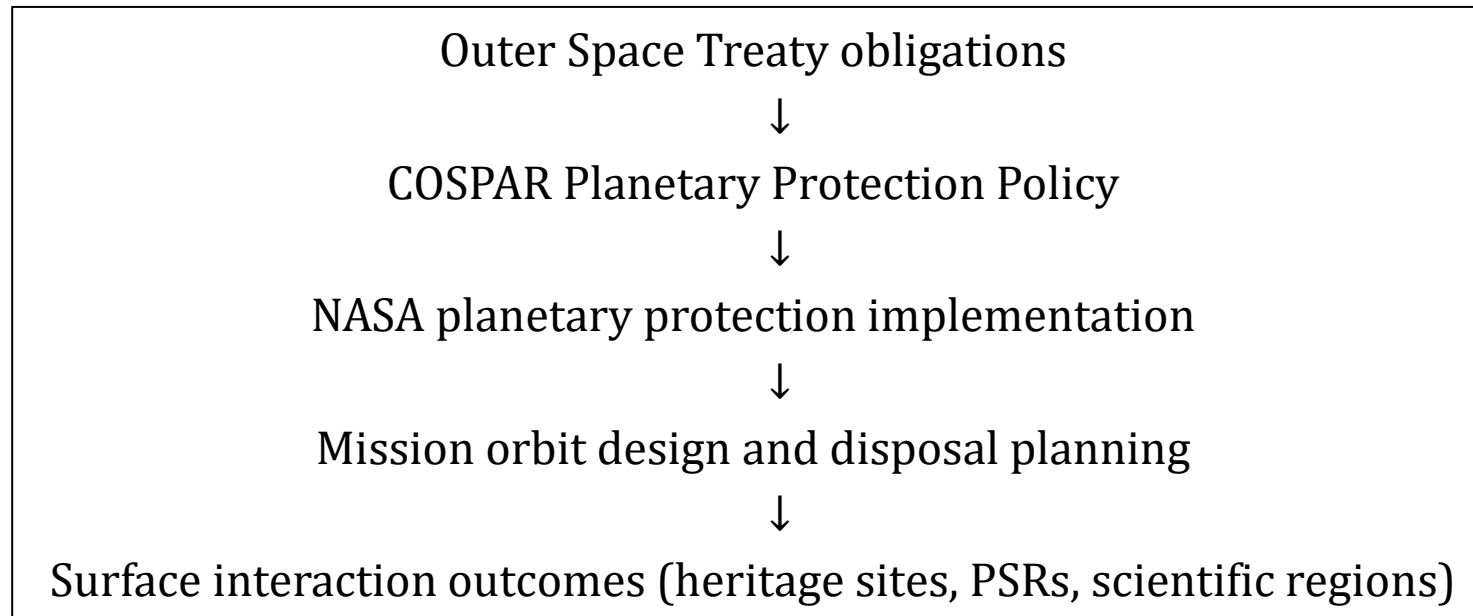
Executive Summary

Lunar exploration expectations operate through a layered framework of treaty obligations, scientific standards, national implementation rules, heritage preservation norms, and regulatory licensing mechanisms.

Recent analyses of low lunar orbit (LLO) dynamical evolution indicate that naturally decaying polar (and near-polar) orbits often produce geographically bounded impact corridors rather than globally random impact distributions. Initial orbital geometry therefore influences where eventual surface interaction is likely to occur.

These dynamics create a connection between trajectory design and policy considerations such as planetary protection, heritage preservation, and due-regard obligations. Predictable orbital decay behavior can help mission planners demonstrate that disposal trajectories avoid sensitive regions such as permanently shadowed regions (PSRs), historic landing sites, and scientific sites of interest.

Planetary Protection & Implementation Flow

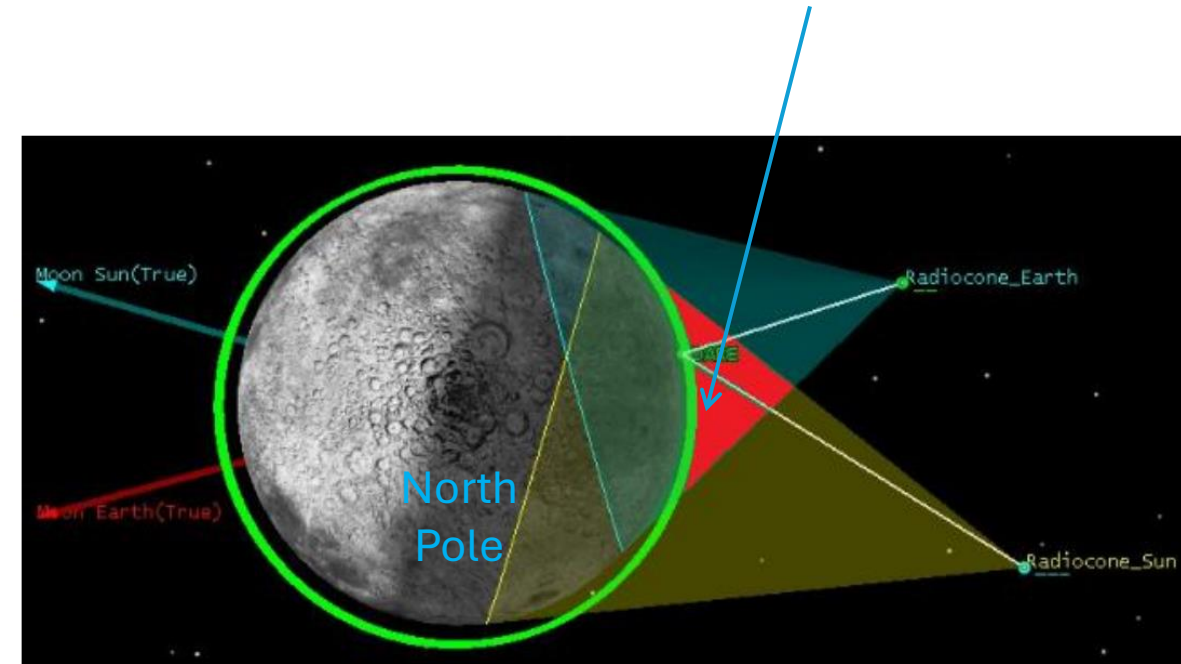


LUNAR MISSIONS: Summary of Key Documents, Reporting Requirements, & Operational Implications for Planetary Protection					
Framework Layer	Key Documents	Relevant Sections	Applicability	Purpose	Reporting / Documentation Requirements
International Law	Outer Space Treaty (OST)	OST Article VI (authorization & supervision); Article IX (due regard & harmful contamination); Article VII (liability)	To all signatories of the treaty (all spacefaring nations)	Establishes responsibility for national space activities and avoidance of harmful contamination or harmful interference.	States must authorize and supervise activities; consultations may be requested under OST Article IX if harmful interference is anticipated.
Planetary Protection Standard	COSPAR Planetary Protection Policy	Lunar Category II; subdivisions IIa / IIb for landed missions	To all lunar missions: Category II (orbiters, flybys, impacts); IIa / IIb (landed missions depending on location)	Defines planetary protection categories and documentation expectations for lunar missions.	Planetary protection documentation including trajectory description, impact probabilities, organic inventory for some landed missions, & identification of potential contamination pathways.
NASA Implementation	NASA NPR 8715.24; NASA STD 8719.27; & NASA Planetary Protection (PP) Handbook	NPR 8715.24 Sections 1–3 (roles, responsibilities, compliance); NASA STD 8719.27 Section 4 (contamination)	NASA Policies are applicable to all NASA and NASA partnered missions	Operational planetary protection requirements for NASA lunar missions.	Planetary protection plans, mission categorization, review documentation, compliance verification through mission reviews. NPR 8715.24 Tables 3.1 & 3.2.
Heritage Protection Norms	NASA's Recommendations to Space-Faring Entities: How to Protect and Preserve the Historic and Scientific Value of U.S. Government Lunar Artifacts; & Artemis Accords	Recommendations to Space-Faring Entities Section 2 (Descent & Landing; no overflight), Section 3 (Mobility; Exclusion Zones), Section 4 (Contamination); Artemis Accords Section 9 (heritage preservation)	Relevant to all lunar mission types regardless of PP category	Encourage preservation of historic lunar landing sites and artifacts.	Operational planning documentation describing how missions avoid disturbance of heritage sites.
U.S. Statutory Requirement	One Small Step Act	Public Law 116-275 Sections 2–3	Applies when NASA lunar missions interact with heritage sites	Requires NASA to incorporate artifact-protection guidelines into lunar contracts and agreements.	Compliance documentation incorporated into contracts and mission plans.
Commercial Licensing Oversight	FAA Payload Review	14 CFR §450.43	Applies to commercial missions regardless of PP category	Reviews payloads for compliance with national security, foreign policy, and international obligations.	Payload review documentation describing mission objectives, trajectory, and compliance with U.S. obligations.

Key Categories of Protected or Sensitive Lunar Locations

Category	Examples	Primary Policy Basis	Operational Concern
Polar volatile regions / PSRs	Shackleton crater; south polar permanently shadowed regions	COSPAR planetary protection considerations; NASA implementation	Protect volatile science integrity and future resource characterization
Historic landing sites	<i>Apollo 11-17</i> ; <i>Surveyor</i> sites; <i>Luna</i> landers	NASA heritage guidelines; Artemis Accords ; One Small Step Act	Prevent plume damage, ejecta disturbance, artifact degradation
Features of Special Interest	Unique geological formations; high-value science regions (e.g., magnetic swirl anomalies); radio quiet zone (RQZ) region on lunar farside	NASA Moon to Mars Architecture: Science Objectives	Avoid contamination or disturbance affecting future science

Radio Quiet Zone (RQZ) on Farside of the Moon:



Radio-quiet region for science observation seen as intersection (light red) of Earth (teal) and Sun (dark yellow) shadow cones on lunar farside, with view normal to lunar equator. [Genova et. al, 2015]

RQZ Approximate Coordinate Range:
 Latitude = 0 deg. (+- 30 deg.)
 Longitude = 180 deg. (+- 30 deg.)

Examples of Lunar Mission Types and Potential Interaction with Sensitive Regions

Mission Type	Example Missions	COSPAR Planetary Protection Category	Potential Interaction with Sensitive Regions	Notes Relevant to Trajectory Design
Lunar Flyby	<i>Artemis I</i> lunar flyby trajectory (example architecture)	Category II	May accidentally impact sensitive regions if trajectory is uncontrolled or disposal is poorly constrained.	Even flyby trajectories require consideration of post-flyby disposal paths.
Lunar Orbiter	<i>Lunar Reconnaissance Orbiter</i> (LRO); various CLPS orbital phases	Category II	Orbital decay may eventually lead to surface impact, potentially in sensitive regions.	Predictable LLO decay corridors are relevant to disposal planning.
Lunar Lander (non-polar region)	CLPS landers at non-polar sites (e.g., 19D, CS-3, CP-11)	Category IIa	Released propellant migration to polar regions	Landing site selection and plume effects must be considered.
Lunar Lander (polar region)	Artemis HLS; CLPS landers near south pole	Category IIb	Direct surface interaction near scientifically sensitive or volatile-rich regions.	Landing site selection and plume effects must be considered.

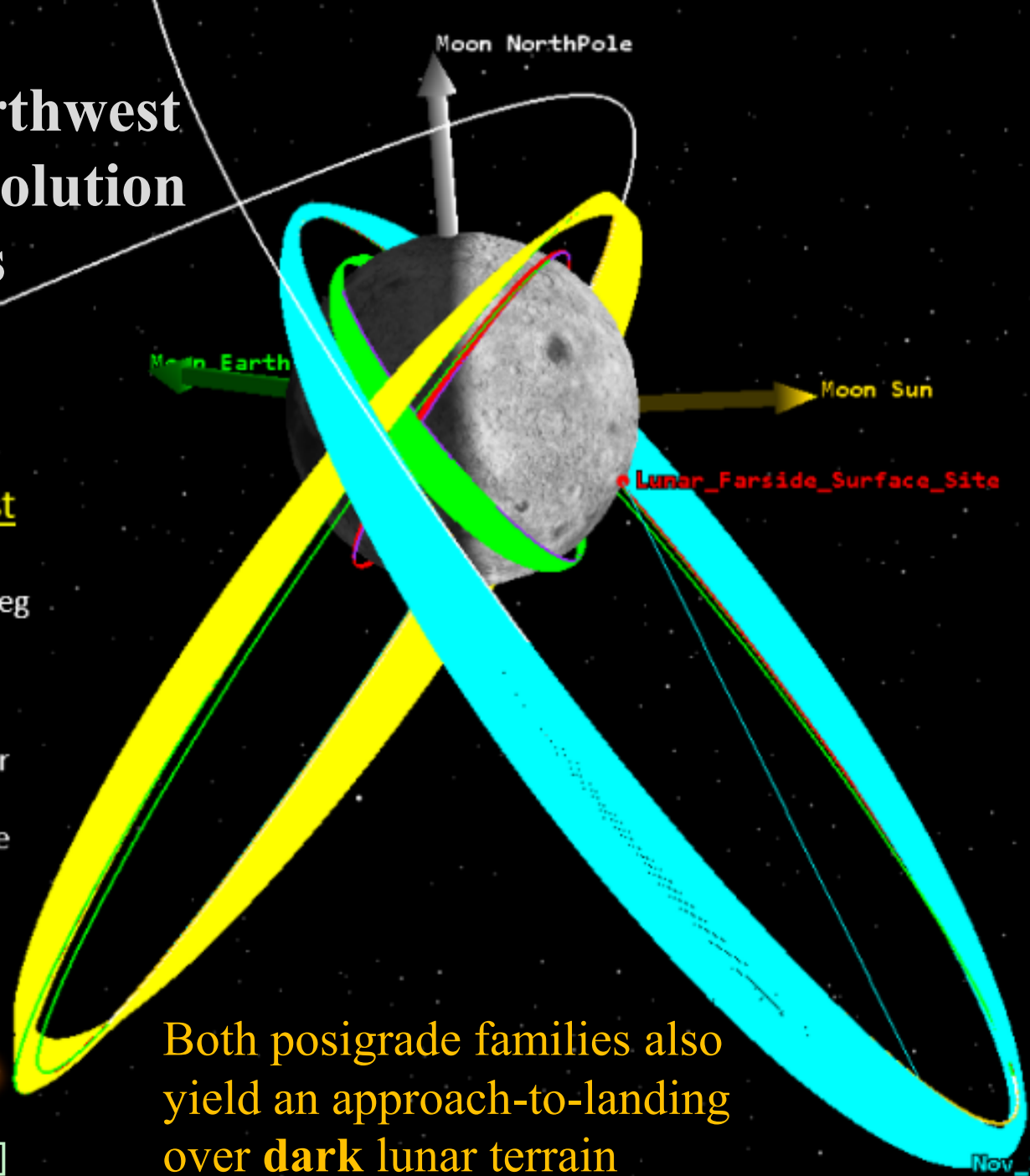
Implications, Applications, & Value of Long-Term Lunar Orbit Propagation Simulations

- **GOAL:** Investigate Long-Term Behavior of Typical Lunar Orbits
- **RESULT #1:** Identification of Lunar Frozen & Stable Orbits starting from typical Low Lunar Orbits (LLOs) and Elliptical Lunar Frozen Orbits (ELFOs)
 - **VALUE** and **APPLICATIONS** of Frozen & Stable Lunar Orbits:
 - **Sustainability:** Location(s) for storage (e.g., propellant or crew supplies)
 - **Contingencies:** Location as a safe-haven for rescue & other off-nominal scenarios
 - **Communications Relay:** Location between lunar surface & NRHO or Earth
 - **Disposal & Planetary Protection:** Lunar Graveyard Orbits; Sample Storage Location
- **RESULT #2:** Identification of Predictable Lunar Impact Behavior starting from typical LLOs
 - **VALUE** of Lunar Surface Impact latitude/longitude clustering:
 - **Understanding the cause:** lunar gravity field (“gravity funneling” due to lunar mass concentrations)
 - **Disposal & Planetary Protection:** de-orbiting of an asset from LLO can be planned without a maneuver
 - **Contingencies:** if an asset has a planned de-orbit via a maneuver, the location of impact can still be known if this maneuver fails

CLPS
CS-3
Mission

Posigrade Northwest & Southwest solution families

Lunar
Path-
finder
Space-
craft
in
Elliptical
Lunar
Frozen
Orbit
(ELFO)



Posigrade Southwest Solution Family:

- *RAAN (Moon-Sun) ~ 300 deg
- *Approx. 4-day wait time in lunar orbit before dawn landing on lunar farside
- *Apolune of posigrade lunar elliptical frozen orbit is positioned on the Earth-side during daylight operations

Posigrade Northwest Solution Family:

- *RAAN (Moon-Sun) ~ 120 deg
- *Approx. 19-day wait time in lunar orbit before dawn landing on lunar farside
- *Apolune of posigrade lunar elliptical frozen orbit is positioned on lunar farside during daylight operations

Both posigrade families also yield an approach-to-landing over dark lunar terrain

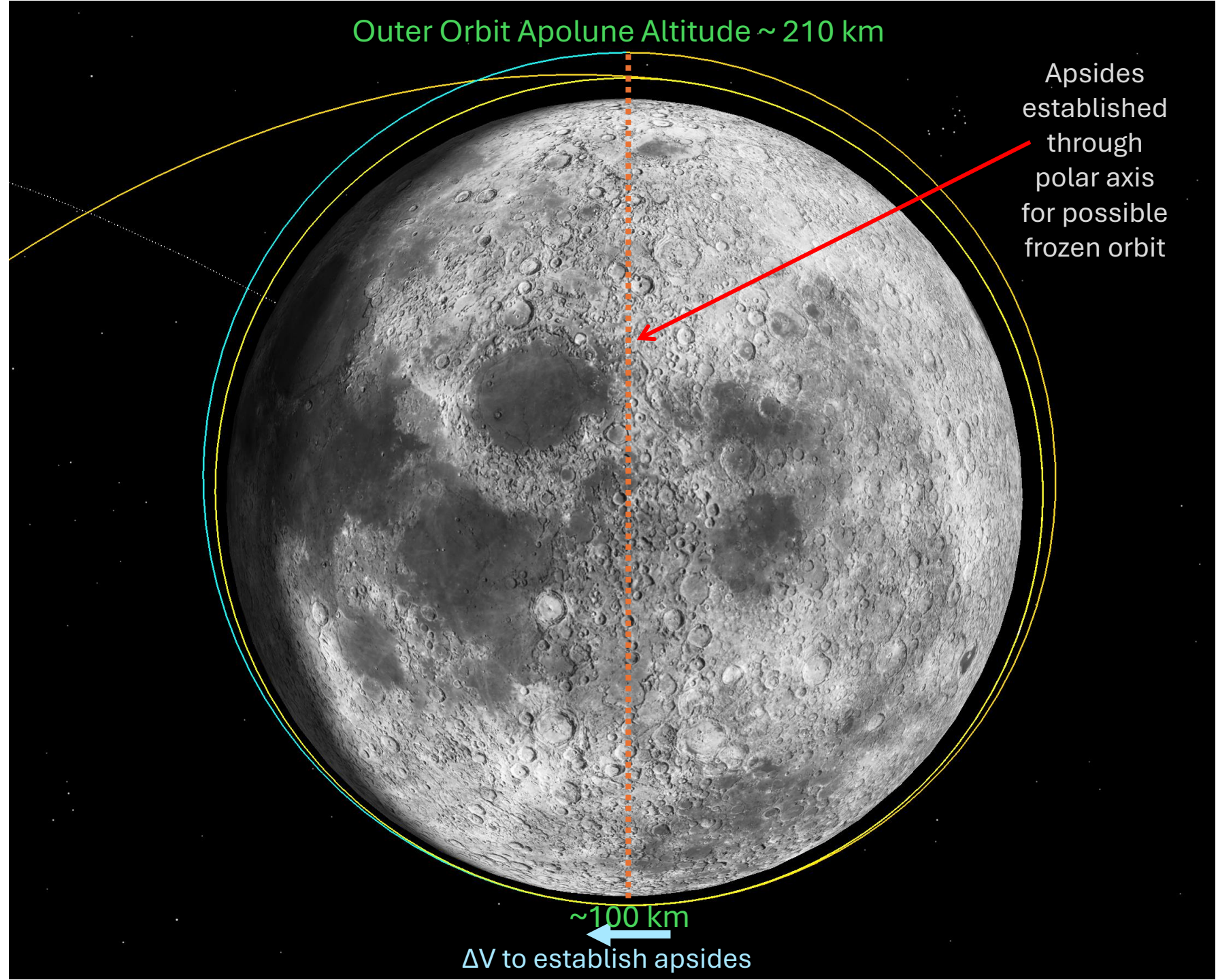
[Genova et al., 2024]

Candidate Lunar Frozen & Stable Orbits

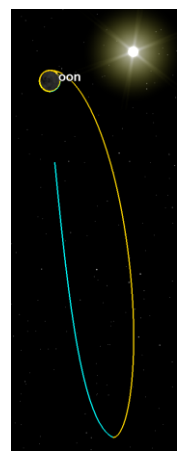
*Orbit Inclination Scan
from 85 to 93 degrees
shows stability over 10
years (see Appendix)

*Orbit dimensions:
~100X210 km

*Transfer shown from:
Elliptical Lunar Orbit
→ 100 km circular orbit
→ ~100X210 stable
and/or orbit



LLO Descent/Ascent Orbit 120X10km



Software: Flight-Proven
STK Astrogator

Minimum Lifetime = 2.62 days

Max Orbit Lifetime = 495.3 days

ALL 6,191 orbits impact the lunar surface within 2-yr of propagation

Orbits with Initial Inclination ~ 92.5 to ~ 93.5 deg. survive > 1 year for all initial argument of perilune values

Force Model:

100X100 Lunar Gravity Field; 30X30 Earth;
4X0 Sun; Point Masses for all other planets;
Spherical Radiation Pressure

Numerical Integrator:

RK78 with Max Abs Error = $1E-13$

Initial FIXED Orbital Elements & Parameters:

- *Epoch: **July 6, 2027**
- *Perilune Altitude = 10 km
- *Apolune Altitude = 120 km
- *LAN: TRANSFER from NRHO in STK MCS

Propagation Duration in STK =

2 yrs (or STOP on 0 km Lunar Altitude
NO TERRAIN)

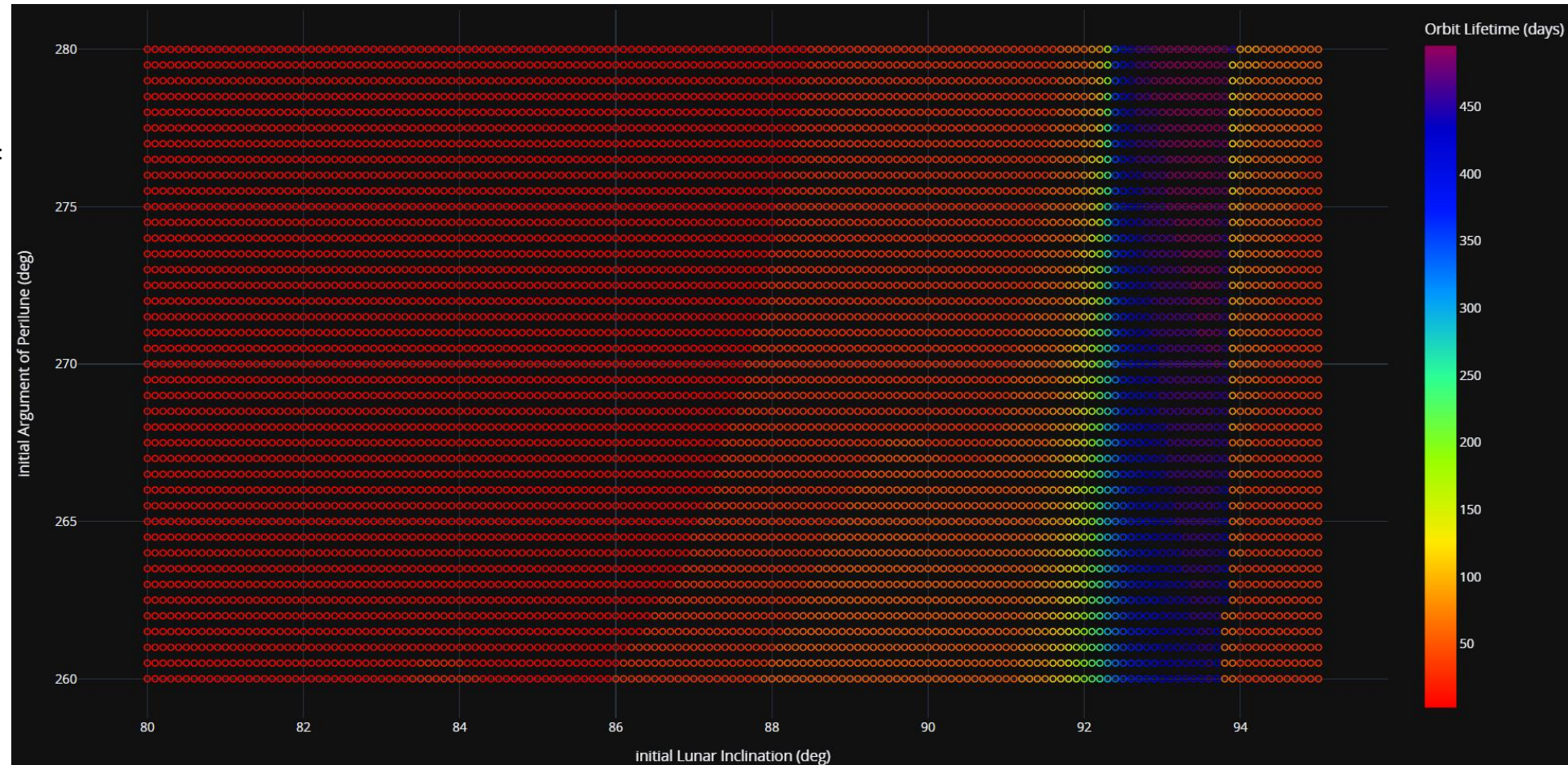
Design Variables (VARIED parameters):

- * i from 80 to 95 deg (in 0.1 deg increments)
- * ω = 260 to 280 deg (0.5 deg increments)

6191 orbits

Response Variables:

- Orbit Lifetime (Final Epoch - Initial Epoch)
- Final Perilune & Apolune Altitudes
- Final ω , LAN, inc., Lat, Long, et al.



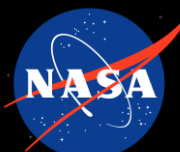
Lunar Heritage, Science, & Orbit Decay Map in 3D

Displaying:

- 1) Spacecraft that have landed on or impacted the Moon (Apollo; Ranger; Luna; Surveyor, etc.); 68 sites
- 2) Permanent Shadowed Craters (PSRs) in Blanket Region (north of 86 deg N & south of 79 deg S)
- 3) Sensitive Regions (Radio Quiet Zone, Magnetic Anomalies, Other Scientifically Significant Sites); 58 sites
- 4) Unnamed Sites: Locations of Orbital Decay from 120X10 km Lunar Orbits (80 to 95 deg. Inclination) 6,191 sites

Near/Earth Side
(shown during day)

Moon NorthPole



Ames Research Center

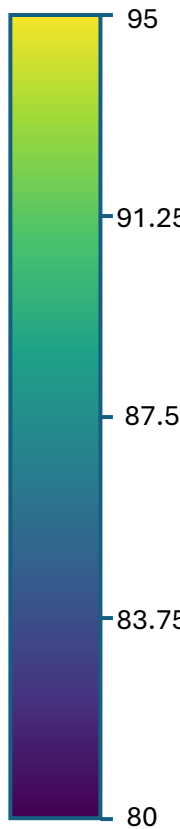
Lunar Farside
(shown at night)

Moon NorthPole



Ames Research Center

Orbit
Inclination
(deg.) for
120X10km
Near-Polar
Scan
(Unnamed
Sites)

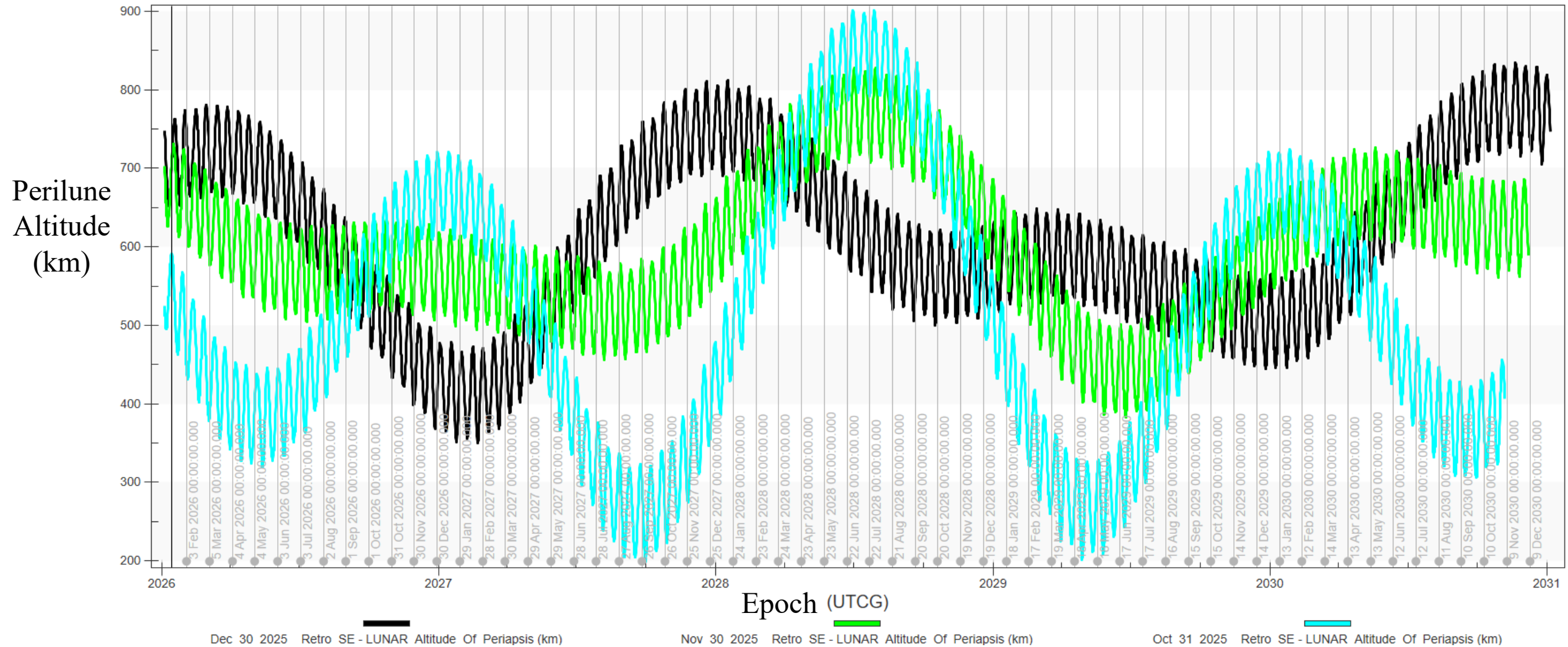


Conclusions & Future Work

- Near-Polar low lunar orbits (LLOs) exhibit **predictable** natural decay
 - Impacts focused in the southern hemisphere for 120X10 km and 100X15 km orbits starting with argument of perilune near 270 degrees
 - 100 km polar circular orbit did show an impact camp in the northern hemisphere, but most impacts were in the southern hemisphere
 - More lunar orbits to be analyzed (e.g., full 360-degree scans in argument of perilune, inclination, & longitude of the ascending node; perilune and apolune altitude scans)
- Impact locations from near-polar LLOs **cluster** via “*gravity funneling*” due to lunar mass concentrations (i.e., “mascons”) as the Moon’s density is non-uniform
- Lunar orbital inclination selection can steer natural decay of near-polar LLOs toward predictable disposal regions
- Stable lunar “graveyard” orbits exist both at low-altitude and in higher altitude elliptical orbits; future orbit scans planned in both altitude regimes

Appendix

Perilune Altitude of ELFOs for Trajectories #1, #5, and #9 (Retrograde Southeast Family) plotted vs. time over 5-year period

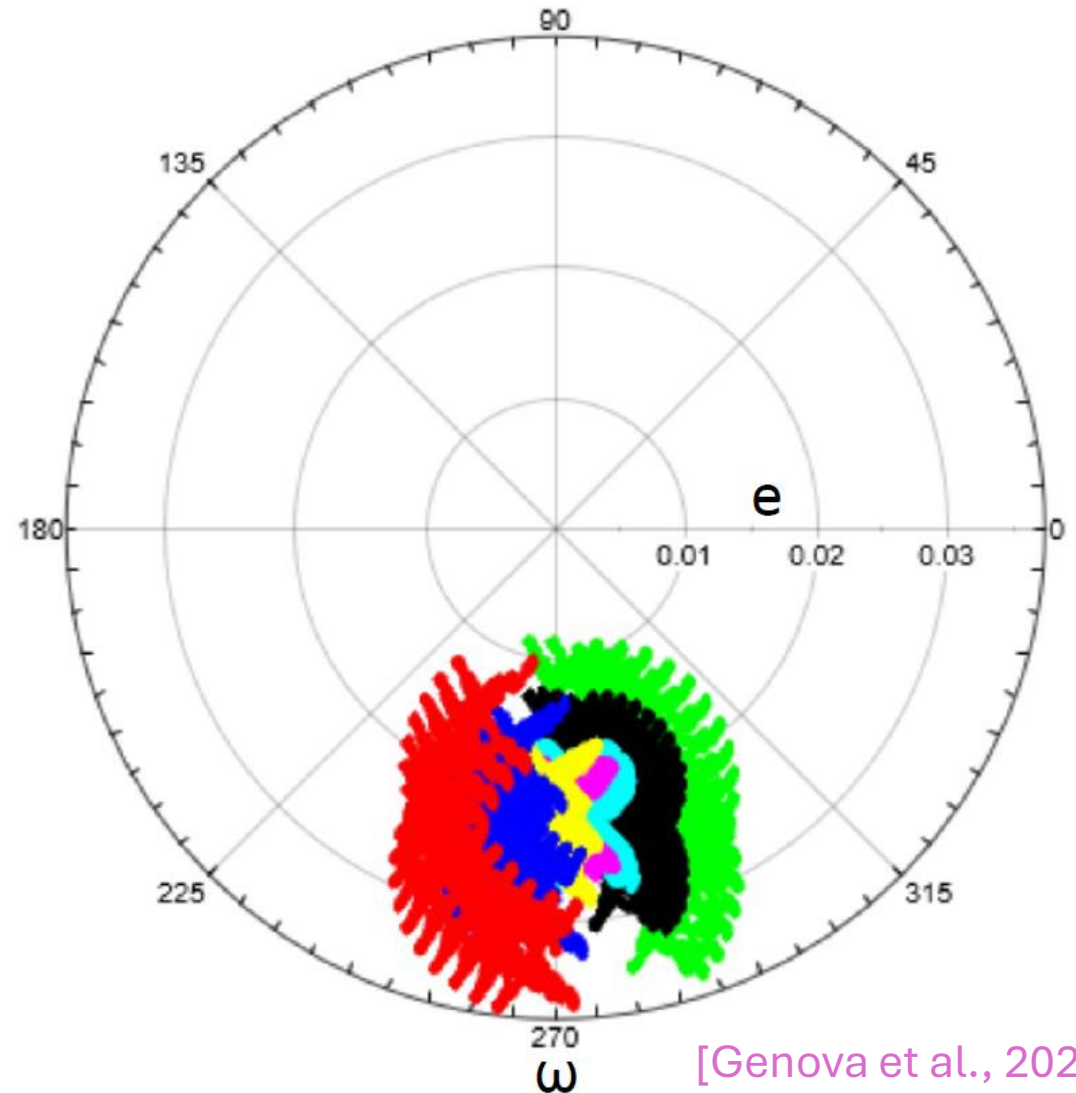
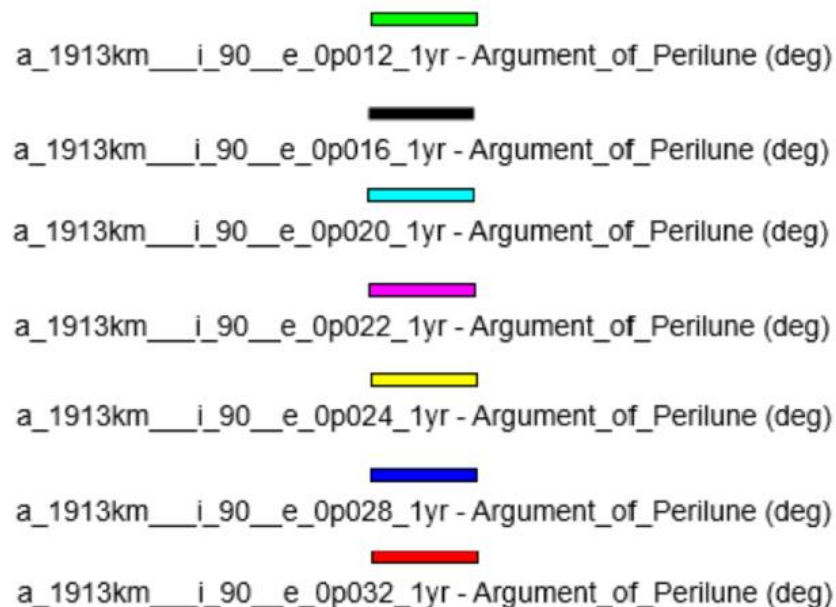


Stability Search for Low Lunar Polar Orbit: Eccentricity scan

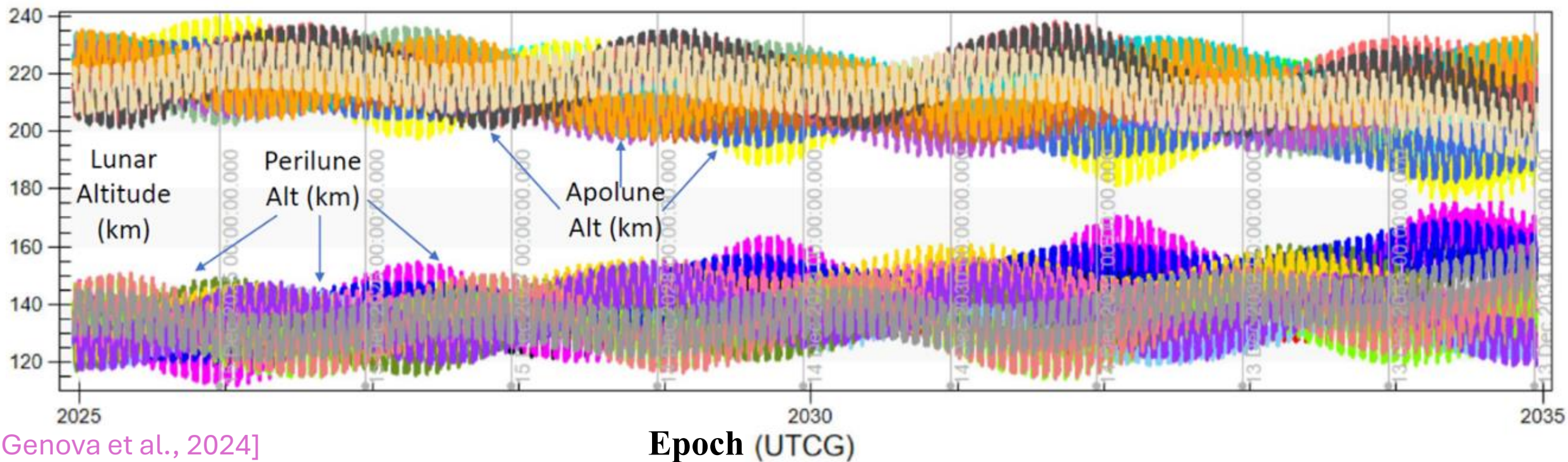
* The semi-major axis, a , of the studied orbit was modified to fit between values published by Lara and above that shown by Folta & Quinn. **The specific semi-major axis value assumed was 1,913 km**, with argument of perilune set to 90 degrees

* After eccentricity scan in STK Astrogator, $e=0.022$ yields most stable orbit

ECCENTRICITY SCAN
Polar Plot: (e, ω)
 $a=1913\text{km}$,
ecc: $[0.012, 0.032]$



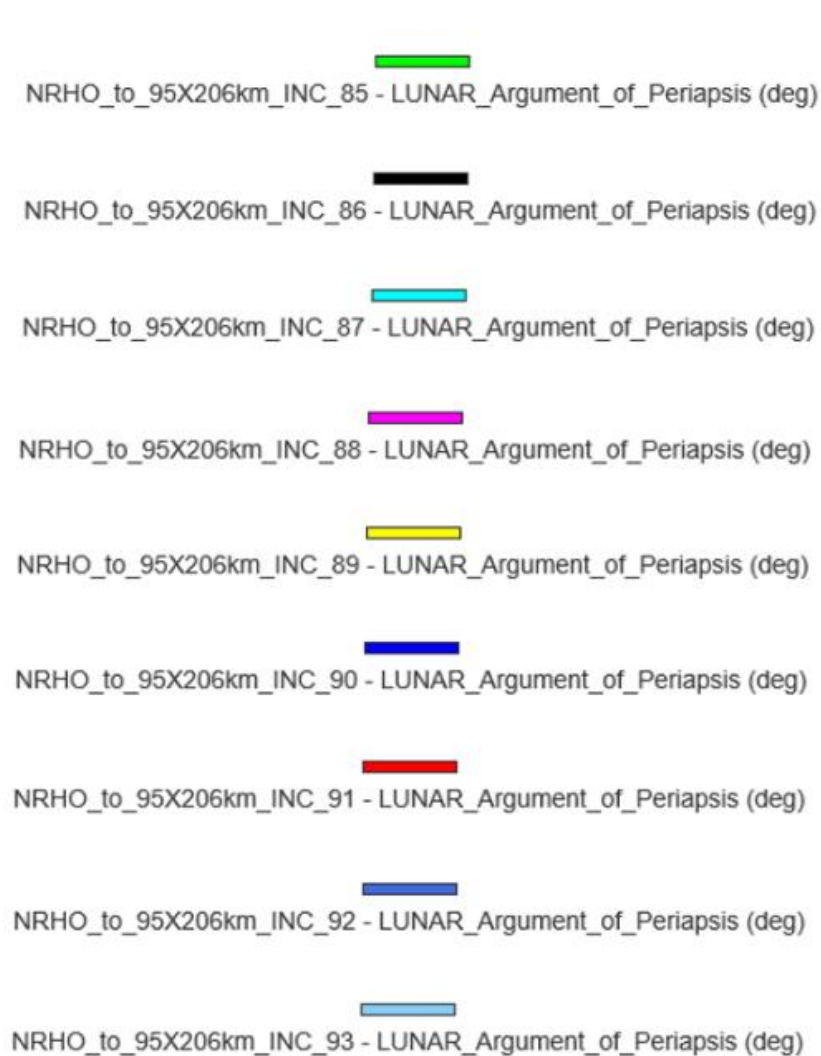
Perilune and Apolune Altitudes plotted for frozen polar LLO vs. Time over 10-year Propagation period for 360-deg range of RAAN (MCI frame) in 30-degree increments with initial epoch in Dec. 2024 and: $[a, e, i, \omega, \nu] = [1,913 \text{ km}, 0.022, 90 \text{ deg}, 0 \text{ deg}]$



[Genova et al., 2024]

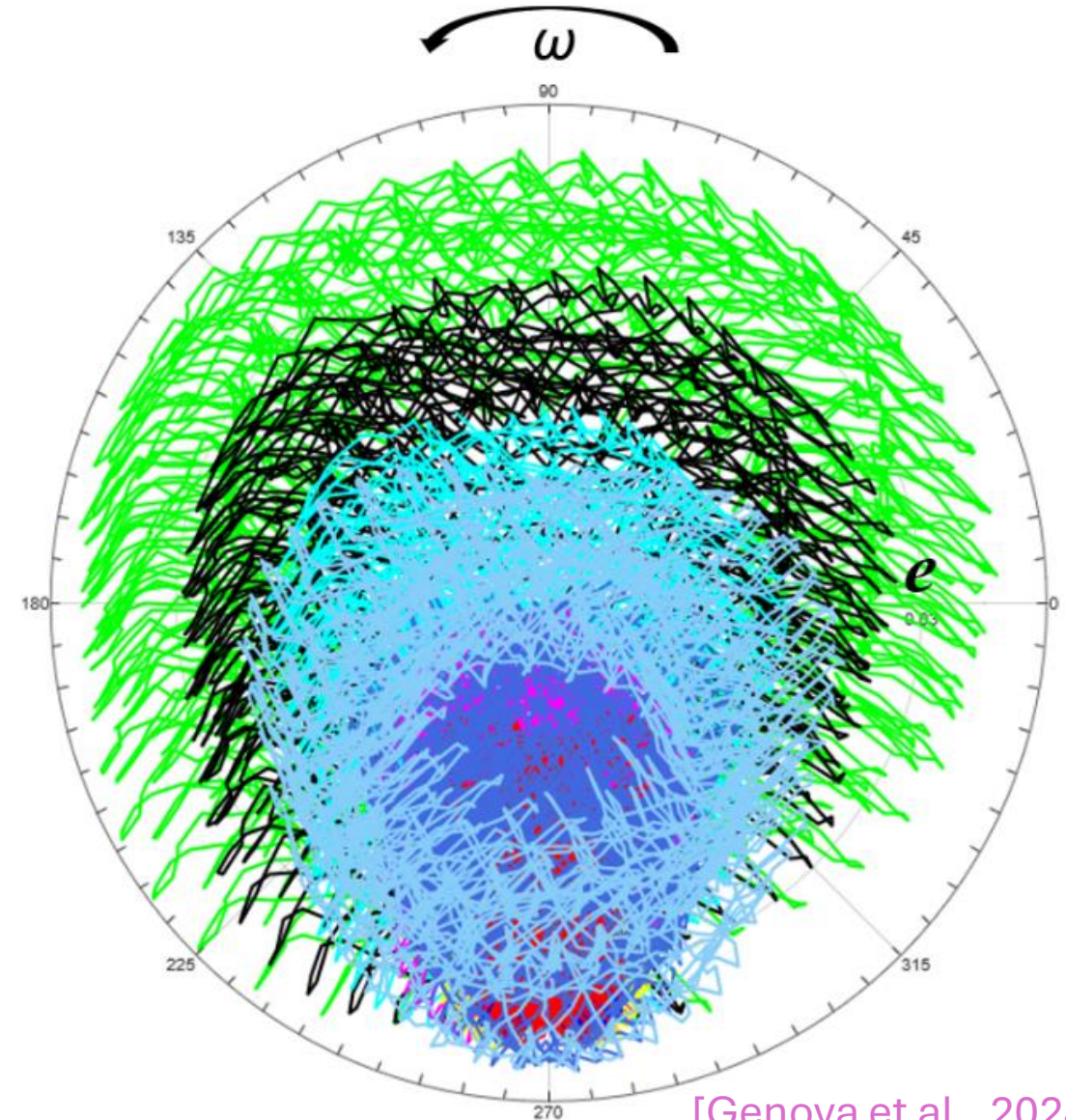
- | | | |
|---|--|---|
| <ul style="list-style-type: none"> ■ a_1913km__i_90_e_0p022_LAN_0_10yr - Perilune_ALT (km) ■ a_1913km__i_90_e_0p022_LAN_120_10yr - Apolune_ALT (km) ■ a_1913km__i_90_e_0p022_LAN_180_10yr - Perilune_ALT (km) ■ a_1913km__i_90_e_0p022_LAN_210_10yr - Apolune_ALT (km) ■ a_1913km__i_90_e_0p022_LAN_270_10yr - Perilune_ALT (km) ■ a_1913km__i_90_e_0p022_LAN_300_10yr - Apolune_ALT (km) ■ a_1913km__i_90_e_0p022_LAN_330_10yr - Perilune_ALT (km) ■ a_1913km__i_90_e_0p022_LAN_60_10yr - Apolune_ALT (km) | <ul style="list-style-type: none"> ■ a_1913km__i_90_e_0p022_LAN_0_10yr - Apolune_ALT (km) ■ a_1913km__i_90_e_0p022_LAN_150_10yr - Perilune_ALT (km) ■ a_1913km__i_90_e_0p022_LAN_180_10yr - Apolune_ALT (km) ■ a_1913km__i_90_e_0p022_LAN_240_10yr - Perilune_ALT (km) ■ a_1913km__i_90_e_0p022_LAN_270_10yr - Apolune_ALT (km) ■ a_1913km__i_90_e_0p022_LAN_30_10yr - Perilune_ALT (km) ■ a_1913km__i_90_e_0p022_LAN_330_10yr - Apolune_ALT (km) ■ a_1913km__i_90_e_0p022_LAN_90_10yr - Perilune_ALT (km) | <ul style="list-style-type: none"> ■ a_1913km__i_90_e_0p022_LAN_120_10yr - Perilune_ALT (km) ■ a_1913km__i_90_e_0p022_LAN_150_10yr - Apolune_ALT (km) ■ a_1913km__i_90_e_0p022_LAN_210_10yr - Perilune_ALT (km) ■ a_1913km__i_90_e_0p022_LAN_240_10yr - Apolune_ALT (km) ■ a_1913km__i_90_e_0p022_LAN_300_10yr - Perilune_ALT (km) ■ a_1913km__i_90_e_0p022_LAN_30_10yr - Apolune_ALT (km) ■ a_1913km__i_90_e_0p022_LAN_60_10yr - Perilune_ALT (km) ■ a_1913km__i_90_e_0p022_LAN_90_10yr - Apolune_ALT (km) |
|---|--|---|

Inclination scan from $i = 85$ to 93 degrees in 1-degree increments for 95X206 km Lunar Orbit

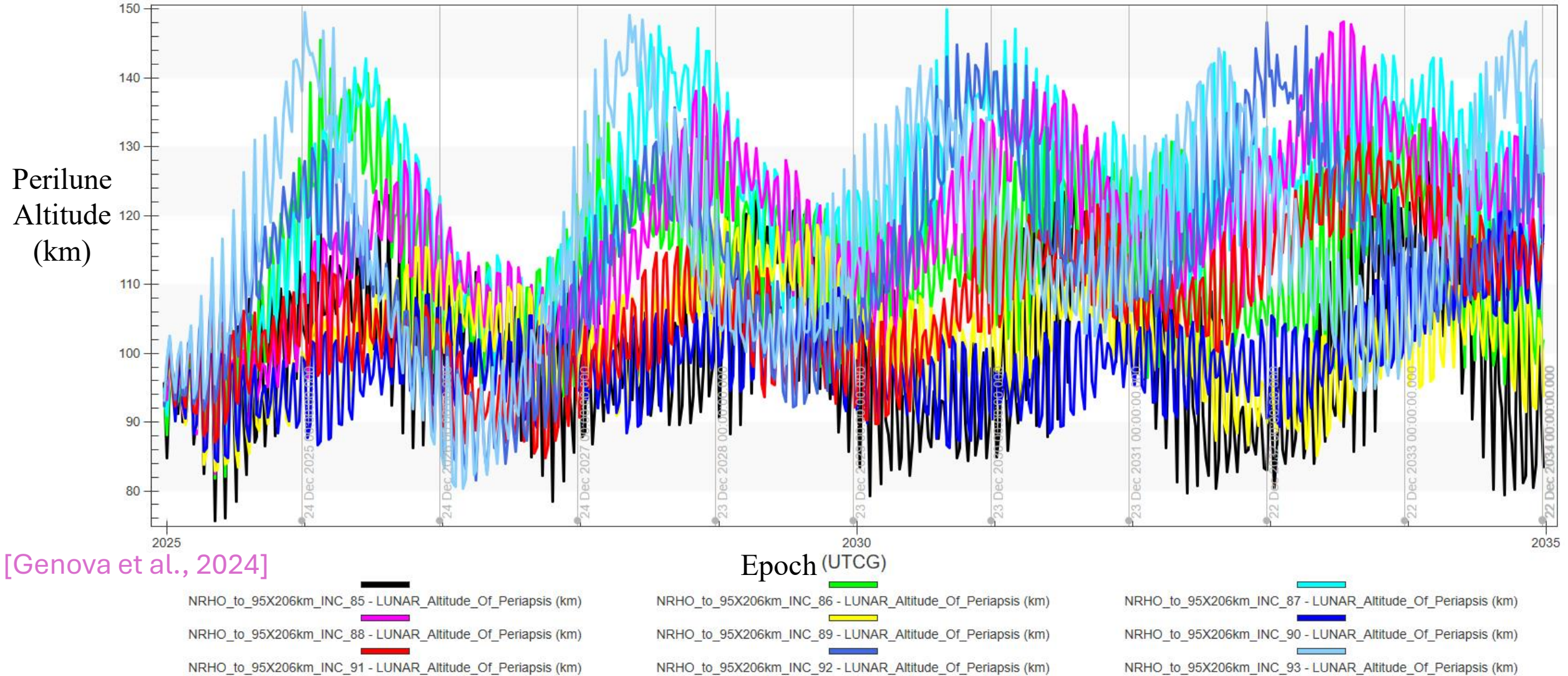


* e and ω displayed on polar plot with 10 years of propagation duration assuming transfer from NRHO

* All orbits survive 10-year propagation with circulating and frozen behavior observed



Perilune Altitudes plotted for 95X206 km lunar orbit vs. Time over 10-year Propagation period for inclination range of 85 to 93 degrees in 1-degree increments with initial epoch on Dec. 24, 2024 assuming transfer from NRHO



LLO Case 1:
LLO Circular Orbit 100km

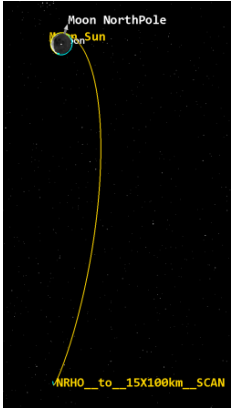
LLO Case 1:

LLO Circular Orbit 100km

Minimum Lifetime = 168 days

91 orbits (out of 151) impact the lunar surface within 2-yr of propagation

ALL ORBITS SHOWN



Software: Flight-Proven
STK Astrogator

Force Model:

100X100 Lunar Gravity Field; 30X30 Earth;
4X0 Sun; Point Masses for all other planets;
Spherical Radiation Pressure

Numerical Integrator:

RK78 with Max Abs Error = 1E-13

Initial FIXED Orbital Elements & Parameters:

- *Epoch of LOI: 4 Jul 2029 04:57:45.895 UTCG
- *Lunar Altitude = 100 km
- *Eccentricity = 0
- * ω = undefined

Propagation Duration in STK =

2 yrs (or STOP on 0 km Lunar Altitude- **NO TERRAIN**)

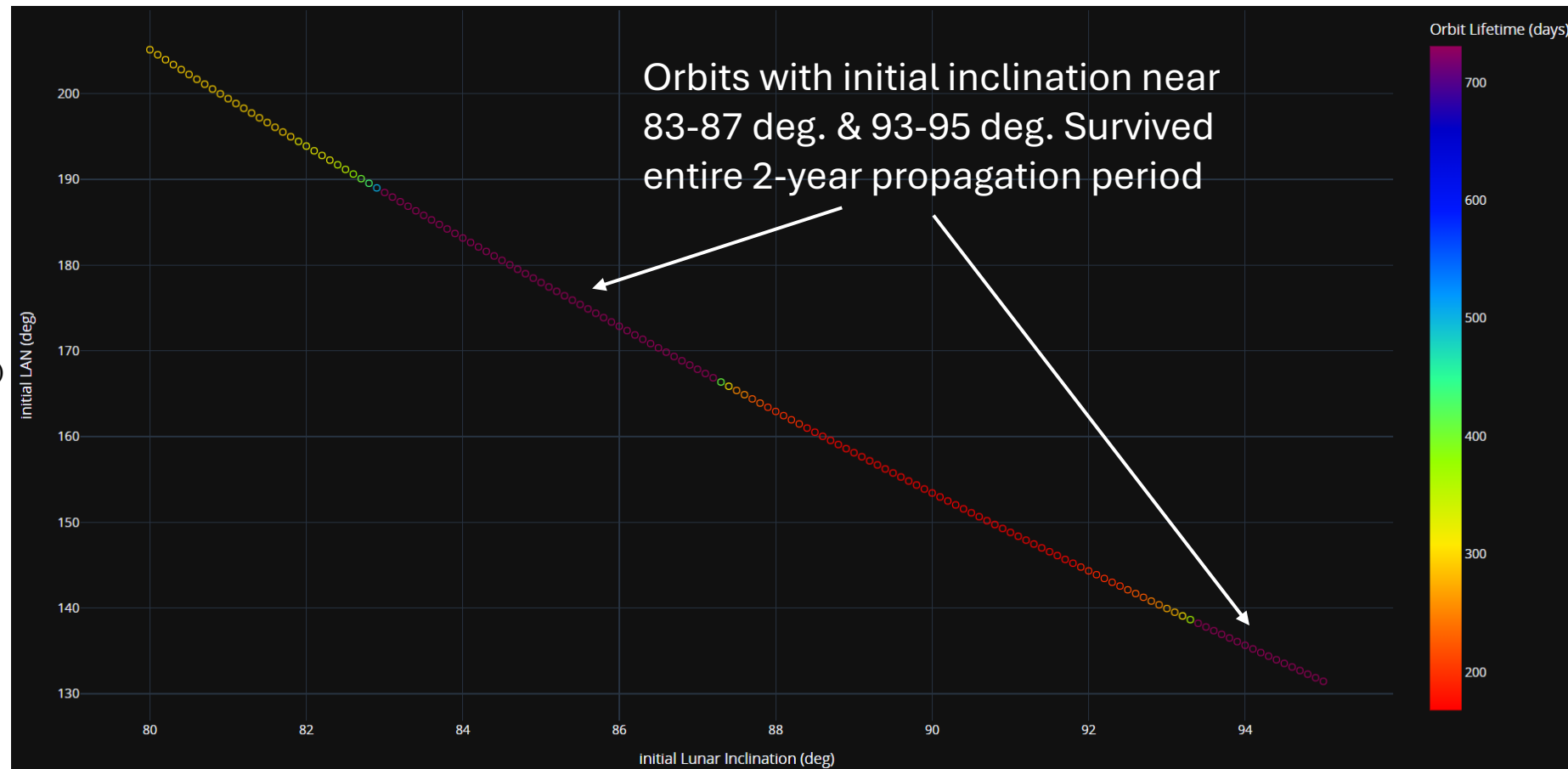
Design Variables (VARIED parameters):

- * i from 80 to 95 deg (in 0.10 deg increments)
- * LAN selected from NRHO transfer

151 orbits

Response Variables:

- Orbit Lifetime (Final Epoch - Initial Epoch)
- Final Perilune & Apolune Altitudes
- Final Lunar Altitude
- Final ω , LAN, inc, Lat, Long
- Many others



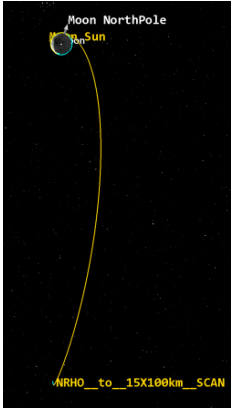
LLO Case 1:

LLO Circular Orbit 100km

Minimum Lifetime = 168 days

91 orbits (out of 151) impact the lunar surface within 2-yr of propagation

ONLY IMPACT ORBITS SHOWN



Software: Flight-Proven
STK Astrogator

Force Model:

100X100 Lunar Gravity Field; 30X30 Earth;
4X0 Sun; Point Masses for all other planets;
Spherical Radiation Pressure

Numerical Integrator:

RK78 with Max Abs Error = 1E-13

Initial FIXED Orbital Elements & Parameters:

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- *Eccentricity = 0
- * ω = undefined

Propagation Duration in STK =

2 yrs (or STOP on 0 km Lunar Altitude- **NO TERRAIN**)

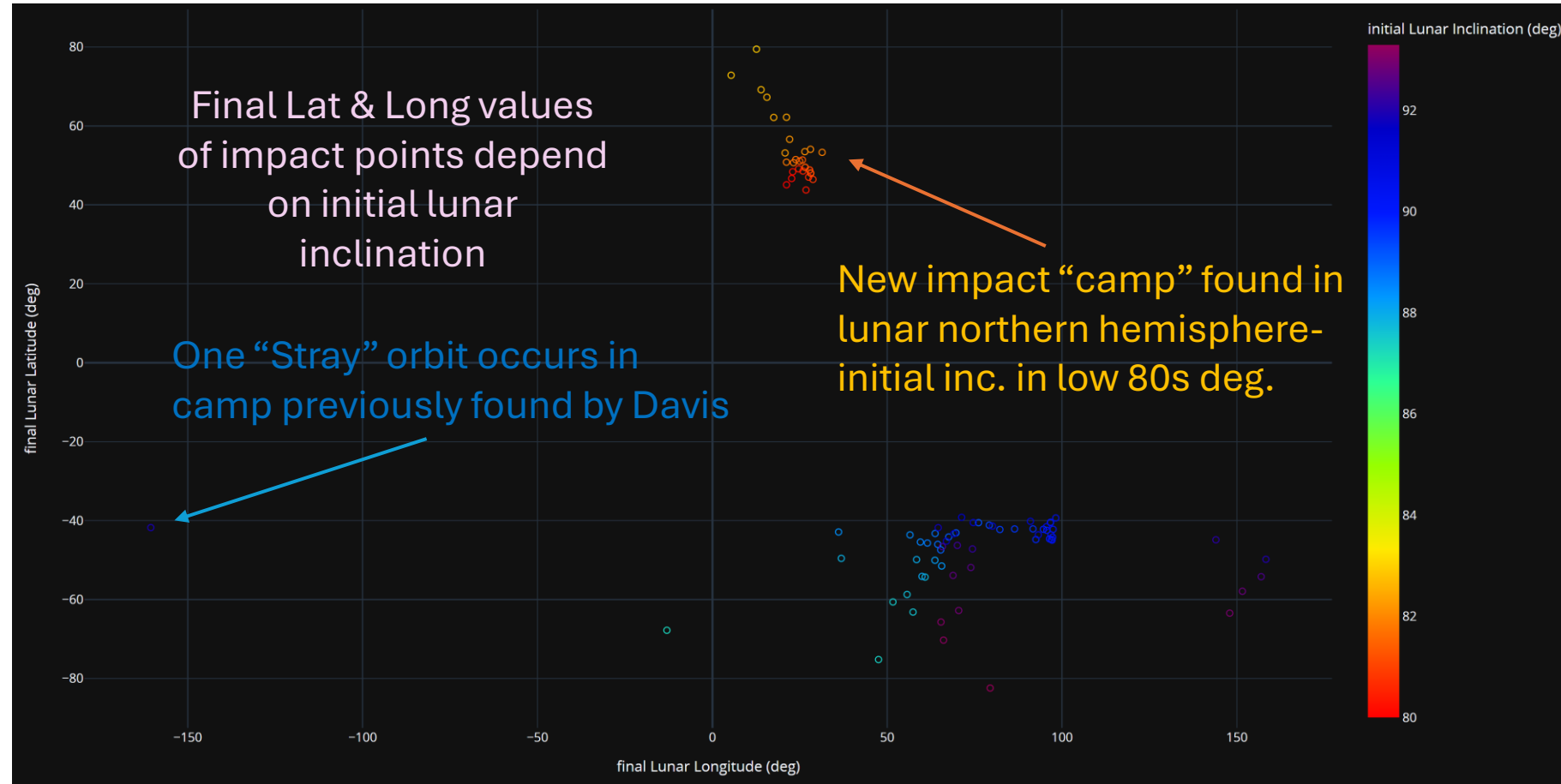
Design Variables (VARIED parameters):

- * i from 80 to 95 deg (in 0.10 deg increments)
- * LAN selected from NRHO transfer

151 orbits

Response Variables:

- Orbit Lifetime (Final Epoch - Initial Epoch)
- Final Perilune & Apolune Altitudes
- Final Lunar Altitude
- Final ω , LAN, inc, Lat, Long
- Many others



LLO Case 1:

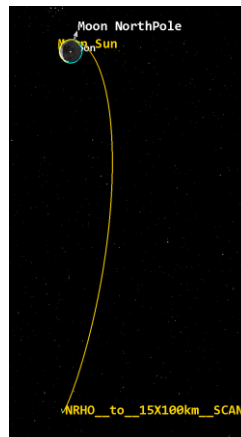
LLO Circular Orbit 100km

Software: Flight-Proven
STK Astrogator

Minimum Lifetime = 168 days

91 orbits (out of 151) impact the lunar surface within 2-yr of propagation

ONLY IMPACT ORBITS SHOWN



Force Model:

100X100 Lunar Gravity Field; 30X30 Earth;
4X0 Sun; Point Masses for all other planets;
Spherical Radiation Pressure

Numerical Integrator:

RK78 with Max Abs Error = 1E-13

Initial FIXED Orbital Elements & Parameters:

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- *Lunar Altitude = 100 km
- *Eccentricity = 0
- * ω = undefined

Propagation Duration in STK =

2 yrs (or STOP on 0 km Lunar Altitude- **NO TERRAIN**)

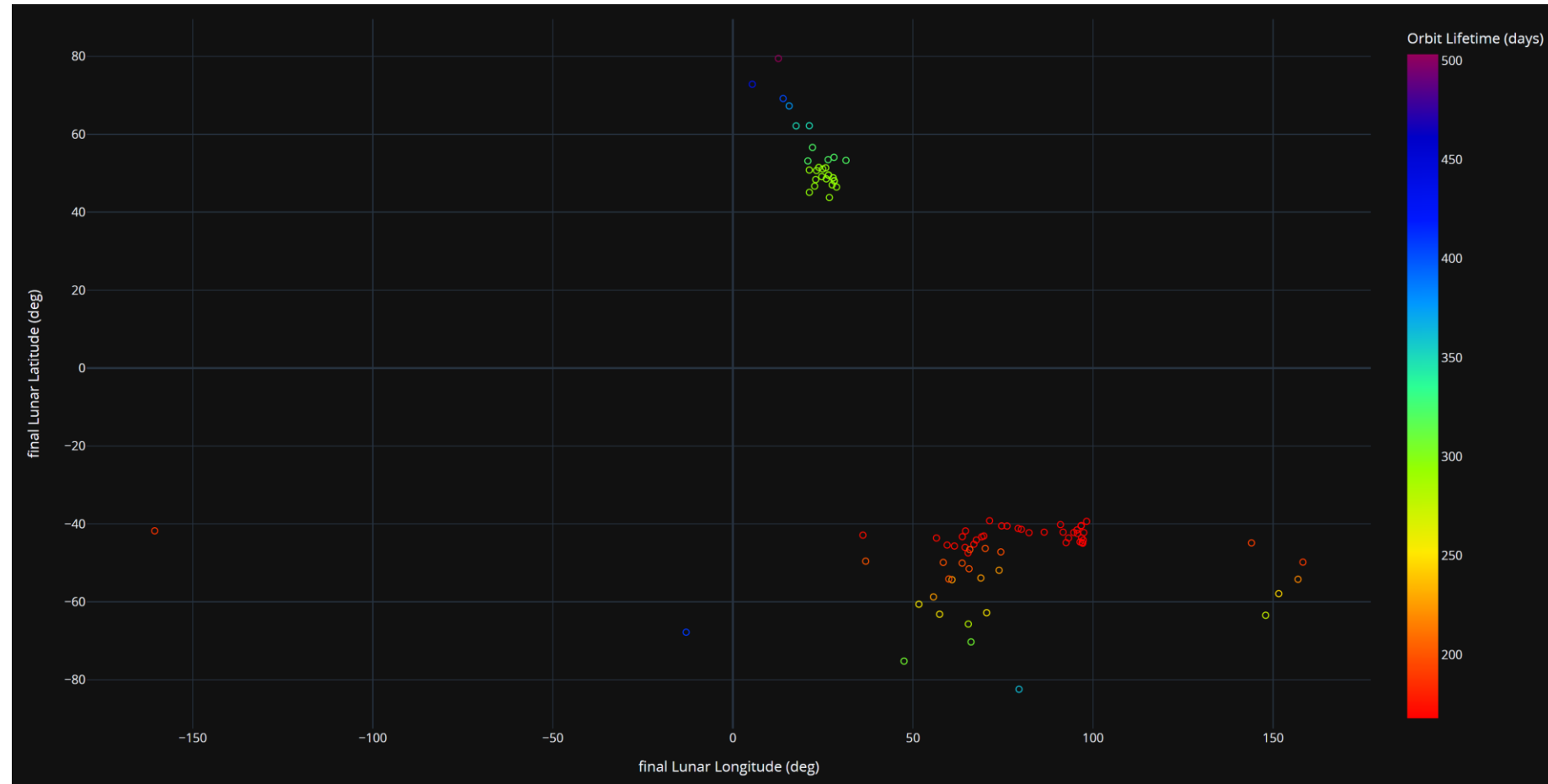
Design Variables (VARIED parameters):

- * i from 80 to 95 deg (in 0.10 deg increments)
- * LAN selected from NRHO transfer

151 orbits

Response Variables:

Orbit Lifetime (Final Epoch - Initial Epoch)
Final Perilune & Apolune Altitudes
Final Lunar Altitude
Final ω , LAN, inc, Lat, Long
Many others



LLO Case 2:

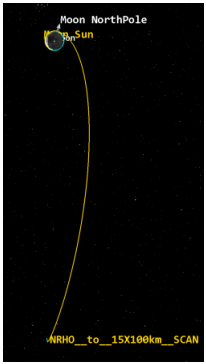
LLO Descent/Ascent Orbit 100X15km

LLO Case 2:

LLO Descent/Ascent Orbit 100X15km

Software: Flight-Proven
STK Astrogator

Minimum Lifetime = 7.8 days



Force Model:

100X100 Lunar Gravity Field; 30X30 Earth;
4X0 Sun; Point Masses for all other planets;
Spherical Radiation Pressure

Numerical Integrator:

RKF78 with Max Abs Error = 1E-13 and
Max Rel Error = 1E-13

Initial FIXED Orbital Elements & Parameters:

*Epoch of LOI: 4 Jul 2029 04:57:45.895 UTCG
*Perilune Altitude = 15 km
*Apolune Altitude = 100 km
*LAN: match NRHO node range via direct input or
TRANSFER from NRHO in STK MCS

Propagation Duration in STK =

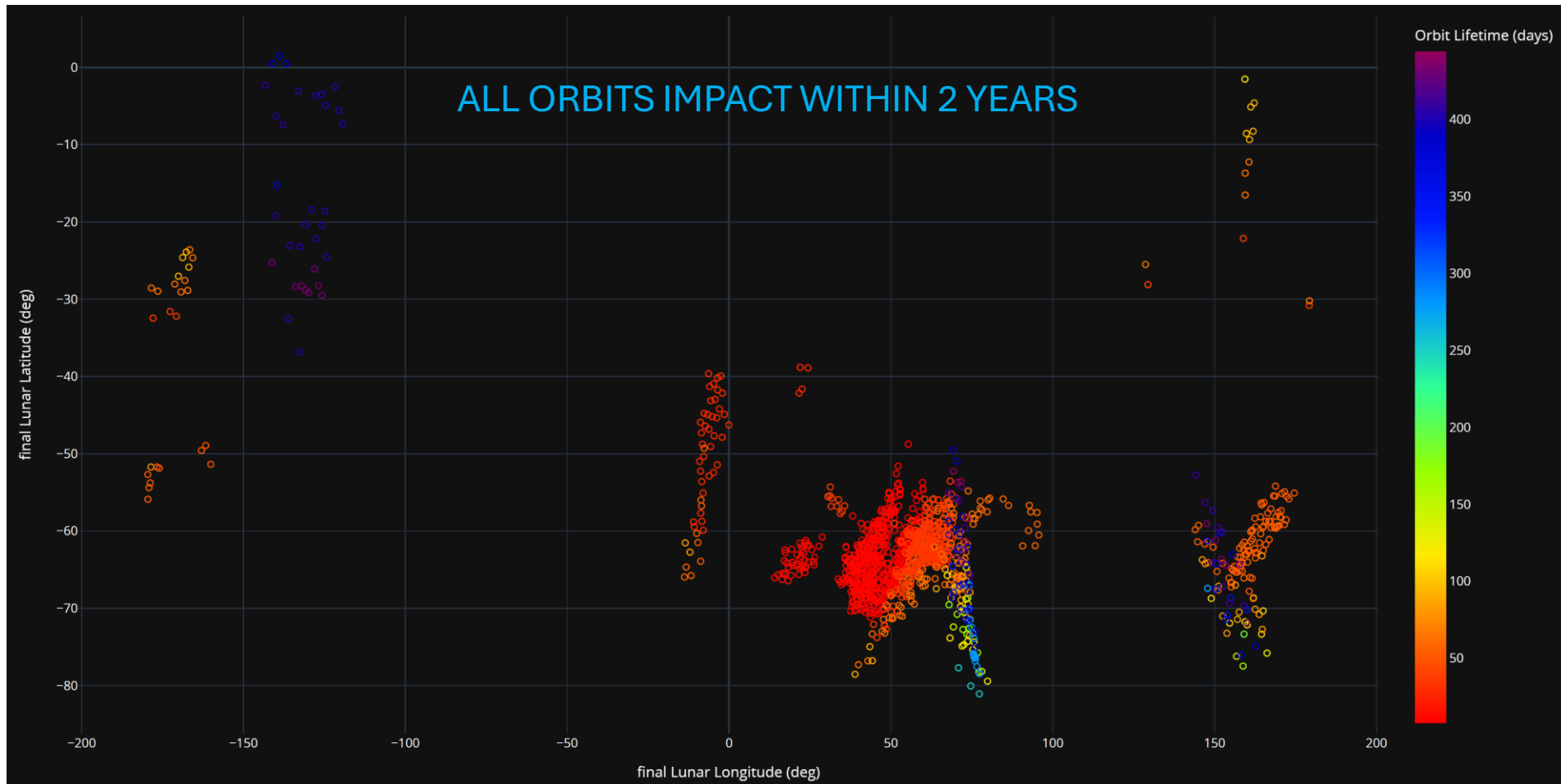
2 years (or STOP on 0 km Lunar Altitude- **NO TERRAIN**)

Design Variables (VARIED parameters):

* i from 80 to 95 deg (in 0.25 deg increments)
* ω = 260 to 280 deg: 1 deg increments
(match range given TRANSFERS from NRHO)
1,281 orbits

Response Variables:

Orbit Lifetime
Final Lat & Long, orbit energy, orbit period, etc.
Set of Keplerian Orbital Elements

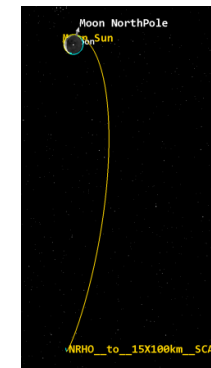


LLO Case 2:

LLO Descent/Ascent Orbit 100X15km

Software: Flight-Proven
STK Astrogator

Minimum Lifetime = 7.8 days



Force Model:

100X100 Lunar Gravity Field; 30X30 Earth;
4X0 Sun; Point Masses for all other planets;
Spherical Radiation Pressure

Numerical Integrator:

RKF78 with Max Abs Error = 1E-13 and
Max Rel Error = 1E-13

Initial FIXED Orbital Elements & Parameters:

*Epoch of LOI: 4 Jul 2029 04:57:45.895 UTCG
*Perilune Altitude = 15 km
*Apolune Altitude = 100 km
*LAN: match NRHO node range via direct input or
TRANSFER from NRHO in STK MCS

Propagation Duration in STK =

2 years (or STOP on 0 km Lunar Altitude- **NO TERRAIN**)

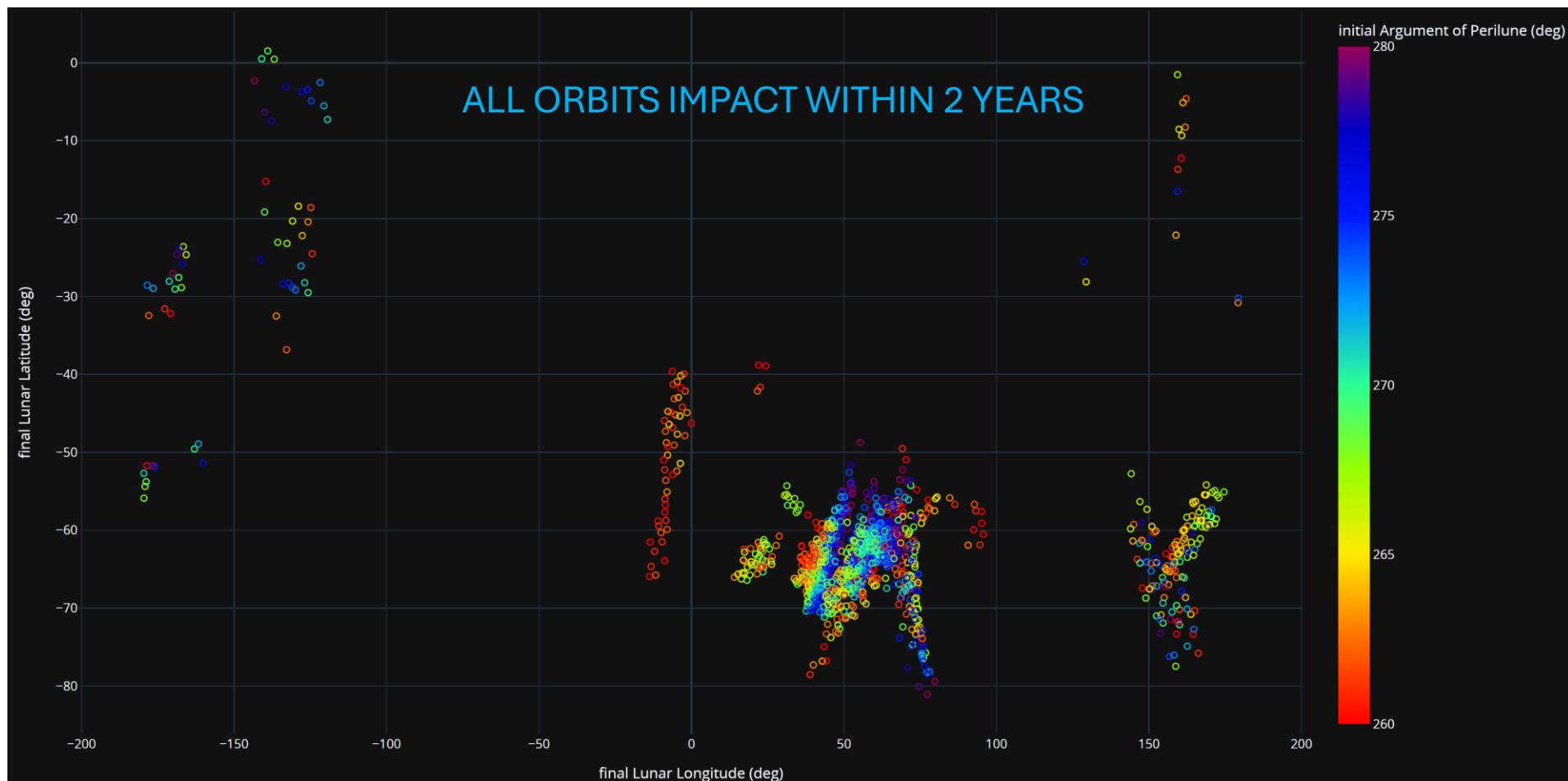
Design Variables (VARIED parameters):

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* ω = 260 to 280 deg: 1 deg increments
(match range given *TRANSFERS* from NRHO)

1,281 orbits

Response Variables:

Orbit Lifetime
Final Lat & Long, orbit energy, orbit period, etc.
Set of Keplerian Orbital Elements

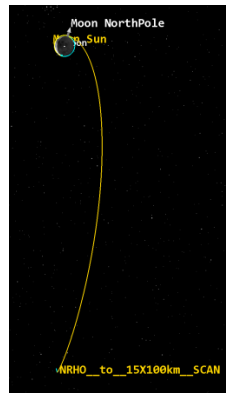


LLO Case 2:

LLO Descent/Ascent Orbit 100X15km

Software: Flight-Proven
STK Astrogator

Minimum Lifetime = 7.8 days



Force Model:

100X100 Lunar Gravity Field; 30X30 Earth;
4X0 Sun; Point Masses for all other planets;
Spherical Radiation Pressure

Numerical Integrator:

RKF78 with Max Abs Error = 1E-13 and
Max Rel Error = 1E-13

Initial FIXED Orbital Elements & Parameters:

*Epoch of LOI: 4 Jul 2029 04:57:45.895 UTCG
*Perilune Altitude = 15 km
*Apolune Altitude = 100 km
*LAN: match NRHO node range via direct input or
TRANSFER from NRHO in STK MCS

Propagation Duration in STK =

2 years (or STOP on 0 km Lunar Altitude- **NO TERRAIN**)

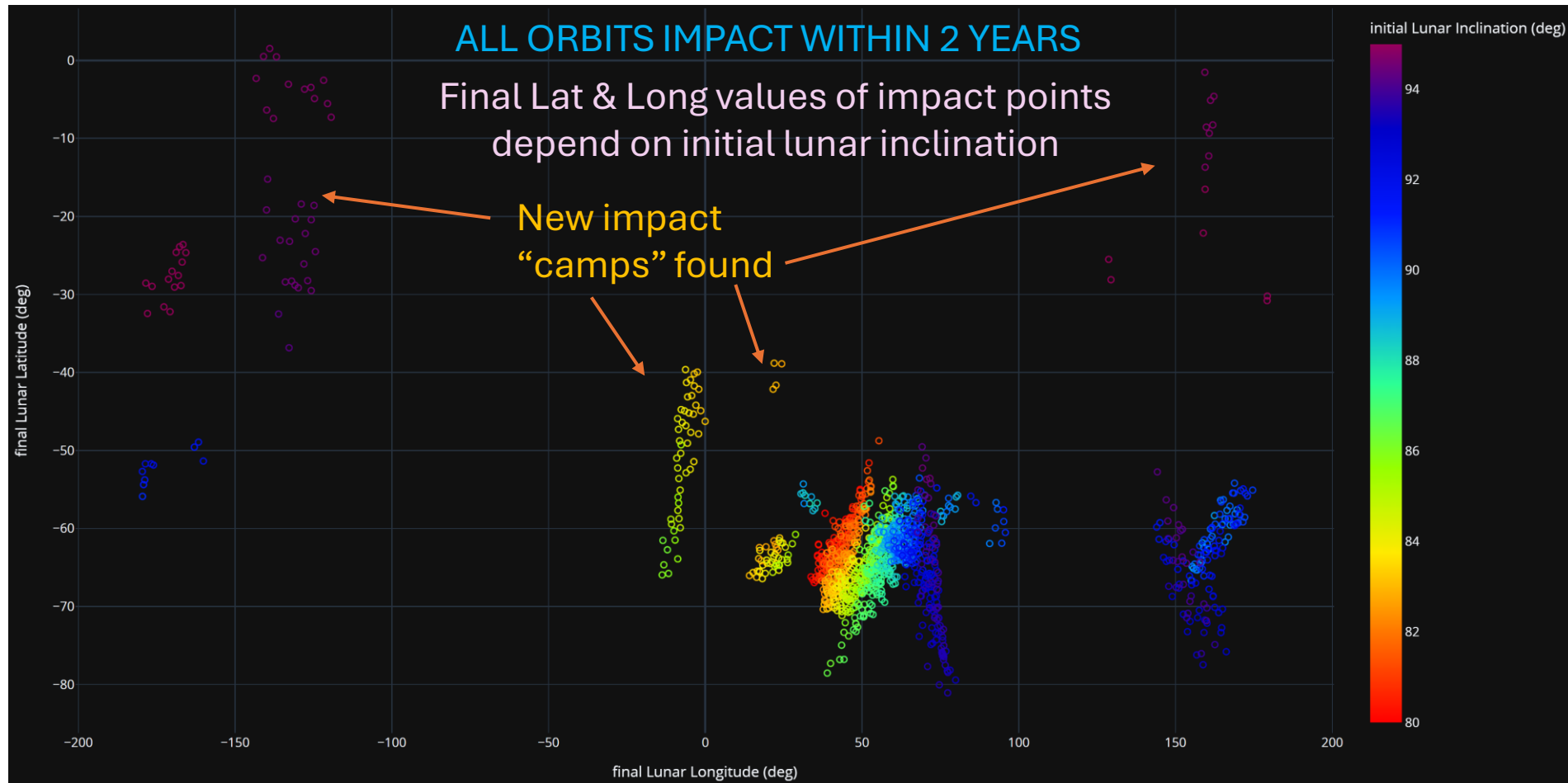
Design Variables (VARIED parameters):

* i from 80 to 95 deg (in 0.25 deg increments)
* ω = 260 to 280 deg: 1 deg increments
(match range given TRANSFERS from NRHO)

1,281 orbits

Response Variables:

Orbit Lifetime
Final Lat & Long, orbit energy, orbit period, etc.
Set of Keplerian Orbital Elements



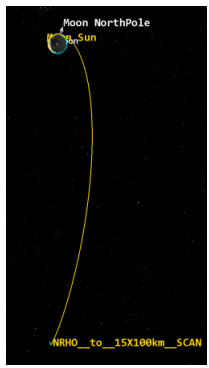
LLO Case 2:

LLO Descent/Ascent Orbit 100X15km

Minimum Lifetime = 7.8 days

ALL ORBITS IMPACT WITHIN 2 YEARS

Orbits with Initial Inclination ~94 deg. survive > 1 year for all initial argument of perilune values



Software: Flight-Proven
STK Astrogator

Force Model:

100X100 Lunar Gravity Field; 30X30 Earth;
4X0 Sun; Point Masses for all other planets;
Spherical Radiation Pressure

Numerical Integrator:

RKF78 with Max Abs Error = 1E-13 and
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TRANSFER from NRHO in STK MCS

Propagation Duration in STK =

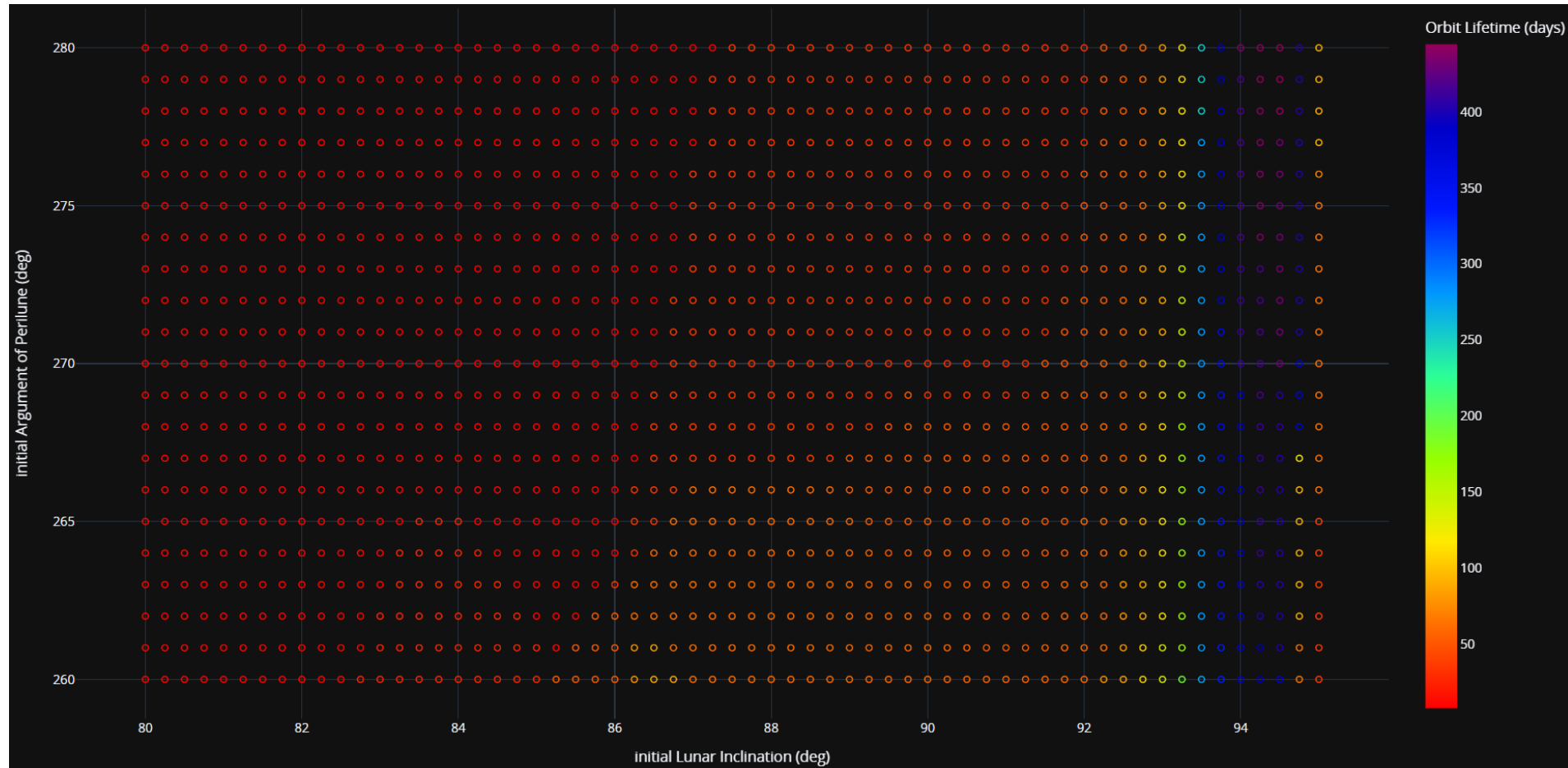
2 years (or STOP on 0 km Lunar Altitude- **NO TERRAIN**)

Design Variables (VARIED parameters):

* i from 80 to 95 deg (in 0.25 deg increments)
* ω = 260 to 280 deg: 1 deg increments
(match range given TRANSFERS from NRHO)
1,281 orbits

Response Variables:

Orbit Lifetime
Final Lat & Long, orbit energy, orbit period, etc.
Set of Keplerian Orbital Elements

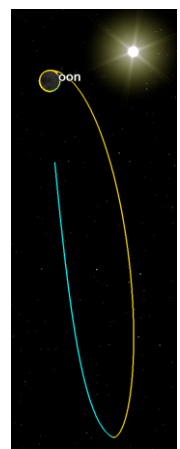


LLO Case 3:

LLO Descent/Ascent Orbit 120X10km

LLO Case 3:

LLO Descent/Ascent Orbit 120X10km



Minimum Lifetime = 2.62 days

Max Orbit Lifetime = 495.3 days

ALL 6,191 orbits impact the lunar surface within 2-yr of propagation

Software: Flight-Proven
STK Astrogator

Force Model:

100X100 Lunar Gravity Field; 30X30 Earth;
4X0 Sun; Point Masses for all other planets;
Spherical Radiation Pressure

Numerical Integrator:

RK78 with Max Abs Error = 1E-13

Initial FIXED Orbital Elements & Parameters:

- *Epoch: July 6, 2027
- *Perilune Altitude = 10 km
- *Apolune Altitude = 120 km
- *LAN: TRANSFER from NRHO in STK MCS

Propagation Duration in STK =

2 yrs (or STOP on 0 km Lunar Altitude
NO TERRAIN)

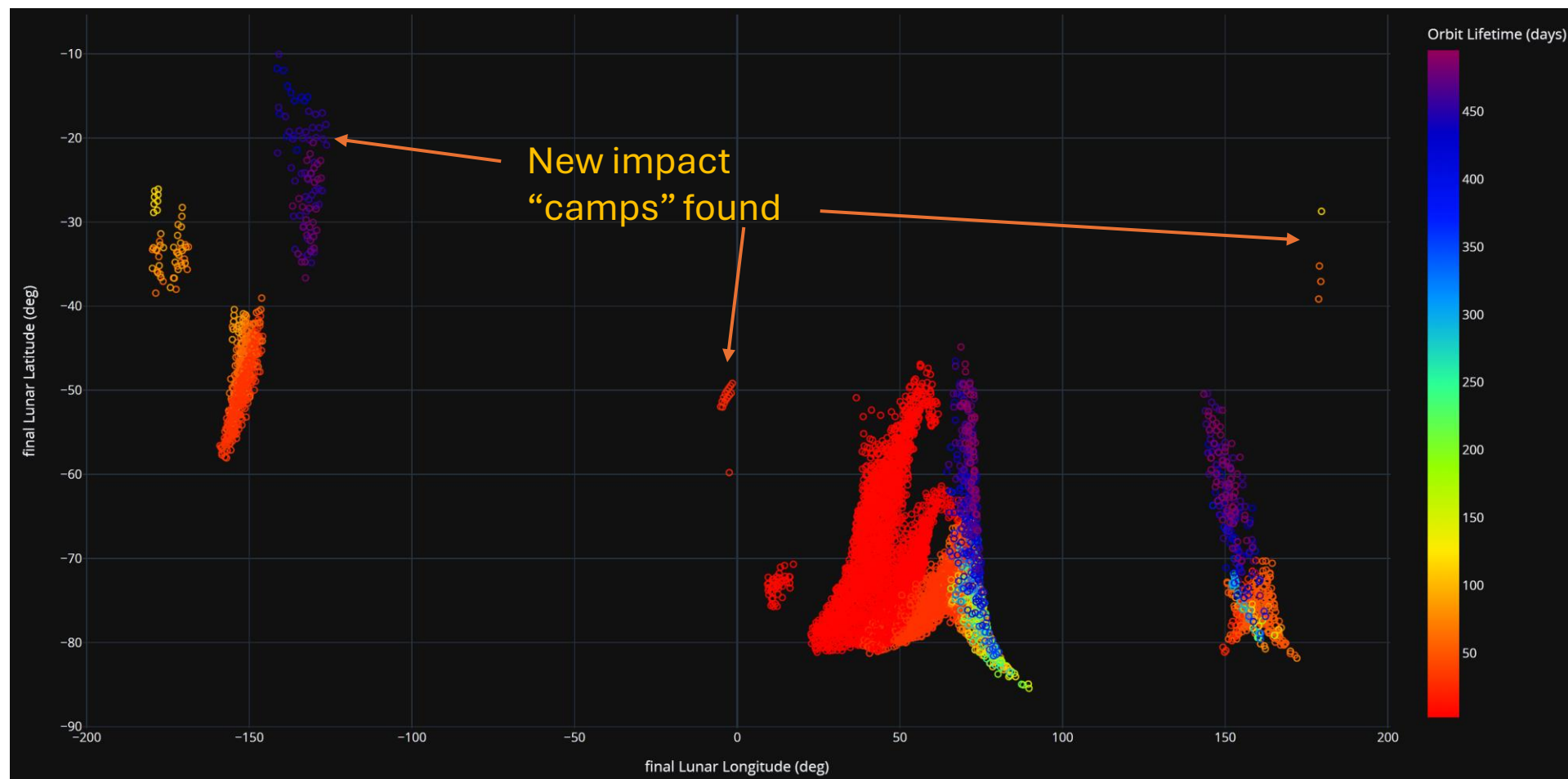
Design Variables (VARIED parameters):

- * i from 80 to 95 deg (in 0.1 deg increments)
- * ω = 260 to 280 deg (0.5 deg increments)

6191 orbits

Response Variables:

Orbit Lifetime (Final Epoch - Initial Epoch)
Final Perilune & Apolune Altitudes
Final ω , LAN, inc, Lat, Long, et al.



LLO Case 3:

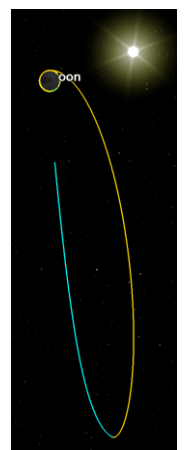
LLO Descent/Ascent Orbit 120X10km

Software: Flight-Proven
STK Astrogator

Minimum Lifetime = 2.62 days

Max Orbit Lifetime = 495.3 days

ALL 6,191 orbits impact the lunar surface within 2-yr of propagation



Force Model:

100X100 Lunar Gravity Field; 30X30 Earth;
4X0 Sun; Point Masses for all other planets;
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Numerical Integrator:

RK78 with Max Abs Error = 1E-13

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- *Apolune Altitude = 120 km
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Propagation Duration in STK =

2 yrs (or STOP on 0 km Lunar Altitude
NO TERRAIN)

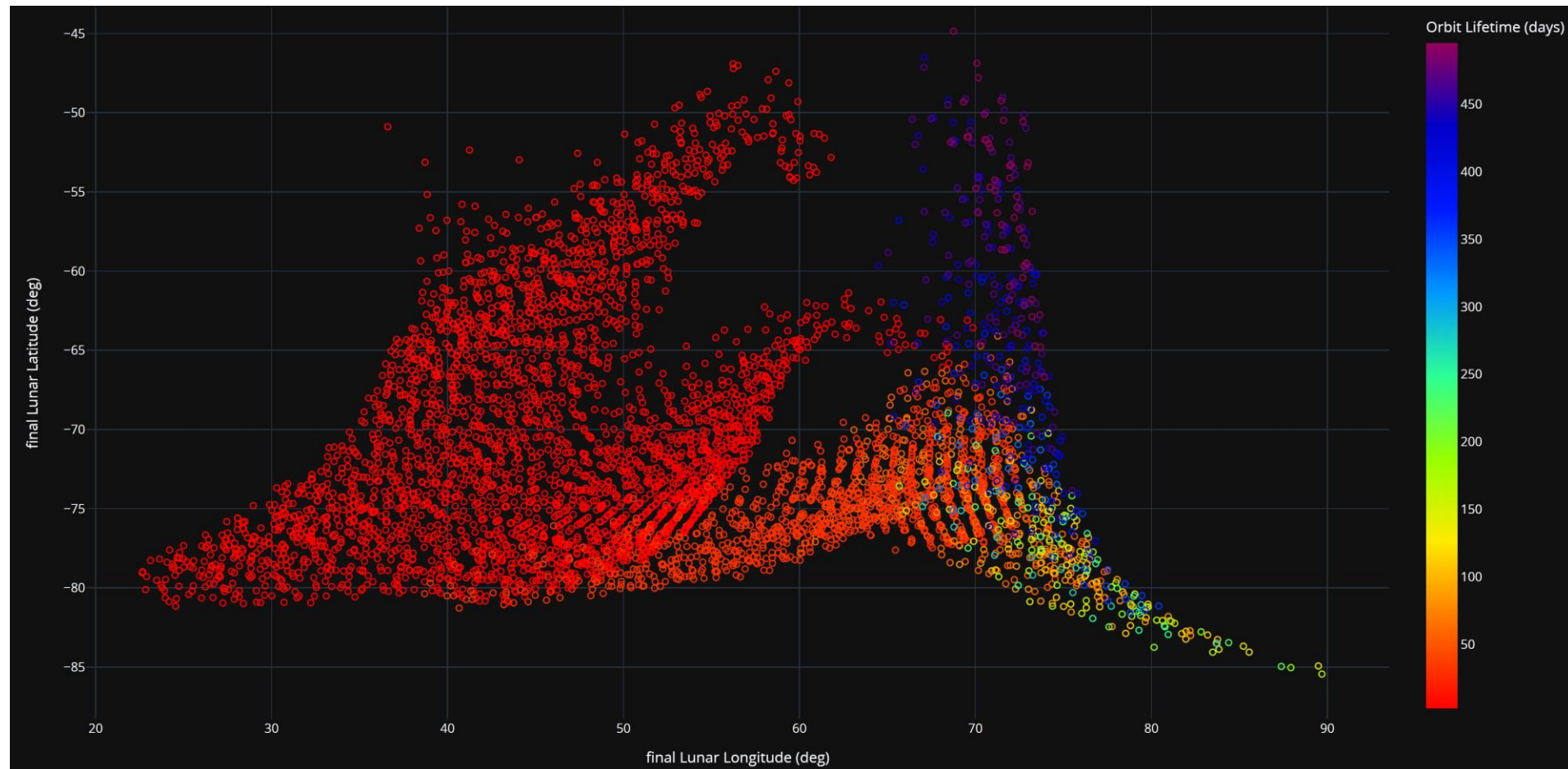
Design Variables (VARIED parameters):

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6,191 orbits

Response Variables:

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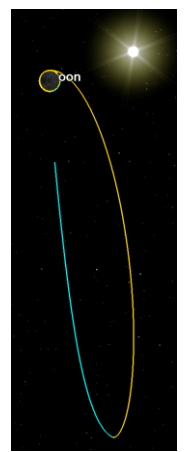
LLO Descent/Ascent Orbit 120X10km

Minimum Lifetime = 2.62 days

Max Orbit Lifetime = 495.3 days

ALL 6,191 orbits impact the lunar surface within 2-yr of propagation

Orbits with Initial Inclination ~ 92.5 to ~ 93.5 deg. survive > 1 year for all initial argument of perilune values



Software: Flight-Proven
STK Astrogator

Force Model:

100X100 Lunar Gravity Field; 30X30 Earth;
4X0 Sun; Point Masses for all other planets;
Spherical Radiation Pressure

Numerical Integrator:

RK78 with Max Abs Error = $1E-13$

Initial FIXED Orbital Elements & Parameters:

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- *Apolune Altitude = 120 km
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Propagation Duration in STK =

2 yrs (or STOP on 0 km Lunar Altitude
NO TERRAIN)

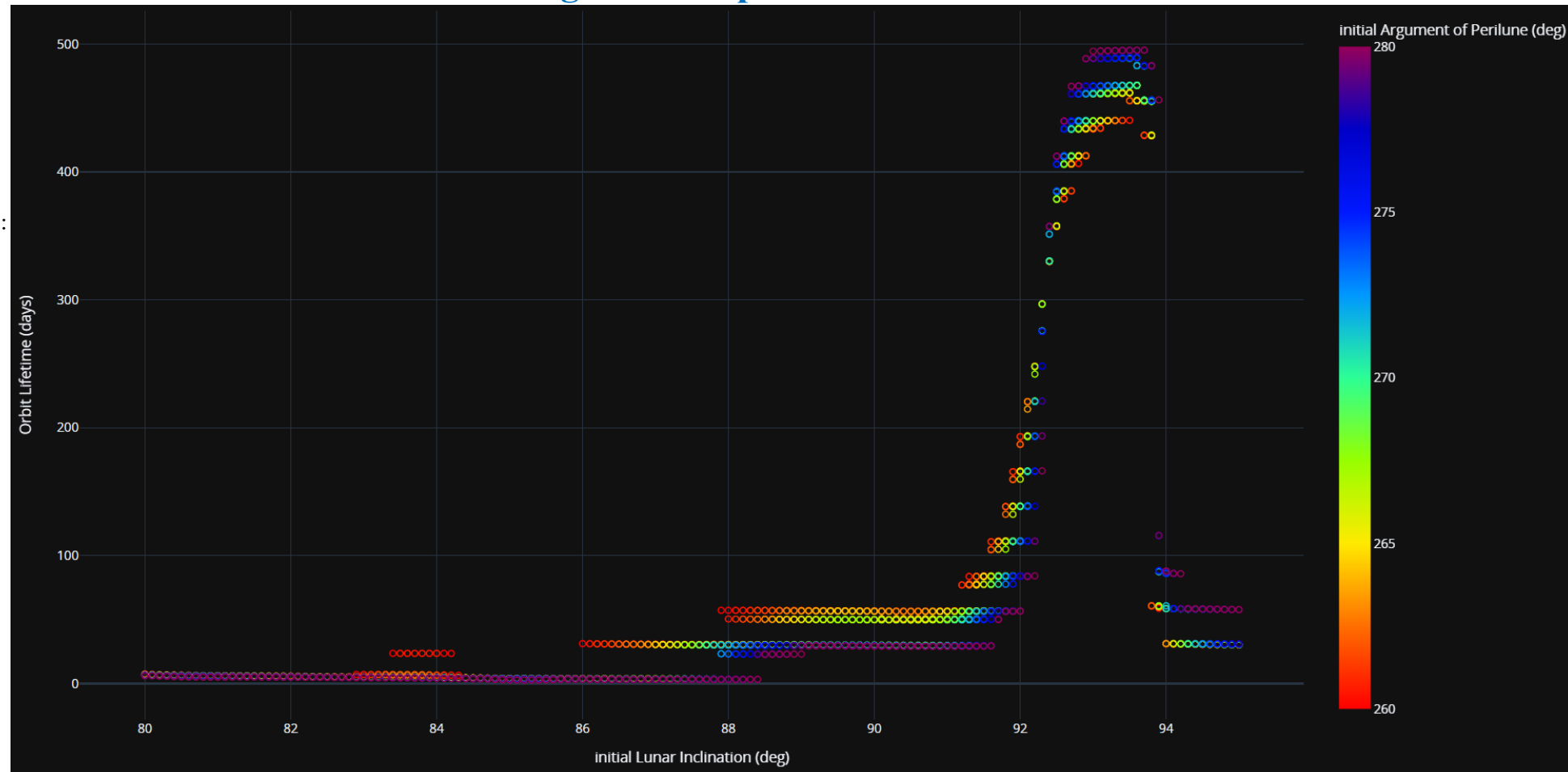
Design Variables (VARIED parameters):

- * i from 80 to 95 deg (in 0.1 deg increments)
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6,191 orbits

Response Variables:

Orbit Lifetime (Final Epoch - Initial Epoch)
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LLO Case 3:

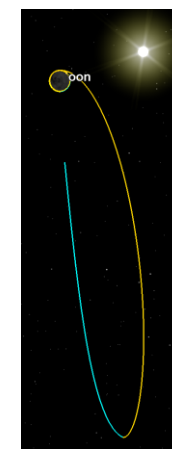
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Spherical Radiation Pressure

Numerical Integrator:

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*Apolune Altitude = 120 km

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Propagation Duration in STK =

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NO TERRAIN)

Design Variables (VARIED parameters):

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* ω = 260 to 280 deg (0.5 deg increments)

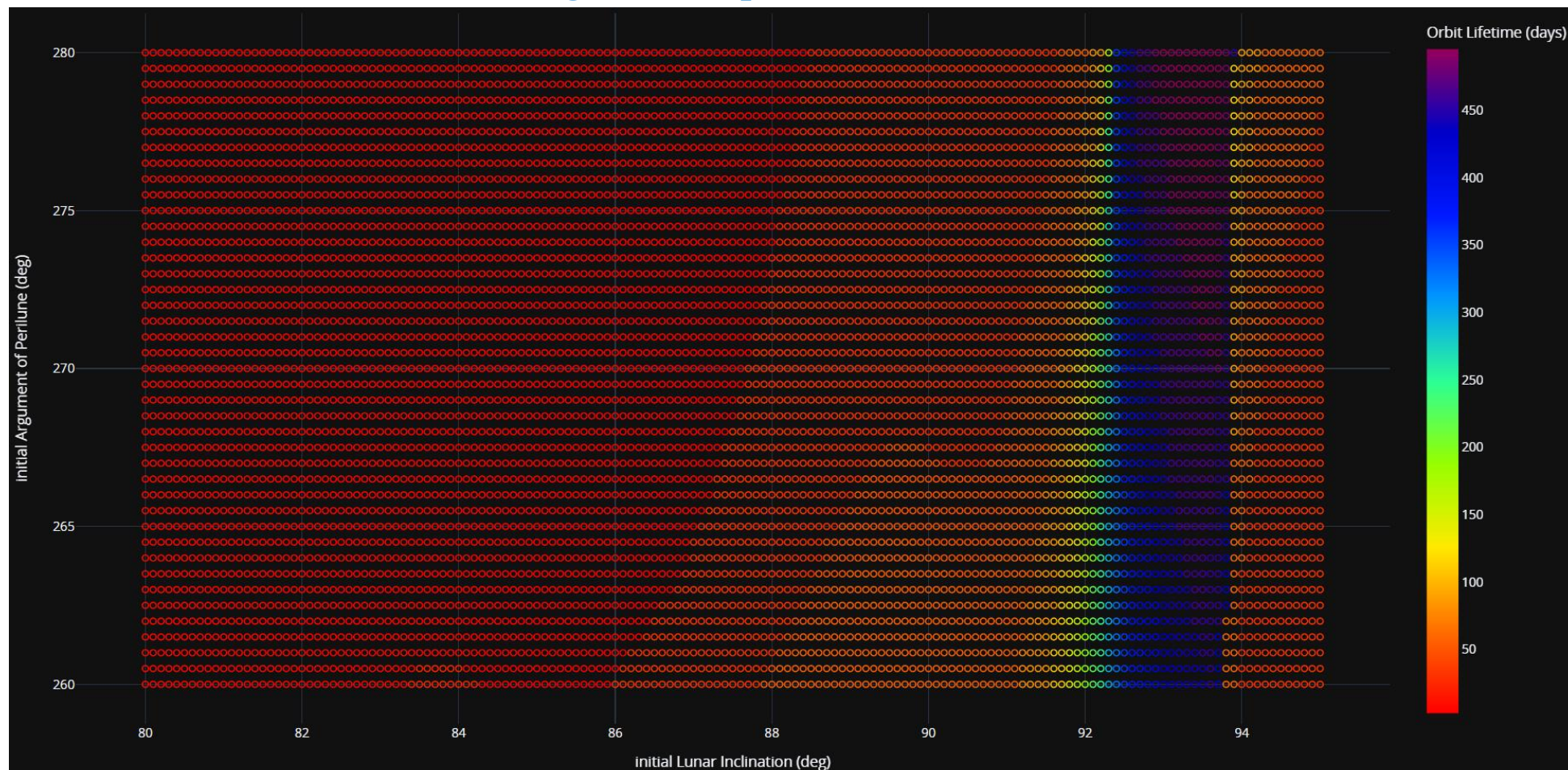
6,191 orbits

Response Variables:

Orbit Lifetime (Final Epoch - Initial Epoch)

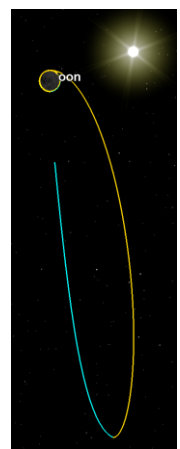
Final Perilune & Apolune Altitudes

Final ω , LAN, inc, Lat, Long, et al.



LLO Case 3:

LLO Descent/Ascent Orbit 120X10km



Software: Flight-Proven
STK Astrogator

Minimum Lifetime = 2.62 days

Max Orbit Lifetime = 495.3 days

ALL 6,191 cases impact the lunar surface within 2-yr of propagation

Force Model:

100X100 Lunar Gravity Field; 30X30 Earth;
4X0 Sun; Point Masses for all other planets;
Spherical Radiation Pressure

Numerical Integrator:

RK78 with Max Abs Error = 1E-13

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- *Epoch: July 6, 2027
- *Perilune Altitude = 10 km
- *Apolune Altitude = 120 km
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Propagation Duration in STK =

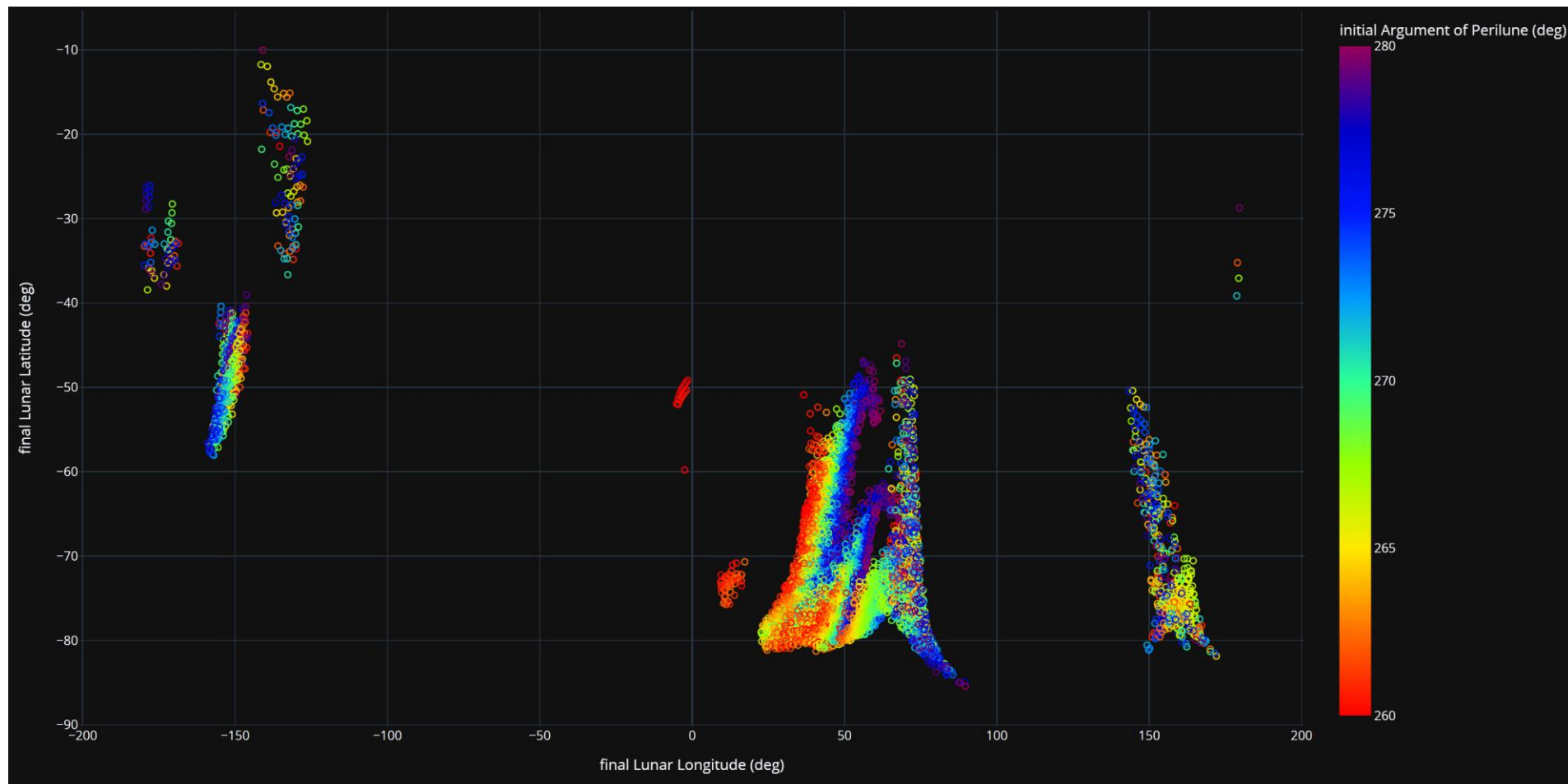
2 yrs (or STOP on 0 km Lunar Altitude
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Design Variables (VARIED parameters):

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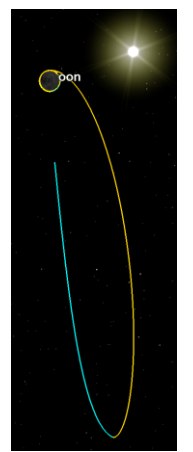
LLO Descent/Ascent Orbit 120X10km

Software: Flight-Proven
STK Astrogator

Minimum Lifetime = 2.62 days

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ALL 6,191 orbits impact the lunar surface within 2-yr of propagation



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RK78 with Max Abs Error = 1E-13

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2 yrs (or STOP on 0 km Lunar Altitude
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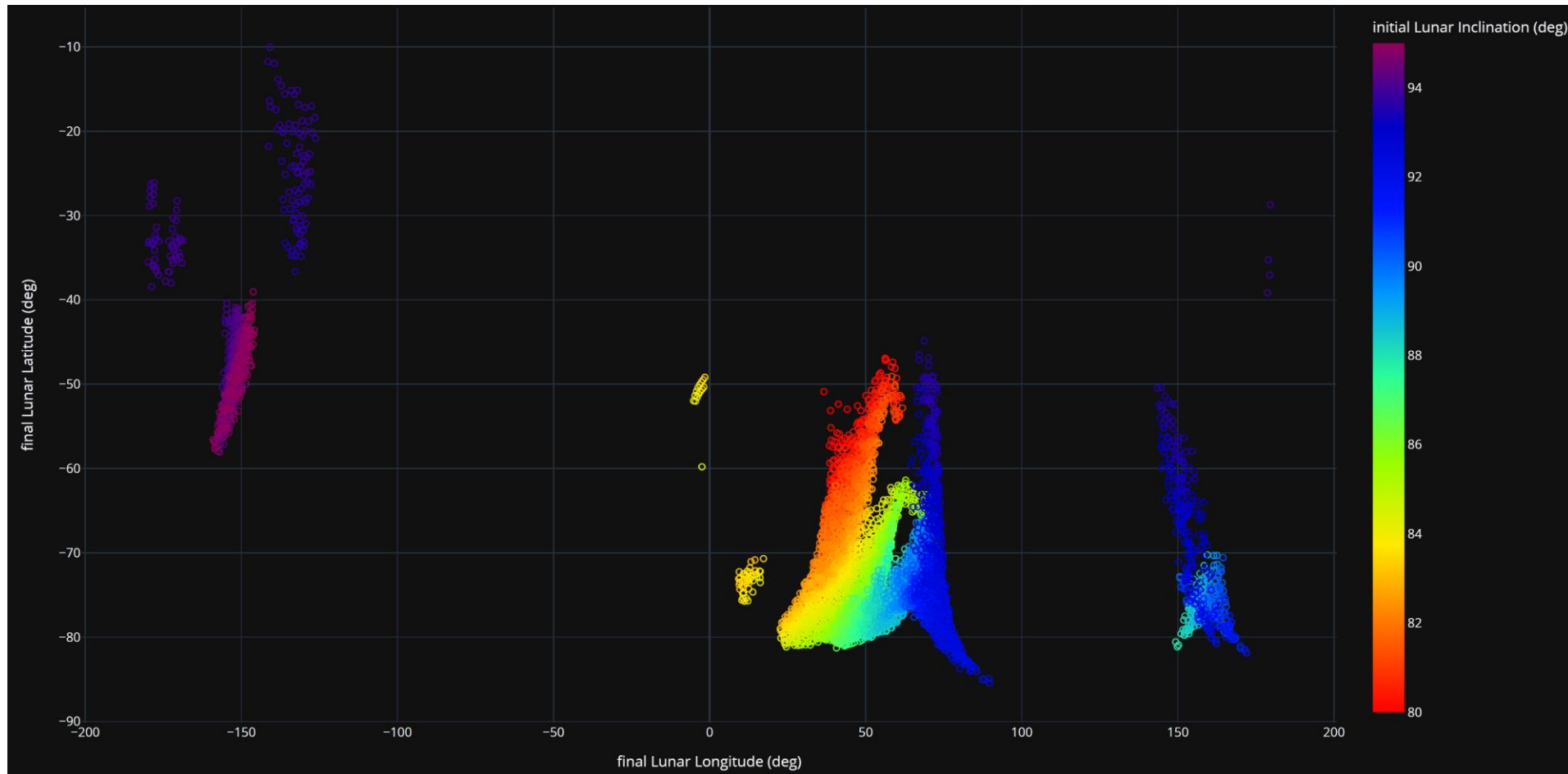
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6,191 orbits

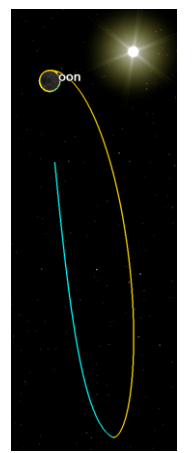
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Orbit Lifetime (Final Epoch - Initial Epoch)
Final Perilune & Apolune Altitudes
Final ω , LAN, inc, Lat, Long, et al.



LLO Case 3:

LLO Descent/Ascent Orbit 120X10km



Software: Flight-Proven
STK Astrogator

Minimum Lifetime = 2.62 days

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Numerical Integrator:

RK78 with Max Abs Error = 1E-13

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- *Perilune Altitude = 10 km
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Propagation Duration in STK =

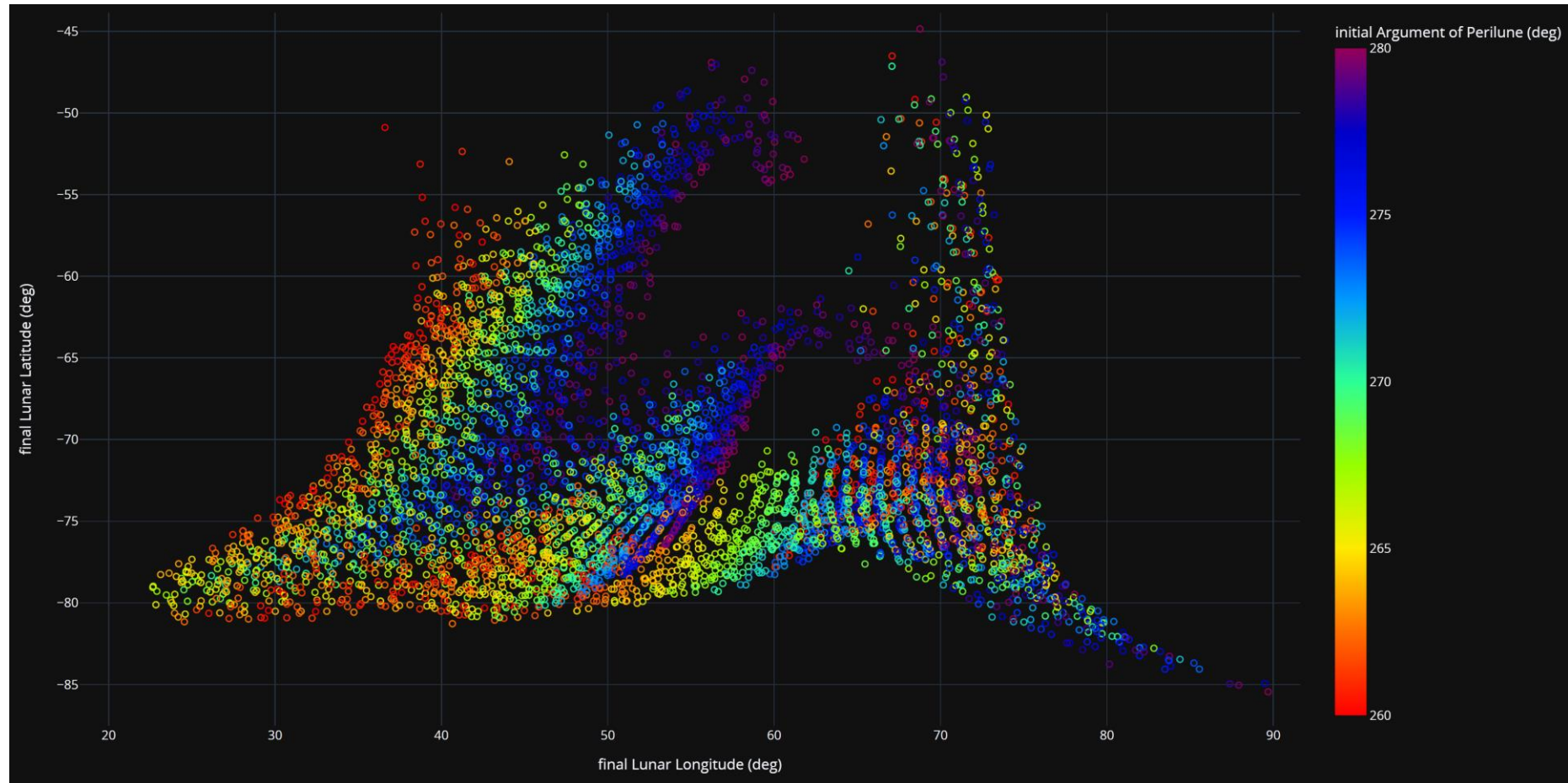
2 yrs (or STOP on 0 km Lunar Altitude
NO TERRAIN)

Design Variables (VARIED parameters):

- * i from 80 to 95 deg (in 0.1 deg increments)
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- 6,191 orbits

Response Variables:

Orbit Lifetime (Final Epoch - Initial Epoch)
Final Perilune & Apolune Altitudes
Final ω , LAN, inc, Lat, Long, et al.



LLO Case 3:

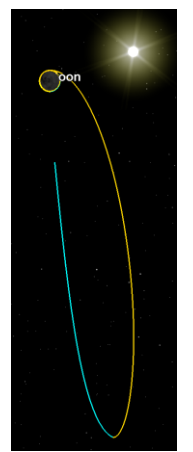
LLO Descent/Ascent Orbit 120X10km

Software: Flight-Proven
STK Astrogator

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ALL 6,191 orbits impact the lunar surface within 2-yr of propagation



Force Model:

100X100 Lunar Gravity Field; 30X30 Earth;
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Propagation Duration in STK =

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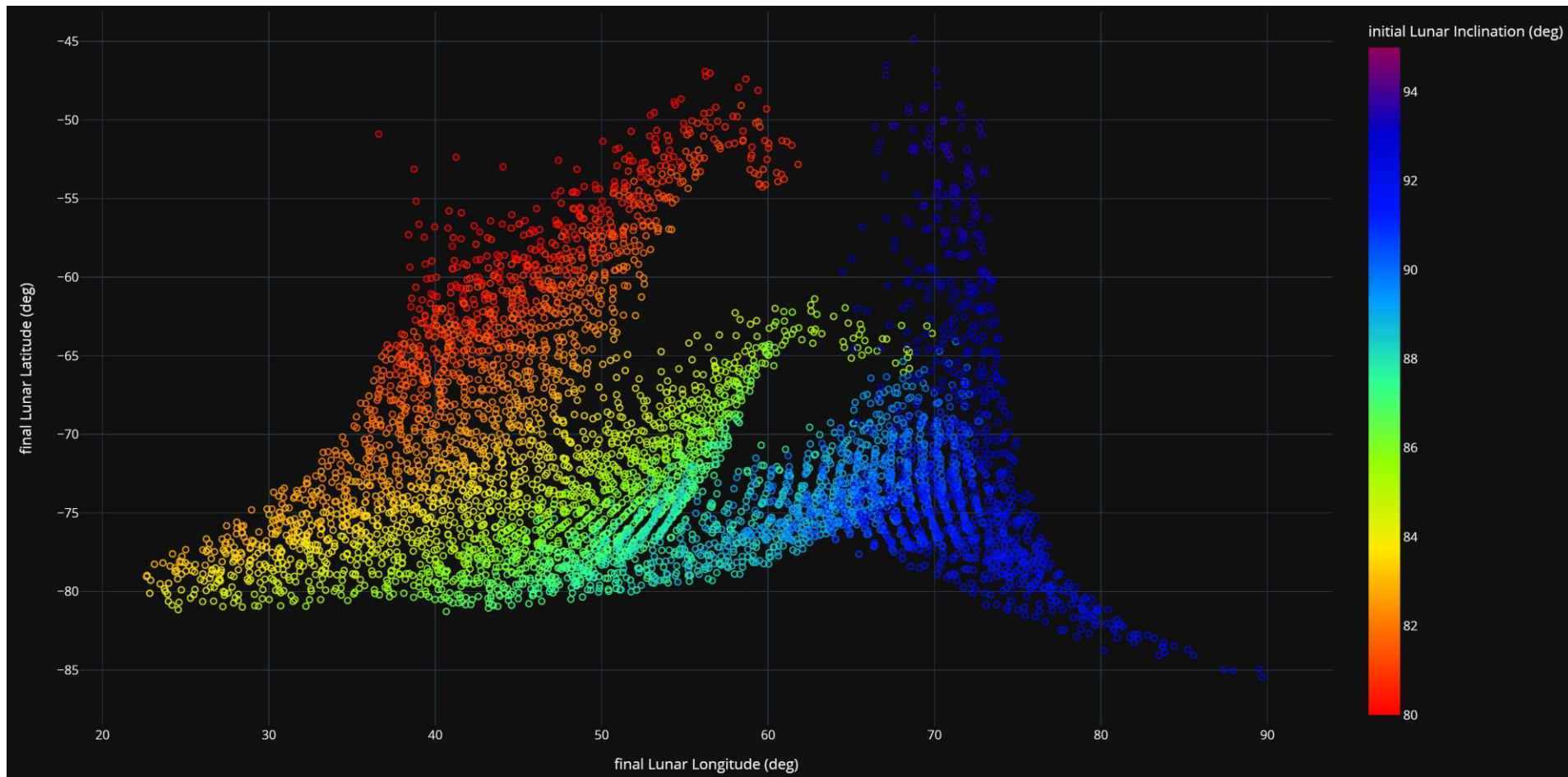
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6,191 orbits

Response Variables:

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Final ω , LAN, inc, Lat, Long, et al.



Summary for Selected Near-Polar Low Lunar Orbit Cases

Lunar Orbit Type	Total # of Cases	# of Cases that Impact the Moon within 2-year Max Propagation Period (%) [Max Propagation Period]	# of Cases that Survive Max Propagation Period (%) [Max Propagation Period]	Minimum Orbit Lifetime among all cases	Maximum Orbit Lifetime among all cases	Notes
100 km Circular (LLO Case 1)	151	91 (60.26%)	60 (39.74%)	168 days	730 days	Cases that survive 2-yr propagation have initial inclination: ~83 to ~87 deg. and ~93 to ~95 deg
100 X 15 km (LLO Case 2)	1,281	1,281 (100%)	0 (0%)	7.8 days	450 days	All cases impact the Moon within 450 days. New impact “camps” found with initial inc.: ~83-87 deg and inc. = 95 deg
120 X 10 km (LLO Case 3)	6,191	6,191 (100%)	0 (0%)	2.62 days	495.3 days	All cases impact the Moon within 495.3 days New impact “camps” possible found with initial inc. ~84 deg and ~ 94 deg

→ ALL CASES: Final Lat & Long lunar surface impact values depend on initial lunar inclination

Catalog of Scientifically Important Lunar Sites (Excluding PSRs & Historic Sites)

Catalog of Scientifically Important Lunar Sites (Excluding PSRs & Historic Sites)

<u>Category</u>	<u>Site</u>	<u>Latitude</u>	<u>Longitude</u>	<u>Scientific Importance</u>
Farside Radio Astronomy	Daedalus Crater	5.9° S	179.4° E	Ideal radio-quiet farside telescope site
Farside Radio Astronomy	Hertzprung Basin	1.4° N	128.7° W	Large farside basin shielded from Earth radio
Farside Radio Astronomy	Apollo Basin	36.1° S	151.8° W	Large basin within SPA
Farside Radio Astronomy	Mendeleev Basin	5.7° N	140.9° E	Farside multiring basin
Farside Radio Astronomy	Korolev Crater	4.0° S	157.4° W	Thick farside crust region; Lunar Geophysical Network Candidate Site
Farside Radio Astronomy	Tsiolkovskiy Crater	20.4° S	129.1° E	Isolated farside mare basin
Farside Radio Astronomy	Mare Moscoviense	27.3° N	147.9° E	Rare farside mare volcanism
Farside Radio Astronomy	Mare Ingenii	33.7° S	163.5° E	Magnetic anomaly region
Farside Radio Astronomy	Mare Marginis	13° N	86° E	Farside limb mare useful for radio shielding

Catalog of Scientifically Important Lunar Sites (Excluding PSRs & Historic Sites)

<u>Category</u>	<u>Site</u>	<u>Latitude</u>	<u>Longitude</u>	<u>Scientific Importance</u>
Seismic Quiet (GW Observatory)	Antoniadi Crater	69.7° S	172° W	Deep farside basin
Seismic Quiet (GW Observatory)	Leibnitz Crater	38.2° S	179.5° W	Thick crust region
Seismic Quiet (GW Observatory)	Finsen Crater	42.4° S	176.8° E	Interior SPA terrain

Catalog of Scientifically Important Lunar Sites (Excluding PSRs & Historic Sites)

<u>Category</u>	<u>Site</u>	<u>Latitude</u>	<u>Longitude</u>	<u>Scientific Importance</u>
Deep Highlands	Dirichlet– Jackson Basin	12° S	161° W	Ancient farside crust
Deep Highlands	Hertzprung Highlands	2° S	128° W	Old highland terrain
Deep Highlands	Apollo Basin Highlands	36° S	151° W	Highland terrain
Deep Highlands	Korolev Highlands	4° S	159° W	Thick crust
Deep Highlands	Tsiolkovskiy Highlands	20° S	129° E	Ancient crustal terrain

Catalog of Scientifically Important Lunar Sites (Excluding PSRs & Historic Sites)

<u>Category</u>	<u>Site</u>	<u>Latitude</u>	<u>Longitude</u>	<u>Scientific Importance</u>
Impact Basin Chronology	Oriente Basin	19.4° S	95° W	Best preserved basin
Impact Basin Chronology	Imbrium Basin	32.8° N	15.6° W	Major mare basin
Impact Basin Chronology	Serenitatis Basin	28° N	17° E	Mare basalt stratigraphy
Impact Basin Chronology	Crisium Basin	17° N	59° E	Isolated mare basin; Lunar Geophysical Network Candidate Site
Impact Basin Chronology	Nectaris Basin	16° S	34° E	Early basin
Impact Basin Chronology	Humorum Basin	24° S	39° W	Flooded basin
Impact Basin Chronology	Smythii Basin	1° N	87° E	Mare volcanism
Impact Basin Chronology	Moscoviense Basin	27° N	147° E	Farside basin
Impact Basin Chronology	Mendeleev Basin	6° N	141° E	Large multiring basin
Impact Basin Chronology	Schrodinger Basin	75° S	132.4° E	Young peak-ring basin with volcanic vents, pyroclastic deposits, & deep crustal material

Catalog of Scientifically Important Lunar Sites (Excluding PSRs & Historic Sites)

<u>Category</u>	<u>Site</u>	<u>Latitude</u>	<u>Longitude</u>	<u>Scientific Importance</u>
Volcanism	Marius Hills	14° N	56° W	Large volcanic complex
Volcanism	Ina Caldera	18.7° N	5.3° E	Possible recent volcanism
Volcanism	Gruithuisen Domes	36° N	40° W	Silicic domes
Volcanism	Compton– Belkovich Volcanic Complex	61° N	100° E	Rare silicic volcanism
Volcanism	Schrödinger Basin	75° S	132° E	Young basin volcanism
Volcanism	Sulpicius Gallus	21° N	11° E	Pyroclastic glass deposits
Volcanism	Rima Bode	13° N	3° W	Volcanic rille
Volcanism	Rima Prinz	26° N	44° W	Volcanic rille
Volcanism	Rima Hadley	26° N	3° E	Classic sinuous rille
Volcanism	Rima Hyginus	8° N	7° E	Collapsed volcanic channel

Catalog of Scientifically Important Lunar Sites (Excluding PSRs & Historic Sites)

<u>Category</u>	<u>Site</u>	<u>Latitude</u>	<u>Longitude</u>	<u>Scientific Importance</u>
Magnetic Anomaly / Swirls	Airy Swirl	18° S	5° E	Small swirl
Magnetic Anomaly / Swirls	Mare Ingenii Swirls	33° S	163° E	Farside swirl
Magnetic Anomaly / Swirls	Mare Marginis Swirls	13° N	86° E	Swirl region
Magnetic Anomaly / Swirls	Gerlache Magnetic Anomaly	75° S	134° W	Strong crustal magnetism
Magnetic Anomaly / Swirls	Descartes Magnetic Region	9° S	16° E	Magnetic anomaly

Catalog of Scientifically Important Lunar Sites (Excluding PSRs & Historic Sites)

<u>Category</u>	<u>Site</u>	<u>Latitude</u>	<u>Longitude</u>	<u>Scientific Importance</u>
Tectonics / Rilles	Rima Sirsalis	12° S	60° W	Long rille
Tectonics / Rilles	Vallis Schröteri	25° N	50° W	Largest rille
Tectonics / Rilles	Rupes Recta	22° S	7° W	Major fault scarp
Tectonics / Rilles	Rupes Altai	25° S	23° E	Large basin rim scarp

Catalog of Scientifically Important Lunar Sites (Excluding PSRs & Historic Sites)

<u>Category</u>	<u>Site</u>	<u>Latitude</u>	<u>Longitude</u>	<u>Scientific Importance</u>
Geochemistry	Imbrium KREEP Terrane	32° N	20° W	Radioactive element enrichment
Geochemistry	Procellarum KREEP Terrane	20° N	45° W	Large geochemical province; Lunar Geophysical Network Candidate Site
Geochemistry	Schickard Basin	44.3° N	55.1° W	Large geochemical province; Lunar Geophysical Network Candidate Site
Geochemistry	Compton– Belkovich Thorium Hotspot	61° N	100° E	Thorium enrichment
Geochemistry	SPA Mantle Exposure	52° S	168° W	Possible mantle materials

Catalog of Scientifically Important Lunar Sites (Excluding PSRs & Historic Sites)

<u>Category</u>	<u>Site</u>	<u>Latitude</u>	<u>Longitude</u>	<u>Scientific Importance</u>
Young Impact Craters	Tycho	43° S	11° W	Young impact crater
Young Impact Craters	Copernicus	9.7° N	20° W	Well-preserved crater
Young Impact Craters	Giordano Bruno	35.97° N	102.89° E	Extremely young crater; Suspected source of NEA 469219 Kamo'oalewa
Young Impact Craters	Jackson	22° N	163° W	Young rayed crater

Catalog of Scientifically Important Lunar Sites (Excluding PSRs & Historic Sites)

<u>Category</u>	<u>Site</u>	<u>Latitude</u>	<u>Longitude</u>	<u>Scientific Importance</u>
Lava Tubes	Marius Hills Skylights	14° N	56° W	Possible lava tube entrances
Lava Tubes	Mare Tranquillitatis Skylight	8° N	33° E	Collapsed lava tube

Catalog of Scientifically Important Lunar Sites (Excluding PSRs & Historic Sites)

<u>Category</u>	<u>Site</u>	<u>Latitude</u>	<u>Longitude</u>	<u>Scientific Importance</u>
Polar Illumination Peaks	Malapert Massif	85° S	0° E	High illumination ridge
Polar Illumination Peaks	Leibnitz Plateau	85° S	30° E	Long sunlight duration

Catalog of Scientifically Important Lunar Sites (Excluding PSRs & Historic Sites)

<u>Category</u>	<u>Site</u>	<u>Latitude</u>	<u>Longitude</u>	<u>Scientific Importance</u>
Hydrogen Deposits	Aristarchus Hydrogen Anomaly	23° N	47° W	Enhanced hydrogen
Hydrogen Deposits	Mare Frigoris Hydrogen Patch	57° N	2° W	Possible hydrated materials