National Aeronautics and Space Administration

AN OBSERVATIONAL APPROACH TO LOW LUNAR FROZEN ORBIT DESIGN

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NASA/GSFC

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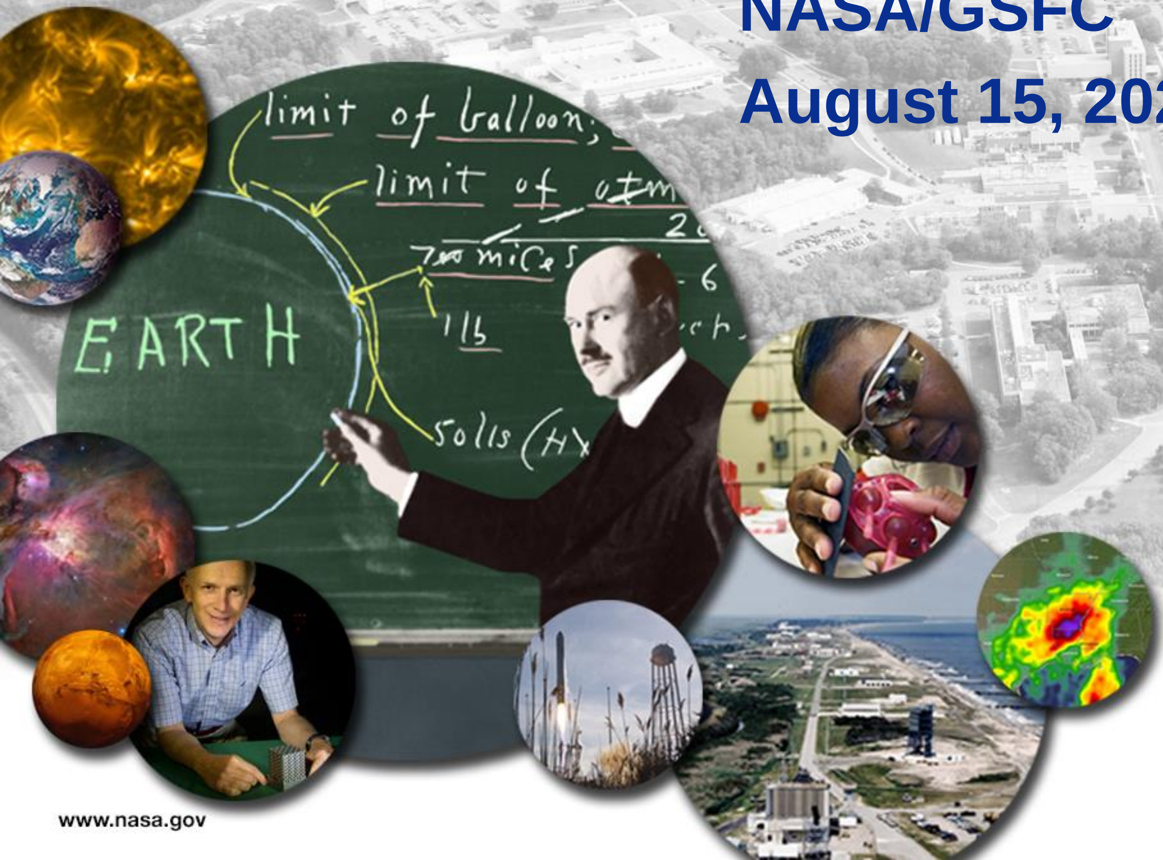

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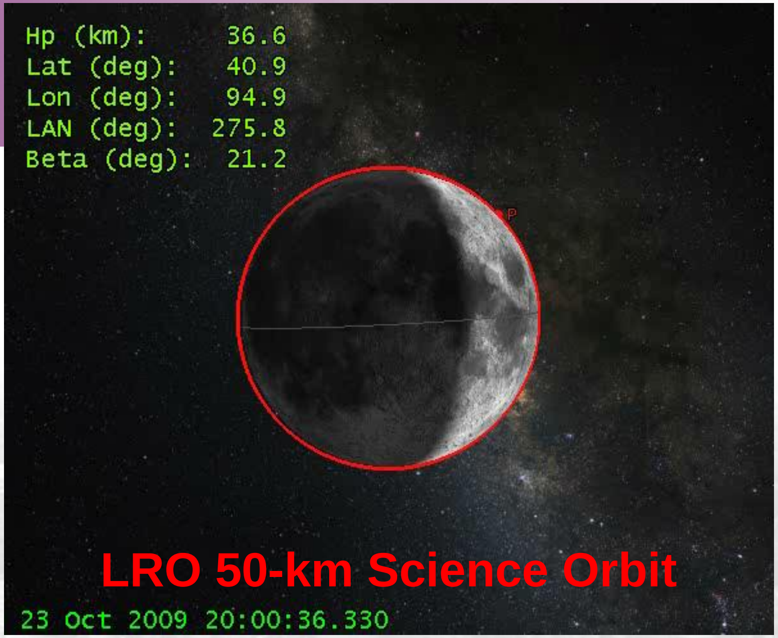
Agenda

- Introduction
- LRO Frozen Orbits
- Search for Frozen Orbit Metric
- Conclusions

Lunar Frozen Orbits

- At the Earth, the J2 potential term induces a secular drift of the line of apsides
- The Moon's "lumpy" gravity field has the tendency to torque around the line of apsides, moving periselene
- The Lunar Reconnaissance Orbiter (LRO) team took advantage of observations from the Lunar Prospector (LP) mission to implement a low (altitude) lunar frozen orbit for LRO instrument commissioning and extended mission phases
- LRO used a frozen orbit to reduce yearly fuel expenditures by >90% and extend its mission by 10+ years



(view is along Earth-Moon line)

Orbit Modeling

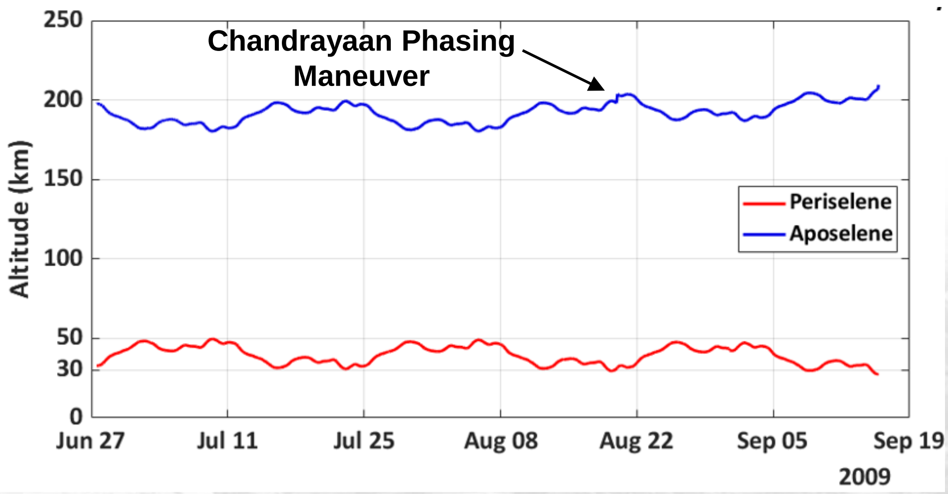
- LRO originally used a 150 x 150 (degree, order) LP150Q lunar gravity model along with the Sun and Moon as point sources (along with solar radiation pressure)
- Upgrades in gravity models came from LRO's LOLA (Lunar Orbiting Laser Altimeter) and finally GRAIL's (Gravity Recovery and Interior Laboratory) instrument teams
- The GRAIL GRGM900C (900 x 900) model is currently used
  - We truncate the model, for computational efficiency, to 270 x 270 for operations and to 150 x 150 for analysis

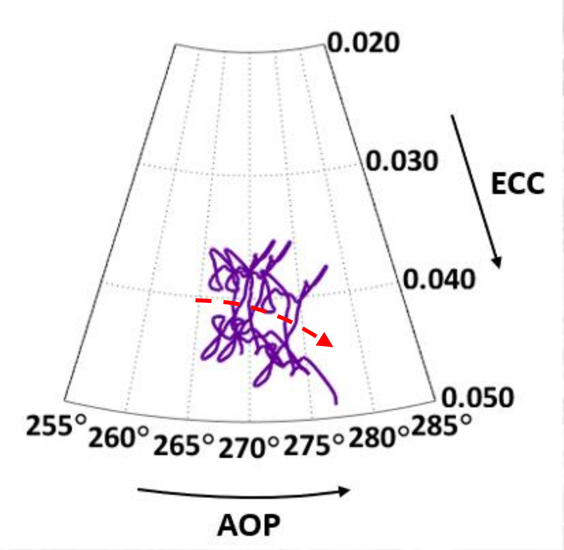
- This frozen orbit analysis looks at the motion of periselene by focusing on key orbit elements at the periselene location
  - The periselene elements include the shape-related altitude & eccentricity (ECC) and Moon-Fixed orientation related inclination (INC), argument of periselene (AOP), and longitude of the ascending node (LAN)

- I believe that using orientation elements in a Moon-Fixed frame helps to tie the perturbations seen to the mass concentrations in the lunar gravity field

LRO Commissioning Orbit

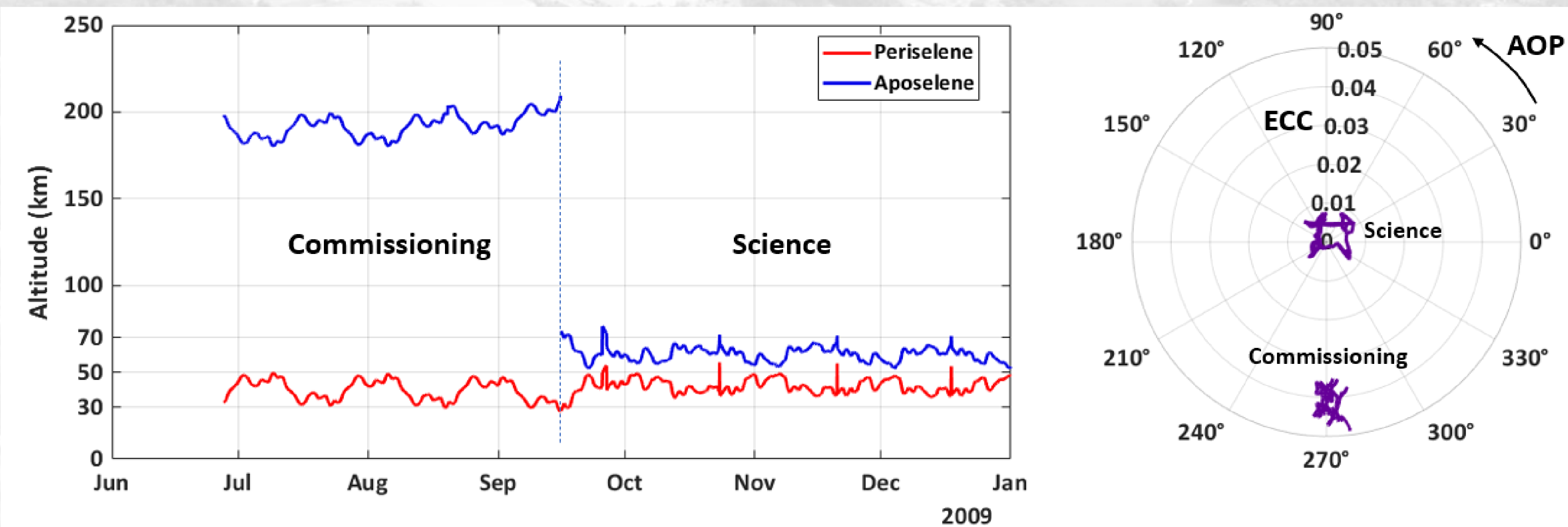
- After launching on June 18, 2009, LRO captured into lunar orbit on June 23, 2009 and maneuvered into a quasi-frozen polar orbit on June 27, 2009
- This 30 x 200 km orbit (min/max) was used to commission LRO's instruments prior to beginning science observations
- LRO's commission orbit had all the hallmarks of a typical low lunar frozen orbit
  - Apsis altitudes are bounded
  - Periselene is near the South Pole (AOP near 270º)
- The commissioning orbit did exhibit drift
  - This was partially due to a maneuver to coordinate observations with Chandrayaan
- Regardless, the quasi-frozen commissioning orbit did its job





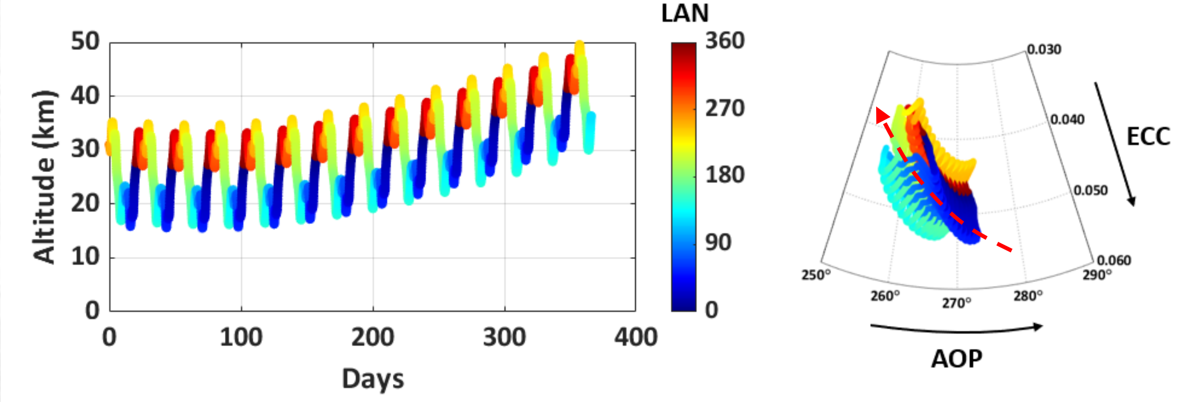
LRO Orbit Comparison

- This comparison shows the differences between LRO's orbits
  - Commissioning: 30 x 200 km, AOP near 270º, quasi-frozen
  - Science: 50 ± 15 km, AOP centered near polar plot origin



LRO's Frozen Orbit Return

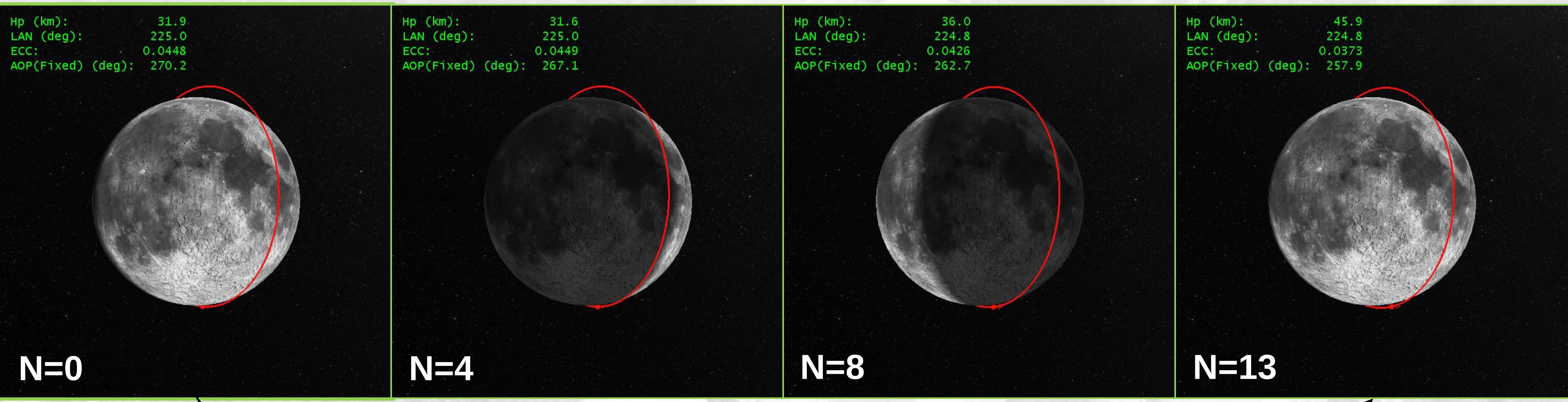
- LRO decided to return to a frozen orbit at the end of 2011 to save on orbital maintenance costs
- An initial attempt looked at the 30 x 200 km commissioning orbit
  - SMA = 1852.4 km
  - ECC = 0.046
  - AOP = 270º
- A 1-year simulation yielded a very "unfrozen" orbit
  - Unbounded periselene altitude
  - Eccentricity vector drift



- Including the orbit LAN as a 3rd dimension in the plot shows the strong correlation across each lunar cycle

Frozen Orbit Targeting

- The correlation of the orbit elements to the LAN led to a simple differential-correction (DC) procedure to find initial conditions that null ECC and AOP growth over a given duration, thus, freezing the orbit
- Using the previous example for SMA = 1852.4



<u>Fixed</u>
LAN, SMA

<u>Vary Initial</u>
ECC, AOP

The DC varies the initial ECC and AOP to drive ΔECC and ΔAOP to zero, after an integer number of lunar cycles

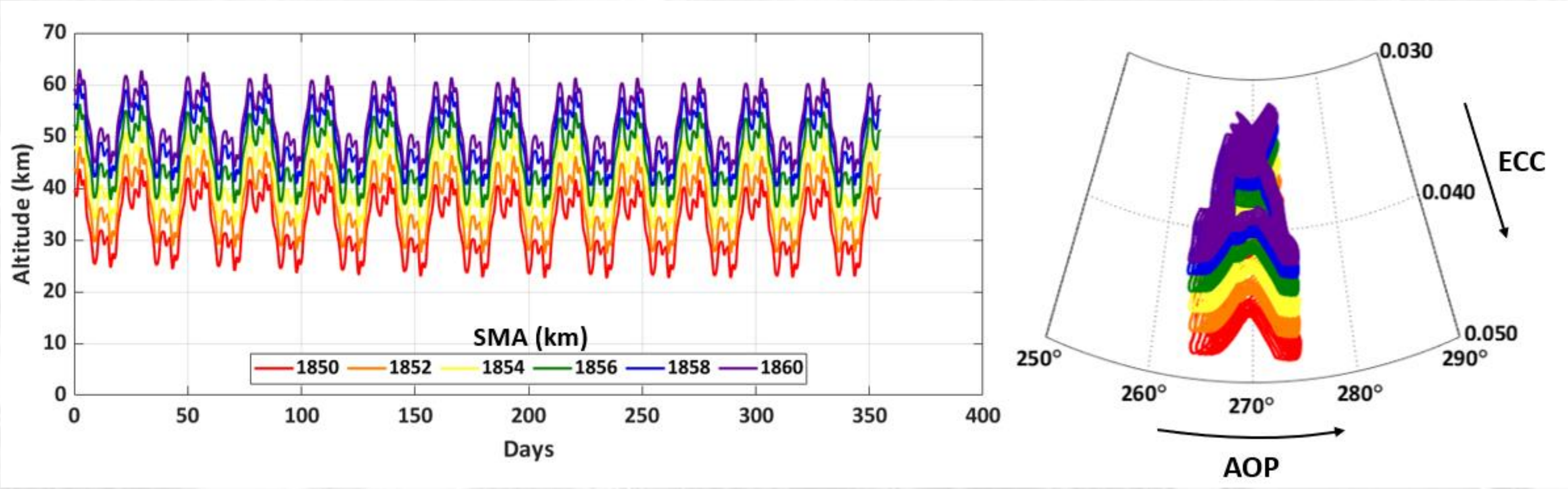
- I've used N = 13 (≈ 1 year)

<u>Fixed</u>
LAN, SMA

ΔECC = -0.0075
ΔAOP = -12.3º
ΔHp = 14.0 km

First Extended Mission Frozen Orbit

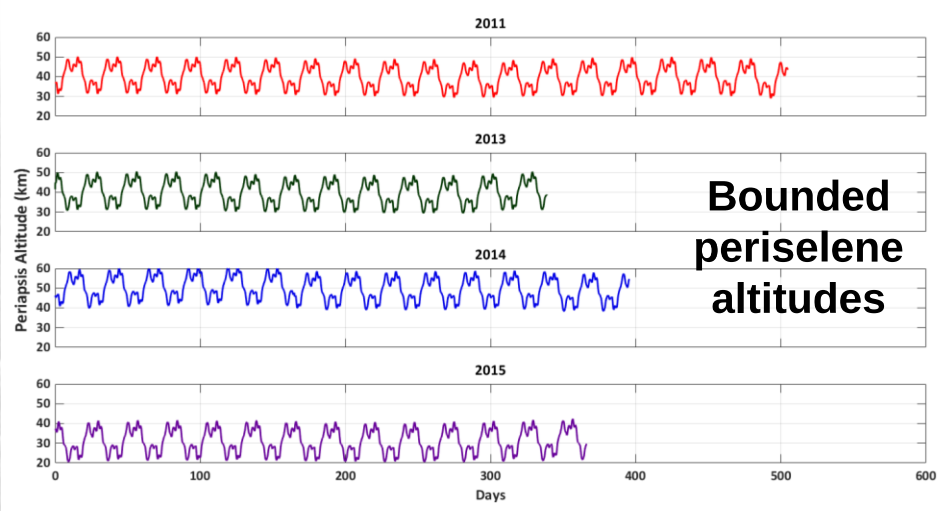
- I created a series of Frozen Orbit cases to present to the LRO Science Team
  - All cases showed bounded periselene altitudes and repeating eccentricity vector patterns
  - Different SMA values led to different minimum Periselene altitudes



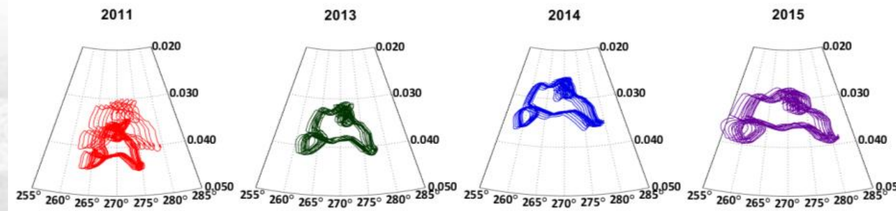
- The science team chose an SMA of 1851 km that corresponded to a minimum periselene altitude of 30 km
- on December 11, 2011, a 2-burn sequence (31.0 & 2.1 m/s) on December 11, 2011 was used to move LRO from its science orbit to a frozen orbit

LRO Frozen Orbit Instances

- A similar DC procedure was used to find initial conditions for 3 frozen orbit resets in 2013, 2014, & 2015 before orbit maintenance was stopped in 2016



Repeating Eccentricity Vector Motion

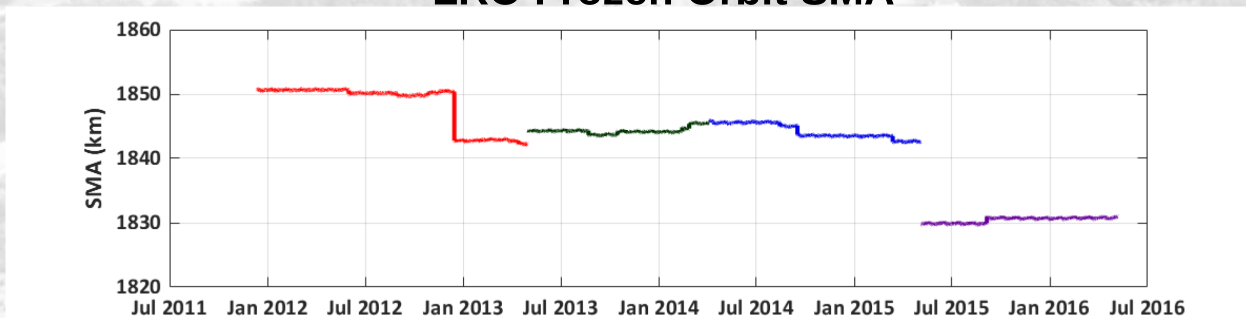


- Moon-Fixed orbit inclination effects the eccentricity vector pattern

Frozen Orbit Reset	Average Inclination (deg)
2011	88.4
2013	87.9
2014	87.4
2015	87.0

Frozen Orbit Reset	ΔV Cost (m/s)
April 29, 2013	2.7
April 03, 2014	3.9
May 04, 2015	5.8

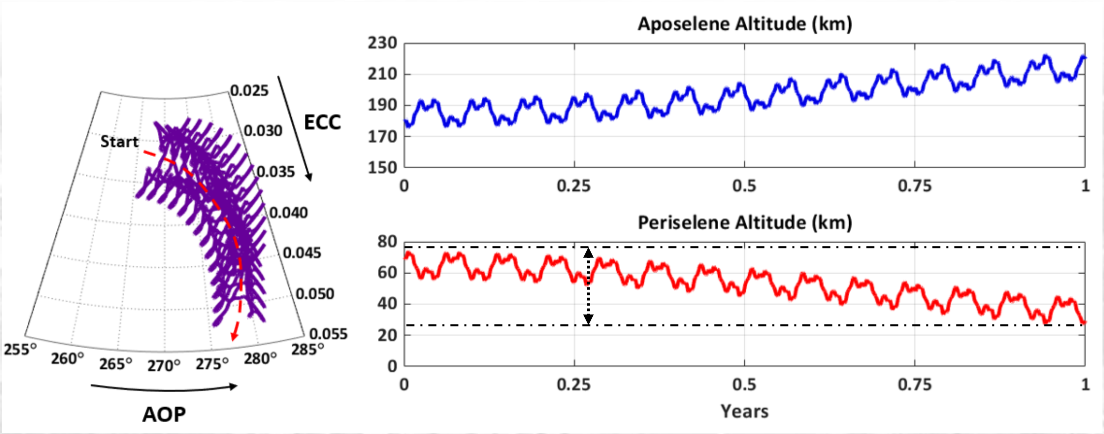
LRO Frozen Orbit SMA



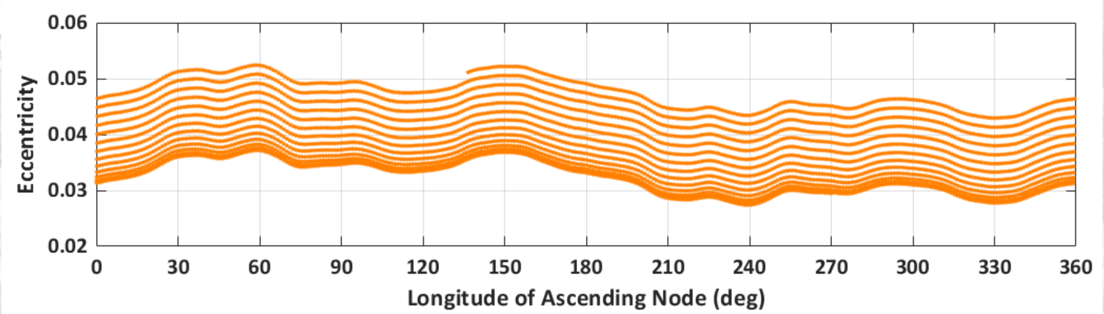
- LRO's frozen orbits were resilient to operational necessities such as ΔV due to momentum unloads and phasing maneuvers

Search for Frozen Orbit Metric

- LRO's frozen orbit experience and further analysis led me to a search for a suitable metric for defining a "best" frozen orbit
- Consider a lunar orbit with the following initial conditions
  - SMA 1862.4 km
  - ECC 0.03
  - INC 90.0 (maintained)
  - LAN 270º
  - AOP 270º
- This orbit is "unfrozen"

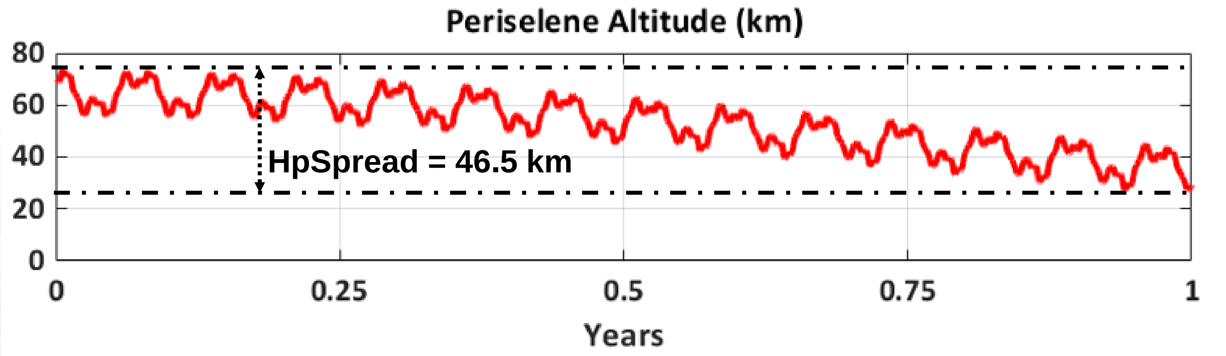


- The orbit could be frozen if we find initial conditions that
  - Minimize the spread in the periselene altitude (HpSpread)
  - Collapses the ECC vs. LAN curves into a single line – indicating repeatability

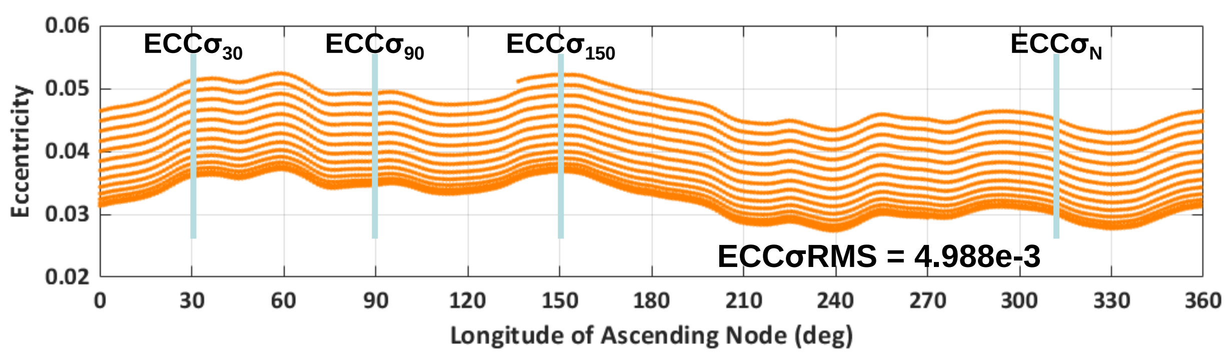


Computing Frozen Orbit Metrics

- The HpSpread metric is simple: max(Hp) – min(Hp)



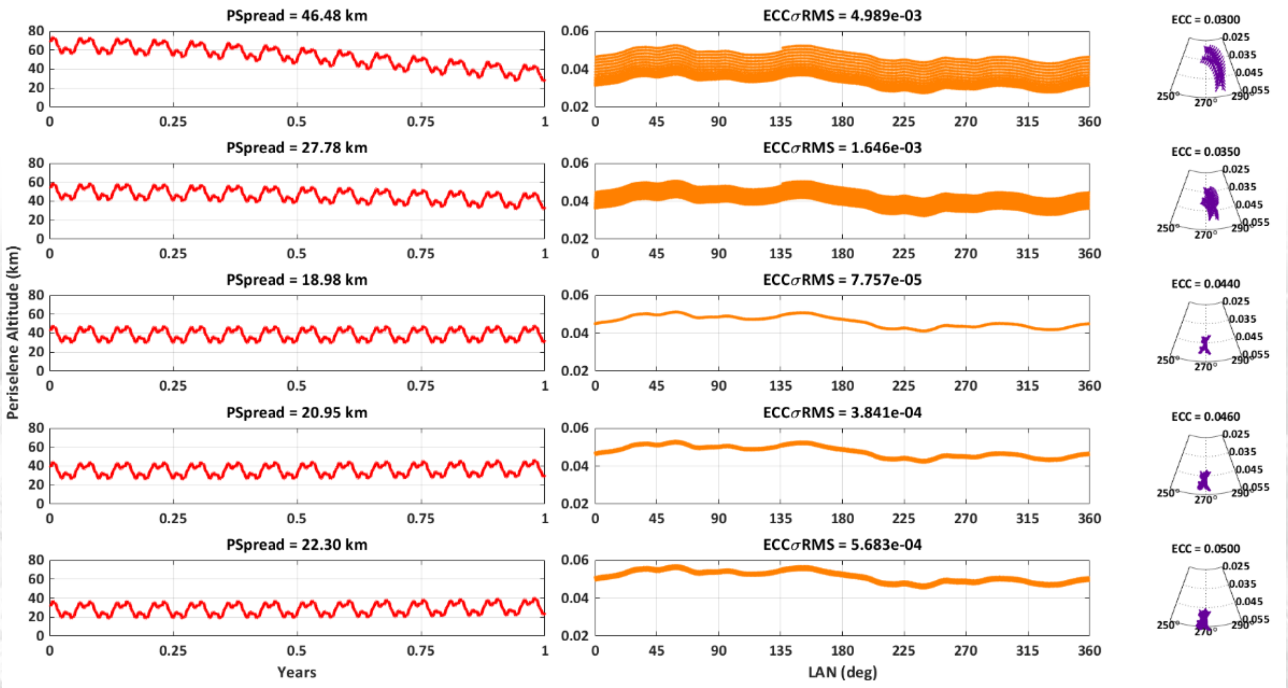
- An eccentricity metric is the root-mean-square of the eccentricity standard deviation computed at fixed LAN values



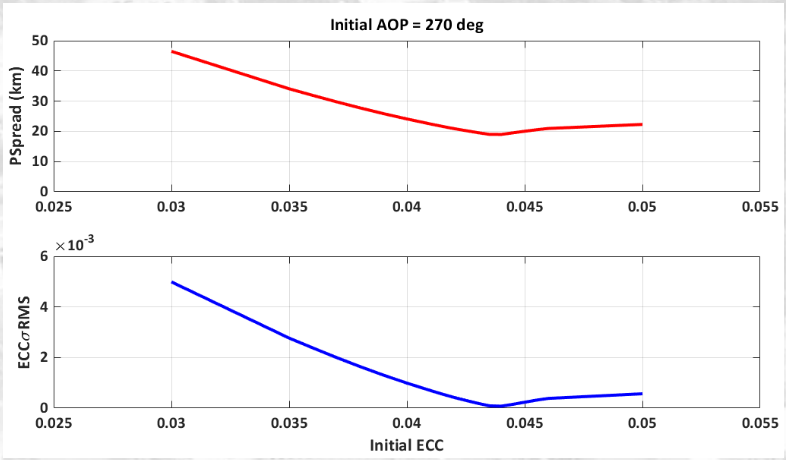
$$ECC\sigma RMS = \sqrt{\sum_{LAN=0}^{LAN=360} \frac{1}{N_{LAN}} (ECC\sigma_{LAN})^2}$$

1D Parametric Scan for Frozen Point IC

- A parametric scan of initial ECC for a fixed AOP (270º) shows the resulting orbits approach and pass through the frozen orbit condition

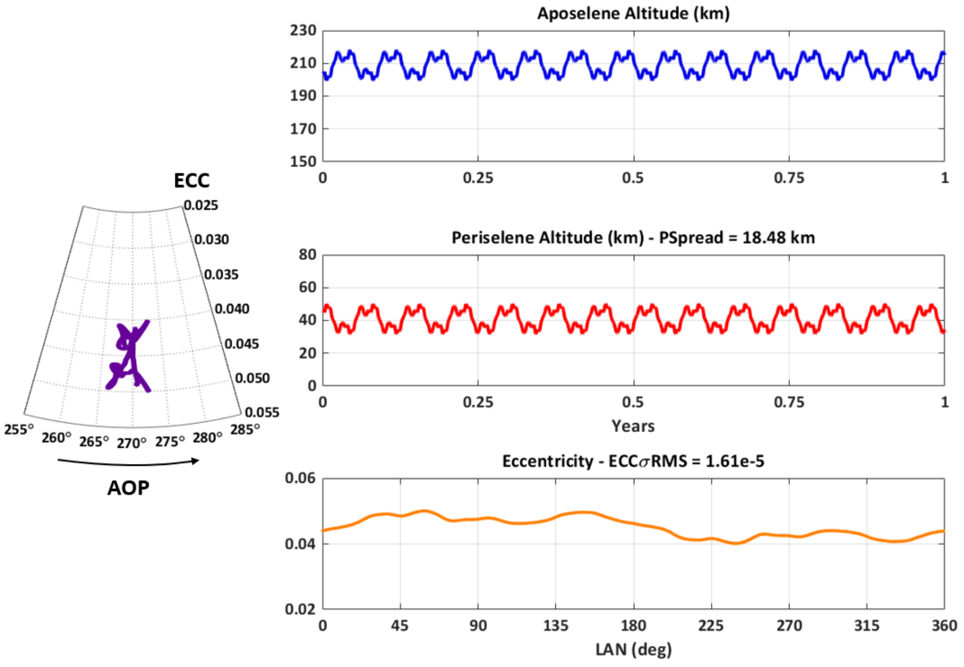


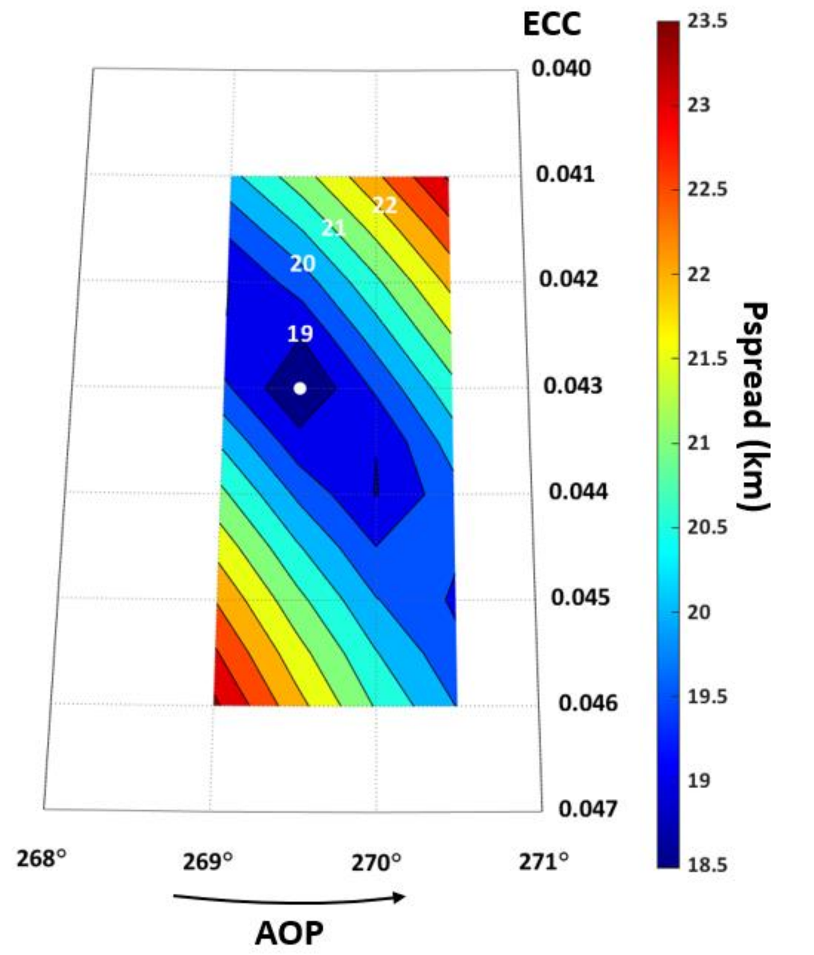
- Parameters reach a minimum at an initial ECC of 0.044
  - HpSpread = 18.98 km
  - ECCσRMS = 7.76e-5
- Both metrics are related – HpSpread is an easy concept to understand while ECCσRMS mathematically reinforces the concept



2D Parametric Scan for Frozen Point IC

- A 2-dimensional scan in initial ECC and AOP found the true frozen point initial condition of (0.043, 269.5º)
  - HpSpread = 18.48 km
  - ECCσRMS = 1.61e-5





Conclusions

- LRO's operations experience allowed for general observations on how to find and differentiate frozen orbit instances
- The differential correction method to null growth in the orbit eccentricity and argument of periapsis is a very simple targeting scheme to find initial conditions
  - This approach relies on comparing conditions at a fixed LAN
- HpSpread (periselene altitude spread) is a simple, observational metric to minimize to find initial conditions for the "best" frozen orbit
- There is a continuum of low lunar frozen orbits that can be differentiated using several factors
  - Choosing the semi-major axis helps to define the minimum periselene altitude
  - The orbit inclination affects the min/max monthly variations in the AOP
  - Free drift of the orbit inclination will require resets in the frozen orbit condition
    - Inclination maintenance costs ≈ 14 m/s per year
  - There is an epoch dependency on the orbit initial conditions (e.g., Earth-Moon distance, 3rd body varying effects due to 18.6 year cycle of Moon's orbit inclination)
- LRO's use of a low-lunar frozen orbit reduced its yearly orbit maintenance costs from 143 m/s to 5 m/s per year – allowing for an extension of 10+ years of operations