Arcus Mission Design

Stable Lunar Resonant HEO for X-ray Astronomy

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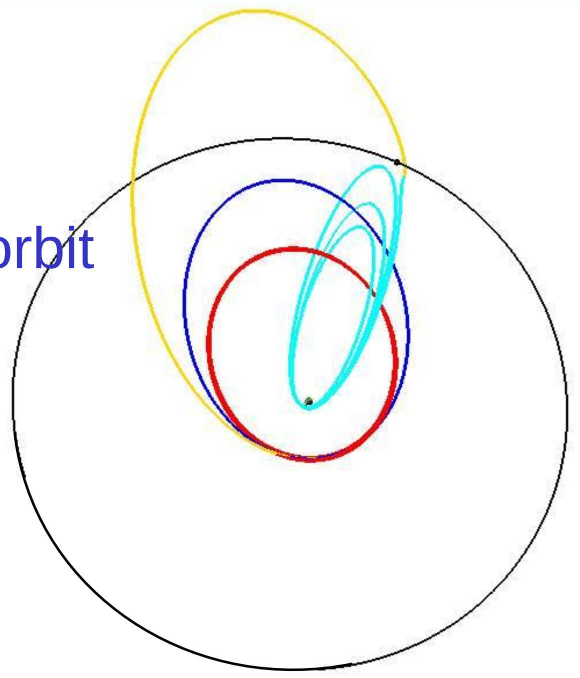
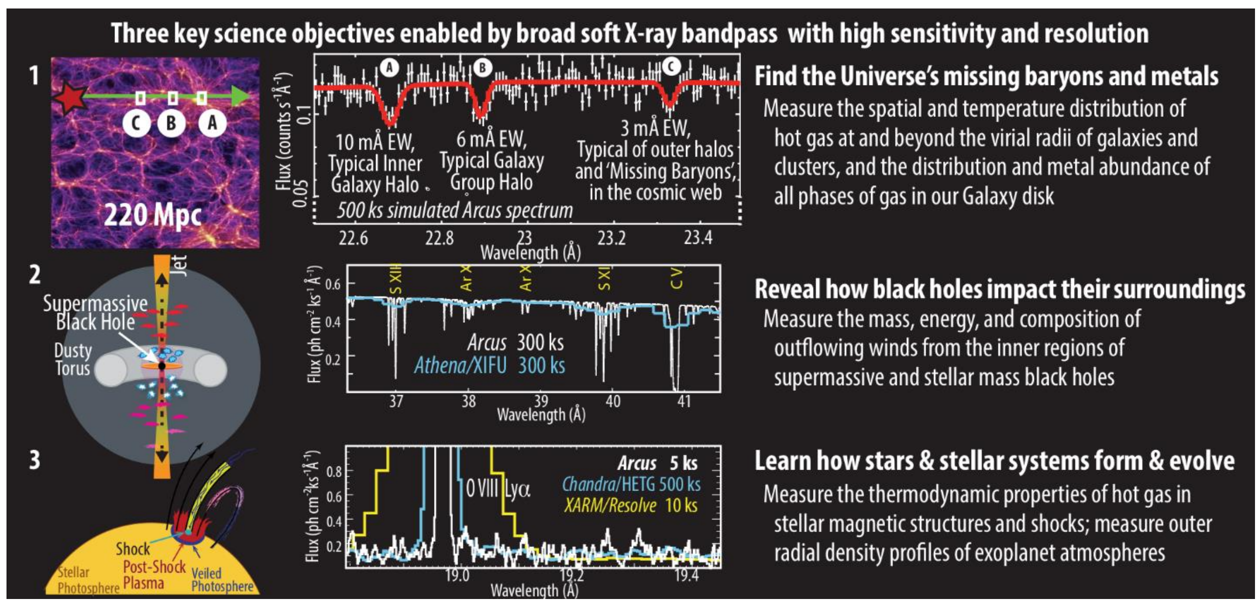
Arcus Mission Design - Overview

- Arcus mission
  - Project currently in Step 1 of NASA SMD 2016 MIDEX AO in Astrophysics
- Spacecraft and instrument
  - X-ray telescope, 14m long
- Transfer trajectory and science orbit
  - Phasing loops to lunar swingby
  - P/4 lunar resonant HEO
- Ground segment design
  - Tracking & Orbit Determination



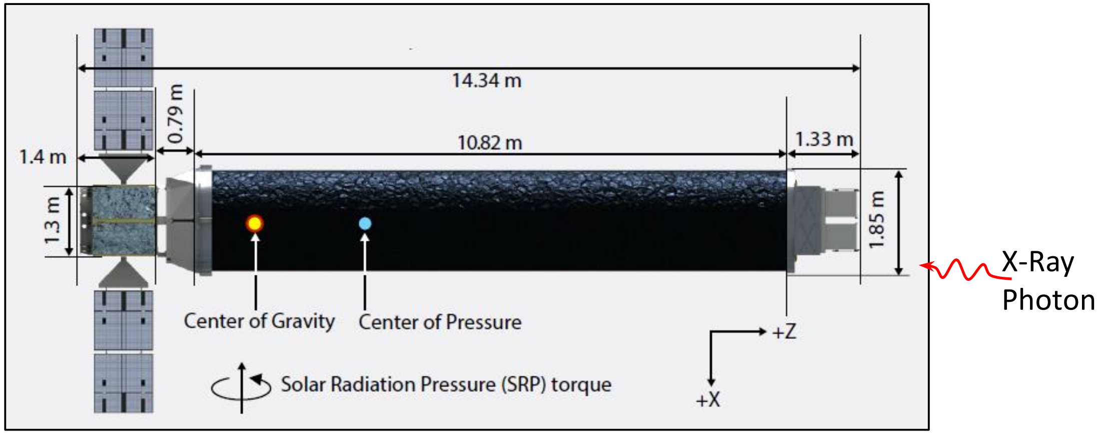
Arcus Science

- Soft X-ray grating spectroscopy
- Understanding the formation and evolution of clusters of galaxies, black holes, and stars
- Find and characterize the universe's missing matter

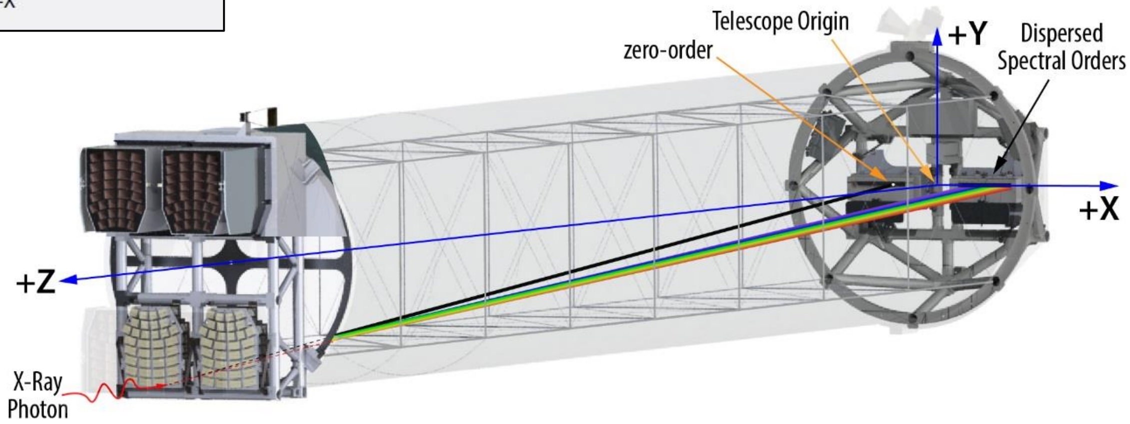


Arcus uniquely opens the soft X-ray bandpass

Arcus Spacecraft and Instrument



- X-ray telescope cannot use a conventional mirror
  - X-rays pass through
- Silicon Pore Optics (SPO): gratings deflect X-ray photos slightly, to enter detector

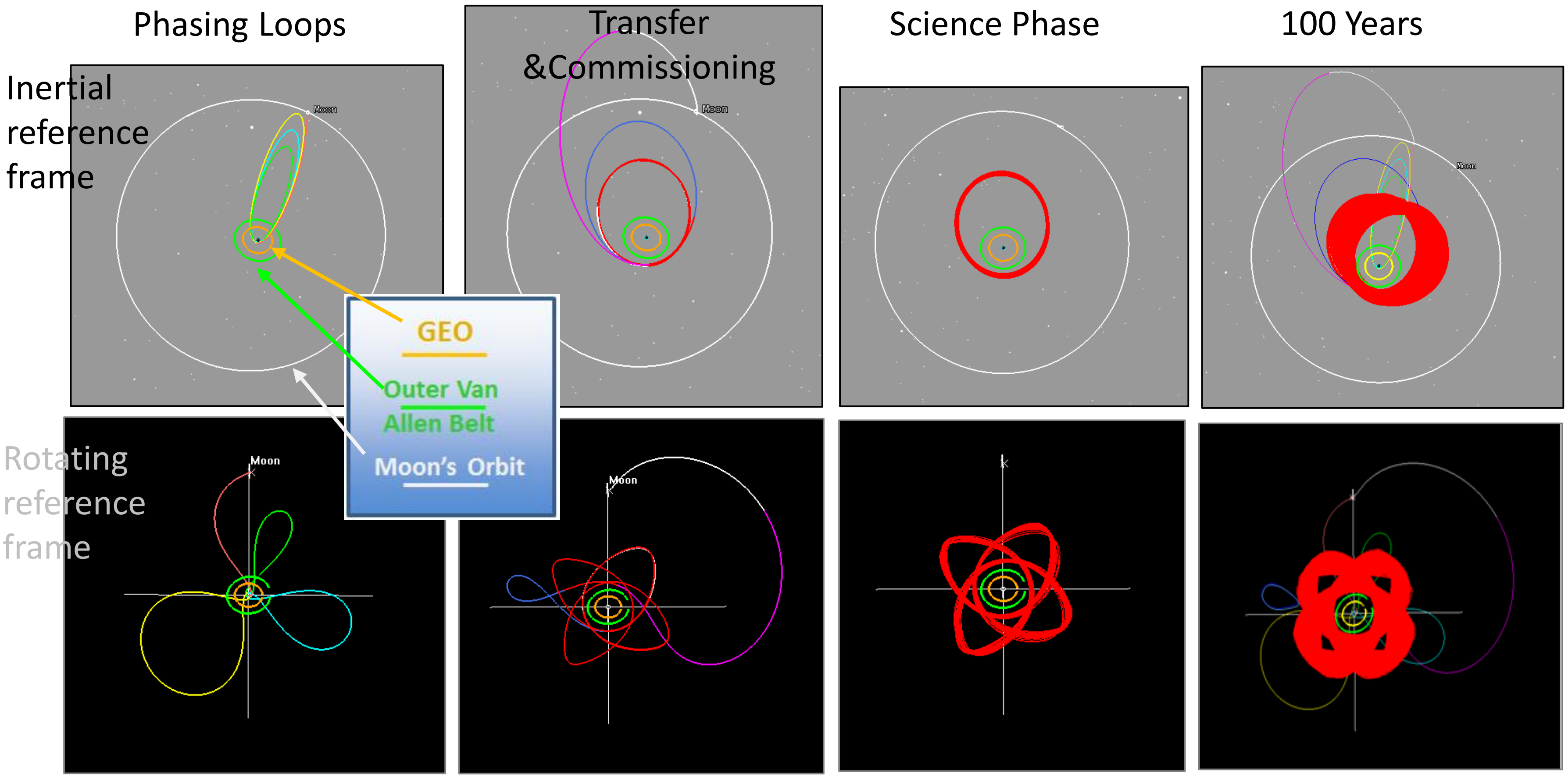


Trajectory Requirements

- The Arcus investigation places very little demand on the orbit design, needing only to be in space, above the Van Allen Belts, and with access to data downlink

	Requirement	Design Reference Mission	Notes
Minimum science orbit altitude above outer Van Allen belts (km)	60,000	71,124	
Science orbit stable for Science Phase duration (yrs)	2	100	Covers 5 yr extended mission
Maximum eclipse duration (hrs)	4. 5	3.5	Some control with launch dates, maneuver tuning
Maximum Earth range (Re)	110	98	For link budget
Maximum delta-V burn (m/s)	175	130	3-thruster configuration
Delta-V budget	373	373	Full tanks
Minimum angle between the Sun vector and the thruster pointing direction (degrees)	> 20	22 – 163	Mitigated with launch date selection
Minimum altitude 300 km above GEO altitude for at least 100 years (km)	38,786	70,000	NASA-STD-8719.14A, §4.6.2.2
Moderate equatorial inclination for good DSN coverage (degrees)	< ~40	31 - 36	Investigating refinements

Arcus Trajectory Design in Earth-Moon System

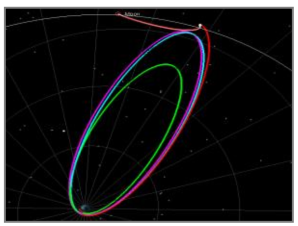


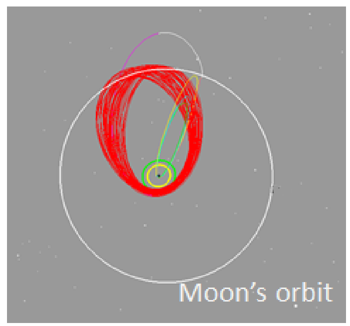
	Phasing Loops	Transfer &Commissioning	Science Phase	100 Years
Perigee Altitudes (km)	200 - 2200	70,000 – 76,000	70,000 – 86,000	70,000 – 95,000
Apogee Altitudes (km)	200 – 520,000	218,000 – 613,000	206,000 – 219,000	195,000 – 220,000

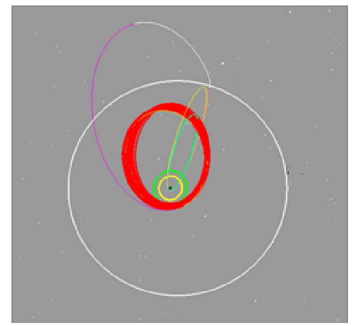
Transfer Trajectory & Science Orbit

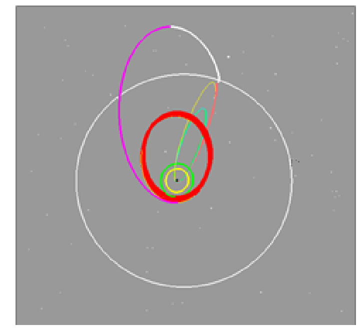
- Comparisons and early trades

2 year propagations





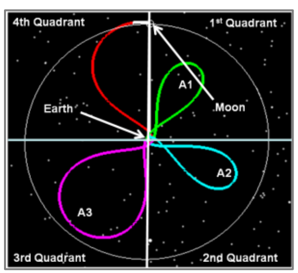




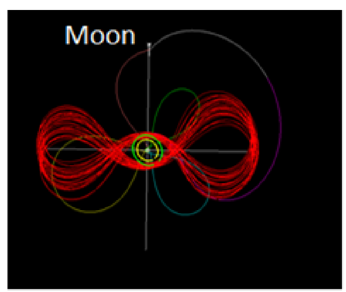
Example concept trajectory

GEO

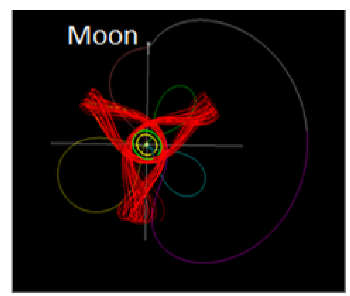
Outer Van Allen Belt 60,000 km



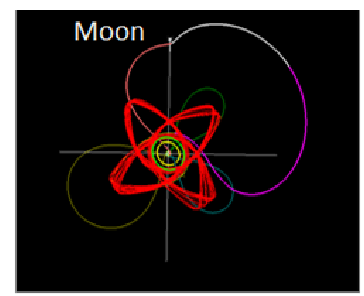
LADEE
Phasing loops to lunar capture



2:1 Resonance TESS-like
Phasing loops to lunar swingby
67,000 x 404,000 km



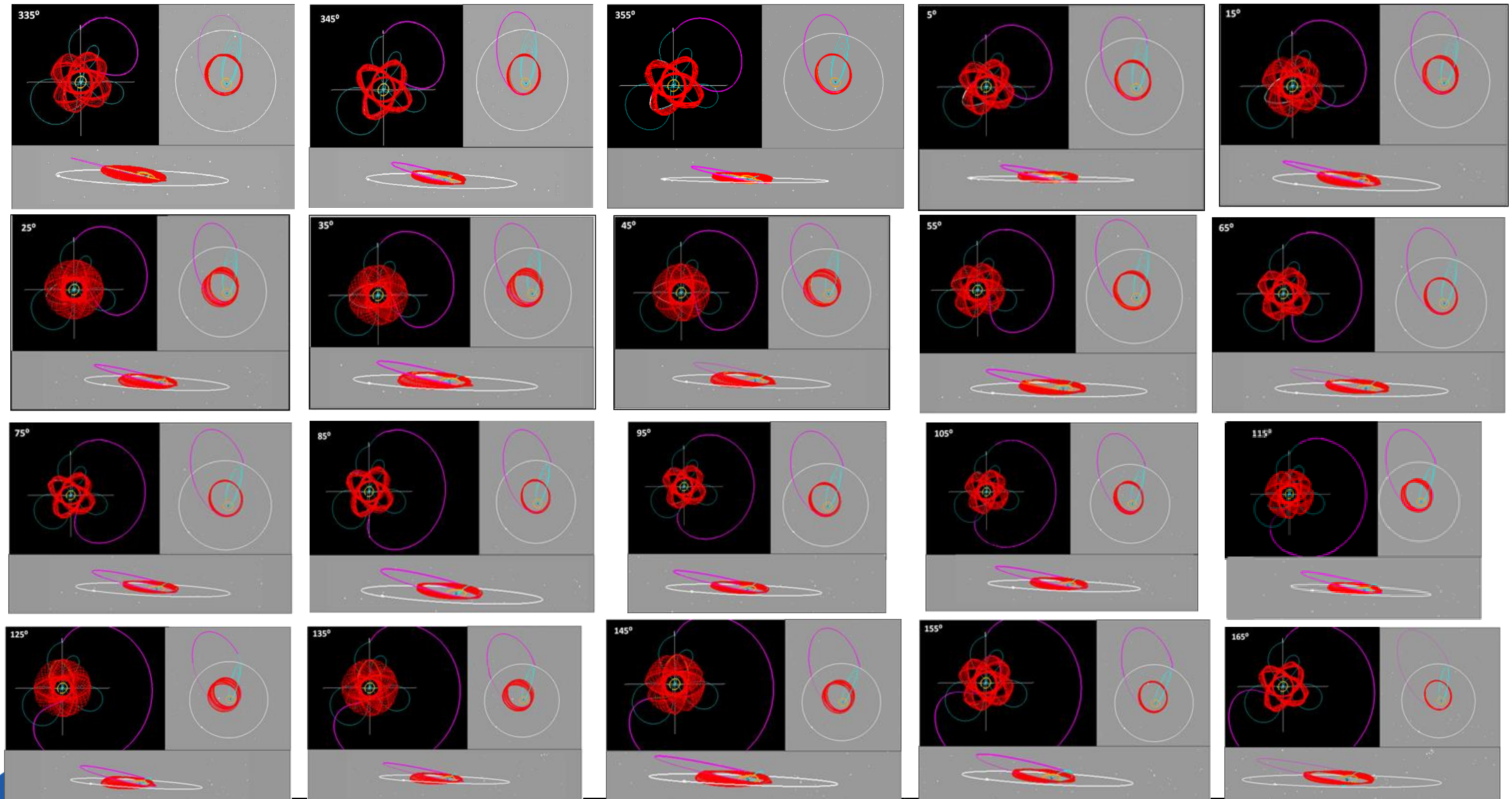
3:1 Resonance IBEX-like
Phasing loops to lunar swingby
78,000 x 284,000 km



4:1 Resonance Arcus baseline
Phasing loops to lunar swingby
72,000 x 220,000 km

Stable HEO with and without Resonance

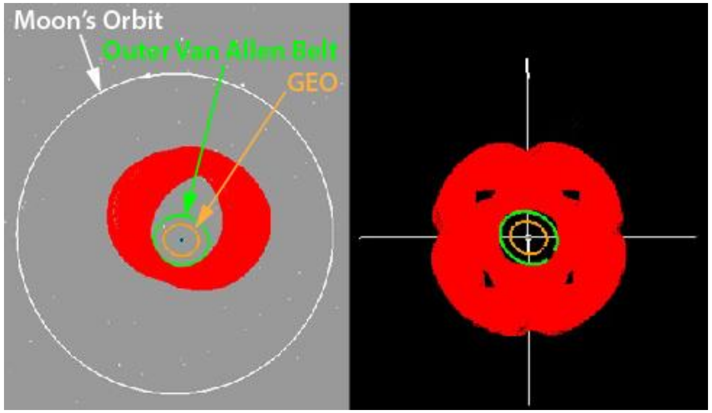
- Targeting accesses the post-swingy perigee orientation relative to the Moon's position



Stability

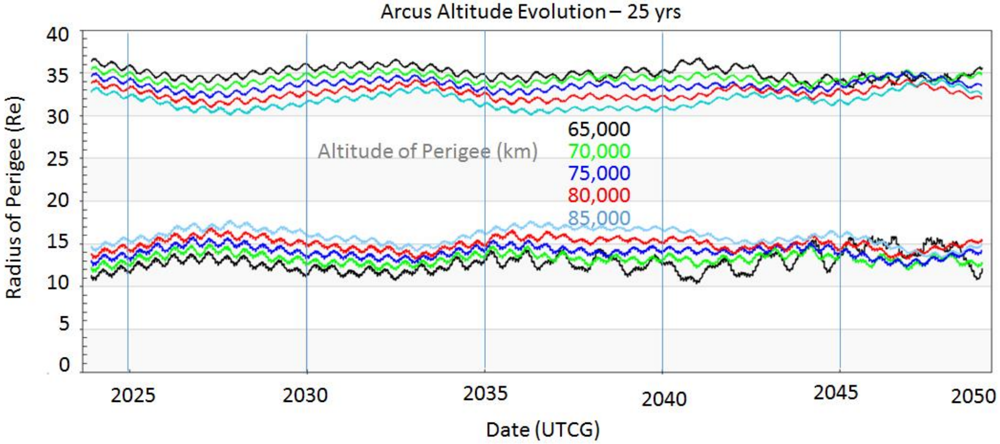
- Orbit precesses but stays resonant
- One measure of stability shows in long term propagation
- Additional stability investigations of
  - SMA
  - Inclination
  - Line of nodes
  - Line of apsides

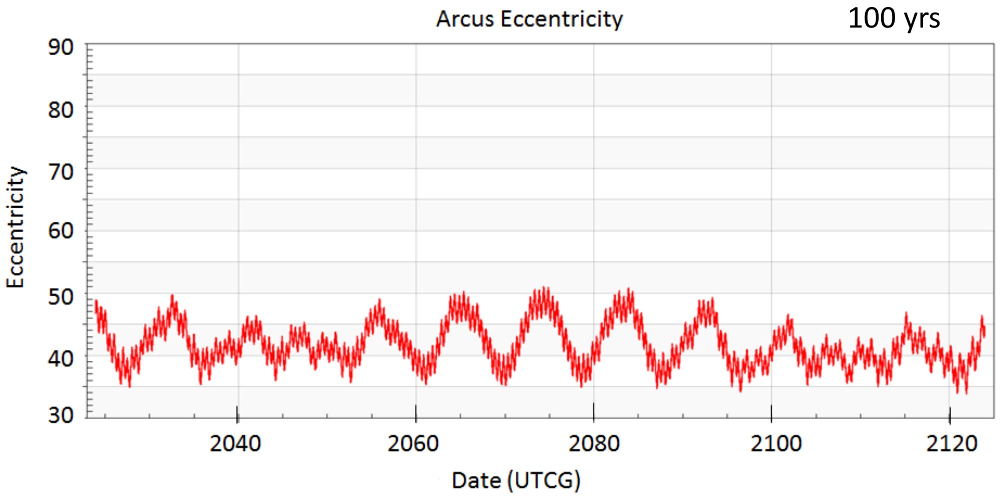
Resonance persists for at least 100 years



Stability – Trends in SMA

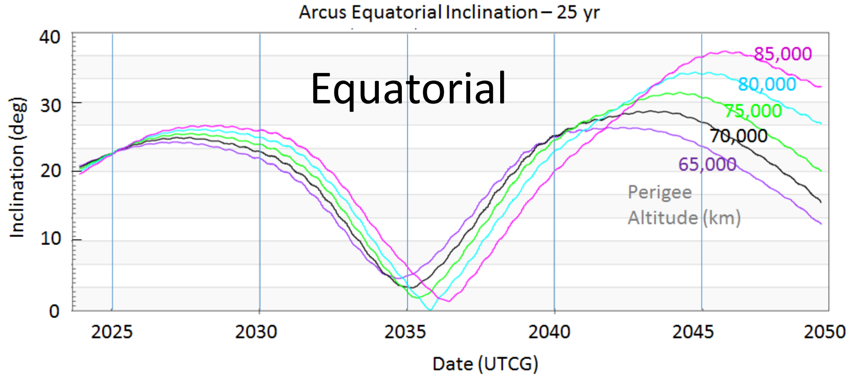
- Most of the trade space of P/4 solutions appears to hold altitude similarly to P/3 and P/2 results.
- Higher apogee altitudes have larger perturbations

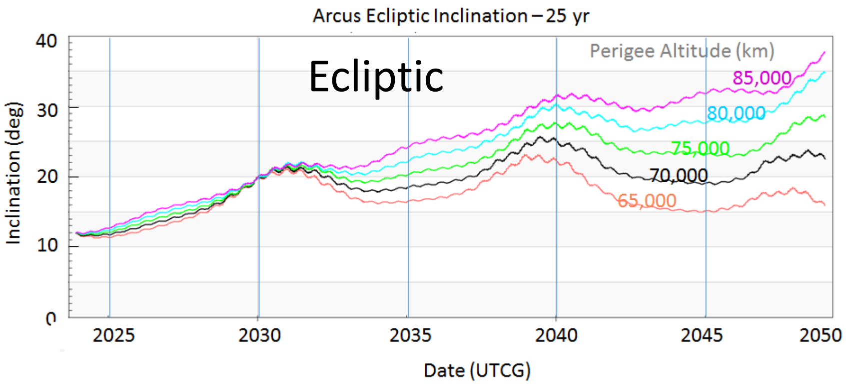


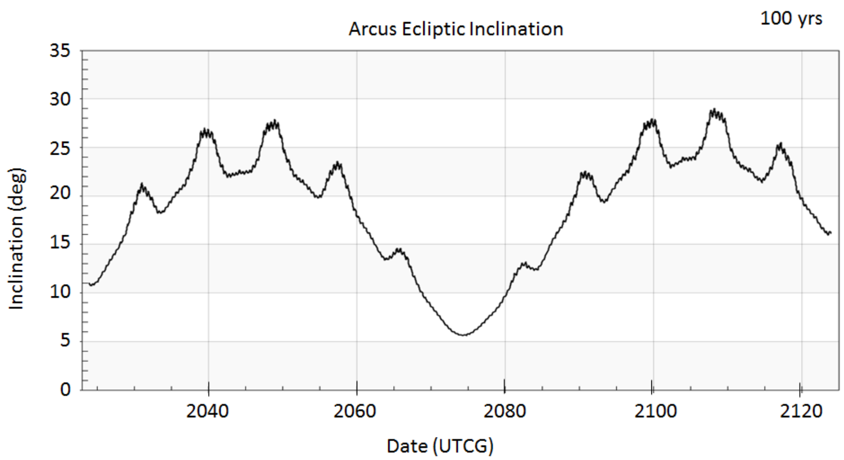


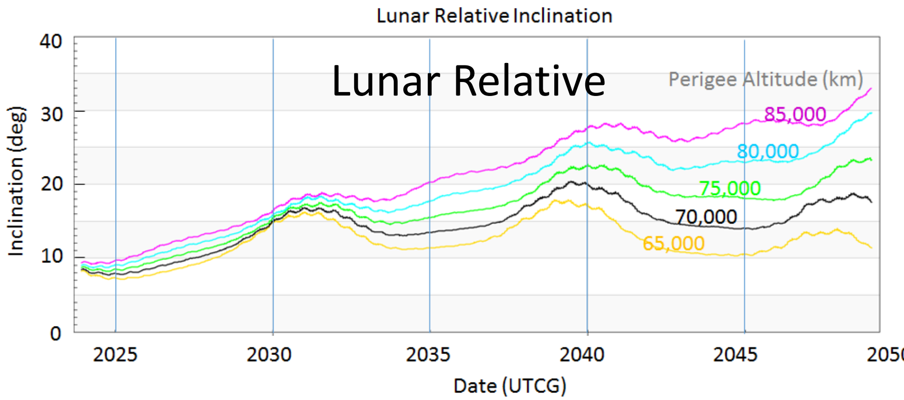
Trends in Inclination

- Short and long cycles
- Reference planes
  - Equatorial
  - Ecliptic
  - Moon's orbit plane



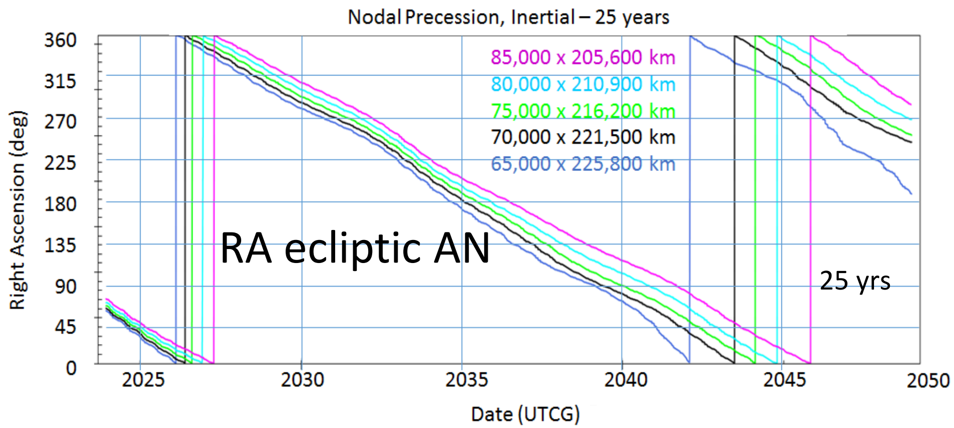


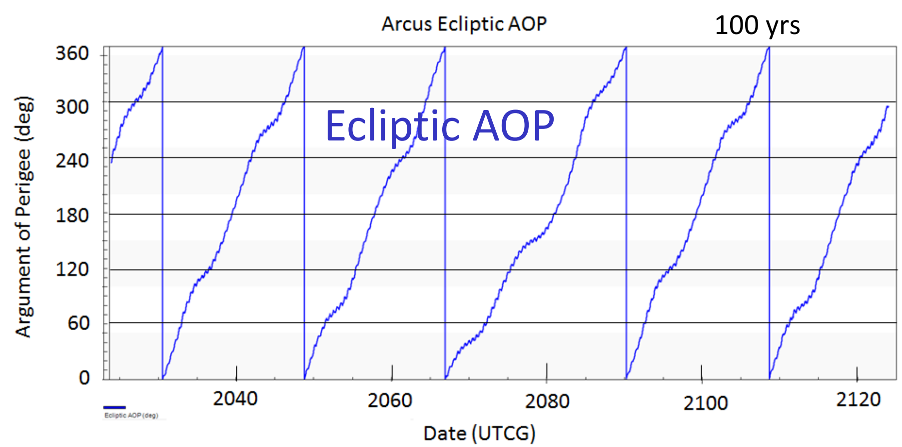




Stability – Nodal & Apsidal Precession 1

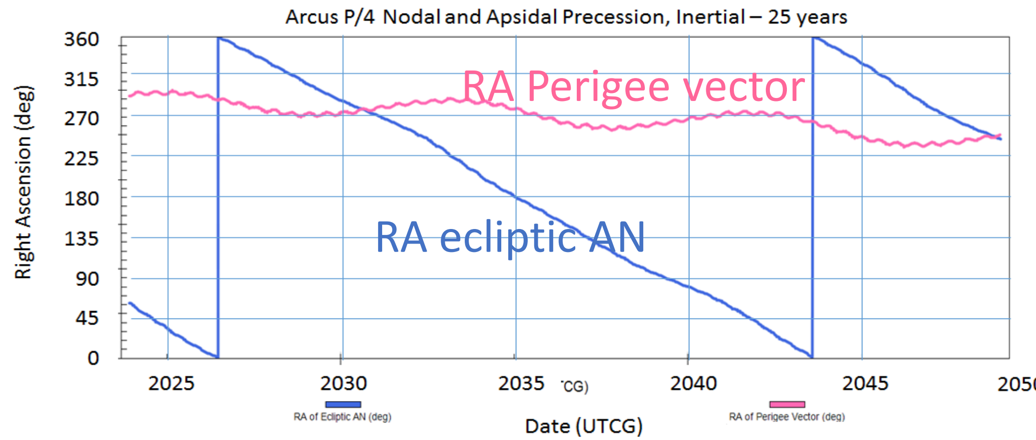
- Ascending node wrt the ecliptic plane
  - Using RA
  - Ecliptic longitude more appropriate for higher ecliptic inclinations
  - Precession varies with eccentricity, probably due to apogee altitude
- Argument of perigee has a long term secular trend
- Inertial direction of perigee is stable
  - (next slide)

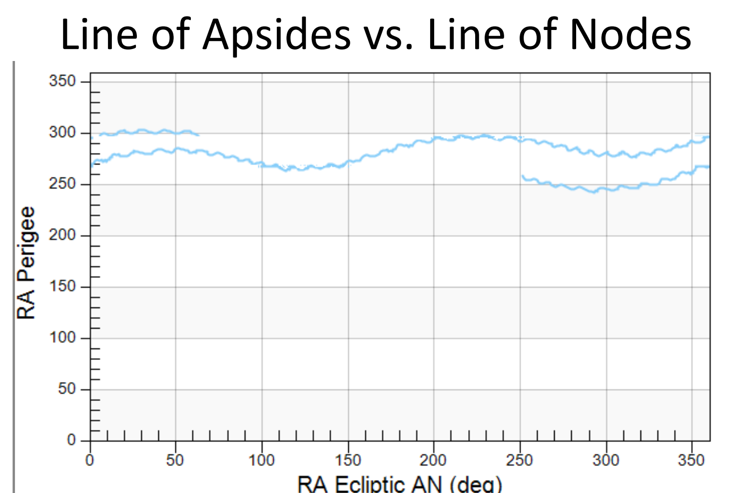




Stability – Nodal & Apsidal Precession 2

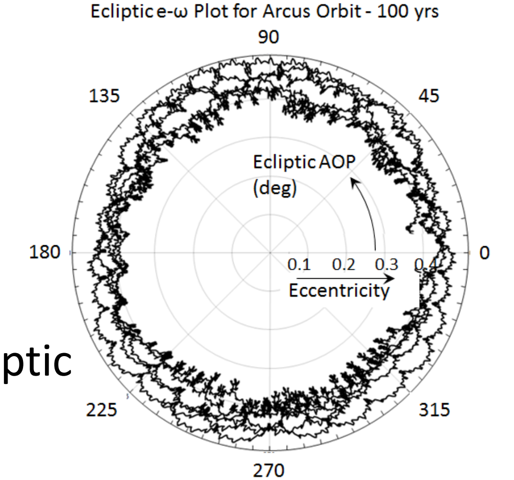
- Inertially, the line of nodes precesses significantly while the line of apsides has a slower trend
  - Measured in Right Ascension
  - 25 year example



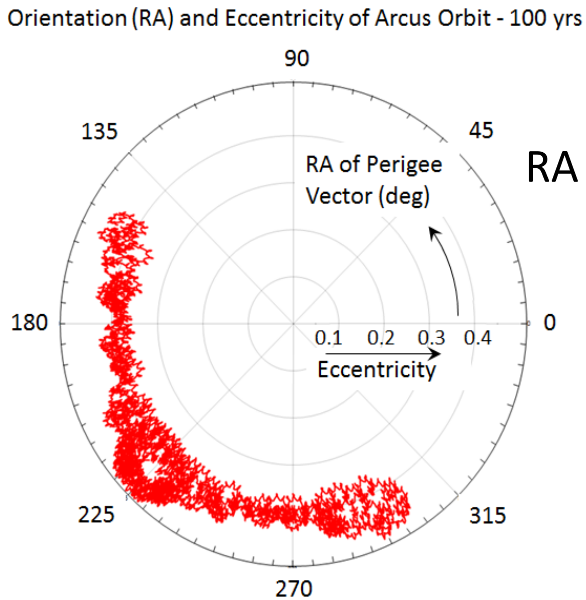


Stability – e-ω Plots

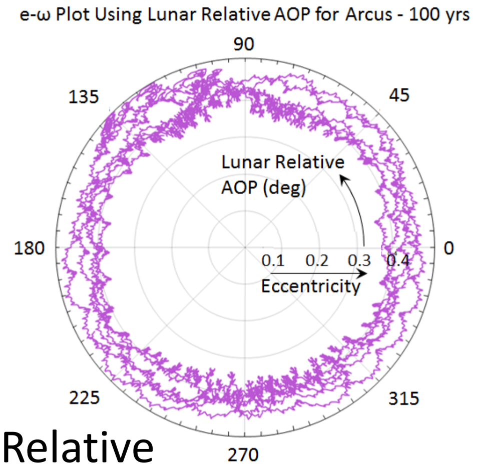
- P/4 is low enough in relation to the Moon that it starts to show characteristics of two-body perturbations
- AOP precesses 0-360º but the perigee vector varies less
- 100 year propagations



AOP, Ecliptic



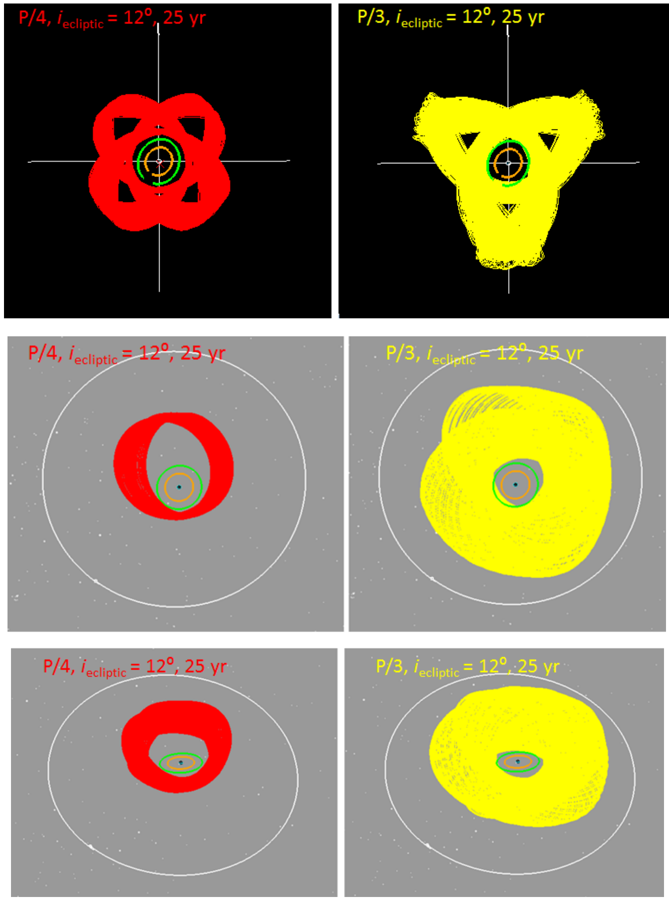
RA of perigee vector



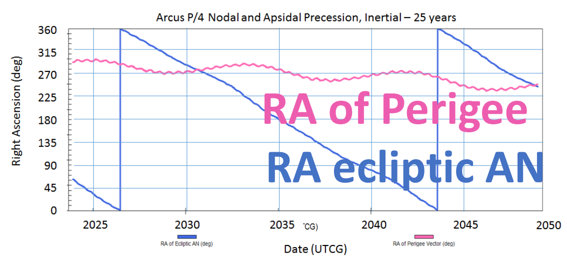
AOP, Lunar Relative

Precession Comparison, P/3 and P/4

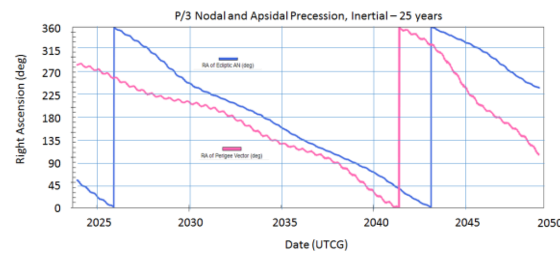
- Similar starting orientation
- 25 year propagations
- Apogee altitude difference between P/3 and P/4 orbits is enough to change the precession of the perigee vector RA
- 7/2 solutions exist between P/3 and P/4. Still to investigate.

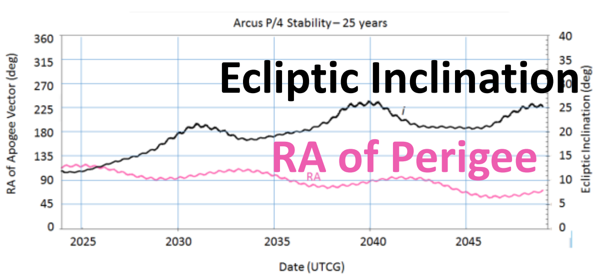


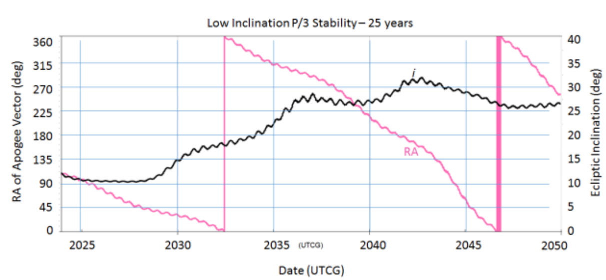
P/4



P/4







Ground Segment Design

- NASA DSN 34-m antennas
  - Selected for high data rate
  - Two-way coherent Doppler & sequential range
  - Three 1-hour TT&C contacts per 6.8-day orbit
    - ascending side, apogee, descending side
  - Fourth DSN support at perigee for science data downloads
- NASA Ames Multi-Mission Operations Center
  - Flight Dynamics System (FDS) based on STK & ODTK
  - Same MMOC & FDS as LADEE mission

Orbit Determination

- With science targets at infinity, the Arcus investigation places very little demand on estimation accuracy.
- Prediction accuracy requirements
  - Maneuver planning
  - DSN acquisition and scheduling
  - No accuracy requirements for science activity planning requirements
- Definitive accuracy requirements
  - Maneuver reconstruction & trending
  - No accuracy requirements for science data processing

OD approach reflects goals to simplify mission ops

Conclusion

- Lunar resonant HEO can offer advantages for science missions
  - Stays above Van Allen Belts
  - ~Weekly operations cadence
  - Most days at high altitude for data collection
  - Perigee altitude supports data downlink weekly
  - Moderate equatorial inclination provides good DSN coverage
  - Thermal stability for spacecraft and instrument
  - Few eclipses
    - Max shadow duration ~4.5 hrs
  - No deorbit maneuver needed
  - Arcus Phase A delta-v budget: 373 m/s