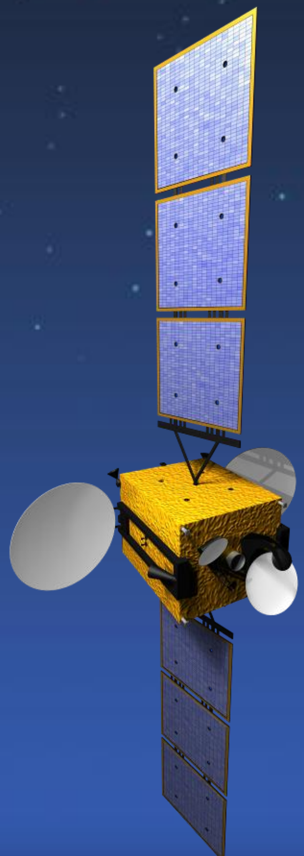
Changing the economics of space

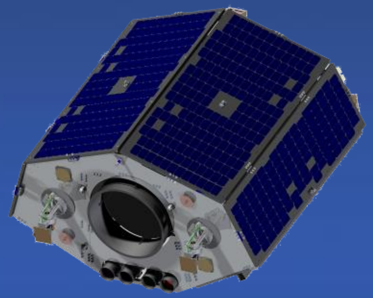
ESMO – Mission Analysis



SRR Workshop

Alison Gibbings

22nd – 26th March 2010



Contents

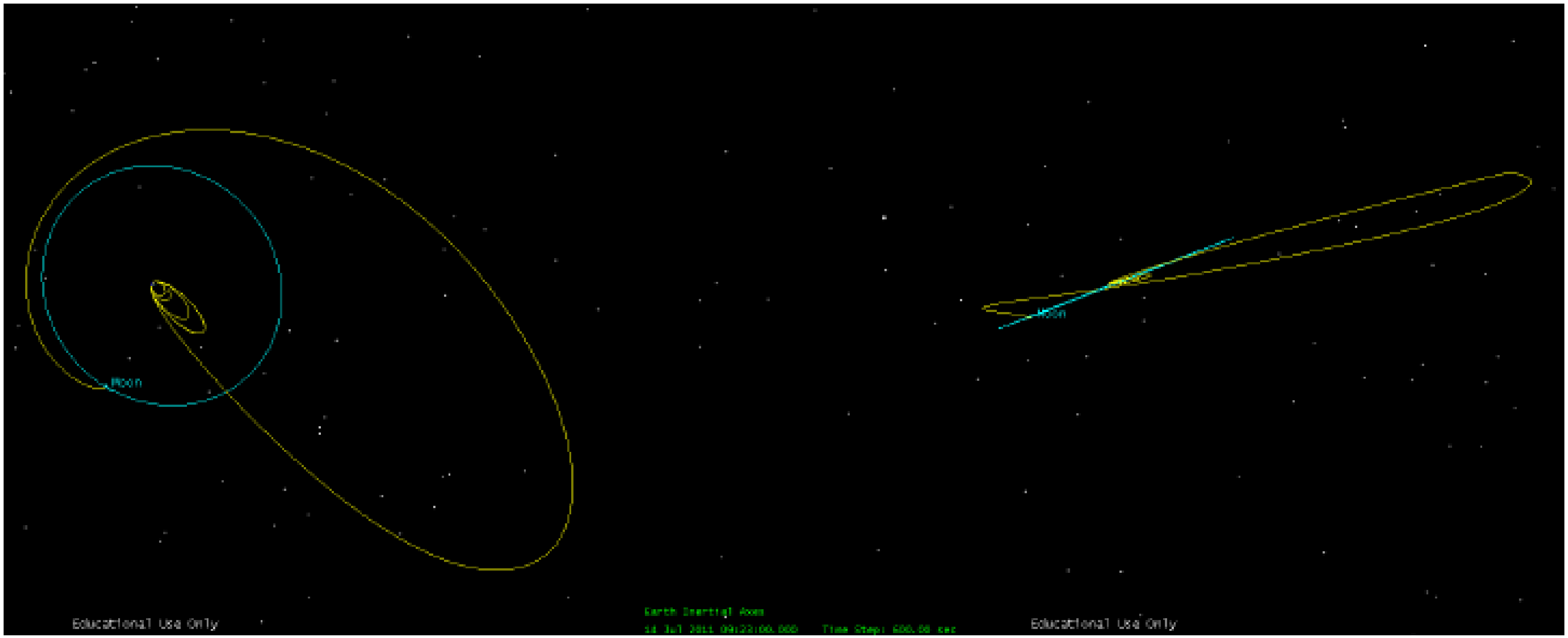
- Review of the existing baseline
- Sensitivity analysis
  - At lunar Injection
  - Along the WSB-Moon transfer, two weeks before injection
- Trade-off to reduce the mission delta-V
  - Varying the apolune
  - Frozen orbit (case 1, case 2, case 3)
- Proposed transfer and orbit insertion
  - WSB transfer
  - Frozen orbit around the Moon
  - Ground access time & eclipse
- Summary
  - Conclusion of results and influence on requirements
- Acknowledgments
- Questions

Existing Baseline

- Utilises a WSB transfer in the Earth-Moon-System
  – Obtain an inclination change and rise at perigee at zero-cost
  – Saving delta-V

- Transfer is divided into two legs
  – Periapsis of GTO to WSB region
  – Departure from the lunar target orbit and propagate backwards to the WSB region
    - Two legs are linked through delta-V manoeuvres
    - Mid-course correction in the WSB region to increase flexibility when targeted the required orbit at the moon

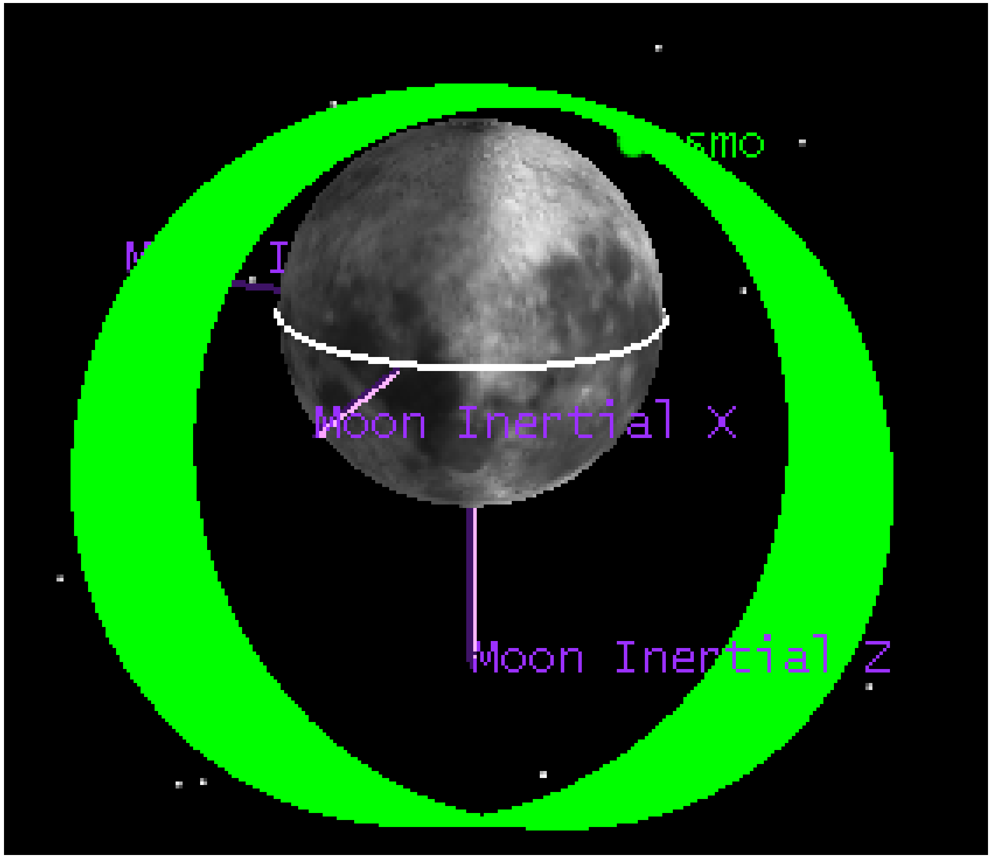
Existing Baseline



- WSB transfer trajectory with phasing leg at the Earth (blue = Moon orbit, yellow = Earth spacecraft trajectory)

Existing Baseline

Orbital Elements	Values
a	3586 km
e	0.4874
i	89.9 °
Ω	63.8 °
ω	292.9 °
v	0 °



Existing Baseline

WSB Transfer	
ΔV at Earth [m/s] (nominal escape)	747.7
ΔV at WSB [m/s] (matching manoeuvre)	71.02
ΔV at Moon [m/s]	297.57
Total ΔV ([m/s]	1116.29
Departure Date [UTCG]	25/02/2012 14:34
Time of flight Earth-WSB [days]	40.82
Time of flight WSB-Moon [days]	60.31
Total time of flight [days]	101.13
Arrival Date [UTCG]	05/06/2012 17:39
Arrival Orbit: semi-major axis [km]	3586
Arrival Orbit: eccentricity	0.4875
Arrival Orbit: inclination [deg]	89.9

Sensitivity at Lunar Injection

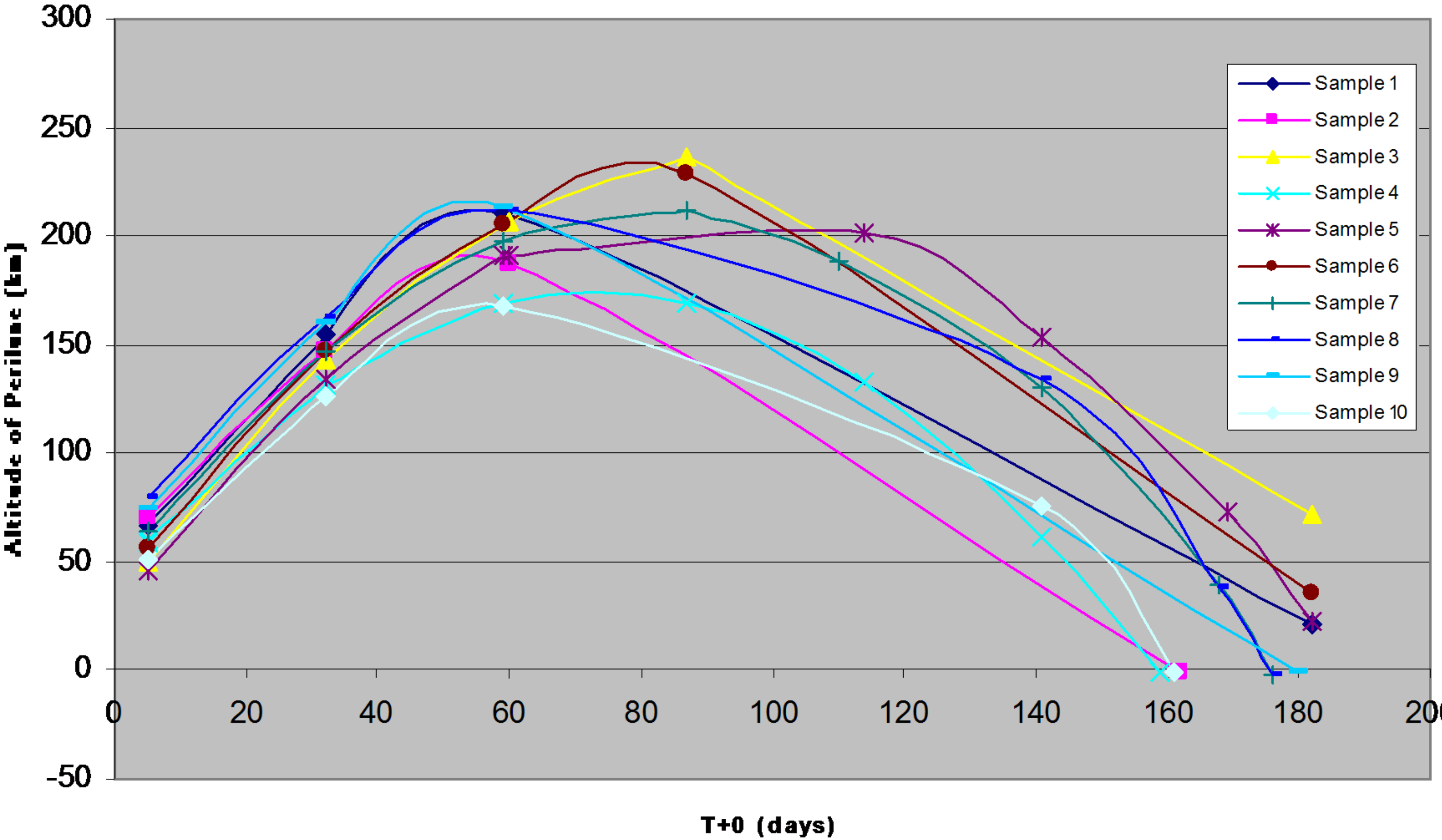
- Introduction of error into the orbital elements of the lunar orbit (existing baseline)

- Error of 1,2,3,4 and 5 %
  - Deviation of ten samples
    - Used Matlab to generated ten cases from random points between upper and lower limits
  - Assessed the altitude of perilune against T+ (Days)

  - Larger the error, the greater the range of data plots

- Has an implication on the **requirement** for the accuracy of the **orbit insertion**

Sensitivity at Lunar Injection at 1 %



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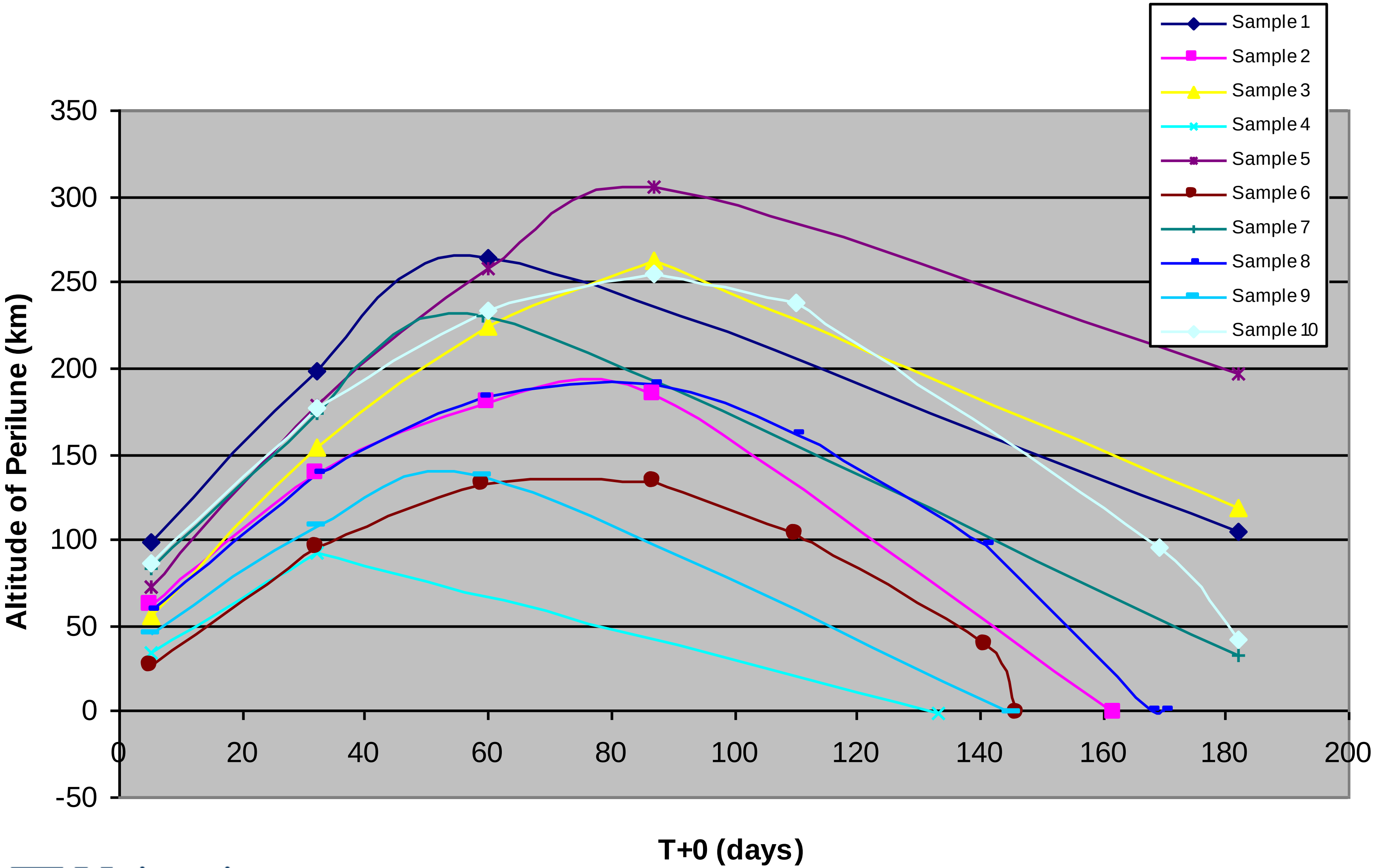
Sensitivity at Lunar Injection at 2 %



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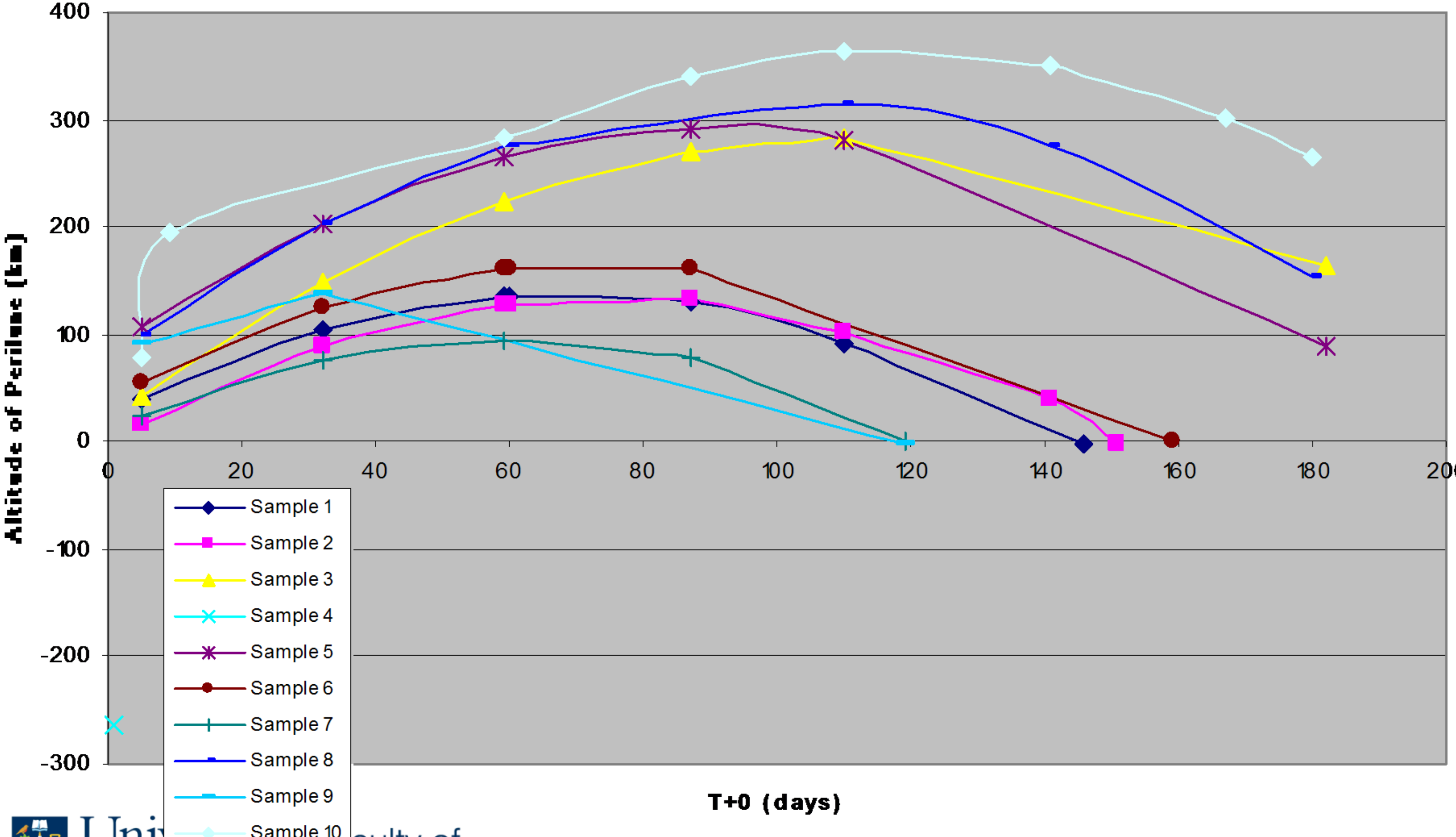
Sensitivity at Lunar Injection at 3 %



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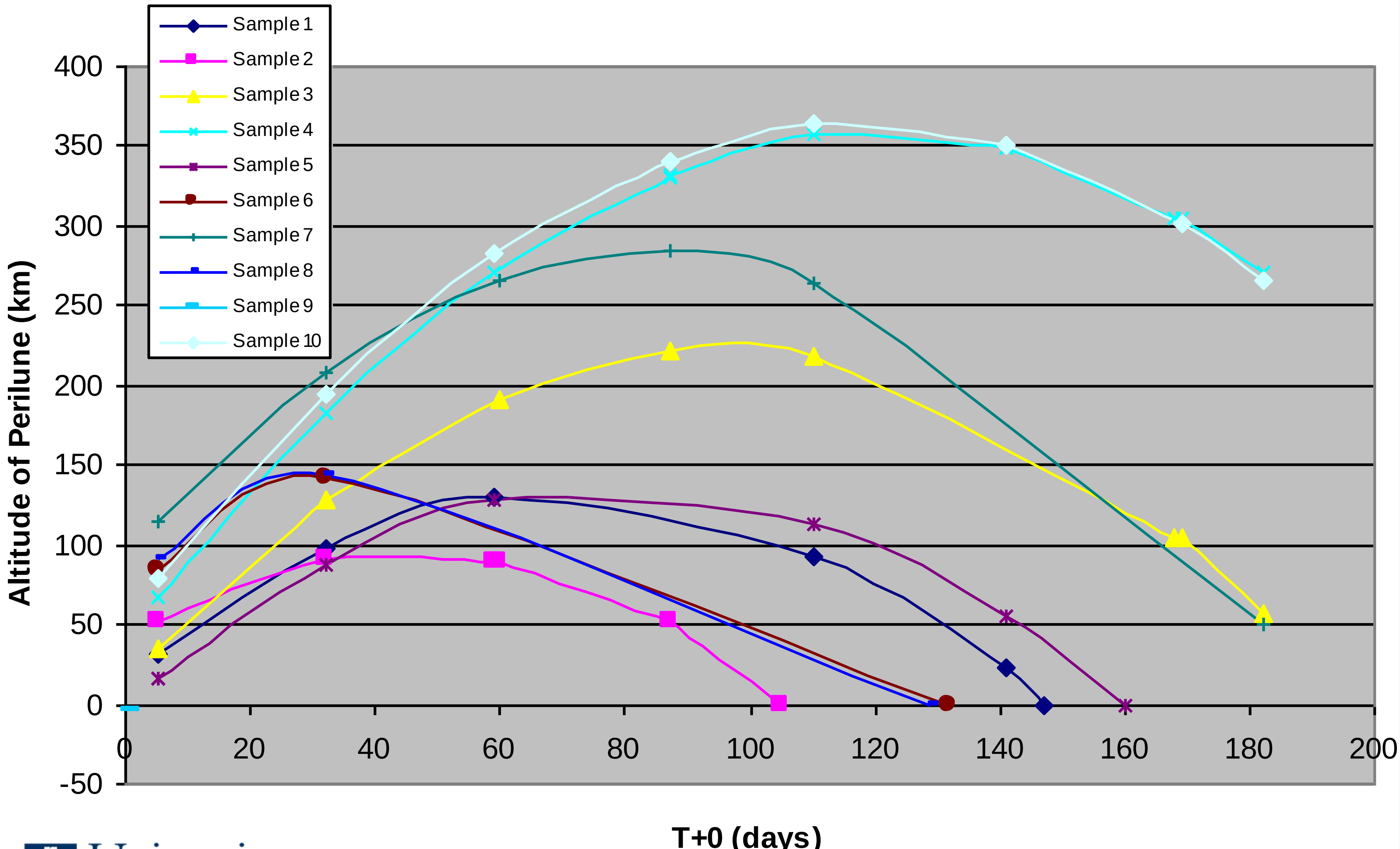
Sensitivity at Lunar Injection at 4 %



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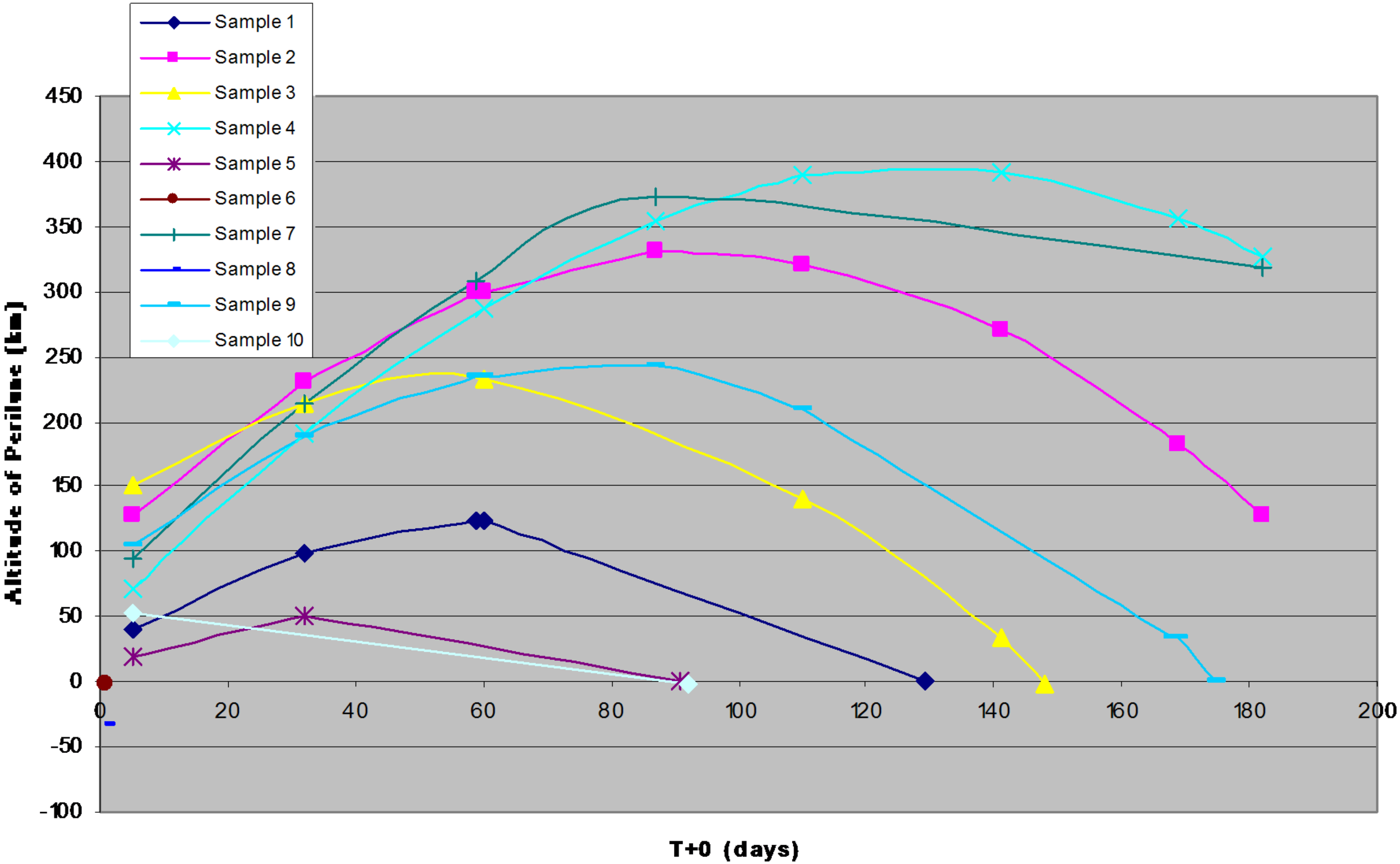
Commercial in Confidence

Sensitivity at Lunar Injection at 5 %



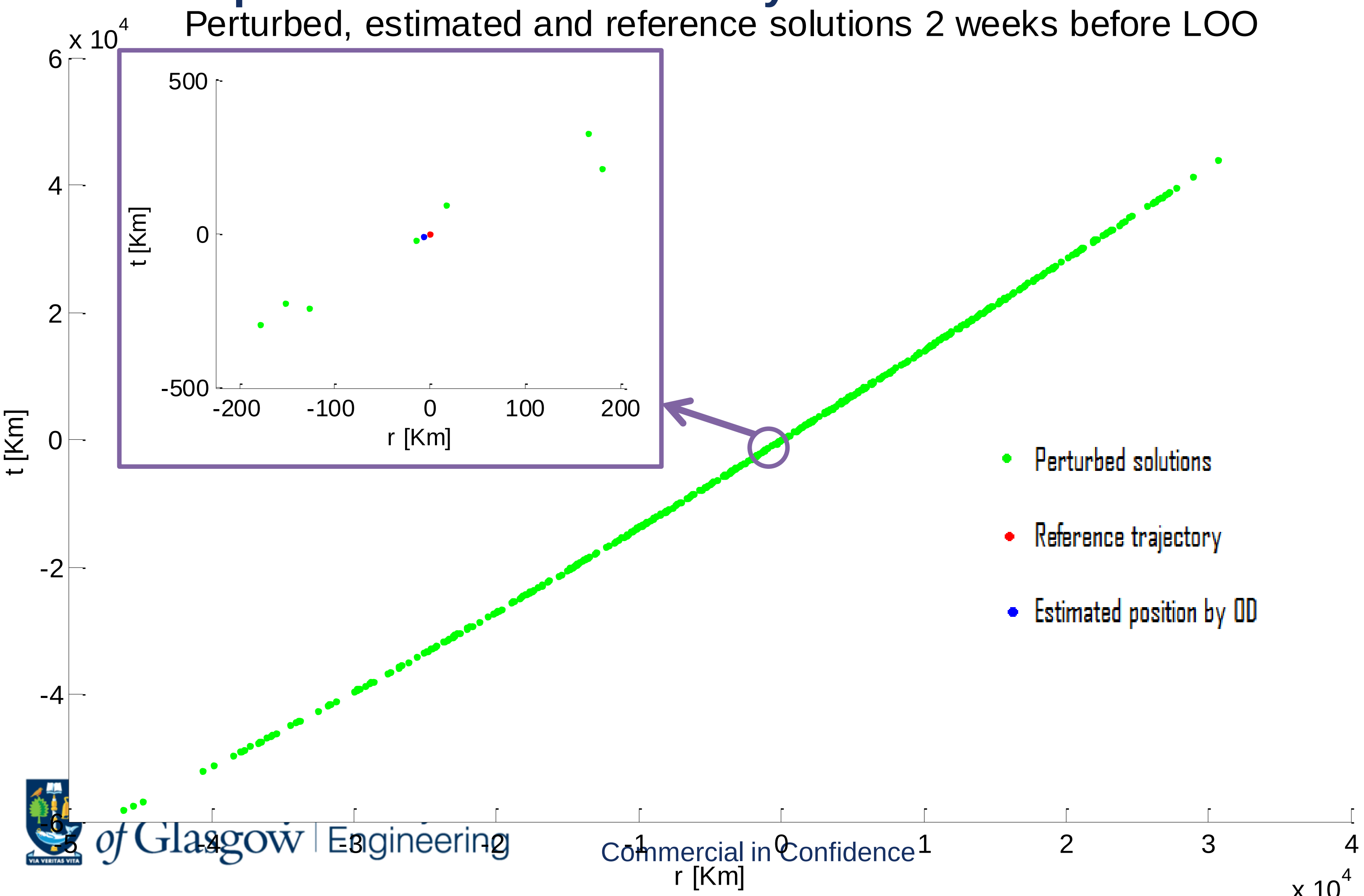
Commercial in Confidence

Sensitivity along the Transfer

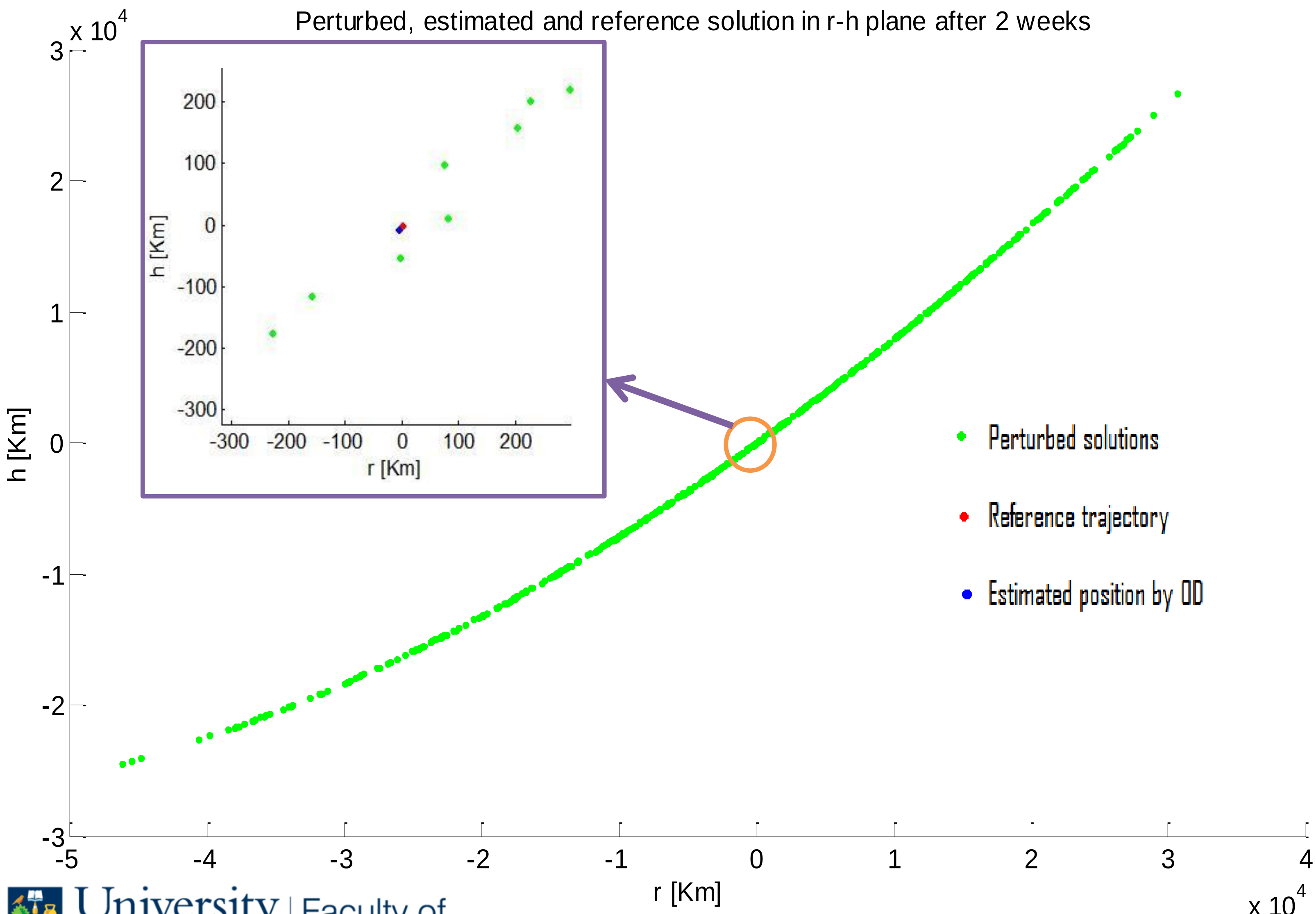
- Using an 1 % error, the trajectory corridor for obtaining lunar orbit injection was assessed.
  - From lunar orbit the trajectory was propagated backwards for two weeks towards the WSB.
  - Propagated 1000 perturbed solutions with the maximum values of error for position and velocity
  - Requirement to know ESMO's position and velocity
    - ODTK verified that the estimated position and velocity after orbit determination was inside the corridor. Therefore confirming that orbit insertion was possible.

Sensitivity at two Week from Insertion

- **Error in radial and transversal position of ESMO**
  - **Requirement on the accuracy of orbit determination**



Sensitivity at two Week from Insertion



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Navigation Strategy

- Using the existing baseline transfer
- From Earth (GTO) to WSB
  - Modelled the orbit determination
    - First obit determination (OD) one week after trans-lunar injection from GTO
    - If required, target correction manoeuvres (TCMs)
      - Correct for the error in the trans-lunar injection burn & typical dispersion error of the launcher (A5)
        - » Error: 1*10-3 km/s in every direction
      - Assumed that an error was created in every TCM (km/s)
        - » Error: 1*10-4 km/s in every direction, caused by the thrusters
  - Outcome is the error in position and velocity, and is measured at the next OD point
    - Typical one OD every three days
    - Leads to a final delta-V/fuel budget for the navigation budget

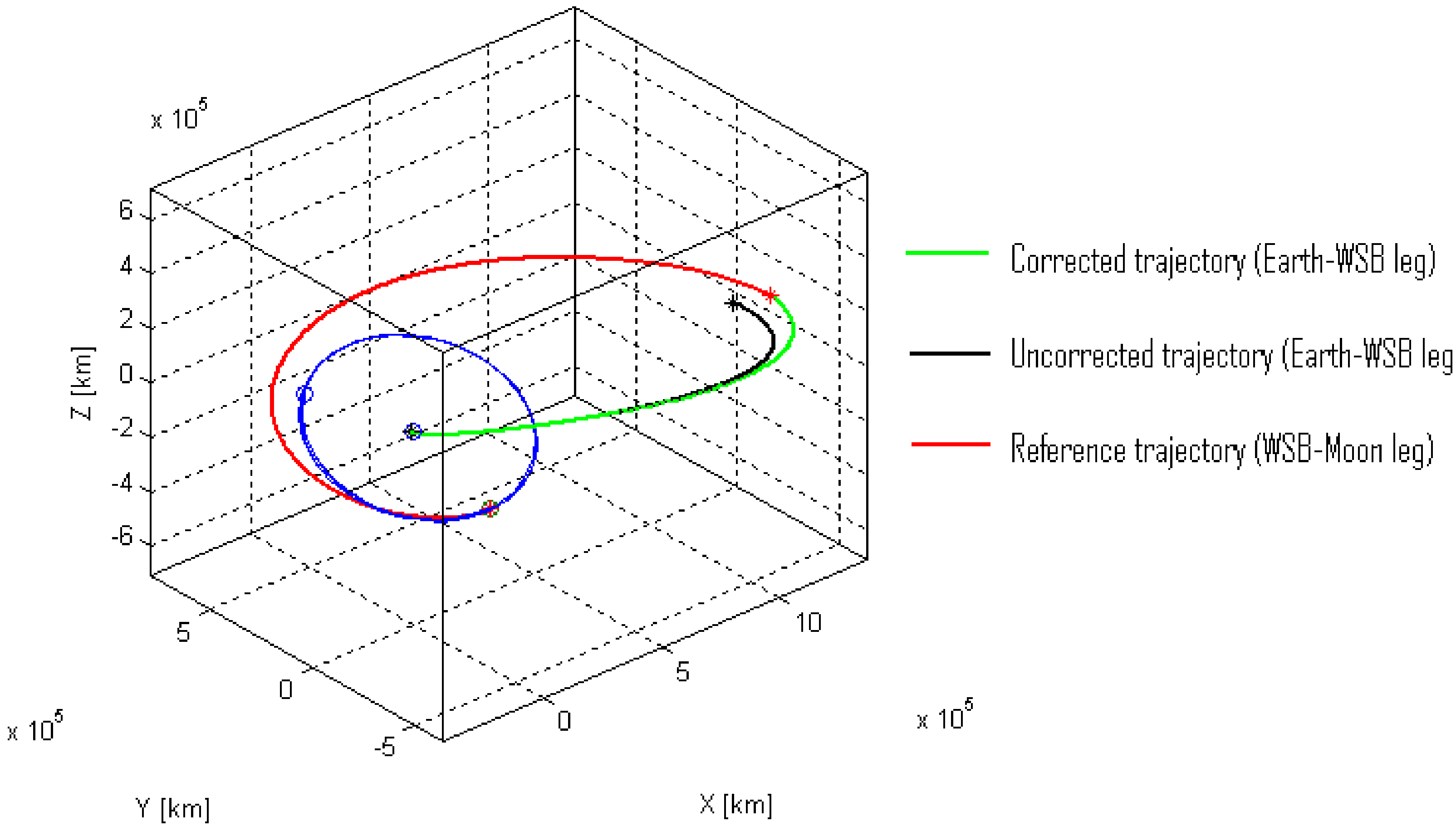
Navigation Strategy

1 st Orbit Determination	Start: 19/3/2011 05:54:30 End: 22/3/2011 05:54:30
TCM 1	Date :22/03/2011 16:42:4 ΔV = 2.09 * 10^-2 km/s
2 nd Orbit Determination	Start: 2/04/2011 12:00:6 End: 5/04/2011 12:00.6
TCM 2	Date: 15/04/2011 20:18:23 ΔV = 5.8369*10^-4 km/s
3 rd Orbit Determination	Start: 19/4/2011 06:24:57 End: 22/4/2011 06:24:57
TCM 3	Date: 24/04/2011 5:29:35 ΔV = 1.1*10^-4 km/s
TCM 4	Date :26/04/2011 15:23:47 ΔV = 5.15* 10^-2 km/s

- Etc…..where ESMO OD & TCM’s actions are focused on maintaining its position and velocity within the trajectory corridor to enable lunar injection.

Navigation Strategy

WSB transfer trajectory in the Earth-centred Earth equatorial system



Navigation Strategy

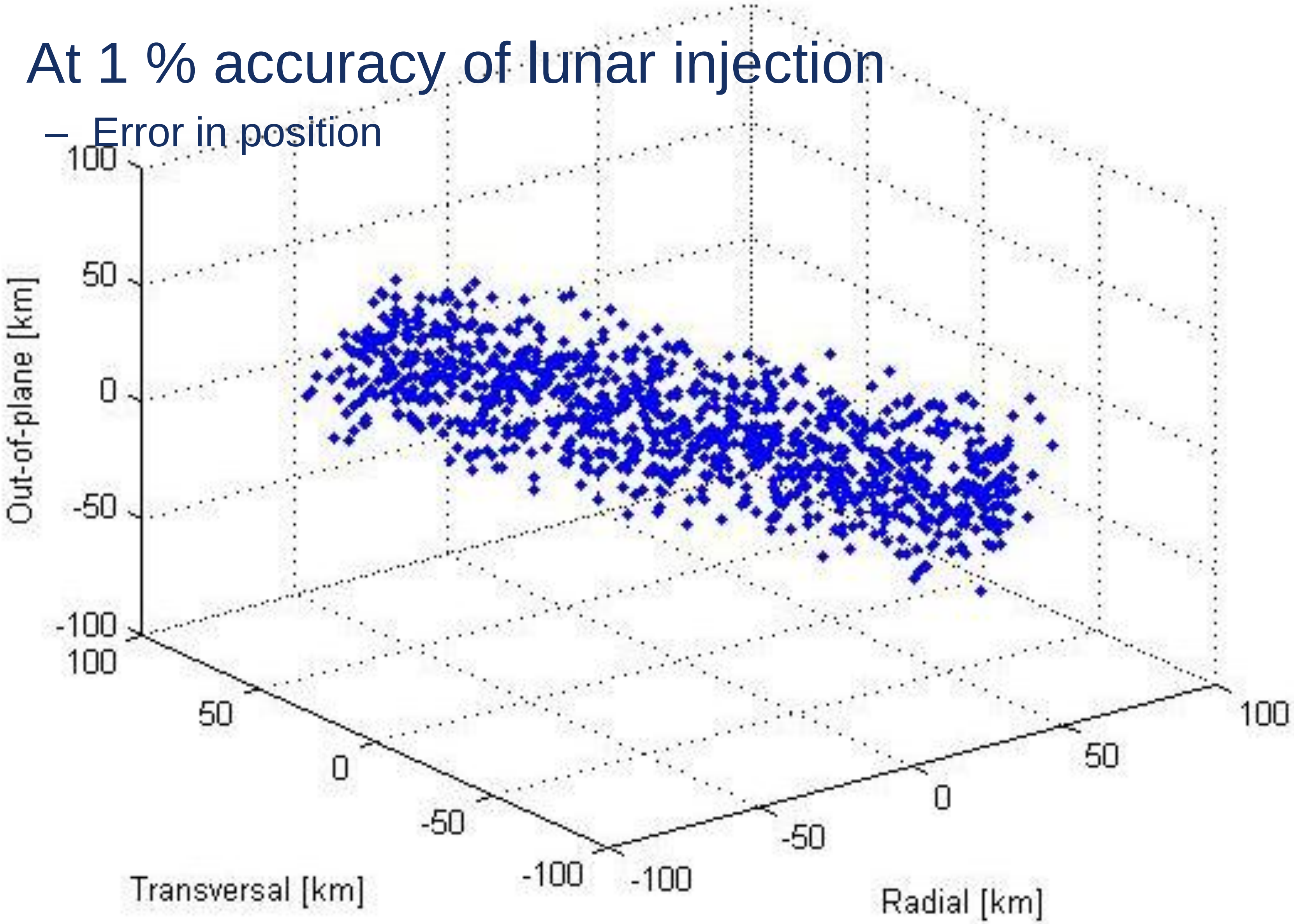
- Total delta-V to perform the four TCMs.
  - Trajectory corridor allowing lunar insertion

Error into GTO-burn manouver	1* 10^-3 km/s
Error Introduced in Every TCM	1*10^-4 Km/s
Final Error in Position @ W.S.B. region	Δr = 93.53 Km

Fuel Budget for TCMs	ΔV = 0.0840 km/s
FINAL MISSON DELTA-V BUDGET	ΔV = 1.1257 km/s

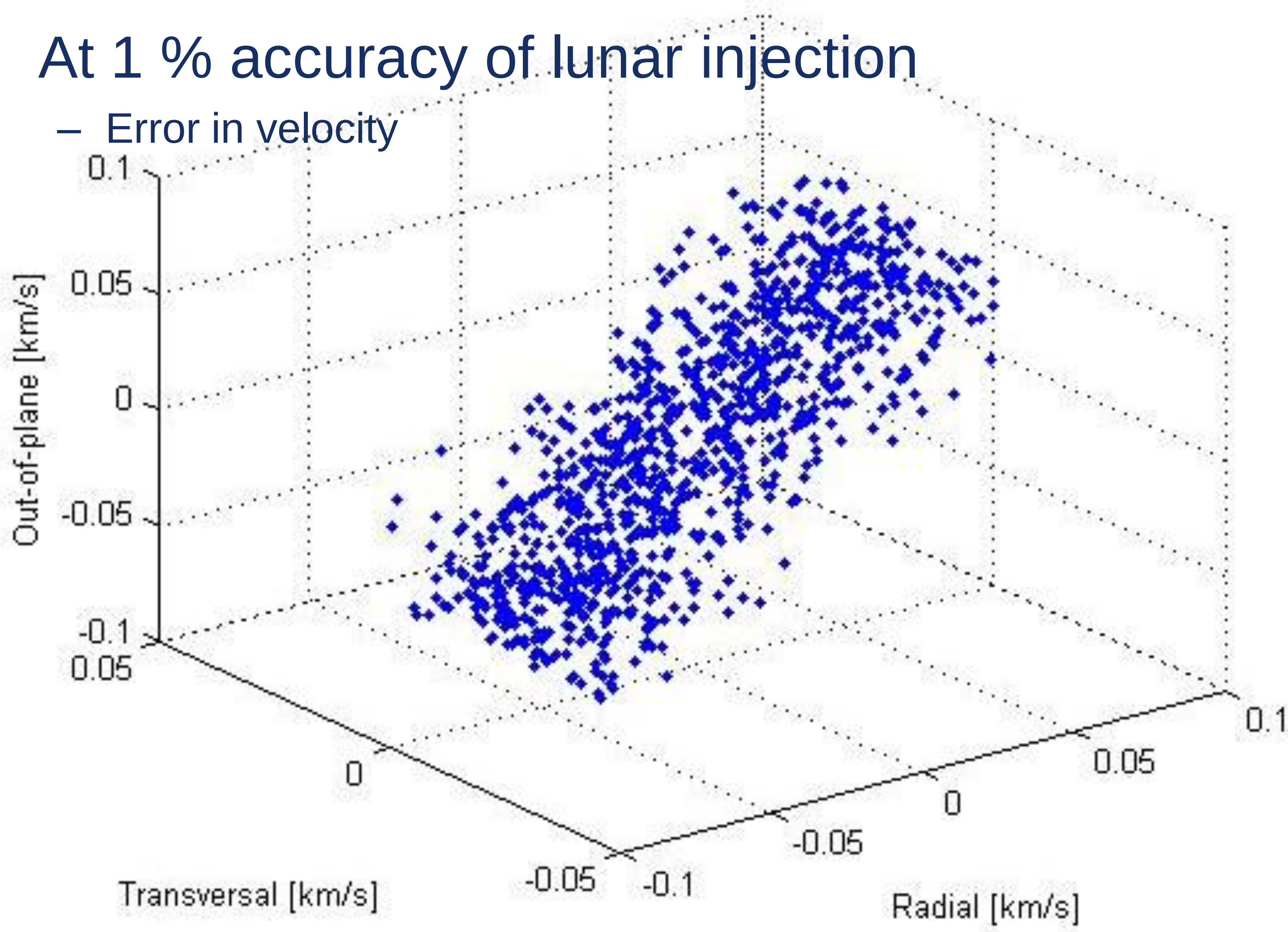
Sensitivity Analysis at the Moon

- At 1 % accuracy of lunar injection
  - Error in position



Sensitivity Analysis at the Moon

- At 1 % accuracy of lunar injection
  - Error in velocity



Recommendations on Orbit Determination

- From the previous plots considering the required accuracy of position and velocity, SpaceART offers the following recommendations:
  - New proposed requirement
    - **Position**
      25 km radial (range)
      10 km along track
      10 km out of plan
    - **Velocity**
      0.008 km/s radial (range rate)
      0.01 km/s along track
      0.013 km/s out of plane
- This is considered to be the worst case condition and should therefore be applied to all aspects of the WSB transfer legs and lunar orbit insertion.

Trade-Off of Delta-V Reduction

- Investigated the possibility of changing the baseline orbital transfer to reduce the total mission delta-V
  - Still providing a stable orbit for 6 months
  - Having multi-passage at 200 km or below at peripasis at the South Pole
    - Resolution requirement of the Narrow angle camera
- Investigated:
  - Varying the apolune of the lunar orbit
    - Orbital lifetime, associated perilune altitude
  - Use of frozen orbits

……..influence on the mission requirements

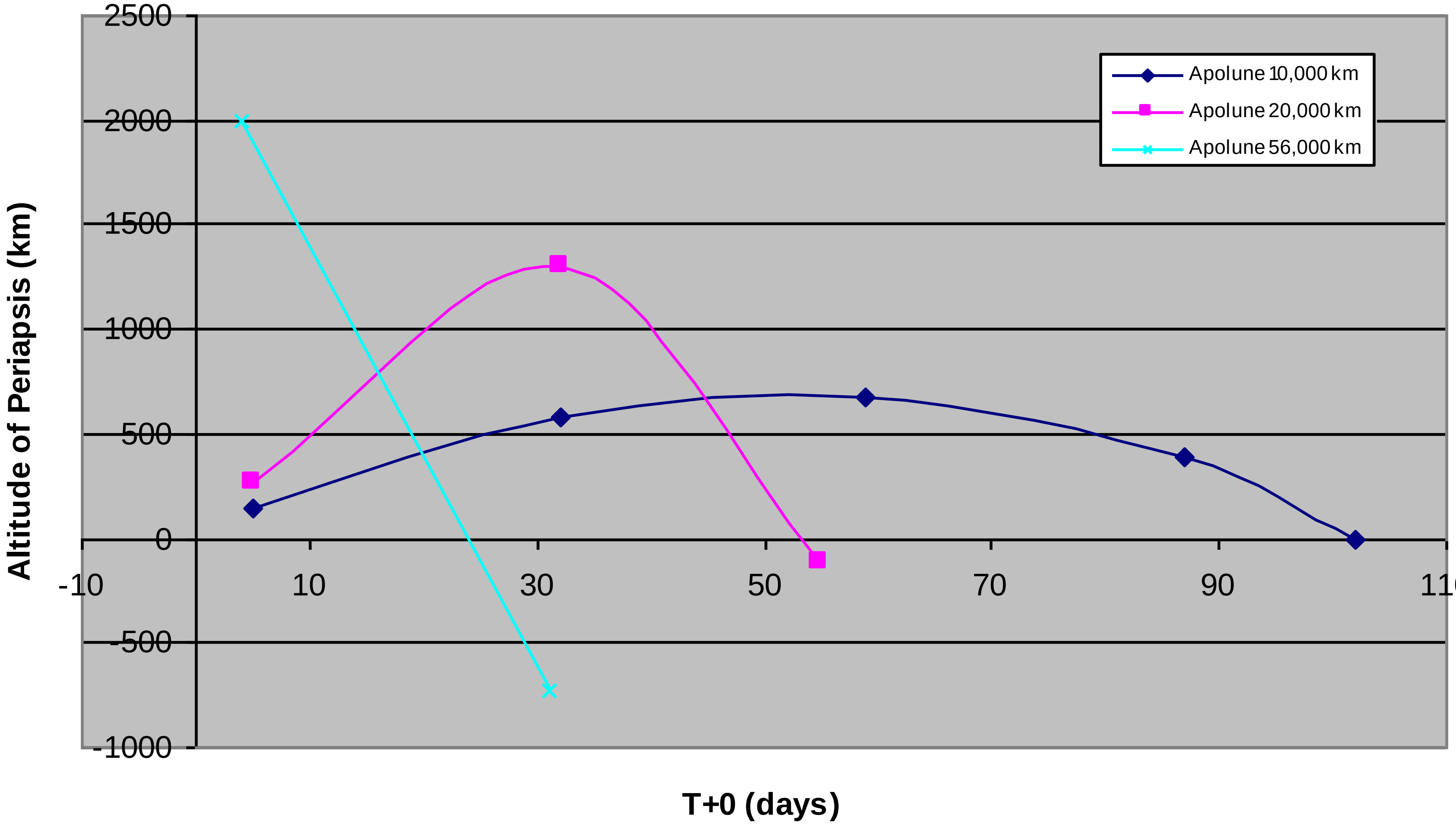
Orbital Analysis – Varying the Apolune

- Varying the apolune
  - Entering a higher lunar orbit
    - Altitude of apolune varied
    - Altitude of perilune at 100 km: comply with the 200 km camera resolution requirement

Orbital Elements	Values
Altitude of perilune	100 km
i	89.9 º
Ω	63.8 º
ω	292.9 º
ν	0 º

- Apolune 10,000 km
- Apolune 20,000 km
- Apolune 56,000 km

Varying the Apolune - Analysis



Frozen Orbits

- Explored the benefits of families of frozen orbits with stable liberation
  - Longer orbital life
  - Minimises station keeping → delta-V
  - Reduces s/c mass

i >= 39.2^{o}

ω 90 or 270^{o}

Ely T, Lieb E (2006) Constellations of Elliptical Inclined Lunar Orbits Providing Polar and Global Coverage The Journal of the Astronautical Sciences, Vol 54, Vol 1, pg 53-67

Ely T (2005) *Stable Constellations of Frozen Elliptical Inclined Lunar Orbits* Journal of the Astronautical Sciences, Vol 53, No 3, pg 301-311

Kumar K, Noomen R(2008) Stability of Highly Elliptical Orbits at the Moon. AIAA/AAS Astrodynamics Specialist Conference and Exhibit, 18th-21st August, Honolulu, Hawaii

Frozen Orbit – Analysis

- Tested the stability of three families of frozen orbits
  - At higher eccentrity and semimajor axis

a	**6542 km**
e	**0.6**
i	**56.2 °**
Ω	104.99 °
ω	**270 °**
M	349.36 °
T	56082.5799 MJD

CASE 1

a	**13084 km**
e	**0.8**
i	**56.2 °**
Ω	103.63 °
ω	**270 °**
M	345.51 °
T	56082.5799 MJD

CASE 2

a	**6808.1 km**
e	**0.73**
i	**56.2 °**
Ω	98.27 °
ω	**270 °**
M	332.92 °
T	56082.55082 MJD

CASE 3

Frozen Orbit – Analysis

- Conditions of analysis
  - For each new orbit, the WSB transfer was re-iterated
  - Resulted in updated values for:
    - Moon insertion date → 4th June 2012
    - RAAN
    - Mean motion

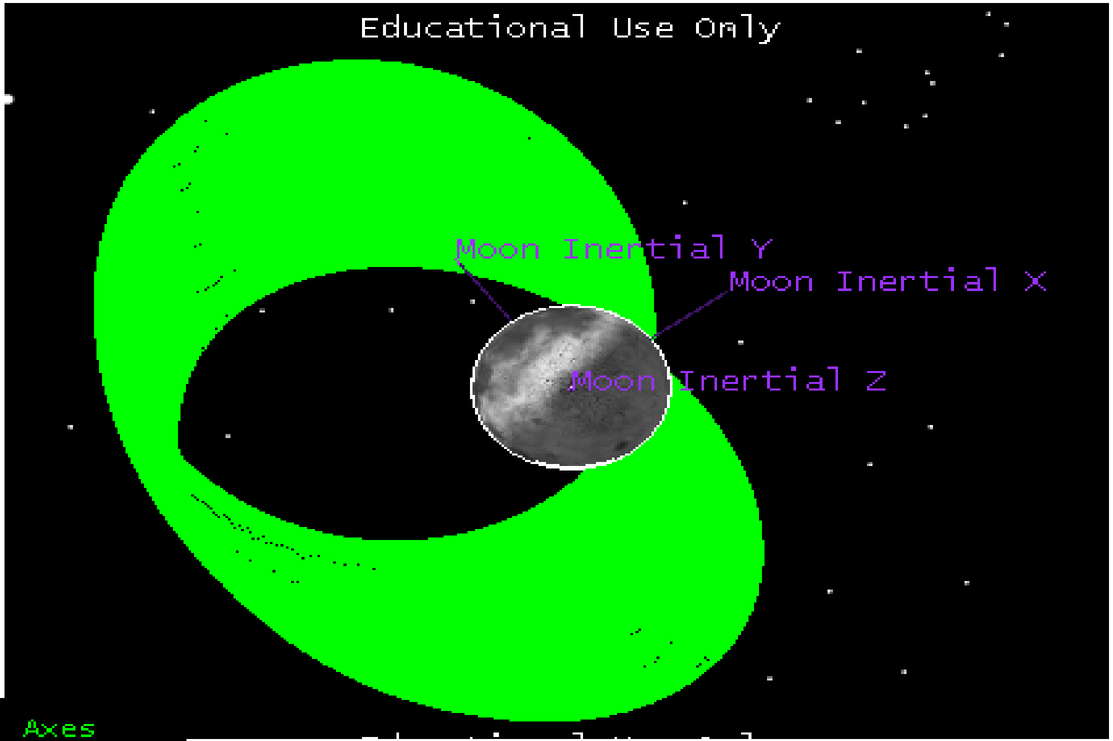
- Used the Moon's gravitational force as a central body
  - Data gained from the Lunar Prospector Orbiter
  - With the Earth and Sun as a 3rd body point mass effect

- Each STK simulation was run for six months

Frozen Orbits – Analysis, Case 1

- **CASE 1**

a	**6542 km**
e	**0.6**
i	**56.2 º**
Ω	104.99 º
ω	**270 º**
M	349.36 º
T	56082.5799 MJD



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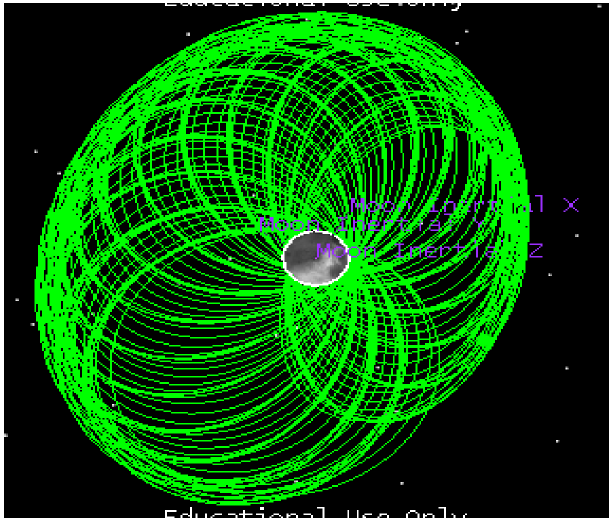
Frozen Orbit – Analysis, Case 1

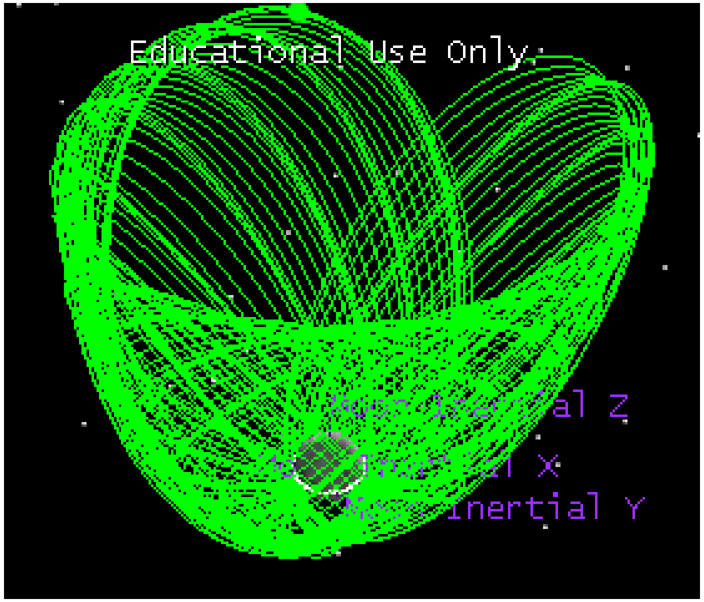
T + (days)	Altitude of Perilune (km)	Argument of Perilune (deg)	Inclination (deg)	Eccentricity
7	820.7632	267.292	55.747	0.608929
34	821.278195	264.418	55.19	0.608816
34	814.794859	264.5	55.209	0.609863
61	751.881313	262.033	54.367	0.619445
62	747.960826	262.202	54.378	0.620096
89	640.36707	260.605	53.303	0.636406
116	513.20599	260.271	52.064	0.655838
143	382.622987	261.086	50.742	0.675958
170	237.199371	263.18	49.488	0.69798
183	123.993065	264.031	48.895	0.715461

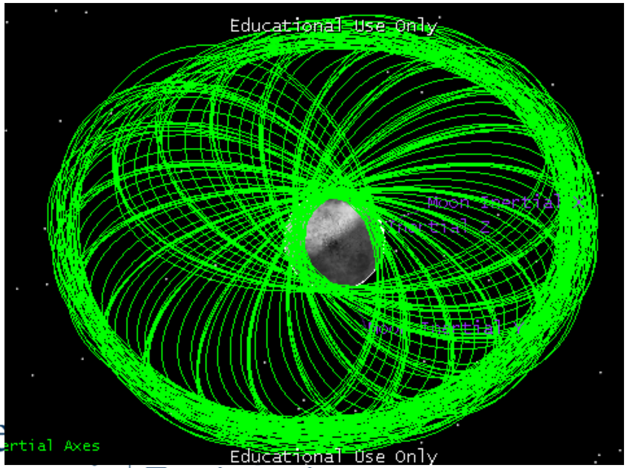
Frozen Orbit – Analysis, Case 2

- **CASE 2**

a	**13084 km**
e	**0.8**
i	**56.2 º**
Ω	103.63 º
ω	**270 º**
M	345.51 º
T	56082.5799 MJD







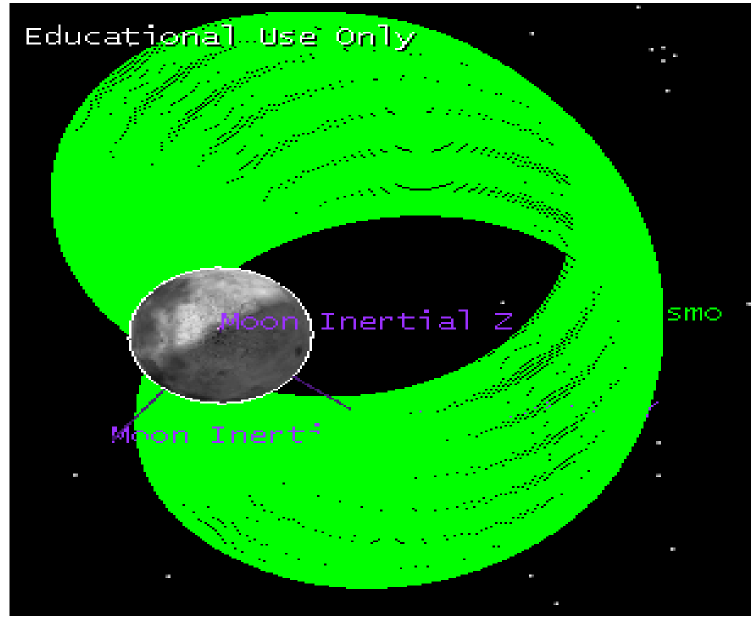
Frozen Orbit – Analysis, Case 2

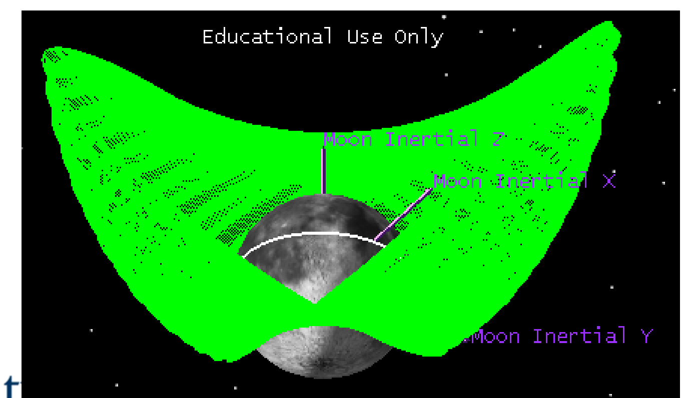
T + (days)	Altitude Of Perilune (km)	Argument of Perilune (deg)	Inclination (deg)	Eccentricity
6	513.214605	267.018	55.081	0.827297
34	1204.384562	279.113	57.69	0.773947
61	2167.882635	274.749	60.941	0.701045
88	1648.570095	266.014	61.262	0.738225
89	1718.745606	265.247	61.237	0.73563
116	538.973873	267.789	59.798	0.824661
143	498.81615	279.162	63.654	0.828001
170	1578.427517	276.41	68.846	0.743906
183	1767.462828	271.237	68.337	0.729623

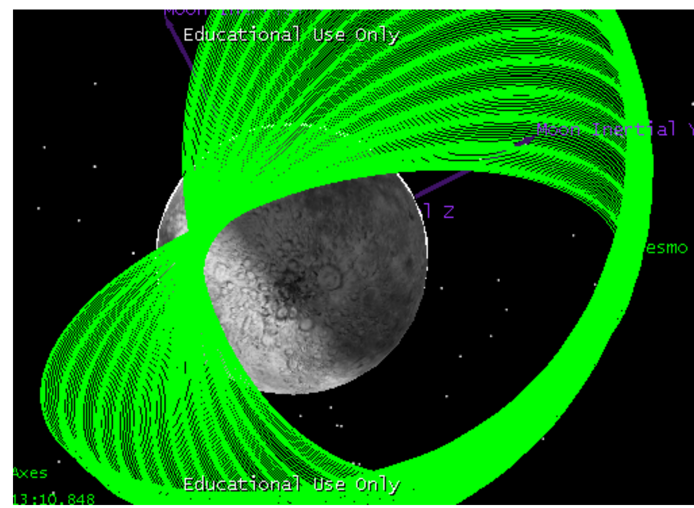
Frozen Orbit – Analysis, Case 3

- **CASE 3**

a	**6808.1 km**
e	**0.73**
i	**56.2 º**
Ω	98.27 º
ω	**270 º**
M	332.92 º
T	56082.55082 MJD







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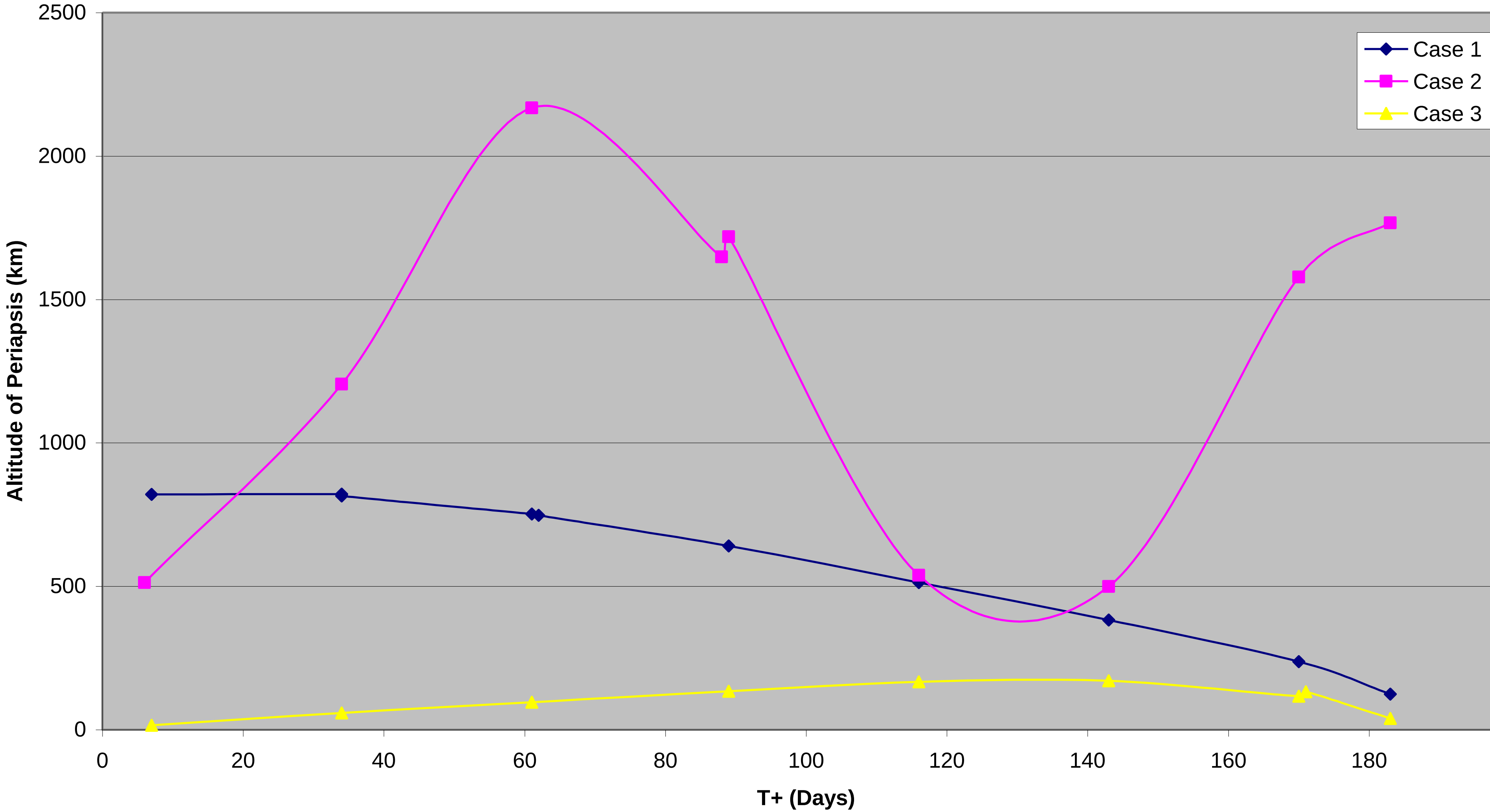
Frozen Orbit – Analysis, Case 3

T + (days)	Altitude Of Perilune (km)	Argument of Perilune (deg)	Inclination (deg)	Eccentricity
7	15.251774	268.343	55.704	0.742376
34	58.809417	269.194	55.408	0.735928
61	96.259455	269.878	55.232	0.730372
89	134.343993	270.378	55.182	0.724739
116	166.80333	270.487	55.215	0.720014
143	170.530942	270.285	55.247	0.719597
170	116.923328	270.366	55.251	0.727148
171	131.937598	270.265	55.286	0.725333
183	38.92874	271.159	55.063	0.73892

Frozen Orbits - Comparison



Frozen Orbits – Delta-V

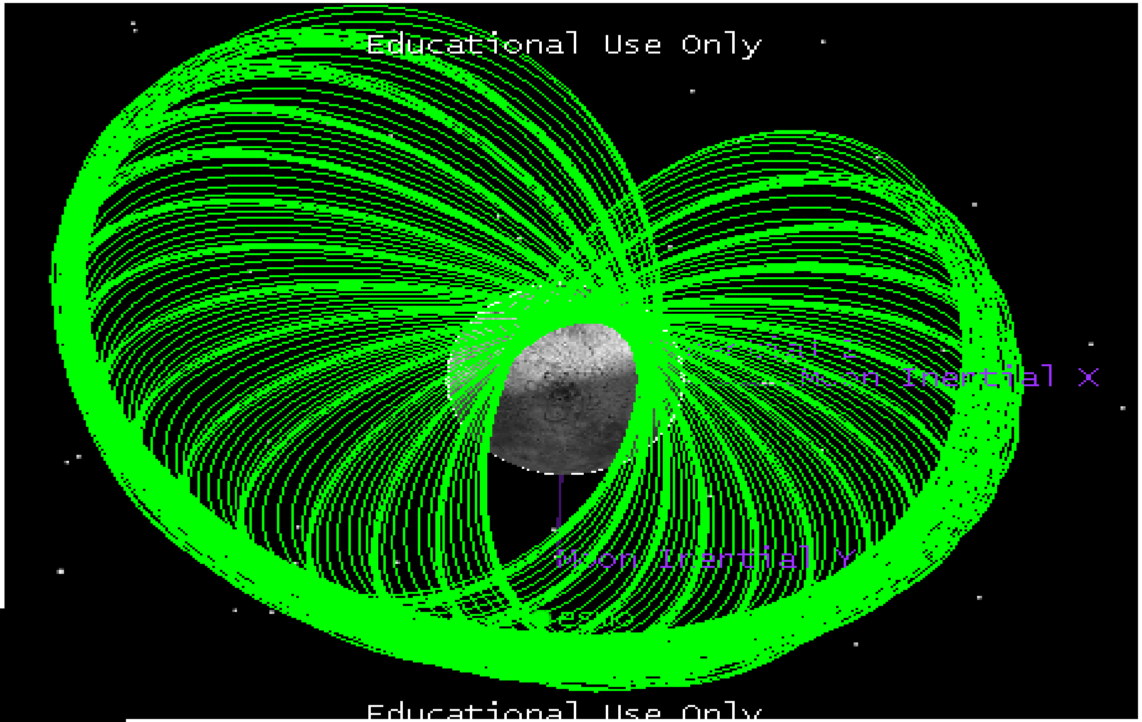
- Case 1 → delta V 946.91 m/s
- **Case 2 → delta V 854.85 m/s (a= 13084 km, e = 0.8)**
- Case 3 → delta V 947.87 m/s

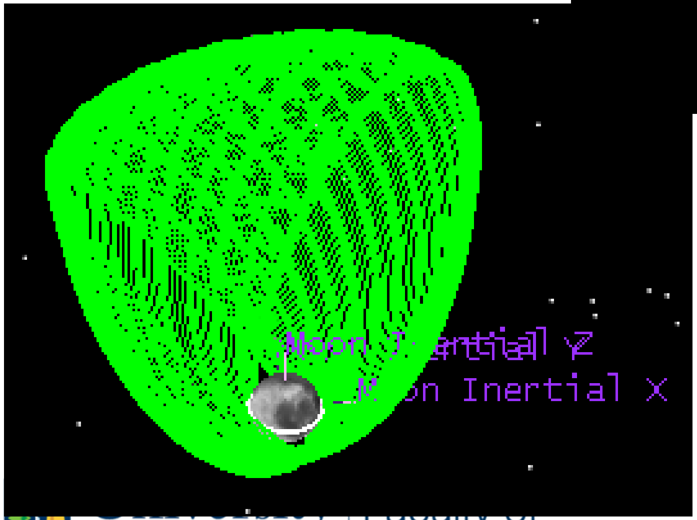
  – Investigated changing the perilune of Case 2, assessing the orbit lifetime and associated altitudes.

  – Found that there was sensitivity to the RAAN (below 100°), resulting in the fast decay of the orbit with an reduction in the semimajor axis

Frozen Orbits – Continued Analysis

a	10084 km
e	0.8
i	56.2 º
Ω	103.63 º
ω	270 º
M	345.51 º





Continued Analysis - Orbital Profile

T + (days)	Altitude Of Perilune (km)	Argument of Perilune (deg)	Inclination (deg)	Eccentricity
6	106.412074	267.768	55.468	0.816841
34	366.039082	275.196	56.174	0.790743
61	796.395115	276.896	58.313	0.747587
88	1105.725242	273.287	59.853	0.716913
89	1162.787506	273.073	60.015	0.712189
116	1002.679975	267.703	60.201	0.728253
143	477.762938	266.284	59.506	0.780311
170	37.913977	271.264	59.561	0.823777
183	167.756208	274.111	60.752	0.810885

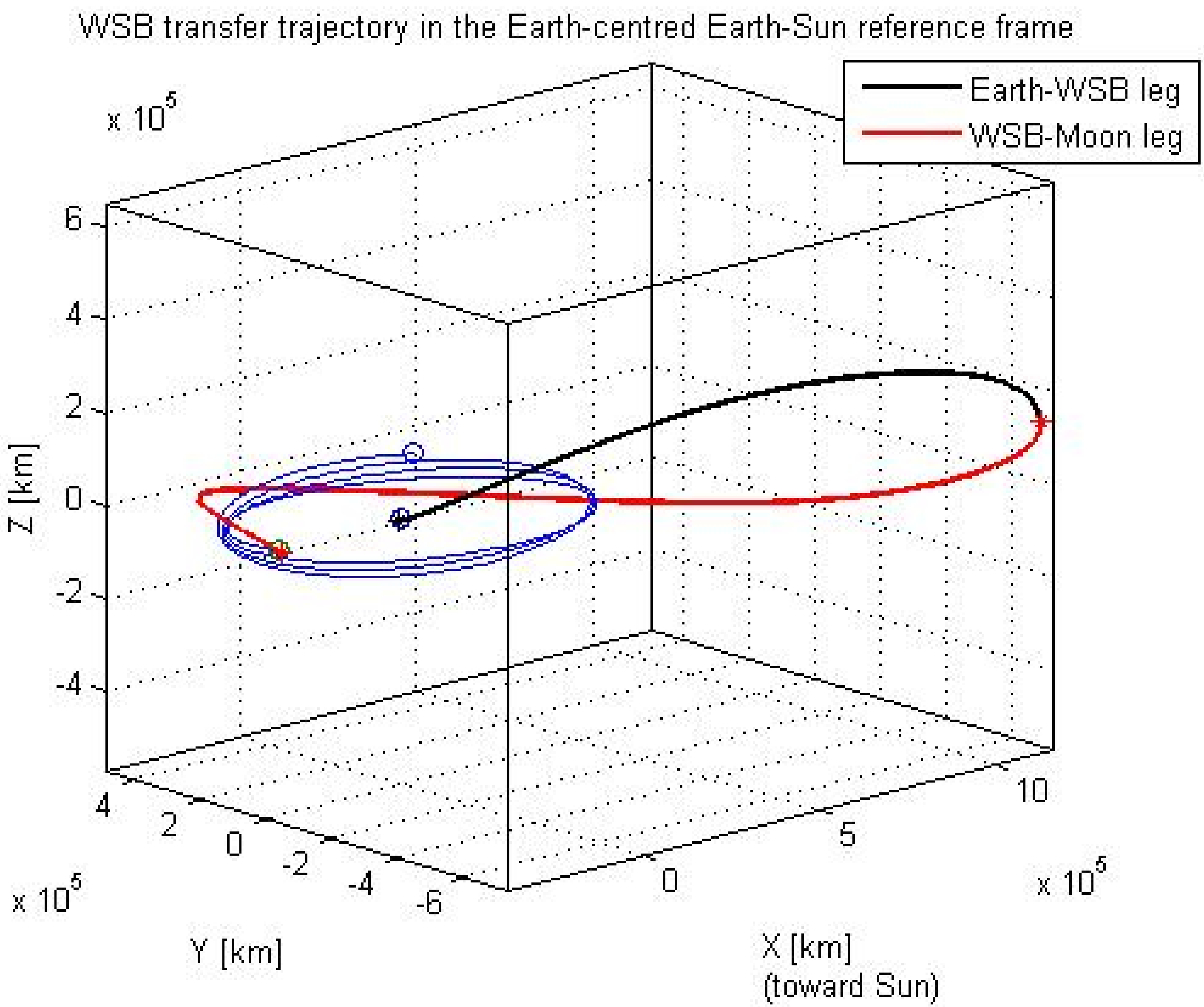
Proposed Transfer and Orbit Insertion

- The updated baseline
  - Earth to WSB
  - WSB to Moon
  - Moon insertion at:

a	13084 km
e	0.8
i	56.2 º
Ω	103.63 º
ω	270 º
M	345.51 º
T	4th July 2012 13.55.03 UTCG

  - Separate burn to lower the perilune
    - Reduce the semimajor axis by 3000 km, additional 47.2 m/s

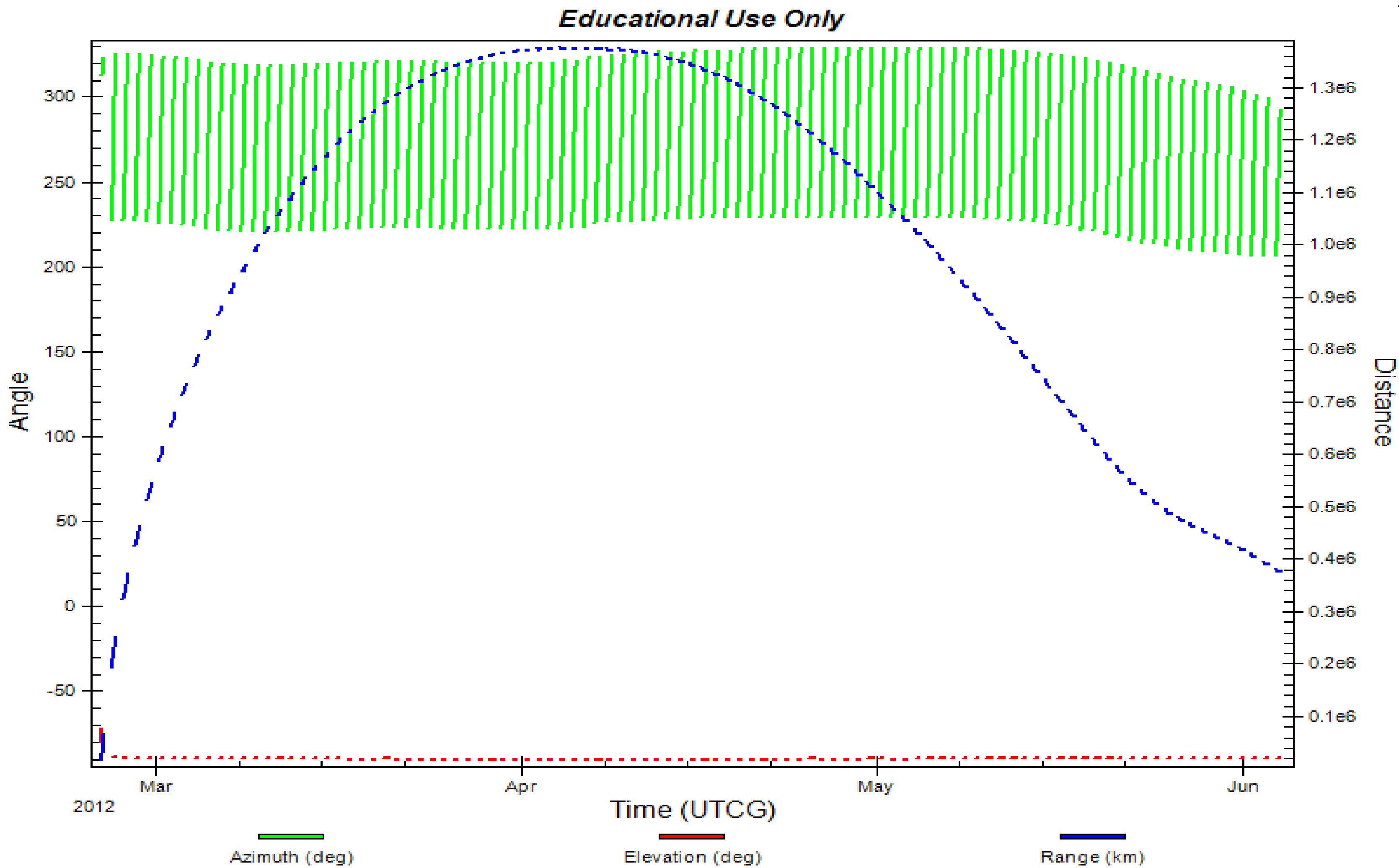
Proposed WSB Transfer



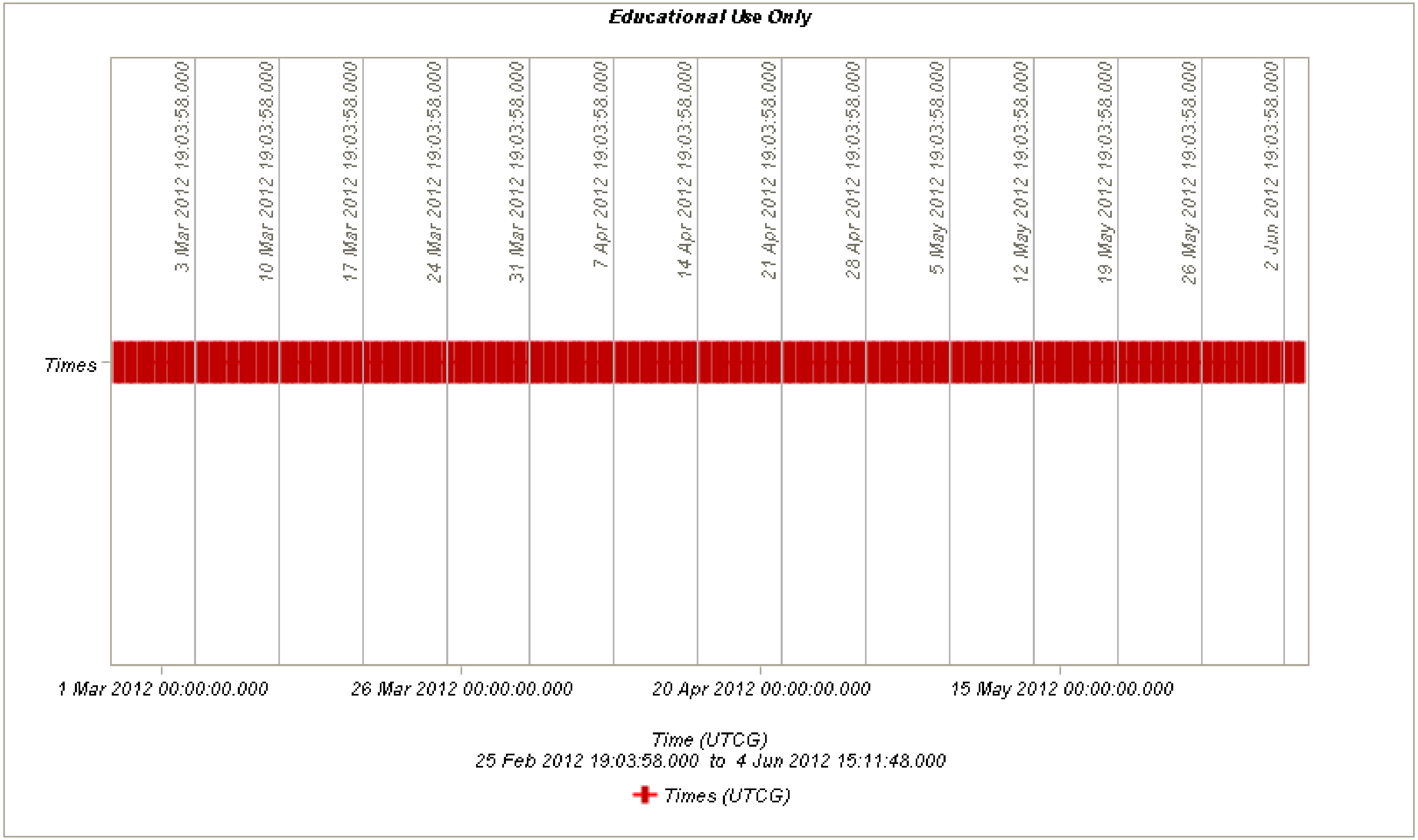
Access - Proposed Baseline Transfer

- Good ground access, despite the single eclipse at Earth departure of ~670 sec (approx. 11 mins).

Access - Proposed Baseline Transfer



Ground Station Access Time



Total Transfer – Summary of Nominal

WSB Transfer Comparison	Baseline	New Transfer to HE Orbit
Total ΔV (plus additional orbit transfer at Moon) [m/s]	**1116.29**	**854.85+47.2** = 902.05
ΔV at Earth [m/s] (nominal escape)	747.7	748.25
ΔV at WSB [m/s] (matching manoeuvre)	**71.02**	**34.16**
ΔV at Moon [m/s] (plus additional orbit transfer)	**297.57**	**72.45+47.2**
Departure Date [UTCG]	25/02/2012 14:34	25/02/2012 19:03
Time of flight Earth-WSB [days]	40.82	40.76
Time of flight WSB-Moon [days]	60.31	59.08
Total time of flight [days]	101.13	99.84
Arrival Date [UTCG]	05/06/2012 17:39	04/06/2012 15:11
Arrival Orbit: semi-major axis [km]	**3586**	**10084**
Arrival Orbit: eccentricity	**0.4875**	**0.8**
Arrival Orbit: inclination [deg]	**89.9**	**56.2**

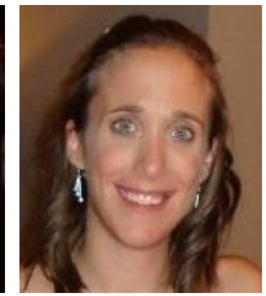
In Summary

- Proposed a new baseline lunar orbit
  - Highly eccentric, frozen orbit
  - Higher altitude of perilune
  - Achieves a stable orbit for 6 months, with possible extension
  - Delta –V saving of 214.24 m/s
  - Completed mission occurs under 1 km/s (902.05 m/s)
    - Not including margins
- Influence on the Requirements
  - Higher periline → payload resolution
  - 11 mins eclipse time → power budget
  - Updated reduction in delta-V → propulsion, s/c mass

Acknowledgements

- Team Composition
  - Supervisor
    - Dr Vasile
  - Mission Analysis
    - Federico Zuiani (PhD)
    - Daniel Novak (PhD)
    - Alison Gibbings (PhD)





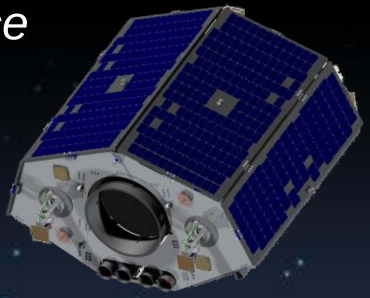

  - Flight Dynamics (incl orbit determination and control)
    - Francesco Rizzi (Erasmus)
    - Cesar Martinez (Erasmus)


Capabilities of SpaceART

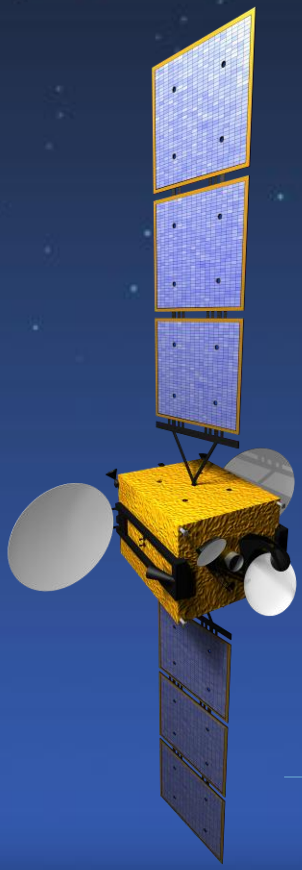
- The design process is based on the following Matlab modules:
  - Orbit simulator (complemented now by a spacecraft simulator)
  - Ground station and measurement simulator
  - Filtering module
  - Optimisation module
- DITAN (direct transcription of optimal control problems with finite elements in time) is used for thrust manoeuvre modeling and optimisation
- STK with Astrogator is used for ground station visibility analysis , eclipse analysis, orbit propagation
- ODTK is used for verification of the OD process

Capabilities of SpaceART

- The orbit simulator contains:
  - Analytical ephemeris
  - 3rd body perturbations
  - Gravity perturbations
  - Light pressure
  - Simplified drag model
- The spacecraft simulator currently contains the following modules:
  - Thermal analysis module
  - Attitude dynamics module
  - Orbit simulation module



Thank You



Any Questions?

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