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# OPTIMAL DESIGN OF LOW-ENERGY TRANSFERS TO HIGHLY ECCENTRIC FROZEN ORBITS AROUND THE MOON

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## ABSTRACT

Scheduled for launch in 2014-2015, the European Student Moon Orbiter (ESMO) offers the opportunity for University students across Europe to design and build a microsatellite. Through the use of an all-day-piggy-back launch opportunity, ESMO will exploit the relative benefits of a Weak Stability Boundary (WSB) transfer to reach the Moon. ESMO will then enter a highly elliptical frozen orbit, gathering high resolution images of the surface of the South Pole. This paper will present ESMO's optimal WSB transfer and insertion into its desired orbit. Highly elliptical frozen orbits have the benefit of a low orbital insertion delta-V that is combined with no or very small long-term variations of eccentricity and argument of periapsis. This significantly reduces the requirements on orbit maintenance. Coupled with the mission & scientific requirements, a highly elliptical frozen orbit is considered to be the optimal orbit design for ESMO. Furthermore, an optimal multi-burn strategy for both Earth departure and lunar arrival is also added to the transfer. This is to minimise gravity losses, error in the navigation budget and to provide flexibility in the final launch date selection. ESMO is considered to be an ambitious mission design.

## I.ACRONYMS

COTS – Commercial off the Shelf
ESMO – European Student Moon Orbiter
GTO - Geostationary Transfer Orbit
LEO – Low Earth Orbit
LOI - Lunar Orbit Insertion
MSB – Multi-burn Strategy
NAC – Narrow Angle Camera
RAAN – Right Ascension of the Ascending Node
SpaceART – Space Advanced Research Team
STK – Satellite Tool Kit
TCM – Trajectory Control Manoeuvred
TLI - Trans -lunar Insertion Manoeuvre
WSB – Weak Stability Transfer

## II. INTRODUCTION

Scheduled for launch in 2014-2015, the European Student Moon Orbiter (ESMO) offers the opportunity for University students across Europe to design and build a microsatellite [1][2]. Through the use of an all-day-piggy-back launch opportunity, ESMO will exploit the relative benefits of a Weak Stability Boundary (WSB) transfer to reach a polar orbit around the Moon. Once in lunar orbit the primary mission objective is to acquire surface images of the South Pole, providing high resolution data over six months. This will be achieved through a Narrow Angle CCD Camera (NAC) at a resolution no more than 200 km at periselenium, above the South Pole. It is therefore critical that a stable polar orbit is achieved.

ESMO is therefore considered to be a highly ambitious mission design. The utilisation of a WSB transfer is used as a means to provide a high degree of flexibility in the selection of the launch opportunity. However, this flexibility, due to the sensitivity dynamics, is slated against the expense of having to use a far more complex navigation strategy. This paper will therefore present the optimal design of ESMO's WSB transfers into a highly elliptical frozen orbit around the Moon. An optimal multi-burn strategy for both Earth departure and lunar arrival is also added to the transfer to minimise gravity losses, navigation error and to provide flexibility in the final launch date selection. Ultimately the analysis details the trade-off between the cumulative saving of delta-V and the mission lifetime of ESMO. High elliptical frozen orbits have the benefit of a low insertion delta-V with no or very small long-term variations of eccentricity and argument of periapsis. This significantly reduces the requirements on orbit correction and station keeping. Coupled with the mission & scientific requirements, a highly elliptical frozen orbit is considered to be the optimal orbit design for ESMO.

## III. 2011-2012 LAUNCH WINDOW

Based on the now outdated 2011-2012 launch window ESMO's orbital transfer consisted of a WSB transfer in the Earth-Moon system [2]. In a typical WSB transfer the spacecraft departs from a Low Earth Orbit by performing a Trans-lunar Insertion Manoeuvre (TLI). The spacecraft then coasts for more than $10^6$ km, until it reaches the WSB region. By performing small correction manoeuvres the spacecraft can then coast toward the Moon. A final Lunar Orbit Insertion (LOI) manoeuvre ensures injection around the Moon. This methodology is adopted for the ESMO mission.

Computationally each WSB trajectory is modelled as two separate legs: one from TLI to the WSB region and one from the WSB region to LOI [8] [9]. A WSB transfer is computed by fixing a given set of departure and arrival orbits, with the departure time, the time of flight for each leg, the manoeuvres at TLI and at LOI as design parameters [10]. Then, the orbital motion is propagated backwards in the TLI-WSB leg and backwards in the WSB-LOI leg. A gradient-based optimiser is then used to match the position of the two legs at WSB and to minimise the total delta-V of the transfer [10] [11]. The latter includes the cost of the TLI manoeuvre, the LOI manoeuvre and a WSB manoeuvre. This is required to match the velocities of the two legs at WSB. The dynamic model used in the propagation includes a complete 4 Body Problem model with gravitational effects of Earth, Sun and Moon [8] [10].

Following the WSB transfer, ESMO's final orbit around the Moon was characterised by the following orbital elements. This is given in Table 1 .

| | |
|---|---|
| a | 3586 km |
| e | 0.4874 |
| i | 89.9 º |
| Ω | 63.8 º |
| ω = | 292.9º |
| ν = | 0º |

**Table 1: 2011-2012 Orbital Elements**

This provided low perigee coverage at the South Pole. To achieve this impulsive transfer and final orbital insertion, the nominal delta-V was 1.12 km/s, with an associated transfer time of 101.13 days. Details of all manoeuvres and the delta-V costs are given in Table 2.

| | |
|---|---|
| Total ΔV [m/s] | 1116.29 |
| ΔV at Earth [m/s] (nominal escape) | 747.7 |
| ΔV at WSB [m/s] (matching manoeuvre) | 71.02 |
| ΔV at Moon [m/s] (plus additional orbit transfer) | 297.57 |
| 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 |

**Table 2: 2011-2012 Breakdown**

This however exceeded the available mission delta-V, and therefore novel methods to reduce this value were considered. Details of which are given in the subsequent text. All analysis presented in this paper, unless explicitly stated, was conducted within the 2011-2012 time frame. Future work is required to re-iterate within the 2014-2015 launch window. Definition of ESMO's mission analysis is on-going within the University of Glasgow Space Advanced Research Team (SpaceART).

## IV. MISSION ANAYLSIS OF ESMO

In the development of ESMO, mission cost and total mass are considered to be critical drivers. This is reflected in the requirement of a piggy-back and/or secondary launch opportunities into a Geostationary Transfer Orbit (GTO) and the extensive use of flight spares and non-space related components (e.g. COTS). This, however, imposes significant constraints on the maximum size of the propellant tanks and thus on the maximum allowable delta-V [2]. The maximum allowable delta-V within the propellant tanks constrains ESMO's mass. This is constrained to 1.15 km/s. Therefore a conservative requirement to perform the mission objectivities at, or under a delta-V budget of 1 km/s was defined. This is against the nominal 1.12 km/s mission delta-V that was required to perform the previous mission analysis baseline.

To account for this restriction, several options were investigated to reduce the total mission delta-V. However, any adjustment in the orbital transfer and lunar insertion still had to remain compliant to the mission and system requirements. In particular, the lifetime of the orbit shall remain stable for six months, while offering multiple passages at 200 km, or below, at periapsis, located at the South Pole. The requirement on the periapsis altitude was derived from the Narrow Angle Camera (NAC) [1].

Initial trade-offs were conducted to assess where delta-V could be saved. Possible locations included at launch, at GTO, and at lunar injection. The majority of the mission delta-V is spent in performing the transfer and the lunar insertion manoeuvre. However, the transfer delta-V could only be marginally reduced. Therefore the main reduction in delta-V was considered at insertion and during the selection of the final lunar orbit. Higher energetic and eccentric lunar orbits were considered. This lead to a significant saving in delta-V, and still fulfilled the mission and scientific requirements.

Initial changes to the lunar orbit selection were made by increasing the apolune altitude; values of 10000, 20000 and 56000 km were chosen. This allowed ESMO to enter a far higher orbit. To comply with the NAC requirements the altitude of perigee was constrained to 100 km. All other orbital elements were kept to the existing 2011-2012 baseline. The higher the apolune orbit the quicker the orbit decayed.

Entering a 10000 km orbit resulted in an orbital lifetime of approximately 4 months, while a 20000 km orbit decayed after 55 days, and a 56000 km orbit decayed under 30 days. This did not comply with the mission requirements in providing a stable orbit for six months. Therefore the authors explored the relative benefits of utilizing a family of frozen orbits around the Moon.

## V. FROZEN ORBITS

From the early 1960s frozen orbit have been the subject of discussion and debate [3]. They offer the possibility of stable liberation with no long-term, large-scale variation in inclination, eccentricity and semi-major axis [4][5][6]. This results in a longer orbital lifetime and minimises and/or eliminates the need for additional station keeping and orbit control manoeuvres. Therefore the utilisation of frozen orbits significantly reduces the requirement on delta-V and the associated propellant mass needed to reach and maintain a selected orbital configuration.

### V.1. Formation of Frozen Orbits

Based on previous work, frozen orbits only occur under fixed conditions of argument of periapsis ($\omega$ = 90° or 270°) and critical inclination ($i \geq 39.2^{\circ}$) [3][4][5][6]. This is given by the following expressions, where $\omega^{op}$ defines the Moon's reference frame [5][6].

Frozen orbits occur when stable liberation ($e - \omega^{op}$) around a fixed point remains constant. Therefore:

$$\frac{de}{dt} = \frac{d\omega^{op}}{dt} = 0 \qquad [1]$$

By applying Lagrange's planetary equations, fixed point solutions occur when:

$$\sin 2\omega^{op} = 0 \qquad [2]$$

Are met by:

$$(5(\cos i^{op})^2 - 1 + e^2) + 5(1 - e^2 - (\cos i^{op})^2 \cos 2\omega^{op}) = 0$$

This leads to the results for:

$$\omega^{op} = 90^{\circ}, 270^{\circ}$$

And

$$e = \left(1 - \frac{5}{3}(\cos i)^2\right)^{\frac{1}{2}} \qquad [3]$$

Furthermore to ensure that the periapsis altitude is above the minimal altitude the following expression is used:

$$a(1-e_{MAX})-R_M \geq h_{MIN} \qquad [4]$$

$R_M$ is the mean radius of the Moon.

Similarity to ensure that the apoapsis altitude is less than a maximal altitude; it is constrained by a related expression:

$$a(1+e_{MAX})-R_M \leq h_{MAX} \qquad [5]$$

Therefore for third body perturbed problems, real solutions only exist when $i \geq 39.2^o$. Below the critical inclination no close-form analytical solutions for frozen orbits will occur. Therefore for any solution where ω = 90° or 270° and the inclination is between 39.2° and 140°, an eccentricity value will exist that can be used to constrain the argument of periapsis and eccentricity to zero. Once these conditions have been adhered to the conditions for a frozen orbit will be satisfied [3].

### V.2. Past Missions - Utilisation of Frozen Orbits

The 1999 Lunar Prospector mission utilised the relative benefits of a quasi-frozen orbit. This consisted of a near circular orbit characterised by a semi-major axis of 1838 km and an eccentricity value of 0.006 [3]. However, the conditions of a fully frozen orbit where not adhered to. A monthly manoeuvre was required to re-initialise the predictive and repetitive pattern of evolution. Without this manoeuvre the argument of periapsis would continue to drift and the spacecraft would eventually impact onto the surface of the Moon.

In comparison the 1994 Clementine mission established an elliptical orbit around the Moon. This was characterised with a semi-major axis of 3000 km and an eccentricity value of 0.37 [3]. Operational data gained from this mission enabled the definitive orbital elements to be compared against the analytical and numerical solutions. This involved long-term propagation, where the collect data matched the predicted pattern.

## V1. FROZEN ORBITS AS APPLIED TO ESMO

In order to enter and maintain a frozen orbit around the Moon, while still adhering to the mission requirements and constraints, the orbital elements of the ESMO mission had to be reconsidered. With limited coverage, and possible impact scenarios the chosen combination of semi-major axis and eccentricity becomes problematic [3].

Therefore the stability of three different families of frozen orbits was evaluated. Data detailing the orbital elements of each are given in Table 3. An argument of perilune of ω = 270° was selected as it provides perilune close to the South Pole.

| Orbital Parameter | Case 1[5] | Case 2 | Case 3 |
|---|---|---|---|
| a | 6542 km | 13084 km | 6808.1 km |
| e | 0.6 | 0.8 | 0.73) |
| i | 56.2 ° | 56.2 ° | 56.2 ° |
| Ω | 104.99 ° | 103.63 ° | 98.27 ° |
| ω | 270 ° | 270 ° | 270 ° |
| M | 349.36 ° | 345.51 ° | 332.92 ° |
| $t_{INSERTION}$ | 56082.5799 MJD | 56082.5799 MJD | 56082.55082 MJD |
| Delta-V | 0.947 km/s | 0.855 km/s | 0.948 km/s |

**Table 3: Families of Frozen Orbits**

Table 3 details $a$ as the semi-major axis, $e$ as the eccentricity, $i$ as the inclination, Ω as the right ascension of the ascending node (RAAN), ω as the argument of the perilune, $M$ as the mean motion and $t_{INSERTION}$ the as epoch of the injection manoeuvre. Each orbit is at much higher values of eccentricity and semi- major axis than ESMO's previous baseline lunar orbit.

For each new case, the WSB transfer was re- iterated. This resulted in changes in the orbit's insertion date, RAAN, and mean motion. The stability of the frozen orbits was tested by propagating the initial orbital elements with STK. It was assumed that ESMO was subjected to the inhomogeneous gravity field of the Moon and the 3rd body effect of the Earth and the Sun. For a Moon orbiting mission the domination perturbation effects is a result from the gravitational attraction of the Earth. The Moon is contained within Earth's sphere of influence. Therefore ESMO will experience a perturbation pull of the Earth [4]. To accurately simulate orbital stability around the Moon it is critical that this perturbation is included within the dynamics. The Moon's gravitational force was modelled with the data gained from the Lunar Prospector Orbiter [7]. The sensitivity to the degree and order of the gravity field model was initially assessed by running STK with 20 and 60 zonal harmonic coefficients. This variation had no significant effect on the final orbital elements. Therefore, all later simulations were performed using a 20th degree and 20th order gravitational model. However, since the existing gravitational models of the Moon have a degree of uncertainty, there may be some unknown discrepancy between the simulated evolution of the Keplerian elements and the experienced in-situ environment. Although, with the data gained from recent lunar missions (i.e. SMART 1, Lunar Reconnaissance Orbiter) future refinement of the gravity model is expected. This will enable analysis to converge onto a true solution. Each simulation was run for six months.

All three cases provided an operationally stable orbit. As expected, there was no longer-term variation in the orbital elements. This is given in Figure 1 (T+ (days) vs altitude of perilune and Figure 2 (T+ (days) vs argument of peripasis.

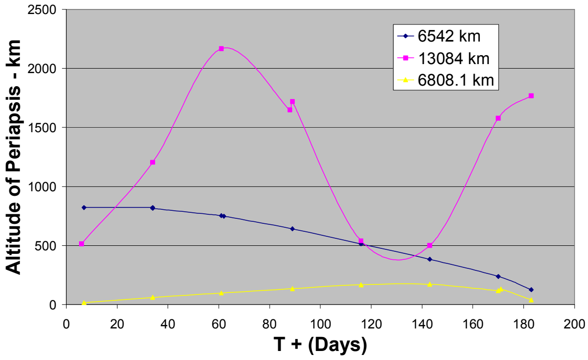

**Figure 1: T+ (Days) vs Altitude of Perilune**

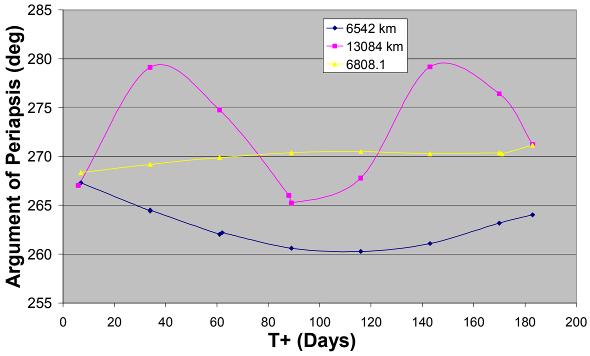

**Figure 2: T+ (Days) vs Argument of Perilune**

However, Case 3 was the only orbit that adhered to the NAC requirement for the entire six months. The mission and system requirements states that the NAC shall take images of the lunar surface for a period of at least six month. Furthermore that NAC shall take images from a polar lunar orbit with periapsis altitude of 200 km [1]. These requirements were only achievable with a much larger delta-V budget of 0.948 km/s. In comparison, Case 1 only offered low periline altitudes once ESMO begins to enter the later phases of the mission. This occurs from 145 days onwards. Although, compared to Case 1 the delta-V reduction is only 0.001 km/s. Case 2 offered a sufficiently lower mission delta-V of 0.855 km/s. However, this orbital configuration did not comply with the NAC requirement. There is a trade-off between the cumulative saving of delta-V, altitude of perilune and mission lifetime.

It is because Case 2 is a highly eccentric orbit, with a large semi-major axis that it has the benefit of offering a much lower mission insertion delta-V, while still maintaining an orbital lifetime. The reduction in delta-V has a cumulative effect in reducing the required mass and volume of propellant. Due to this substantially lower delta-V Case 2 was selected for further analysis.

## V11. TRADE-OFF ANALYSIS

### V11.1. Reduction in Semi-major Axis

During the trade-off process, the mission delta-V was considered to be far more important than the resolution requirement of the NAC. However a good compromise between delta-V cost and image resolution can be obtained with a slightly lower altitude frozen orbit. Starting from Case 2 a lower altitude orbit was obtained by progressively reducing the semi-major axis in steps of 500 km. For each step, the variation in orbital lifetime was assessed against the mission delta-V.

### V11.11 Sensitivities of the RAAN

During this analysis, it was discovered that there were sensitivities to the orbital injection RAAN and the injection date. Some values of RAAN below 100º resulted in the faster decay of the orbit. This corresponded with a reduction in the semi-major axis. This seems to be a characteristic of using highly elliptical frozen orbits. To optimise and then constrain the WSB transfer and orbit selection, the stability of the arrival orbit relative to the RAAN and arrival date was performed. Using multiple values of RAAN and arrival dates, each proposed orbit was propagated for six months. The RAAN ranged from 0-180º and the arrival date ranged +/- 16 days. Clusters of unstable RAAN and arrival dates were found. This is outlined in Figure 3. The red areas indicate an unstable orbit; where as the green areas indicate a stable orbit. The results will be used in future work to induce constrains into the trajectory optimisation process.

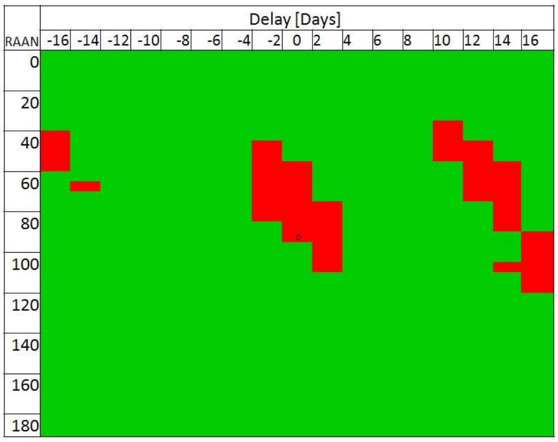

**Figure 3: Orbit Sensitivity to $T_0$ and RAAN. Green: Orbit Stable after Six Months. Red: Decay within Six Months**

## VIII. ORBIT SELECTION

Despite the restrictions on RAAN and arrival dates, the progressive reduction of the semi-major axis of Case 2 enabled the formation of a stable frozen orbit. This was considered to be a good compromise between altitude and delta-V cost. The orbital elements are given in Table 4.

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

**Table 4: Case 2 - Orbital Elements**

This orbit provides coverage at a low altitude of perilune for approximately 55 days. This complies with the NAC coverage, although at all other times the altitude of perilune is varying. This has the benefit of offering additional flexibility in the operations of the NAC. Also of note, towards the end of the mission at day 170, there is the option to end the mission which benefits from the low altitude of perilune (37.92 km). A forced de-orbiting manoeuvre has an estimated delta-V of 0.021 km/s, lowering the perilune down to the lunar surface. If not, the perilune of the orbit will naturally increase, allowing for a possible extension of the mission. This adheres with the decommissioning and de-orbiting requirement [1].

However, in modifying ESMO's desired lunar orbit, the WSB transfer had to be partially redesigned. In comparison to the previous baseline ESMO would initially insert into a much higher, more eccentric orbit. This, as given in Table 5 has the following characteristics:

| | |
|---|---|
| a | 13084 |
| e | 0.8 |
| i | 56.2º |
| Ω | 103.63º |
| ω | 270º |
| M | 345.51º |
| t | 4th July 2012 13.55.03 UTCG. |

**Table 5: WSB Modified Orbital Elements**

This orbit, as an example, combines the benefits of the frozen orbital characteristics with a low insertion delta-V. Following which a bi-impulsive transfer is used reduce the semi-major axis by 3000 km (*a* = 10084 km). This costs an additional 47.2 m/s, but ensures partial compliance to the NAC requirement. Figure 4 and Figure 5 illustrates the STK simulation of the final orbit configuration. Table 6 details the scenario's delta-V cost and transfer time.

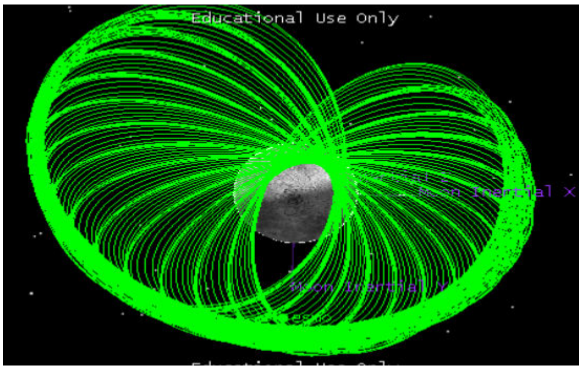

**Figure 4: STK Simulation of the Orbital Configuration**

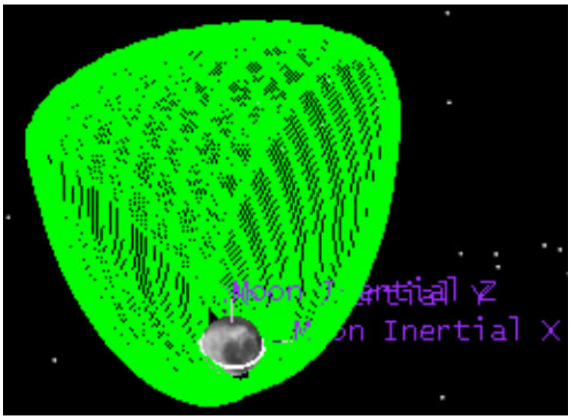

**Figure 5: STK Simulation of the Orbital Configuration**

| | |
|---|---|
| Total $\Delta V$ (plus additional orbit transfer at Moon) [m/s] | 854.85+47.2 = 902.05 |
| $\Delta V$ at Earth [m/s] (nominal escape) | 748.25 |
| $\Delta V$ at WSB [m/s] (matching manoeuvre) | 34.16 |
| $\Delta V$ at Moon [m/s] (plus additional orbit transfer) | 72.45+47.2 |
| Departure Date [UTCG] | 25/02/2012 19:03 |
| Time of flight Earth-WSB [days] | 40.76 |
| Time of flight WSB-Moon [days] | 59.08 |
| Total time of flight [days] | 99.84 |
| Arrival Date [UTCG] | 04/06/2012 15:11 |

**Table 6: Updated Baseline Scenario**

Despite having to perform an additional burn, the proposed transfer offers a mission delta-V savings of 0.214 km/s. Therefore the final mission delta-V is 0.902 km/s, with a transfer time of 99.84 days; 40.76 days for the GTO to WSB leg and 59.08 days from the WSB to Moon leg. This is under the available nominal delta-V from the propulsion system of 1 km/s.

However, the delta-V value of 0.902 km/s is considered nominal, and so does not include any margins or Trajectory Correction Manoeuvres (TCMs). Furthermore, in addition to the impulsive delta-V, a 5 % gravity loss, 3 % navigation and a 5 % contingency margin must also be added onto the total delta-V mission budget. This shall be added in later work. Additionally, all analysis is to be re-iterated for the proposed 2014-2015 launch window.

The final orbit was then assessed in terms of its ground station characteristics and eclipse duration. During the launch and early orbit phase, the first ground station is Kourou, following which nominal access is achieved through the Villafranca access point. Villafranca provides ground station access time during both stages of the WSB transfer, up to and including lunar orbital insertion. Work is ongoing to assess ESMO's ground access time relative to a number of possible ground stations. Those, in addition to the aforementioned above, under consideration include: Raisting (Germany), Malindi (Keyna) and Perth (Australia). Singular and combined use of multiple ground stations are also been investigated.

## IX. IMPLEMENTATION OF A MULTI-BURN STRATEGY

Due to the need to reduce the error in the major delta-V manoeuvres, and the available thrust levels delivered by the engines, a Multi-Burn Strategy (MBS) was introduced. This occurred at Earth departure and at lunar arrival. This was achieved by splitting the trans-lunar injection manoeuvre into a number of intermediate burns. Similarly, at the Moon, the orbit insertion manoeuvre was decomposed into a few smaller size burns. The MBS is similar to the one proposed in [8]. MBS avoids performing a single manoeuvre with a high delta-V and, of most significance, complies with the launch date flexibility requirement. The latter requirement is given in [1].

Each WSB transfer opportunity occurs roughly once-a-month, and therefore, depending on the exact launch date, ESMO may have to spend some additional days in an Earth parking orbit. A RAAN change may also be required as the orbit drifts due to the inhomogeneous gravity field of the Earth and to lunar -solar perturbations. A worst case delay of 30 days was considered for the definition of the MBS. The trans-lunar injection manoeuvre was split into four separate manoeuvres. The first two are of similarly large magnitude. This is to raise the apogee of the GTO. After the second burn there is a wait time of 28 days, following which a small apogee manoeuvre is performed. The last burn inserts ESMO into the WSB trajectory.

Compared to the single direct injection burn from GTO into the WSB transfer, the MSB adds approximately 50 m/s to the total cost of the transfer. The increase is due to the perturbing effect of atmospheric drag, J2 and 3rd body effects. However, utilising a MBS offers higher launch date flexibility, a reduction of the gravity losses per manoeuvre and an expected reduction of the navigation delta-V. This is in comparison to the small rise in delta-V.

The MBS at the Moon brings ESMO to the orbit with $a$ = 13084 km. An additional 47.2 m/s is then required to acquire the desired final operational orbit. Hence, the total cost of the new solution is 949.3 m/s against the nominal 1116.2 m/s of the previous baseline. This leads to a gain in delta-V. The complete transfer is represented in Figure 6 and Figure 7. In particular Figure 7 shows a detail of the MBS at the Earth with the spirals to progressively increase the apogee.

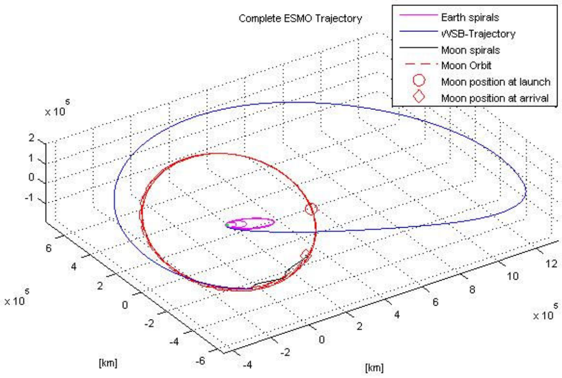

**Figure 6: New Baseline Transfer with Multi-burn Strategy.**

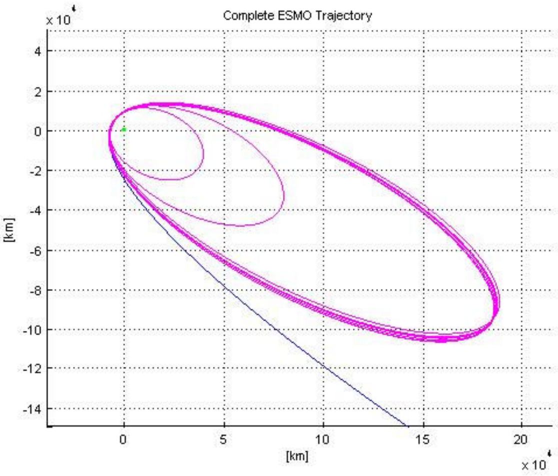

**Figure 7: Multi-burn Strategy - Earth Spirals**

## X. CONCLUDING REMARKS

ESMO can be characterised as a highly ambitious and challenging mission. To adhere to the stringent mission delta-V requirements, the use of a highly eccentric frozen orbit is proposed. Existing under precise conditions of eccentricity, inclination and argument of periapsis, frozen orbits can be used to reduced or eliminate the need for station keeping; thereby saving delta-V. This is considered highly beneficial in the development of small spacecraft with a low thrust and $I_{sp}$ budget. Coupled with the use of a multi-burn strategy and WSB transfer, this paper presents a viable option for ESMO's mission analysis and design. Future work is required to re-iterate within the 2014-2015 launch window. Definition of ESMO's mission analysis is on-going within the University of Glasgow's SpaceART research group.

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