ORBIT DETERMINATION AND CONTROL FOR THE EUROPEAN STUDENT MOON ORBITER

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ABSTRACT

Scheduled for launch in 2014-2015 the European Student Moon Orbiter (ESMO) will be the first lunar micro-satellite designed entirely by the student population. ESMO is being developed through the extensive use of flight spared and commercial of the shelf units. As such ESMO is significantly constrained by the available mission delta-V. This provides a considerable challenge in designing a viable transfer and stable orbit around the Moon. Coupled with an all-day piggy-back launch opportunity, where ESMO has little or no control over the launch date, ESMO is considered to be an ambitious design. To overcome these inherent challenges, the use of a Weak Stability Boundary (WSB) transfer into a highly eccentric orbit is proposed. However to ensure accurate insertion around the Moon, ESMO must use a complex navigation strategy. This includes mitigation approaches and correction strategies. This paper will therefore present results from the ongoing orbit determination analysis and navigation scenarios to ensure capture around the Moon. While minimising the total delta-V, analysis includes planning for orbital control, scheduling and the introduction of Trajectory Correction Manoeuvres (TCMs). Analysis was performed for different transfer options, final lunar orbit selection and available ground stations,

I. ACRONYMS

ESMO –European Student Moon Orbiter
GTO – Geostationary Transfer Orbit
NAC – Narrow Angle Camera
OD – Orbit Determination
STK – Satellite Tool Kit
TCM – Trajectory Correction Manoeuvres
WSB – Weak Stability Boundary
LEO – Low Earth Orbit
TLI – Trans Lunar Insertion

II. INTRODUCTION

Scheduled for launch in 2014-15, the European Student Moon Orbiter (ESMO) will be the first lunar micro-satellite designed entirely by the student population. Using chemical propulsion, ESMO is devised to reach and enter a polar orbit, with a primary mission objective to acquire surface images of the South Pole. High resolution data gained over a six month period with a maximum periselenium attitude of 200 km will be achieved. This is gained through a Narrow Angle CCD Camera (NAC). To complement the scientific return, optional secondary payloads includes: a small radar, a radiation monitor, a passive microwave radiometer, and a telecommunication experiment to test a lunar internet protocol [1].

The final polar orbit will be achieved through use of a Weak Stability Boundary (WSB) transfer. This is coupled with an all-day piggy-back payload launch opportunity. Currently ESMO has little or no control over the launch date. A WSB transfer therefore has the additional benefit of offering a higher degree of flexibility in the final selection of the launch vehicle and associated reduction in delta-V. However, this benefit, due to the sensitivity dynamics in the navigation error, must be considered against having to use a far more complicated navigation strategy. The WSB transfer trajectory must therefore utilise mitigation approaches and correction strategies.

This paper will present the orbit determination (OD) analysis of ESMO and an optimal orbit control strategy to ensure capture at the Moon. ESMO will be injected into a highly elliptical lunar orbit at the end of the WSB transfer. While still satisfying the mission requirements, orbit determination and control is used to define a trajectory corridor. A number of TCMs are planned and executed throughout the transfer. The ultimate goal is to ensure orbital insertion with minimal delta-V. The paper will therefore present results for different launch conditions, target orbits and available ground stations for the orbit determination process.

III. 2011-2012 LAUNCH WINDOW

Based on the previous 2011-2012 launch window ESMO's orbital transfer consisted of a WSB transfer in the Earth-Moon system. This was followed by orbital insertion around the Moon that was characterised by the following orbital elements:

a = 3586 km
e = 0.4874
i = 89.9 º
Ω = 63.8 º
ω = 292.9 º
v = 0 º

This provided an operationally low orbit that offered perigee coverage at the South Pole. A WSB transfer, as illustrated in Figure 1 was selected as it offers an inclination change and raise of perigee at zero cost, therefore saving delta-V.

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 106 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 [2][3]. 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. 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. 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.

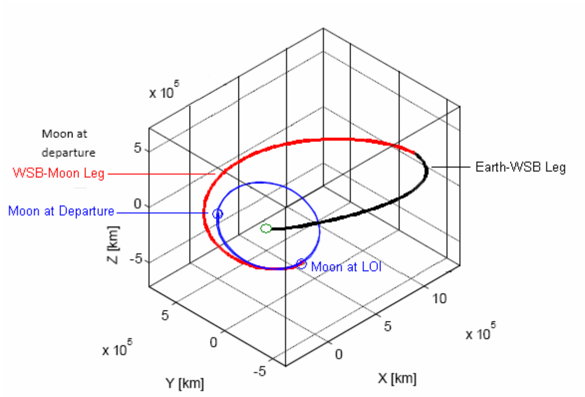

Figure 1: WSB Transfer Trajectory in the Earth-Centred Equatorial Reference Frame

In a nominal transfer, only the three manoeuvres mentioned above are required. However, given the inherent instabilities within the WSB region and taking also into consideration the required flexibility with respect to launch opportunities, ESMO's orbital transfer is highly sensitive to changes in its baseline parameters. This can result in unpredictable behaviour. Modelling is therefore required to account for these parameters and to provide an estimation for the required level of accuracy within the orbit determination process.

All analysis presented within this paper has been conducted within the original eighteen month, 2011-2012 launch window. Work is currently underway to re-iterate the analysis for the updated 2014-15 launch opportunity.

IV. ACCURACY OF ORBIT DETERMINATION

To successfully derive the accuracy requirement for orbital determination throughout the WSB transfer, leading to lunar insertion, the required level of accuracy at lunar insertion needs to be defined. An error in determining the exact lunar injection manoeuvre would directly translate into ESMO entering a deviated orbit around the Moon. This would imply a longer or shorter mission lifetime. Therefore early analysis focused on investigating the influence of error (i.e. sensitivity) in the initial lunar orbital elements and its associated affect on estimating the orbital lifetime around the Moon. This permitted the derivation of a lunar insertion accuracy requirement.

IV.1 Sensitivity Analysis

In order to assess the sensitivity of ESMO's orbit around the Moon, random error within the orbital elements at the lunar injection point was introduced. The error ranged from 1 % -5 %. For each error, ten sets of modified orbital elements were randomly generated. A MATLAB function, implementing latin hypercube sampling rules, (as given below), was used to generate the randomly generated data between upper and lower limits.

For a 5 % error:

```
a = 10084;
e=0.8;
i=56.2;
o=103.63;
w=270;
M=345.51;

deltanom=lhsu([a-0.005*a e-0.005*e i-0.005*i o-0.005*o w-0.005*w M-0.005*M],[a+0.005*a e+0.005*e i+0.005*i o+0.005*o w+0.005*w M+0.005*M],10)
```

The orbital elements for each case was then propagated forward in time for six months or until ESMO crashed onto the surface of the Moon. Each simulation was achieved using the AGI Satellite Tool Kit (STK). For each case data was recorded as a function of altitude of perilune against time

The increase in error corresponded with an increase in probability that ESMO would experience a reduction in orbital lifetime. Given in Table 1, for a 1 % error in orbital insertion ESMO may experience a reduction in lifetime of approximately twenty days. For a 5% error, ESMO experienced a ninety-nine day reduction it is orbital lifetime. This was referenced against the mission requirement to provide a stable orbit for six months [4].

Error in Orbital Insertion (%)	Decay Time, T+ insertion (Days)
1	159
2	133
3	119
4	105
5	81

Table 1: Influence of Insertion Error against Orbital Decay Time

Error within the orbital elements can also be translated into error within the radial, transversal and out-of-plane components of position and velocity at the Moon. As illustrated in Figure 2 and Figure 3, at 1 % error this translation can be expressed relative to Earth. When measuring the position and velocity of ESMO, this therefore details the required capability of the ground stations. It was deemed acceptable that a reduction in orbital lifetime is an acceptable compromise against the mission objectives and the orbit determination requirements.

Therefore a 1 % sensitivity error was used throughout the remaining analysis.

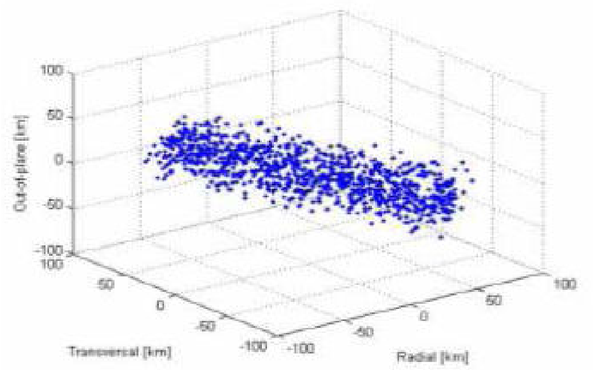

Figure 2: Relative Error in Position Projected along the Radial, Transversal and Out-of-Plane Reference Frame. The co-ordinate (0,0,0) Represents the Nominal Solution

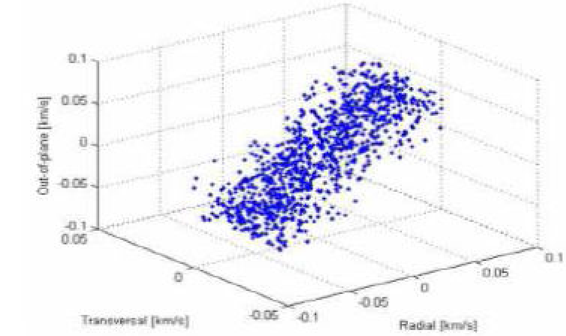

Figure 3: Relative Error Velocity Projected along the Radial, Transversal and Out-of-Plane Reference Frame. The co-ordinate (0,0,0) Represents the Nominal Solution

IV.II. Capture Corridor

Using a 1 % error in the orbital elements at lunar injection, a region of state space (position and velocity) at different times ($t_{insertion}$ - Δt) prior to the lunar orbital insertion was formed. This is known as the capture corridor and defines a set of positions and velocities that ESMO must have in order to be captured at the Moon at $t_{insertion}$.

Therefore the associated size of the capture corridor defines the current knowledge of ESMO's position and velocity along both legs of the WSB transfer. Orbit determination, must therefore be able to discriminate with 99 % probability between whether or not ESMO is inside or outside the corridor. Without this analysis it will not be possible to predict whether or not ESMO is on course for lunar insertion. Inaccuracies in the injection manoeuvre where not included within this analysis.

To assess the relative size of the corridor at $t_{insertion} - \Delta t$, the corridor must first be considered at $t_{insertion}$. Figure 4 defines the relative radial-transversal and out-of-plane reference frame at ESMO's nominal injection point. At the injection point, the insertion accuracy is given as a function of the error in position and velocity. This error is then propagated backwards. The set of backwards propagated states defines a region (or cloud) in the state space that surrounds the nominal solution. Each point inside the cloud represents a pair of position and velocity that will lead to capture at lunar insertion if the state is propagated forward.

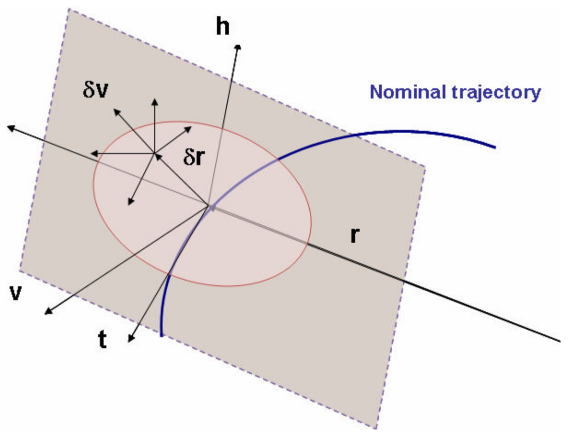

Figure 4: Schematic of the r-h Plane at the Lunar Orbit Insertion Point

The displacement, **δr** , on the r-h plane and corresponding variation in the nominal trajectory, **δ**v , can then be defined. The displacements and velocity variations were randomly generated within a given range. The perturbed state vector
[r +δr v + δv] was then propagated backwards for Δt.

The displacement vector **δ**r is defined as:

$$\delta \mathbf{r} = \delta r\left[\cos\theta, 0, \sin\theta\right]^T \qquad [1]$$

And the velocity variations **δ**v are defined as follows:

$$\delta \mathbf{v} = \delta v\left[\cos\vartheta\cos\phi, \cos\vartheta\sin\phi, \sin\vartheta\right]^T$$
$$\bar{\phi} = \frac{\phi}{2\pi}; \quad \bar{\vartheta} = \frac{\cos(\vartheta+\pi/2)+1}{2} \qquad [2]$$

The angle θ is sampled from the interval [0 2π], with uniform distribution. The quantities **φ** and **θ** are taken randomly within the interval [0, 1], with uniform distribution. **δ**r is taken from the interval [0, ε_r], with uniform distribution, where ε_r is the error on the position. With this choice it implicitly assumed that there is 100 % probability that the displacement is in that interval. Therefore there is a 100 % probability that if ESMO is within the corridor then it is captured. The reverse is not true in general. For the velocities, **δ**v , is taken from the interval [0, ε_v] with uniform distribution.

The model was built up sequentially. 10000 perturbed state vectors were propagated at lunar injection, backwards for one week, two weeks and up to the WSB point. The resulting positions and velocities were then projected on the r-h and r-t planes at epoch. Figure 5 shows a sketch of a perturbed solution intersecting the r-h plane. This has been propagated backwards from the point of lunar insertion.

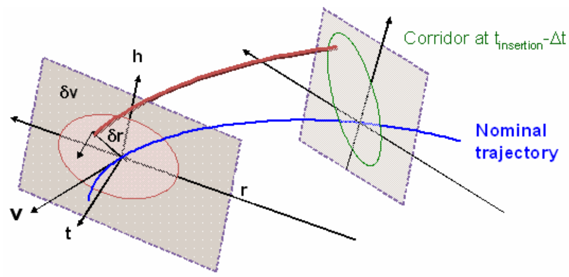

Figure 5: Schematic of the Backwards Propagation.

Figure 6 - Figure 8 shows the results of the backwards propagation (position and velocity dispersion) at one week from lunar ejection. This is relative to the r-h plane. In comparison Figure 10 - Figure 13 displays the results of the propagation solutions two weeks before lunar injection. The green dots are the perturbed solutions forming the trajectory corridor, and the red dot is the reference trajectory of the existing baseline. The velocity plots give only the variation with respect to the nominal value; therefore they are centered on 0. As long as ESMO is located within the trajectory corridor then orbital insertion around the Moon can be achieved.

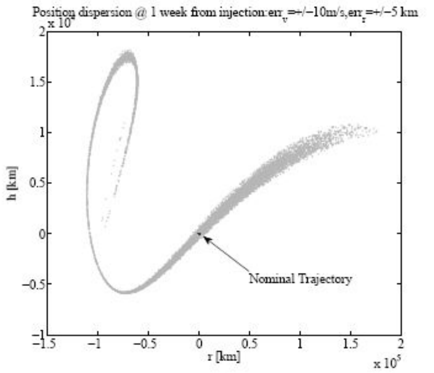

Figure 6: Position Dispersion at One Week from Lunar Injection, r-h plane

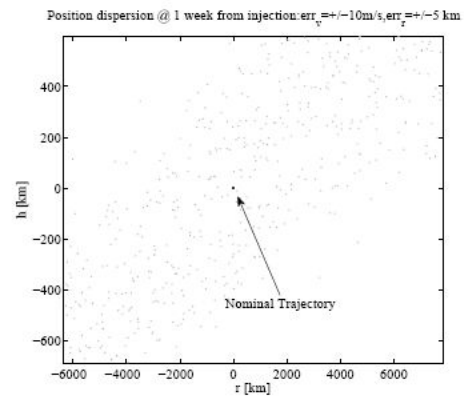

Figure 7: Position Dispersion at One Week from Lunar Injection, r-h plane (Close up around the Nominal Transfer

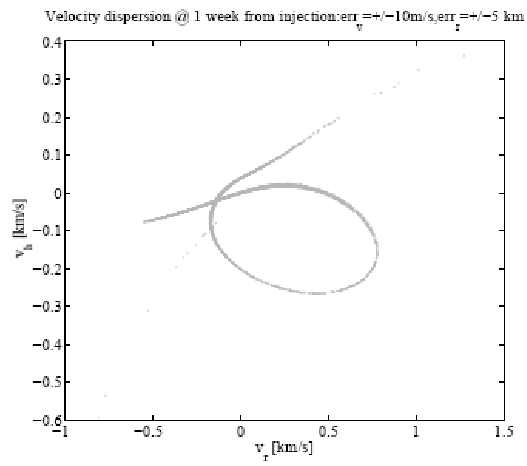

Figure 8: Velocity Dispersion at One Week Lunar Injection, r-h plane

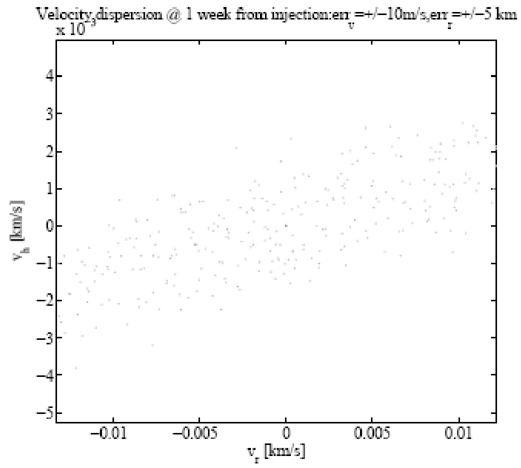

Figure 9: Velocity Dispersion at One Week Lunar Injection, r-h plane (Close up around the Nominal Transfer)

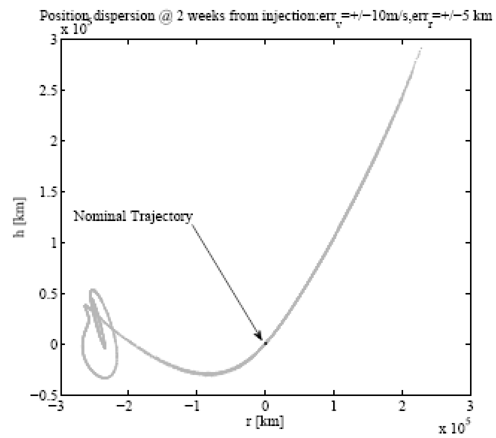

Figure 10: Position Dispersion at Two Weeks from Lunar Injection, r-h Plane

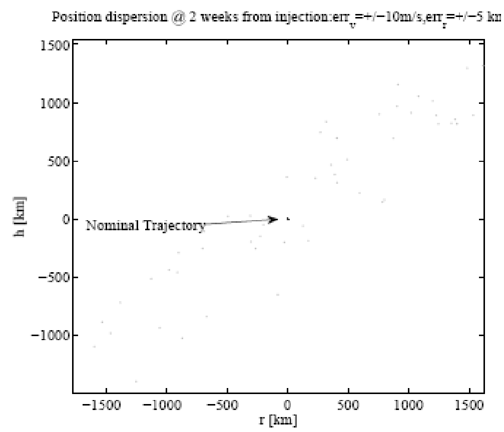

Figure 11: Position Dispersion at Two Weeks from Lunar Injection, r-h Plane (Close up around the Nominal Transfer

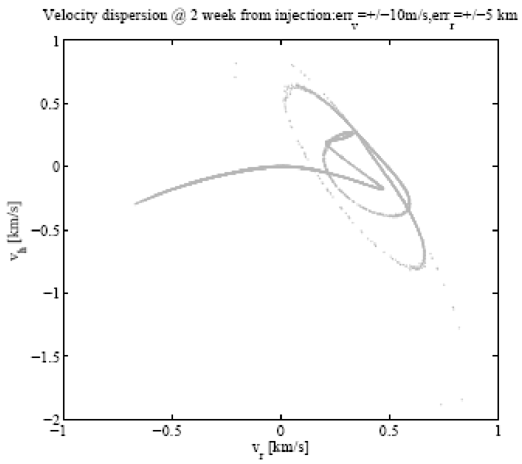

Figure 12: Velocity Dispersion at Two Weeks from Lunar Injection, r-h Plane.

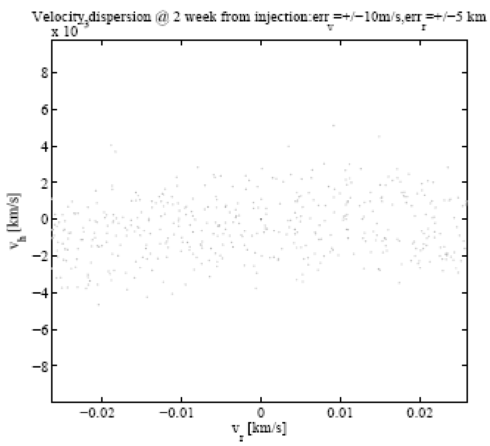

Figure 13: Velocity Dispersion at Two Weeks from Lunar Injection, r-h Plane (Close up around the Nominal Transfer.

These figures were generated with ε_r = 5 km and ε_v = 10 m/s and represent only the projection of the corridor on the r-h plane. Similar figures can be obtained by projecting the corridor on the r-t plane.

The trajectories corresponding to the curl will not reach the WSB region and do not represent feasible transfers. Furthermore, it is important to note how the corridor tends to get thinner in the normal and transversal directions while it seems to stretch along the radial direction. Based on the propagation of the corridor, and considering the required accuracy of position and velocity at the farthest point from the Earth (WSB region), along the transfer trajectory, it was possible to derive the orbit determination accuracy. This is reported in Table 2 and details the measured accuracy of the range (position) and velocity of ESMO relative to the ground stations. All measurements are assumed to be obtained from Doppler data. This is considered to be a new 'worst-case' requirement on the ground stations tracking systems. Furthermore, this requirement should therefore be applied to all aspects of the WSB transfer and orbit insertion maneuver.

Position	Velocity
25 km radial (range)	0.005 km/s radial (range rate)
10 km along track	0.001 km/s along track
10 km out of plane	0.001 km/s out of plane

Table 2: Orbit Determination Accuracy Requirements at 2 weeks from $t_{injection}$

V. ORBIT DETERMINATION

It is important now to determine if the accuracy requirements could be met with tracking stations allocated to ESMO. Therefore a realistic model of the orbit determination problem has been created and thoroughly simulated. The measurement process is simulated by introducing random and systematic error in the nominal trajectory and then applying a filtering process to obtain a good estimation of the position of ESMO.

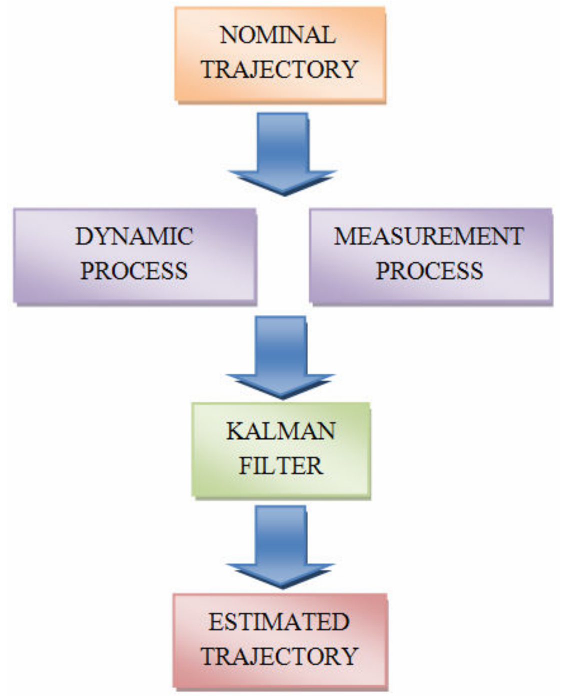

Figure 14: Measurement simulation model.

The set of measured quantities considered are ρ and $\dot{\rho}$, the range and range rate from the ground station and its time variation, α, β, $\dot{\alpha}$ and $\dot{\beta}$, the pointing angle in azimuth and elevation and their angular rate. The actual measurement was simulated by perturbing the nominal (i.e. "true") measurement with a random noise with normal distribution. Ionosferic and tropospheric refraction was not taken into account since these effects could be easily be corrected with dedicated mathematical models.

Values for 3σ were assumed on the basis of the characteristics of the different ground stations considered and on different operating frequency bands. Where available, pointing errors data of the actual ground station were used. However, the errors on the range and angular rates are based on assumptions and will be validated in future work.

The measurement are then processed through a Kalman filter. This is a well known dynamic optimal filter which was first employed in the Apollo program. Two variants of the filter were implemented: the Extended Kalman Filter (EKF) and the Unscented Kalman Filter (UKF). The UKF in particular is especially suitable for non-linear or highly non-linear process or observation models. Moreover it avoids the calculation of the Jacobian matrix.

In the following example, a three-day OD campaign from Malindi ground station, using a Ku-band has been simulated. Table 3 reports the errors which have been assumed in the computations.

Measurement error	3σ
$\Delta\rho$	15m
$\Delta\dot{\rho}$	7.5 cm/s
$\Delta\alpha$	10''
$\Delta\dot{\alpha}$	10^{-7} deg/s
$\Delta\beta$	10''
$\Delta\dot{\beta}$	10^{-7} deg/s

Table 3: Random errors on measurements for OD simulation.

Figure 15 and

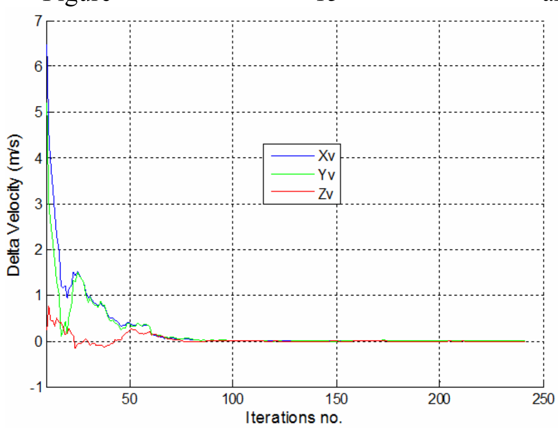

Figure 16 clearly show the effectiveness of the filtering process in mitigating the random noise. The error on position and velocity at the end of the OD campaign is acceptable given the accuracy requirements analysed in the previous section.

OD duration	3 days
Difference in position $\overline{\Delta r}$	1.616 km
Difference in velocity $\overline{\Delta v}$	0.0092 m/s
$\rho(\Delta r)$	0.4284 km
$\rho(\Delta v)$	0.0039 m/s

Table 4: Position and velocity errors at the end of the OD process.

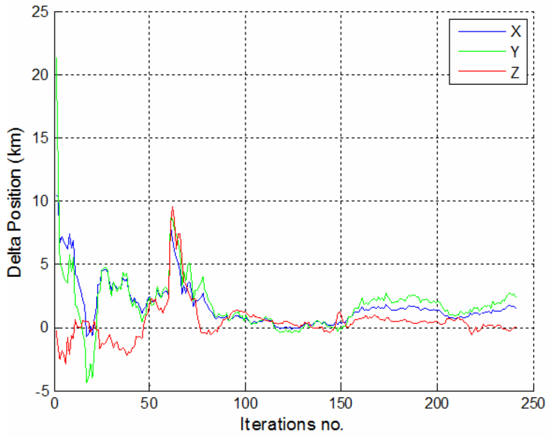

Figure 15: Position error of the filtered measurement.

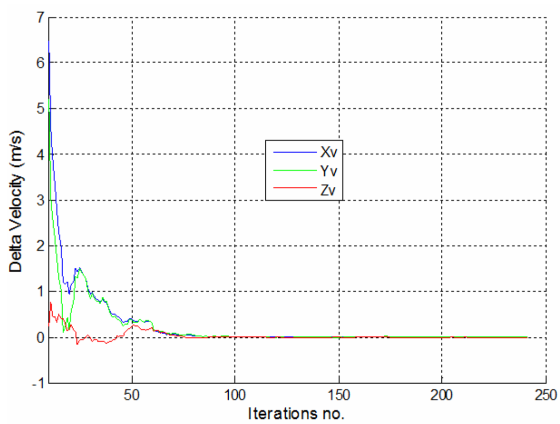

Figure 16: Velocity error of the filtered measurement.

VI. NAVIGATION STRATEGY

The formation of a capture corridor also provides a methodology of defining a robust navigation strategy. The premise is to manoeuvre and maintain ESMO within the capture corridor with enough margin to accommodate any orbit determination errors [5].

Intermingled along the transfer and in between the orbit determination segments are Trajectory Correction Manoeuvres (TCMs). TCMs are used to ensure that ESMO's position and velocity remains located within the trajectory corridor, thus enabling the correct lunar insertion. The goal of each TCM is to reach the nominal reference trajectory; minimising the distance with respect to the nominal point in the WSB region. To ensure capture around the Moon, ESMO must be inside the capture corridor seven days before lunar insertion. Therefore after each orbit determination segment a TCM may, or may not, be required.

Orbit determination must therefore be planned in advance and it is therefore assumed to occur over a three day period. This is to guarantee a good level of convergence. It is also assumed that the first orbit determination process occurs one week after the trans-lunar injection from GTO.

Throughout the navigation analysis process, sources of inherent error were also included. This included the trans-lunar injection burn and atypical dispersion errors of the launcher [6]. The error in the major delta-V manoeuvres was assumed to be 1 m/s in every direction. It was also assumed that each TCM in itself was affected by an error (due to misfiring of the thrusters) that must be accounted for. This error was assumed to be 0.1 m/s in every direction. Each TCM, in comparison to the launcher dispersion errors, were assumed to be smaller in magnitude and so created less error. These assumptions are to be verified. As before, a symmetric interval [-ε ε] around each nominal component of the delta-V was considered and values were sampled, with uniform distribution, from the hypercube [-ε ε].

Following each TCM, the possible outcome of errors in both position and velocity of ESMO is measured at the next orbit determination point. Therefore ESMO should be visible during the performance of all TCMs. The sum of all the TCM's will lead to an increase in the mission delta-V and propellant budget.

Planning (time and date) of the TCMs was achieved using the fmincon function of the MATLAB Optimisation Toolbox. Two TCMs where defined by their time of execution (t_{TCM}), magnitude (ΔV_{TCM}), and orientation from their right ascension (α_{TCM}) and declination (δ_{TCM}). These parameters can vary between an upper and lower boundary. Each boundary was chosen appropriately.

Fmincon optimizes the parameters of the vector:

$$\overline{X} = \left[t_{TCM_1} \quad \Delta V_{TCM_1} \quad \alpha_{TCM_1} \quad \delta_{TCM_1} \quad t_{TCM_2} \quad \Delta V_{TCM_2} \quad \alpha_{TCM_2} \quad \delta_{TCM_2} \right]$$

Numerous simulations were run that detailed different orbit determination and TCM sequences. These were further defined with different ground station characteristics. In accordance to the mission requirements all data pertaining to orbit determination would be gathered from either the Malindi (Kenya), Weilheim (Germany), Perth (Australia) or Kourou (French Guyana) radar tracking ground stations [5].

Figure 17 illustrates a possible navigation strategy. This includes six TCMs and four orbit determinations. After the GTO burn an initial orbit determination campaign is performed. ESMO is tracked through a given arc of the trajectory. Using state estimators provided by the orbit determination process, two TCMs are planned. However, only one of them is performed before a second orbit determination process occurs. After which another two TCMs are planned, and so forth. In the event that a second or third set of TCMs can not be performed before the WSB region is reached, it is possible to stop the sequence. The second leg of the WSB transfer is repeated using the same method until ESMO reaches one week prior to lunar insertion. For each possible navigation scenario, one hundred possible solutions were performed. This data provided a statically acceptable survey.

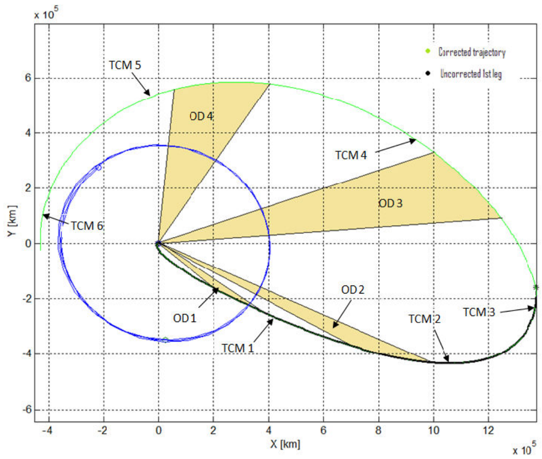

Figure 17: Example of a Possible Navigation Strategy

One possible example, as given in Table 5 utilises the Raisting ground station which at the current moment is being considered as the possible location for the ground segment of ESMO. Throughout the transfer six orbit determination campaigns were planned and eight TCMs where selected (four in each leg). 100 simulations were run to get a statistically accurate assessment of the performance of the OD and TCM process. The addition delta-V required to perform the two burns at GTO, along the transfer, all TCMs, velocity matching one week before lunar arrival and at lunar injection equates to around 60 m/s. When added, the final delta-V budget (1.12 km/s) coincides with the maximum available delta-V budget of ESMO. Even under the worst case condition the TCMs would only require a 5 % increase in available delta-V.

GTO-WSB Leg	
OD 1	Start 19/03/2011 End 22/03/2011
TCM 1	23/03/2011, ΔV=8.011 km/s
OD 2	Start 03/04/2011 End 06/04/2011
TCM 2	07/04/2011 ΔV=3.026 km/s
OD 3	Start 18/04/2011 End 21/04/2011
TCM 3	22/04/2011 ΔV=2.433 km/s
TCM 4	26/04/2011 ΔV=50.992 km/s
Moon-WSB Leg	
OD 4	Start 04/05/2011 End 07/04/2011
TCM 5	07/05/2011 ΔV=1.189 km/s
OD 5	Start 17/05/2011 End 20/04/2011
TCM 6	21/05/2011 ΔV=1.152 km/s
OD 6	Start 31/05/2011 End 03/06/2011
TCM 7	03/06/2011 ΔV=0.998 km/s
TCM 8	09/06/2011 ΔV=1.930 km/s
Additional ΔV (m/s)	63.7

Table 5: Example of Orbit Determination (OD) and the Performance of TCMs

	Final Position match [km]	Final Velocity [km/s]	Total ΔV [km/s]
AVERAGE	39.500	1.23 10^{-4}	1.1152
DEVIATION	20.260	1.23 10^{-4}	0.0046

Table 6: Difference from nominal trajectory with the proposed navigation strategy in 100 simulations.

Earth-WSB leg		Y	M	D	H	M	S
TCM 1	AVERAGE	2011	3	23	7	28	30
	DEVIATION	0	0	0	5	14	18
TCM 2	AVERAGE	2011	4	7	7	63	30
	DEVIATION	0	0	0	4	17	18
TCM 3	AVERAGE	2011	4	21	9	29	32
	DEVIATION	0	0	0	7	16	17
TCM 4	AVERAGE	2011	4	26	16	5	47
	DEVIATION	0	0	0	0	0	4
WSM-Moon leg		Y	M	D	H	M	S
TCM 1	AVERAGE	2011	5	7	9	37	31
	DEVIATION	0	0	1	7	16	17
TCM 2	AVERAGE	2011	5	21	7	27	32
	DEVIATION	0	0	1	7	18	18
TCM 3	AVERAGE	2011	6	3	8	28	30
	DEVIATION	0	0	1	6	16	17
TCM 4	AVERAGE	2011	6	9	6	31	47
	DEVIATION	0	0	1	8	8	18

Table 7: TCM scheduling in 100 simulations.

In Figure 18 and Figure 19 shows that the final position at obtained implementing the OD/TCM process is always inside the required corridor.

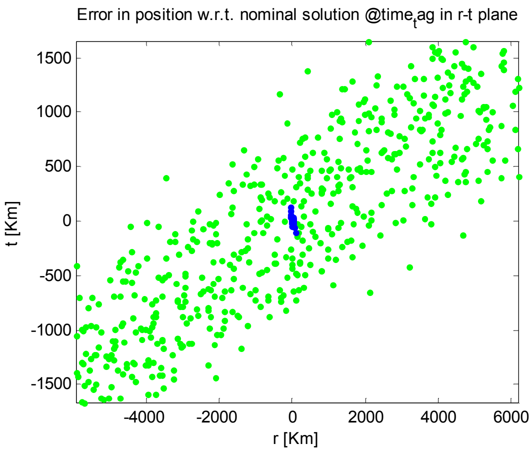

Figure 18: Error in position in the r-t plane: corridor (green), corrected trajectory (blue).

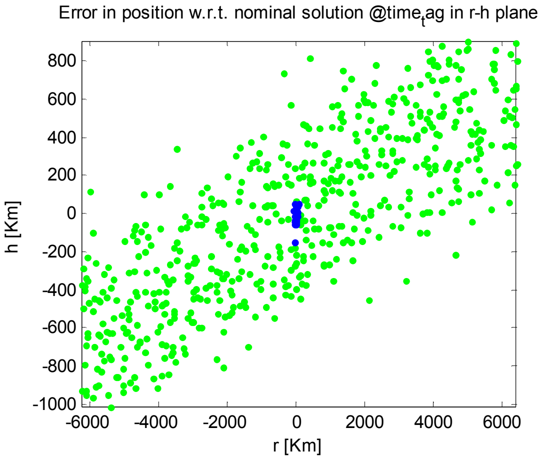

Figure 19: Error in position in the r-h plane: corridor (green), corrected trajectory (blue).

To assess the worst case relative accuracy in the orbit determination process we hypothesized to use Malindi ground station with S-band thus having a higher beam width 50”. The scenario still consisted of six orbit determination points and eight TCMs executed throughout the transfer. Despite the significantly low performance, the additional delta-V needed only rose to 63.6 m/s. This suggests that the inaccuracies in the TCMs burns are more relevant to the final results (required delta-V) than errors in the orbit determination process. Other simulations were performed that varied the sequence and number of orbit determination points and TCMs. Modelling the Malindi ground station (S band, 50” beam width) with four orbit determination campaigns and six executed TCMs resulted in an additional delta-V of 61.7 m/s. Considering the reduced performed in the ground station it again suggests that the TCM burns are the governing factors in matching ESMO’s position against the reference trajectory. Executing fewer manoeuvres introduces less uncertainty into the scenario. However, more analysis is required into the interrelating factors – time of the orbit determination process, TCM executions - that otherwise govern this process

VII. CONCLUDING REMARKS

This paper presented a first analysis of the orbit determination requirement and possible navigation strategies for ESMO. The proposed corridor-targeting approach yields good results at a relatively low delta-V cost. This is coupled with mild orbit determination accuracy. This approach therefore seems to be ideal for small spacecraft missions that are constrained with a low mission delta-V. However, in defining a navigation strategy, the accuracy of the ground station tracking system must be considered. The data suggests that less accurate tracking systems could lead to erroneous decision when estimating the spacecraft’s position and velocity. This is coupled with an uncertain error in each TCM burn. Throughout this analysis the TCM’s were not optimised. Further work will address this optimisation and the tailored orbit determination process of ESMO. Work is ongoing to re-assess the associated mission analysis within the 2014-2015 launch window.

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