AUTOMATIC LAUNCH WINDOW ANALYSIS (ALWA), STAND ALONE TOOL OR ASTOS FEATURE

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ABSTRACT

The insertion of a satellite in a target orbit with certain ground fixed constraints requires the solution of several problems. This influences the mission design for ascent phases and orbit correction phases. At a certain and exact time the position and velocity of the vehicle have to match with the state defined by orbital and ground constraints. In this scenario, all the parameters of the launcher, the satellite, the launching facility, the intermediate orbits, the target orbit and the insertion epoch have to be defined during the mission design process. In respect to all active constraints, the launch window duration can vary between several minutes to few seconds.

With a long experience in the simulation and optimization of launch trajectories, Astos Solutions presents the Automatic Launch Window Analysis (ALWA) tool for a fast launch window computation. Based on limitation as delta-v budget, launchpad coordinates, transfer orbits and final injection parameters, ALWA computes launch times and time spans based on lift-off parameters, plane-change inclinations and right ascension of ascending nodes, number of revolutions on transfer orbits and transfer time.

The selection of suitable launch possibilities may be refined by adding further constraints as maximum transfer time, ground stations visibility and eclipse avoidance. The ground station visibility constraint can be exploited to either use existing stations or to place mobile stations according to the computed states. The challenge is to find solutions in a great combinatorial space, analyzing them within a reasonable working time. ALWA can be used for preliminary launch trajectory design; the resulting launch windows can be the input for further detailed analysis as a direct "pork-chop plot". Additionally the results of ALWA can be refined within the Aerospace Trajectory Optimization Software (ASTOS) [4].

With this approach a wider range of launching possibilities can be analyzed as loops of analytical computations without the complications and the time demand of numerical solutions. This would allow the launch service providers to deal with the frequent launch delays. Moreover this tool could identify critical aspects already during the mission design phase, allowing for an early modification in the design process. This translates in a consistent cost reduction.

1. ASTOS SOLUTIONS

Astos Solutions is a young company with a long history and expertise in simulation and optimization of ascending trajectories and spacecraft orbits. Its Aerospace Trajectory Optimization Software (ASTOS) is a widely used tool for solving launcher, re-entry and orbit trajectory problems without any programming. A General Environment for Simulation and Optimization Platform (GESOP) is also available for not aerospace related problems. In the latest years small tools have been created to target specific applications: among others GAMAG for magnetic cleanliness and LAT for launcher selection.

2. MOTIVATION

In the early phase of concept studies of satellites the determination of launch windows for their transportation systems must be respected and an easy and fast tool is needed to evaluate the transportation systems. This will support the conceptual design of the satellite itself on the one hand and will lead to more detailed optimization procedure with an already reduced set of possible starting parameters.

For established space transportation systems like Soyuz and Ariane 5 it can help to find launch window with required duration and to even increase payload mass. In this way safety could be improved and costs reduced.

3. STATE OF THE ART

Selecting suitable launch windows for space transportation systems is already an important factor.

There are several in-house software solutions at launch providers and agencies not commercially available.

AGI solves a small part of the problem with the STK/Conjunction Analysis Tools (STK/CAT) for close approach missions of satellites. There the launch

window is identified only by the probability that the launcher will hit or approach an existing satellite. These can be selected by the user or automatically by STK/CAT when in range. The user can check target satellites from NORAD TLE database or specify satellites with own parameters.

It is known, that several software solutions exist helping the user to select an adequate launch window for their mission. But the combination of the search for a launch trajectory connected with the satellite deployment that includes a point injection is a novel approach. This results in a time-independent launch start and it is applicable also to the rendezvous scenario. This achievement has been the guideline for the ALWA development.

4. RENDEZVOUS MANOEUVRES

The Automatic Launch Window Analysis (ALWA) tool currently supports analysis of "ground fixed target injection" and "chaser and target" rendezvous approach strategies.

4.1. Ground fixed target injection

The ground fixed target injection mission sets up a launch and transfer strategy to inject a satellite in an orbit with a specific position in relation to a fixed ground coordinate thus allowing the satellite to reach its first apogee (or perigee) at the zenith above the requested ground location.
This transfer is defined by the launchpad location, the target position, transfer and target orbits which sets up the constraints.
For the verification of ALWA a Soyuz mission had been used. The launchpad location is placed on Guiana Space Centre, Kourou and the target position is located above Turin, Italy. The transfer is conducted on three orbits with a first circular parking orbit, an elliptical intermediate orbit, and the final arc of the elliptical target orbit. The first two orbits allow analysis of unconstraint number of revolutions with a final arc to apogee on target orbit.
The task covers the amount of revolutions at all transfer orbit. Important is the fulfillment of the requirement about the transfer time and the Earth rotation from Kourou to Turin, so that the launch orbit plane will rotate into the target plane.

4.2. Chaser and target

The chaser and target rendezvous mission is an approach of a chaser vessel to a space station or platform.
This strategy doesn't need a distribution of transfer orbits to reach the target, because the launch time is the target plane intersection of the launchpad location, but instead it relies on phasing orbits to directly reach the target on the same position or a station keeping point on a lower orbit.
The revolutions on a phasing orbit depend on the angular position of the target in relation to the chaser vessel when injected into the target orbit. The difference in true anomaly is then reduced by phasing.
For verification a STS Space Shuttle mission and an ATV mission are used due to their different approach scenarios. The limiting factors are mainly the true anomaly of the target at launch time and the maximum allowed phasing orbits to reach the final position.

5. COMPUTATION

ALWA builds on classic orbit mechanics, spherical geometry and combinatorial elements.
It also includes different functions to solve both rendezvous tasks with a core segment for both and single segments needed for one tasks.
The core segment includes the "plane intersection and change" function, and "transfer-time fitting" is used for ground fixed target injection missions and "phasing orbits" is used for chaser and target missions.

5.1. Transfer-time

In case of ground fixed target injection mission the vessel has to stay on the launch transfer orbit as long as the Earth has rotated the target location into the launch orbit. Furthermore the vessel has to reach the target position (e.g. apogee) at that time.
Thus the rotation time from the launch pad location in plane to the target location in the same plane has to fit the transfer time in all intermediate orbits until the injection position.

Spherical geometry is used to determine the local time of the target plane intersection between the launchpad and target location. This defines the transfer time of one day. This smallest duration can be extended by an integer number of days. This will extend the overall mission duration, but also the possibility to achieve longer and energy reduced launch windows.
The maximum transfer time can be specified by user input.

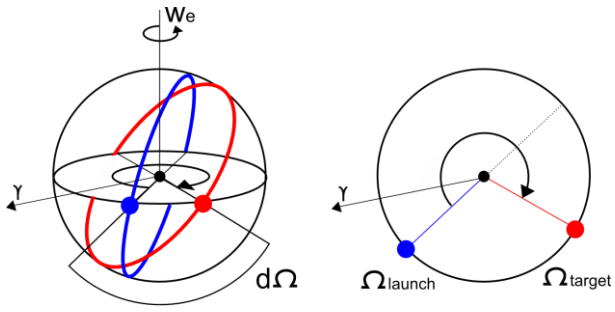

Figure 1. Ground fixed target plane rotating into launch plane setting the transfer time.

$$\Delta T = \frac{360° - (\Omega_{target} - \Omega_{launch}) + (d \cdot 360°)}{\omega_{earth}} \quad (1)$$

Where d is the number of allowed days for transfer, $\Omega_{target}, \Omega_{launch}$ the ascending nodes, ω_{earth} the angular velocity of the Earth and ΔT the resulting transfer time.

Combinatorial orbit distribution

Transfer time is distributed between all the specified transfer orbits and orbit arcs. The amount of time can be freely distributed on all orbits with a limitation in orbit sequences. ALWA uses a stepping in orbits, so when an orbit is reached once, the satellite can't come back into a lower orbit. This is due to delta-v constraint: it provides only orbit lifting and no orbit degradation.

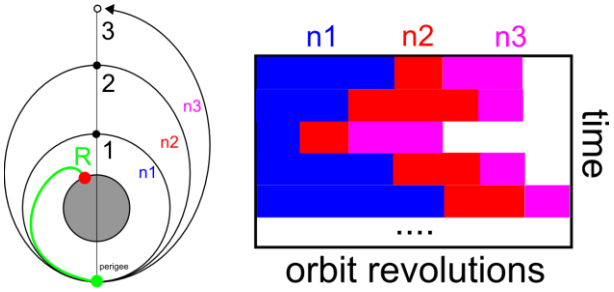

Figure 2. Transfer Orbits & n-sets for Orbit Revolutions

The distribution itself is done by means of combinatorial computation that allows finding a set of solutions (n-Sets) with time variations smaller than the orbit period of the first transfer orbit.

$$\Delta T = n_1 \cdot T_{p1} + n_2 \cdot T_{p2} + n_3 \cdot T_{p3} + T_{rest} \quad (2)$$

Where Tp is the period of one orbit, $n_{1,2,3}$ the corresponding number of revolutions and T_{rest} the remaining time.

Finding solutions for all n_x in Eq. 2 shows a logarithmic behavior and increases with the amount of allowed days d in Eq. 1 leading to longer transfer times (Fig. 5).

Nodal Regression

Depending on the inclination, during longer orbit transfer times the satellite will present nodal regression of right ascension of ascending node (RAAN) $\dot{\Omega}$ and of the argument of perigee $\dot{\omega}$ due to Earth's oblateness. This is calculated by the amounts of orbits for each set and will be feed into the plane intersection and change function where it will adjust the target plane properties. In this way the connection point will be respected in its new plane and position to fulfill the overall transfer time constraint.

$$\dot{\Omega} = -\left[\frac{3}{2}\frac{\sqrt{\mu} J_2 R^2}{(1-e^2)^2 a^{7/2}}\right]\cos i \quad (3)$$

$$\dot{\omega} = -\left[\frac{3}{2}\frac{\sqrt{\mu} J_2 R^2}{(1-e^2)^2 a^{7/2}}\right]\left(\frac{5}{2}\sin^2 i - 2\right) \quad (4)$$

Where J_2 is the Earth's second dynamic form factor, μ the standard gravitational parameter, e orbit eccentricity, a semi major axis, i inclination and R radius.

5.2. Plane intersection and change

This n-Set of solutions with time rests interfaces the plane intersection and plane change function and serves as a limitation for the plane change.

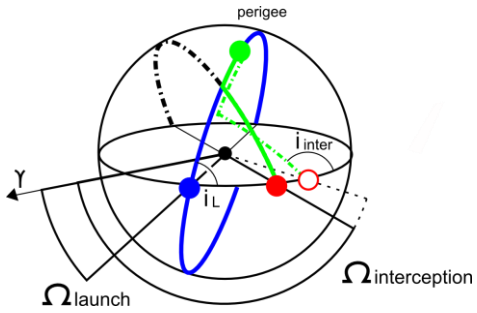

Figure 3. Intersection schematic with two paths to perigee due to changed RAAN & inclination

Within this function a combinatorial variation of the launch plane parameters are executed. The RAAN and inclination are varied in respect to the optimal target orbit parameters. This results in an interception arc from launchpad to the first transfer orbit and from transfer orbit to its perigee. It connects the orbit to the following transfer orbits and thus with the already determined duration on all following transfer orbits.
This "dog-leg" interception arc has to fulfill the criterion of each rest time in the n-Set.
This criterion check is done for launches at ascending and descending nodes and is also extended for one additional orbit on the first transfer orbit. This additional orbit is included in transfer-time fitting function where a minimum of one orbit is set. This allows finding solutions on interception path very near to the perigee connection point, where an additional revolution beyond it to the next occurrence can be obtained.

RAAN and inclination of the launch orbit are set depending on the optimal parameter of the target plane. This gives an output of RANN, inclination, local launch time to the optimal in-plane intersection time and delta-v for correcting the interception arc to the target plane. All values are stored in a look-up table for post-processing.

Plane intersection uses position vectors Eqs. 5-7 of the interception point on launch plane (sub-index 1). Similar equations are computed for the target plane (sub-index 2).

$$\begin{aligned} r_{x1} &= r_1\left[\cos\Omega_1 \cdot \cos(\omega_1+\theta_1) - \sin\Omega_1 \cdot \cos i_1 \cdot \sin(\omega_1+\theta_1)\right] \\ r_{y1} &= r_1\left[\sin\Omega_1 \cdot \cos(\omega_1+\theta_1) + \cos\Omega_1 \cdot \cos i_1 \cdot \sin(\omega_1+\theta_1)\right] \\ r_{z1} &= r_1 \cdot \sin i_1 \cdot \sin(\omega_1+\theta_1) \end{aligned} \quad (5\text{-}7)$$

Where *r* is the radius, $r_{x,y,z}$ the radius components, θ true anomaly and ω argument of perigee.

Both radius vectors r_1 and r_2 meet the criterion of equal vector length ($r_1 = r_2$) and vector direction; a set of linear equations can be used to numerically solve the problem. Eq. 7 and the similar for the target plane can be written as Eq. 8.

$$\begin{aligned} r_{z1} &= r_{z2} \\ r_1 \cdot \sin i_1 \cdot \sin(\omega_1+\theta_1) &= r_2 \cdot \sin i_2 \cdot \sin(\omega_2+\theta_2) \\ (\omega_1+\theta_1) &= \sin^{-1}\left(\sin i_2 \cdot \frac{\sin(\omega_2+\theta_2)}{\sin i_1}\right) \end{aligned} \quad (8)$$

This can be used to solve the y-component in Eq. 6 for $r_{y1} = r_{y2}$.

In this way the true anomaly θ_2 can be determined and be used to solve the linear equations for θ_1.

5.3. Phasing Orbits

In case of chaser and target mission the transfer-time fitting isn't needed or set to the single perfect solution of orbit plane intersection.
Then plane intersection and change is executed and extended by the phasing orbit function. This will determine interception solution to the orbit plane of the target that can be reached twice a day, but it includes a new constraint of a rotating, not ground-fixed target. Therefore the true anomaly of the target at launch time is set. Either this can be done by an external set of data points or by a starting position at a given epoch and then calculated for following days.
The interception position on target plane and the changed position of the target due to flight times from launch to interception position is used for the phasing maneuver. The amount of time and delta-v is added to the look-up table values and the orbital parameters for the phasing orbits are also stored.
ALWA allows for an interception position directly on the target orbit or below. The first option just adds an additional maneuvers to a lower orbit where the second option begins.
The user can specify the minimum phasing orbit altitude and the allowed duration of all phasing combined. This can be done analytically without combinatorial methods.

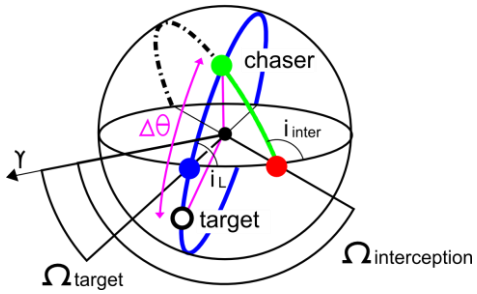

Figure 4. Chaser & target object with a difference in true anomaly

The difference in true anomaly $\Delta\theta$ between chaser and target object can be reduced by allowing phasing orbits of *n* revolutions and obtaining the angular distance on the phasing orbit $\omega_{orbit(n\cdot T_p)}$ Eq. 9.

$$\omega_{orbit(n\cdot T_p)} = n \cdot 2\pi + \Delta\theta \quad (9)$$

Where $\omega_{orbit(n\cdot T_p)}$ is the angular distance on phasing orbit and *n* the allowed number of phasing orbits.

Transfer time is obtained by Eq. 10 that is limited by the mission duration, so *n* and phasing orbit parameters have to be set adequately.

$$T_p = \frac{1}{3}\frac{\omega_{orbit(n\cdot T_p)}}{\dot{\omega}_{target\,orbit}} \quad (10)$$

Where $\dot{\omega}_{target\,orbit}$ is the angular velocity of the target orbit and T_p transfer period from old to new position.

6. POST-PROCESSING

The look-up table with all solutions can be post-processed to allow launch window analysis. There are two options to represent the results in the best way. Graphs for delta-v vs. time can be plotted as a timeline to emphasis all launch windows and the transfer time on one glance. Alternatively delta-v can be plotted over a compressed timeline where all results are represented only in respect to their nearest target plane intersection.

Included in the final analysis all launch window opportunities and durations are determined.

6.1. Timeline and compressed timeline

The complete timeline shows the needed delta-v of the launch time in respect to the absolute local launch time. This supports the user to select suitable launch dates when a preferred transfer time is needed.
The compressed timeline to one day shows the same data basis in respect to the relative local launch time of each day. This supports the user selection, when a maximum launch window is needed. This effect is achieved by the overlay of all solutions and it allows a comparison of not neighboring launch windows by means of merging them. In this case longer launch windows are generated with the consequence of varied transfer times changing any time step, because the next time step isn't of the same day.
The look-up table contains a cloud of solution points; in order to analyze them, extended filtering is executed. This allows a visual representation and the possibility for the user to find launch window opportunities.

Figures 5-7 represent so-called "pork chop plots" for delta-v in relation to the start time, but only the best delta-v level at that time interval.

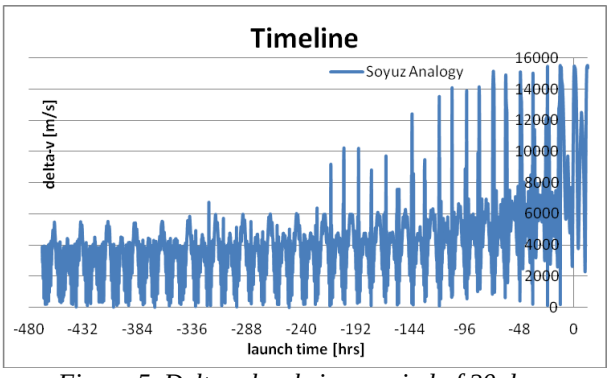

Figure 5. Delta-v levels in a period of 20 days

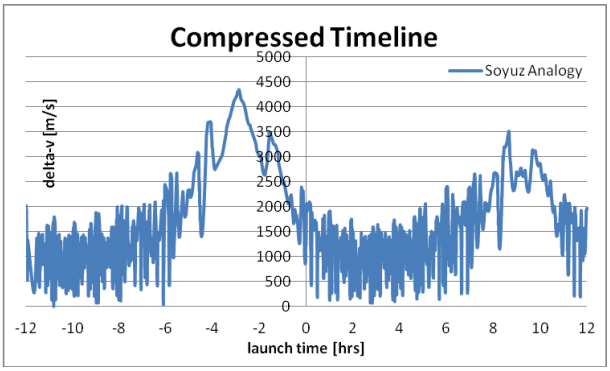

Figure 6. 20 day data compressed over a period of one day in respect to plane intersection at launch coordinate

The overlay of all days on a period of 24 hours and a new filtering reduced the delta-v levels drastically and extended the launch window gaps.

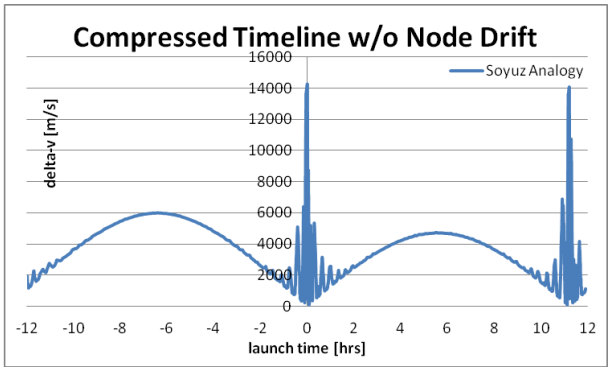

Figure 7. 20 day data without nodal regression compressed over a period of one day in respect to plane intersection at launch coordinate

Fig. 7 data is based on the same parameters as in Figure 6, but with deactivated nodal regression. In this case the merging and filtering is not able to lower the peaks at around 0 hour and 11 hours; moreover the launch window sinks e.g. between 1 hour and 5 hours are not broadened.

6.2. Filters

Filtering performs a comparison of all variables of one set with another set in respect to the minimum delta-v at the same time interval. All data pairs of one set are regarded as a static function for linearization and comparison.
The filter will compare a data pair of one set with an interpolated pair of the next sets to eliminate set pairs with higher delta-v until only the minimal value for one time interval remains.
In Fig. 8, a) all data pairs between 1 and 2 days before reference plane intersection are processed and only the best, thus smallest, values for delta-v are accepted by the filter.

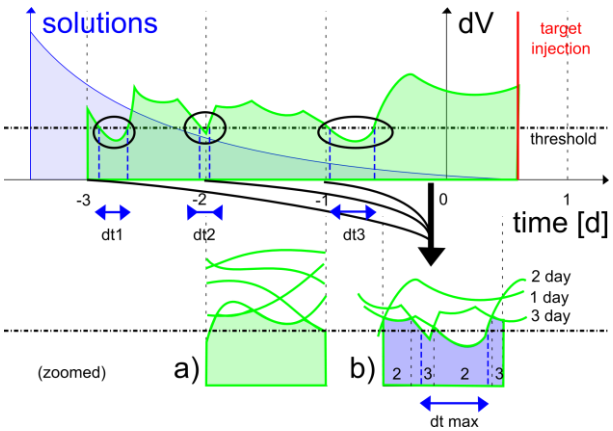

Figure 8. Example of delta-v and solutions vs. time.

Fig. 8 includes the time compression of values on one day and both filtering methods (a and b). Moreover the

launch window gap finder is presented with its threshold.

The filter method is executed once for the complete and once for the compressed timeline. The filtering occurs between discrete time intervals and the delta-v data points in this interval are compared by the algorithm. For each curve representing an n-set of data, the delta-v is compared to the delta-v data points of another n-set in this exact time interval. The distribution of the data points in this interval can widely vary and accordingly the filtered best data points. When the compressed timeline is created, more n-sets will share a common time-interval and thus another distribution of data points in this interval. If only the filtered results of the complete timeline will be compressed from an overall interval of n days into just one day and then filtered, it will be faster due to less comparison cycles of the algorithm, but the comparison can be influenced by an already effected distribution of data points by the first filter run.
Therefore the filter algorithm uses the original data points for both cases to minimize the effect of comparison resulting in one run for the complete timeline (partly shown in Fig. 8 a)) and a separate filtering run for a compressed time line (Fig. 8 b)).

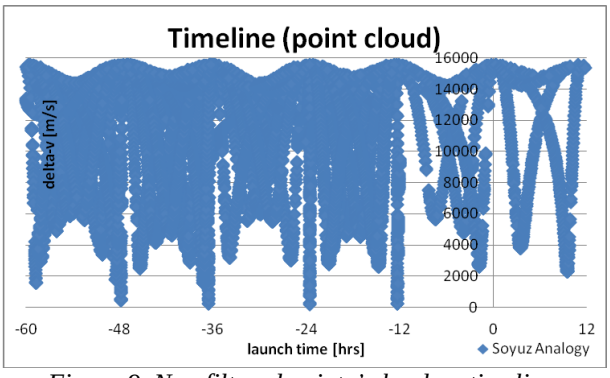

Figure 9. Non filtered points' cloud on timeline.

In Fig. 9 it is possible to see sections of seemingly static functions (on the right) due to less combinatorial solutions of transfer orbits. Indicated in Fig. 5 a).

Threshold

To decrease iteration loops and thus software run time thresholds can be set to only feed realistic and practicable values to the filter. This can be a specific value or a variable limit as a percentage of the minimal and maximal values computed. This is helpful for preliminary analysis and first mission design.

Another threshold can be set to limit the launch windows. All values below this threshold will be regarded as possible launch window opportunities and will be marked in respect to the remaining solutions (see Fig. 8).

Launch Window Duration

With the launch window marker threshold a gap finder algorithm will find all coherent launch windows meeting this criterion and it also distinguishes between individual windows (Fig. 8).
The results show that compressed timeline results provided longer windows when more days for transfer-time fitting are allowed. This is due to merging effects.
Additionally there is a sort of "saturation" effect: the Soyuz mission shows a delta-v convergence at twelve days for transfer. The inclusion of more transfer days had minimal or no effects to launch window durations, but it increases the computation time.

6.3. Resuming from post-processing to processing

To reduce waiting time for first results, the amount of days for the transfer-time fitting can be changed after the first analysis run. ALWA is able to resume from the previous day's set and calculate the sets for following days and add those new values to the look up table and feed it to the post-processor. In this way the user is able to stepwise increase the analysis without reiterating through already processed and stored data.

6.4. Constraint filtering

ALWA is designed to include additional parameters besides classical orbital mechanics and energetic constraints.
To command the stepwise orbit change from one transfer to the other, communication link visibility is a key factor. This can be included during transfer-time fitting when all orbit revolutions and the final perigee and apogee positions are known. This can be used to correlate their position with a set of ground stations or with positions from databases. Alternatively it is also used to define the position of mobile ground stations if needed. This can be done with spherical trigonometry when propagation parameters like antenna pattern, elevation and azimuth are known.

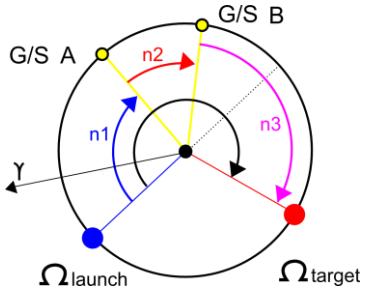

Figure 10. Ground station G/S locations for the perigee passage of the transfer orbits.

Similar to the ground station constraints, beta angles for

eclipses or sun interferences can be included for perigee and apogee positions. These are needed for communication link design, for thermal and power house keeping.
Further beta angle determination besides the orbit apses can be performed by geometrical methods to identify go and no-go criteria: if the orbit plane is sensitive to specific beta angles that lead to eclipses and interferences.

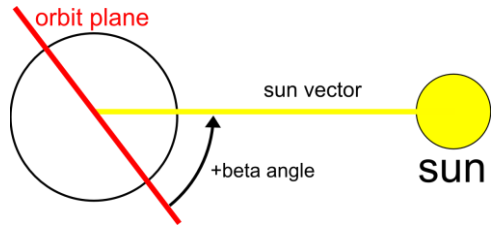

Figure 11. Beta angle for plane evaluation

For detailed examinations a stepwise overview of all orbits has to be done updating the celestial body position with ephemerides data.

7. CONCLUSION AND FUTURE PERSPECTIVES

Currently there is no commercial launch window analysis tool available enabling combined analysis and extending of launch windows. Therefore Astos Solutions developed ALWA as stand-alone tool. Moreover ALWA could be efficiently used as a pre-analysis tool to identify highly probable launch window solutions that will be fed to the Aerospace Trajectory Optimization Software (ASTOS) where a more detailed mission analysis and trajectory simulation can be performed

Future steps are the inclusion of lunar orbit injection and the extension of the rendezvous (chaser target) functionality.
Other interesting expansions are the integration of a databases of ground station locations and their parameters; moreover the interface to ephemeredes data for beta angle and eclipse event avoidance.

With this approach the selection of launch windows could be performed at an early phase of the design process with the advantage of reducing expensive iterations during the later design phases due to launch window problems.

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