# ENHANCEMENT OF DLR/GSOC FDS FOR LOW THRUST ORBIT TRANSFER AND CONTROL

*Stefanie Lück, Sofya Spiridonova, Michael Kirschner, Ralph Kahle, Reinhard Kiehling*

DLR German Space Operations Center, Oberpfaffenhofen, 82234 Weßling, Germany

## ABSTRACT

On behalf of possible future missions with electric propulsion (EP) controlled by DLRs German Space Operations Center (DLR/GSOC) the present operational multi-mission Flight Dynamics System (FDS) is enhanced to support the preparation and operations of such types of project. For designing an easily extendable framework, various low-thrust scenarios were considered. Each low-thrust phase is modelled by a thrust profile comprising non-equidistant thrust vector and constant thrust level. Based on this design several multi-mission FD software modules are enhanced, e.g. Orbit Determination (OD) and generation of Orbit Related Information (ORI). The low-thrust transfer trajectories are optimized by means of the software package ASTOS/GESOP [1]. Demonstrating the extended FDS capabilities by means of a GEostationary Orbit (GEO) positioning reference mission shows an excellent consistency between resulting ephemerides by the optimizer in comparison to the FDS, validating the correct processing of thrust profiles within the implemented system.

***Index Terms—*** GTO-to-GEO transfer, low-thrust

## 1. INTRODUCTION

### 1.1. Motivation

Electric propulsion engines are characterized by low thrust magnitudes $F$ between $0.001\,N$ and $1\,N$ but high specific impulses $I_{sp} = v_e/g_0$ (with $v_e$ denoting the average exhaust velocity along the axis of the electric engine and $g_0$ terming the gravity acceleration at the Earth's surface). Typical values for the $I_{sp}$ are between $300-1000\,s$ for electro-thermal thrusters, $1000 - 2600\,s$ for stationary plasma thrusters and $2500 - 4000\,s$ for electrostatic thrusters, whereas the $I_{sp}$ of a typical chemical $400\,N$ apogee motor firing engine amounts only to approx. $300\,s$. For a more detailed overview of high specific impulse thrusters and their characteristics see [2]. Due to its higher $I_{sp}$ compared to classical chemical systems, the EP is more effective for causing a velocity increment leading to the advantage that less fuel is needed to bring a satellite into its operational orbit. Thus the payload mass could be increased accordingly, which enhances the overall efficiency of the mission.

Depending on the considered low-thrust scenario, the potential maneuver duration can last up to several hundred days which requires an upgrade of the existing DLR/GSOC FDS. With our existing FDS, extended maneuvers with constant thrust direction in inertial or orbital system can be modelled. As a first approach, the modeling of low-thrust phases in the enhanced FDS has been achieved by thrust profiles that allow time dependent thrust directions and long-lasting maneuver durations. The thrust level itself remains constant over the burn duration since an electric engine usually cannot be modulated [3, 4].

In the next subsections possible low-thrust scenarios for application in the area of geostationary missions are characterized and challenges are explained. The second section of the paper outlines the requirements on the enhanced FDS followed by a presentation of its resulting design. The application of the enhanced FDS is exemplarily shown in the third section by means of a low-thrust transfer from Geostationary Transfer Orbit (GTO) to GEO. Finally, achieved objectives are summarized and future work is discussed.

### 1.2. LEO-to-GEO transfer

One possible scenario for low-thrust application is the transfer from LEO to GEO, whereby orbit altitudes between $200\,km$ and $2000\,km$ are referred to as Low Earth Orbits (LEOs). In low Earth altitudes perturbations due to atmospheric drag and Earth gravity gain a higher influence, dominated by $J_2$ caused by the flattening of the Earth. Moreover, crossing the Van-Allen belt is the most important limiting factor of the satellite's life time.

### 1.3. GTO-to-GEO transfer

The GTO is a high elliptical orbit starting with a low perigee around $250\,km$ altitude and an apogee close to GEO altitude ($35786\,km$) for a typical ARIANE 5 launch. Dependent on the current orbit altitude different environmental torques act on the satellite as atmospheric drag, long exposure to radiation from the Van-Allen belt, gravity of Earth in lower Earth orbits as well as solar radiation pressure and lunisolar attraction in higher Earth orbits.

Using low-thrust implies a long propulsion phase duration of up to 150 days to reach GEO. The transfer can be divided into the following four phases:

1. Check out of spacecraft (typically several days)
2. First phase of EP (typically 1-2 weeks)
3. EP cruise phase (typically 120 days)
4. Final EP phase (typically 1-2 weeks)

Whereas during the first 2 phases (i.e. the first 2-3 weeks) a world-wide ground station (GS) network shall provide nearly continuous contact to the satellite, GS passes are thinned out during the $3^{rd}$ phase in order to save costs. In the last $(4^{th})$ phase the satellite is approaching its target longitude and in general 1 station provides continuous visibility of the spacecraft during this critical phase. This scenario is analyzed in more detail within this paper.

### 1.4. GEO station keeping

For station keeping operations of geostationary satellites EP systems are used more and more to compensate perturbations due to lunisolar gravitational attraction, solar radiation pressure and effects due to the non-spherical gravity field of Earth.

## 2. FDS REQUIREMENTS AND DESIGN

### 2.1. FDS requirements

The low-thrust enhancement of the FDS requests modifications to existent software and interfaces as well as a development of a general parametrization of low-thrust maneuvers applicable for a broad variety of low-thrust scenarios. The following list summarizes top-level requirements to the enhanced FDS:

- The parametrization of the low-thrust maneuver shall be applicable to the GTO-to-GEO transfer outlined in subsection 1.3.
- The FDS shall be easily extendable to further low-thrust scenarios.
- The enhanced FDS shall be compliant with the existing FDS in view of internal and external interfaces.
- Numerical orbit propagation including low-thrust phases shall be handled to provide valid events, orbit information and ephemeris data (Cartesian, Keplerian, antenna pointing).
- OD of low-thrust phases incl. thrust level reconstruction shall be handled.

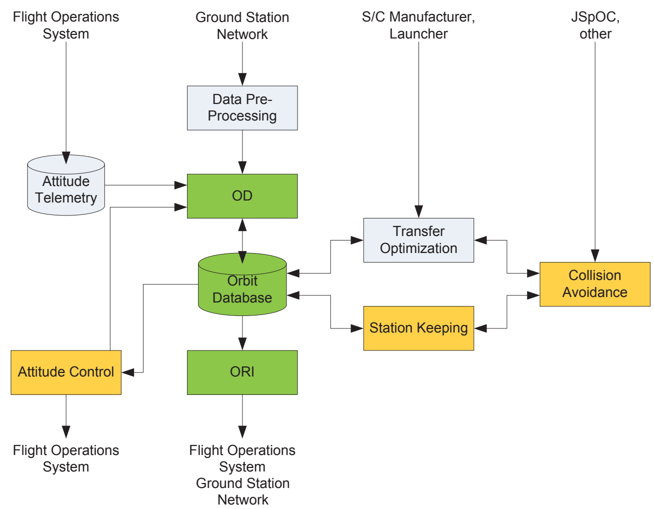


**Fig. 1**. FDS design

### 2.2. FDS design

The modifications of the FDS design due to low-thrust enhancement are depicted in Figure 1. Software is displayed using rectangles, whereas databases are represented by containers. Green coloring marks already adapted software or databases and orange coloring marks software to be adapted in future versions. Uncolored programs and databases remain unchanged. The particular software and interfaces are discussed in detail in the following paragraphs:

#### *2.2.1. Attitude telemetry*

Based on the attitude telemetry and the thruster mountings, the thrust directions can be reconstructed, which is needed by the OD software.

#### *2.2.2. Attitude control component*

Based on the nominal thrust profile at begin of the mission or after the re-optimization of the thrust profile during the transfer phase, attitude control data are generated, which has to be uploaded to the satellite.

#### *2.2.3. Data pre-processing*

This software comprises algorithms performing a transformation of tracking data received from a ground station network to a format readable by the OD software. The data originates either from ground stations, e.g. angle tracking data and ranging measurements, or spacecraft telemetry, e.g. GNSS navigation data.

#### 2.2.4. *Orbit database*

The orbit database interface comprises one or more records containing orbit information of a specific epoch, corresponding spacecraft parameters and optional maneuver data. The maneuver data has to be enhanced to handle low-thrust maneuvers. Therefore, the so called thrust profile format is introduced as a new maneuver format. This format includes the EP phase start epoch, thrust level, mass flow, reference frame and the number of thrust records. Each thrust record consists of a time stamp providing the delta time to the EP phase start epoch and a unit vector $\boldsymbol{e} = (e_1, e_2, e_3)$ for the thrust direction in either inertial or orbital frame. Thrust records are non-equidistant with more sampling points around perigee and a lower number of sampling points near to the apogee.

#### 2.2.5. *Orbit Determination (OD)*

The OD software implemented in the FDS is a general and precise orbit determination, orbit prediction, thrust reconstruction and tracking data simulation program for Earth-orbiting satellites with operational applications ranging from LEO to GEO. The precise force modeling includes an Earth gravitational field, atmospheric drag, solar radiation pressure, Sun and Moon third body perturbations. The numerical integration of the orbit and variational equations with the Shampine and Gordon multi-step predictor-corrector method is based on the Adams-Bashfort-Moulton algorithm, [5]. This software is enhanced to cope with thrust profiles for EP applications.

#### 2.2.6. *Orbit-Related Information (ORI)*

This software generates ephemerides (e.g. Cartesian, Keplerian and antenna pointing), events (e.g. AOS/LOS times, shadow transit times, visibility times, apsides, etc.) as well as GS visibility and timeline plots based on the orbit database including optional maneuver information. This software is enhanced to cope with thrust profiles for EP applications.

#### 2.2.7. *Transfer optimization*

For generation of optimized low-thrust profiles, the General Environment for Simulation and Optimization (GESOP) software package of Astos Solutions is used [1]. While GESOP provides the optimization, simulation and plotting environment, a model has to be written for every specific optimization problem including its particular differential equations, boundary conditions, path constraints and cost functions. Thus, a dedicated model was implemented to define an optimization problem for the spacecraft low-thrust transfer from GTO to GEO under the condition of lowest fuel consumption. Among other optimization methods, GESOP offers the Sparse Optimization Suite (SOS) direct collocation method which is currently used for low-thrust applications at GSOC. Being capable to handle tens of thousands of variables and constraints and featuring an automatic mesh refinement algorithm, this method is best suited for low-thrust trajectory optimization problems [1].

Internally, the low-thrust optimization model developed at GSOC utilizes the modified equinoctial elements introduced in [6]:

$$\begin{aligned} p &= a(1-e^2) & h &= \tan(i/2)\cos\Omega \\ f &= e\cos(\omega+\Omega) & k &= \tan(i/2)\sin\Omega \\ g &= e\sin(\omega+\Omega) & L &= \Omega+\omega+\nu, \end{aligned} \tag{1}$$

depending on the Keplerian elements. The Gaussian equations of motion are implemented within the model as they were obtained in [6], providing the time-derivatives of the modified equinoctial elements as functions of the perturbing acceleration components in the directions perpendicular to the radius vector in the direction of motion, along the radius vector outwards and normal to the orbital plane in the direction of the angular momentum vector.

The model defines six final boundary conditions on the optimized trajectory, of which five,

$$\begin{aligned} & p(t_f) = 42164.137 \text{ km} \\ & f(t_f) = 0 & h(t_f) &= 0 \\ & g(t_f) = 0 & k(t_f) &= 0, \end{aligned} \tag{2}$$

define the geostationary orbit, where $t_f$ is the final epoch of transfer, while the sixth constraint is optional and allows to target a particular final longitude.

Along with a setup file, the low-thrust model requires information on the initial spacecraft position and velocity given in form of a GSOC FDS state vector record. The ultimate outcome of the optimization and the simulation process is an optimized thrust profile which is appended to the initial state vector record in form of a single thrust profile.

#### 2.2.8. *GEO station keeping*

Compared with the injection maneuvers, station keeping maneuvers are small maneuvers usually performed by $10\,N$-thrusters modeled as extended maneuvers with fixed thrust directions (inertial frame, orbital frame) within the FDS. For the use of electric propulsion new station keeping strategies have to be developed and optimized for geostationary satellites.

#### 2.2.9. *Collision avoidance*

The collision avoidance software provides risk of collision estimates by detecting the closest approach between two objects. This software is vitally important as GTO-to-GEO transfers are long-lasting transfers with a higher risk of collision on the one hand at the beginning of the transfer due to a very low perigee and on the other hand close to the GEO region during the last weeks of the transfer. If a significant collision risk is detected, a dedicated collision avoidance maneuver might be necessary, which has to be considered in the transfer optimization or station keeping process, as applicable.

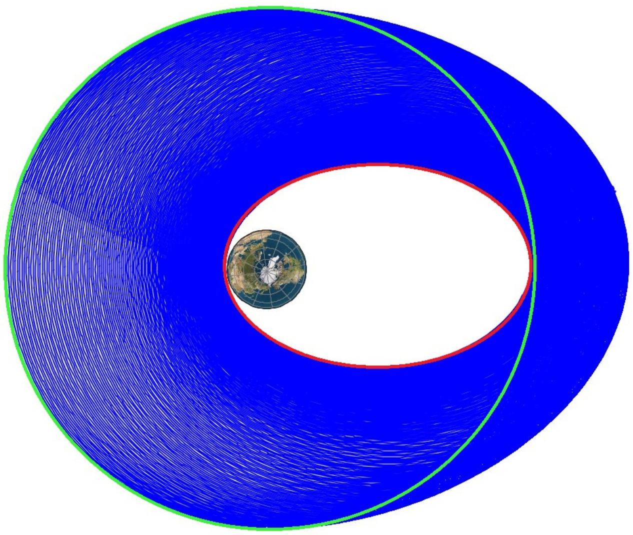

**Fig. 2**. Entire GTO-to-GEO transfer

## 3. ANALYSIS OF A SAMPLE SCENARIO

### 3.1. Description of scenario

This section outlines the application of the enhanced FDS by means of a low-thrust transfer from GTO to GEO of a fictitious geostationary communication satellite using EP with target longitude over Europe. The spacecraft parameters refer to a 2-ton class communication satellite, see Table 1.

**Table 1**. Spacecraft parameters

| | |
|---|---|
| Mass $[kg]$ | 1687.0 |
| Area (Solar radiation pressure) $[m^2]$ | 20.0 |
| Area (Drag) $[m^2]$ | 20.0 |
| $I_{sp}$ $[s]$ | 2600.0 |
| Thrust level $[N]$ | 0.3 |

The epoch orbital elements referring to the true equator and equinox of date are depicted in Table 2, describing a typical ARIANE 5 transfer orbit with a perigee near $200\,km$ altitude and an apogee close to geostationary altitude. The set of orbital elements $\{a, e, i, \Omega, \omega, M\}$ denotes semimajor axis, eccentricity, inclination, right ascension of the ascending node (RAAN), argument of perigee and mean anomaly at epoch of begin of EP phase, compare 1.3. The orbital elements are osculating elements.

**Table 2**. Epoch orbital elements

| Epoch (UTC) | 2013/08/08 23:59:34.3 | | |
|---|---|---|---|
| $a$ $[km]$ | 24371.0 | $\Omega$ $[°]$ | 0.0 |
| $e$ | 0.73009 | $\omega$ $[°]$ | 0.0 |
| $i$ $[°]$ | 6.0 | $M$ $[°]$ | 0.0 |

To raise the perigee to geostationary altitude, one low-thrust maneuver represented as a thrust profile is performed. Thrust level and mass flow are assumed to be constant over the burn duration of approx. 138 days. A thrust profile example used in this analysis is shown in Table 3 for the start and ending of the EP phase. The overall $\Delta v$ amounts to $2200\,m/s$ compared to the theoretical value of $\Delta v = 1490\,m/s$. The total optimized transfer is shown in Figure 2 in inertial frame, where the red ellipse represents the standard GTO and the green circle indicates the GEO.

**Table 3**. Thrust profile

| Epoch (UTC) | 2013/08/08 23:59:34.3 | | |
|---|---|---|---|
| Reference Frame | Inertial | | |
| Thrust level $F_n$ $[N]$ | 0.3 | | |
| Mass flow $[kg/s]$ | 0.000011766 | | |
| No. of thrust records | 3448 | | |
| Time stamp $[ddd : hh : mm : ss.sssss]$ | $e_1$ | $e_2$ | $e_3$ |
| 000:00:00:00.00000 | 0.00195 | 0.99951 | -0.01475 |
| 000:00:00:54.24226 | -0.05769 | 0.99722 | 0.02623 |
| ... | | | |
| 138:17:22:15.19338 | -0.04463 | -0.99999 | -0.17020 |
| 138:19:35:21.03387 | 0.12680 | -0.99617 | -0.13346 |

In order to ensure a sufficient visibility of the long-lasting transfer, the assumed GS network consists of a minimum of three ground stations distributed over Europe, East Asia and North America. During the first two weeks of the mission nearly continuous ground contact is assumed for initial operations and check out of the spacecraft, whereas in the following cruise phase GS contacts are reduced to $2.5\,h/day$ at an average in order to minimize costs. In the last phase of the transfer and during the IOT phase permanent contact is provided by the European GS. Depending on project requirements, additional stations might be included into the network for redundancy reasons.

In the following two subsections, the transfer phase is analyzed in detail regarding tracking data simulation, orbit prediction and OD as well as GS scheduling.

### 3.2. Thrust level reconstruction

During the early phase of the transfer a careful thrust level reconstruction shall be performed in order to calibrate the EP

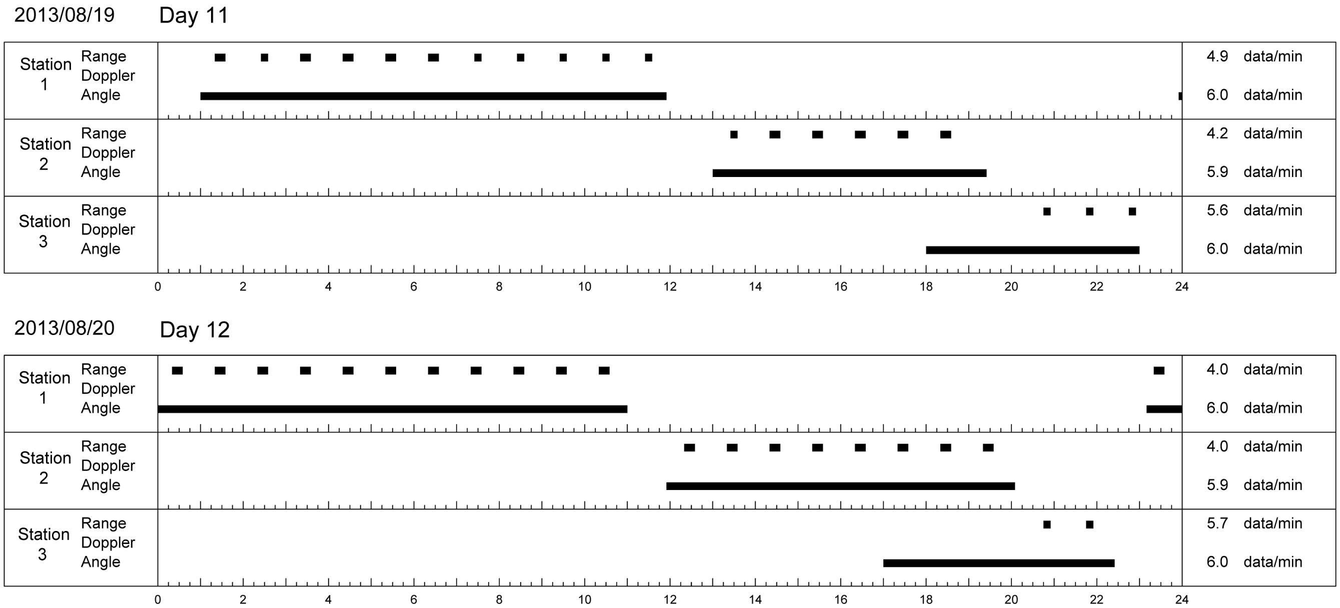


**Fig. 3**. Tracking data timeline for maneuver days 11 - 12

performance. In this phase nearly continuous ground contact is foreseen providing comprehensive tracking data for this task. This section provides a sample simulation of this process validating the implemented orbit determination module as described in the following.

An orbit determination including thrust level reconstruction is performed using simulated tracking data of 48 hours starting on day 11 at 0 UTC. To initialize the whole simulation, the trajectory is propagated to the start epoch taking into account the thrust profile given in Table 3.

Starting from the initial orbital elements, a tracking data simulation for two following days is performed assuming the nominal thrust profile and EP performance. The tracking data schedule for this first part of the transfer phase is assumed to provide hourly range measurements lasting $10\,min$ and permanent azimuth and elevation angle measurements as depicted in Figure 3. Measurement data are generated each $10\,s$. No bias or timing bias are taken into account in this scenario.

In the next step the OD software is used to process a thrust level calibration applying the previously simulated tracking data for two days. For this purpose, the nominal thrust level $F_n$ used for the thrust profile generation is increased by $0.03\,N$ to $F_a = 0.33\,N$ simulating a thrust level bias of $\pm 10\%$. $F_a$ is used as the a priori thrust level for the following OD, which estimates the orbital elements and the thrust level by using the simulated tracking data. The underlying least-squares algorithm needed 10 iterations for a successful orbit determination, resulting in an estimated thrust level of $F_e = 0.3000004 \pm 0.0000006\,N$, which fits perfectly to the nominal thrust level $F_n$ and which demonstrates the robustness of the enhanced OD software against thrust level uncertainties.

### 3.3. Retrieval of satellite after thruster failure

To save costs for the GS network it is often proposed to reduce the GS contacts during the cruising phase to once per day or two days for about 2 hours. As an example, Figure 4 shows GS visibility for days 63 to 67 (2013/10/10 to 2013/10/14) of our sample scenario, together with arbitrarily scheduled contacts each of approx. $2\,h/d$ for the corresponding GS Sta1, Sta2 or Sta3, respectively. In view of the large gaps between the selected passes it is important to know, whether the satellite can be successfully acquired even if a thruster failure occurs shortly after the previous contact.

To analyze this situation, the angular offsets between the GS pointing directions are computed by the ORI software for nominal and non-nominal trajectories, i.e. with EP working and EP switched off, respectively. The results are shown for 3 investigated cases in Figures 5, 6 and 7 covering the time spans from the start of the investigated GS pass noted in the head of the figures. The plots contain the above specified angular pointing offset between nominal and non-nominal trajectory as well as the elevation profile for the considered GS. The planned GS contacts (cf. Figure 4) are represented by blue-shaded areas. The dashed line indicates the critical upper limit of $0.6°$ for the pointing offset derived from the typical S-band antenna beam size (3 dB) for the assumed ground stations. It should be noted, that in case of a Ku band GS network the beam size and therefore this limit would be much smaller (i.e. approx. $0.1°$).

The first considered case is an accidental EP engine cut off just after the pass of Sta1 on 2013/10/11 around 8 UTC,

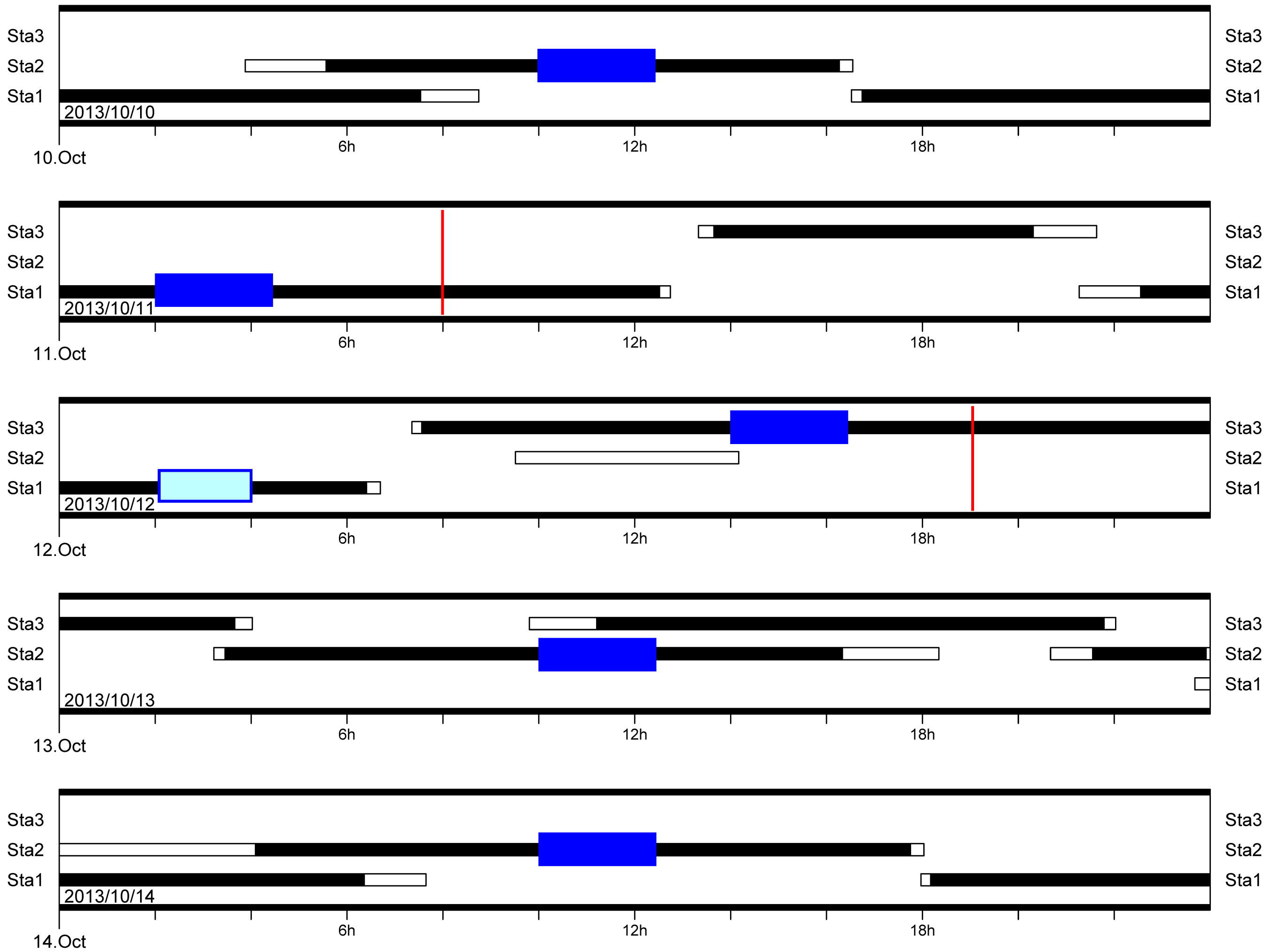


**Fig. 4**. GS visibility and scheduling for days 63 - 67

indicated by a red bar in Figure 4. The beginning of the next scheduled contact is assumed to be on 2013/10/12 at 14 UTC within the visibility of Sta3. Figure 5 shows that the pointing offset has a minimum during the planned contact indicated by shaded blue areas in the figure, but is always above the critical limit. Therefore acquisition of the satellite could be a problem and it might be necessary that the GS has to implement a search strategy in order to find the satellite.

As a second example it is assumed that there is an EP engine cut off on 2013/10/12 at 19 UTC after the contact of Sta3. The results for the pointing offsets for the next planned contact within the pass of Sta2 on 2013/10/13 are shown in Figure 6. It turns out that in this case the pointing offset is well below the critical limit during nearly the whole visibility for Sta2.

These examples show that the GS contacts need to be planned more carefully. Considering the $1^{st}$ case represented by Figure 5, it is investigated whether an improved GS scheduling could relax the situation. A different schedule of the contact within the pass of Sta3 on 2013/10/12 would not resolve the problem, because the pointing offset is over the critical limit during the entire pass. Therefore the situation for the previous pass for Sta1 starting on 2013/10/11 21 UTC is analyzed. The result is given in Figure 7 showing that the pointing bias is under the critical limit during the first 7 hours of the pass, i.e. until 2013/10/12 4 UTC. Therefore a scheduling of Sta1 at 2 UTC instead of Sta3 at 14 UTC can facilitate the acquisition of the satellite on 2013/10/12 in case of an EP cut off after the contact at the day before. This is indicated by the light-blue shaded areas in Figure 4 and Figure 7.

It should be noted that the present exemplary analysis covers only the situation around day 65 of our sample mission with a station scheduling of about 1 contact per day. As the results depend on the current orbital elements, the GS scheduling and the location of the station contact on the orbital arc (i.e. close to apogee/close to perigee), a comprehensive mis-

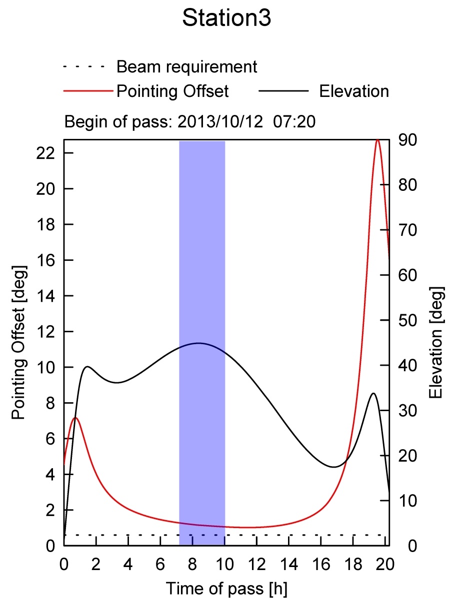


**Fig. 5**. Pointing offset for Sta3

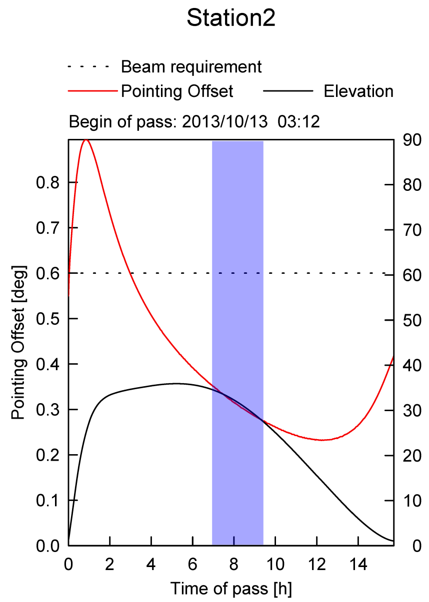


**Fig. 6**. Pointing offset for Sta2

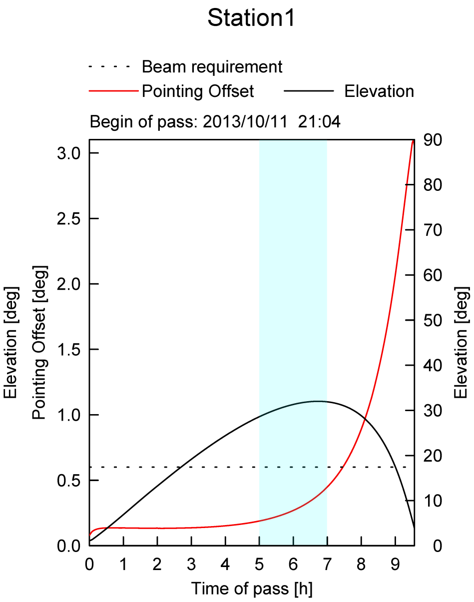


**Fig. 7**. Pointing offset for Sta1

sion analysis has to be performed before the realization of such a mission covering all phases of the transfer to GEO. Therefore there could be phases where not such a problem as described exists, but it cannot be excluded currently, that there are phases where the problem is even worse which might lead to a denser GS scheduling in order to avoid the problem. But more station contacts would increase the costs of the mission and therefore it is to make a trade-off between risk and costs in view of a safe re-acquisition of the satellite.

### 3.4. Validation of the enhanced FDS

The resulting state vector received by a propagation over the 138 days of the entire low thrust phases 2, 3 and 4 performed with the enhanced DLR/GSOC FDS is compared with the result of the ASTOS/GESOP [1] system, both are shown in Table 4. It turns out that the absolute deviation between both calculations differ by approx. $40\,km$ in position and $5\,m/s$ in velocity, respectively. This difference is considered as extremely small.

**Table 4**. Propagation of entire transfer

| | ASTOS/GESOP | Enhanced FDS |
|---|---|---|
| Epoch (UTC) | 2013/12/01 08:19:04.06971 | |
| $x$ $[km]$ | 26620.378 | 26618.347 |
| $y$ $[km]$ | -2710.135 | -2749.746 |
| $z$ $[km]$ | 750.635 | 749.667 |
| $v_x$ $[km/s]$ | 0.217 | 0.222 |
| $v_y$ $[km/s]$ | 4.154 | 4.154 |
| $v_z$ $[km/s]$ | 0.038 | 0.039 |

The deviations can be explained by different interpolation algorithms between thrust direction sampling points. The enhanced FDS utilizes linear interpolation over time whereas the model solved with ASTOS/GESOP interpolates over the equinoctial angle $L$ and uses more sampling points internally. Presumably a higher level of agreement might be received by increasing the number of sampling points within the thrust profile, especially around the perigees.

Note that in a more realistic simulation, the transfer trajectory would be refined on a regular basis as in a real mission. In this case, the maximum propagation period would be well below four weeks, implying much smaller position deviations between trajectory optimization and orbit propagation.

## 4. CONCLUSION AND OUTLOOK

Future possible satellite missions controlled by DLR/GSOC will use electric propulsion, e.g. for the transfer from GTO to GEO. For the purpose to operate such types of missions, the present multi-mission FDS was enhanced in order to be capable to process thrust profiles representing low-thrust phases. A successful OD incl. thrust level reconstruction for a continuous low-thrust phase for the transfer from GTO to GEO was demonstrated.

The low-thrust transfer trajectories are received by optimizing thrust profiles by means of the software package ASTOS/GESOP [1]. This package was configured within the present FDS with astrodynamics models used at DLR/GSOC to ensure maximum compliance between Mission Planning/Analysis results and operational realization. Comparison between the trajectories received from the ASTOS/GESOP package and those computed by the FDS validates the correct processing of thrust profiles within the implemented FDS.

For future work other low-thrust scenarios will be analyzed, e.g. orbit raising from LEO to GEO and GEO station keeping. In this first step, we considered the thrust level to be constant over a thrust phase. For the future the need for extension to variable thrust levels and refined transfer trajectories incl. operational and technical constraints, e.g. thrust interruption during eclipses, will be analyzed.

In addition, GTO-to-GEO transfers are long-lasting transfers with a higher risk of collision. Therefore collision avoidance maneuvers have to be considered in the transfer optimization.

## 5. REFERENCES


[1] Astos Solutions GmbH, *GESOP 7 User Manual*, 7 edition.

[2] Christophe R Koppel, "Advantages of a continuous thrust strategy from a geosynchronous transfer orbit, using high specific impulse thrusters," in *14th International Symposium on Space Flight Dynamics–ISSFD XIV February*, 1999, pp. 8–12.

[3] Robert Mckay, Malcolm Macdonald, James Biggs, and Colin McInnes, "Survey of highly non-keplerian orbits with low-thrust propulsion," *Journal of Guidance, Control and Dynamics*, vol. 34, pp. 645–666, 2011.

[4] Jinjun Shan, Yuan Ren, J. Shan, and Y. Ren, "Low-thrust trajectory design with constrained particle swarm optimization," *Aerospace Science and Technology*, vol. 36, pp. 114–124, 2014.

[5] Lawrence F Shampine and (joint author.) Gordon, M. K. (Marilyn Kay), *Computer solution of ordinary differential equations : the initial value problem*, San Francisco : W. H. Freeman, 1975, Includes index.

[6] M. J. H. Walker, J. Owens, and B. Ireland, "A set of modified equinoctial orbit elements," *Celestial Mechanics*, vol. 36, pp. 409–419, Aug. 1985.