AIRBUS

DEFENCE AND SPACE

Project

NAVIGATION CONCEPTS FOR MULTI-REVOLUTION SEP TRANSFERS

Title

EXECUTIVE SUMMARY

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Change log

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Acronyms

AGF	Attitude Guidance function
AOCS	Attitude and Orbit Control System
EOR	Electric Orbit Raising
EPS	Electric Power System
FDIR	Failure Detect°, Isolation and Recovery
GTO	Geostationary Transfer Orbit
IOT	In-Orbit Test
KOM	Kick-off Meeting
LEO	Low Earth Orbit
LEOP	Launch and Early Orbit Phase
MEO	Medium Earth Orbit
OBGF	On-Board Guidance Function
OH	Optical head
PPS	Plasma Propulsion System
SA	Solar Array
SOW	Statement of Work
STR	Star Tracker
TGF	Thrust guidance function
TT&C	Tracking, Telemetry & Command
WP	Work Package

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1 INTRODUCTION

1.1 Scope of the document

This Executive Summary presents the results of the ESA study “Navigation Concepts for multi-revolution SEP transfers”.

1.2 Context

The use of electrical propulsion is one of the means that can be used in order to improve the efficiency of space access, attempting to reduce the cost of satellite payload mass into orbit.

With solar electric propulsion, the duration of the transfers, and thus the operations, is longer than with chemical propulsion, and involve more repetitive tasks. Thus, agreeing that legacy ways to operate single chemical propulsion satellites cannot be repeated to handle SEP satellites, for the sake of workload and cost reduction, SEP satellite operations should put in place more automatic procedures and/or use autonomous guidance. This approach emphasizes human tasks for added value operations such as debris collision avoidance, outages and other specific exotic mission phases.

The scope of this activity deals with operating SEP satellite with various levels of autonomy, and it includes:

- assessing the needs for different class of mission relevant to the current space business context,
- analyzing current technological solutions and methods applicable to electric propulsion mission,
- deriving, simulating and analyzing operational concepts for the identified study cases,

1.3 Definition of the study cases

To assess a large range of operational concepts, we select a set of study cases, with different challenges, which cover:

- *Different orbital regimes*; from LEO to interplanetary.
- *Different variations of autonomy level*;
- *Different numbers and different use of ground stations*;

2 OPERATIONAL CONCEPTS OF THE STUDY CASES

2.1 Definition

The operational concept captures means, functions and processes expected at satellite, ground segment and organisational levels to complete successfully a multi-revolution solar electric propulsion transfer.

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2.2 Major transfer phases

An EOR transfer considers several phases:

Phase 1	▪ Satellite configuration at launcher lift-off. ▪ Satellite injection and initialization sequence ▪ Configuration for EOR phase ▪ In-Orbit Test (IOT) phase
Phase 2	▪ Spiraling phase operations sequences: this is usually the longest phase which consists in actually executing the electric propulsion transfer.
Phase 3	▪ This is the end of the spiraling electric propulsion phase. It is dependent on mission, but it is generally mission's orbit insertion or final phasing.

In the current study, we focus mainly on the operational concepts for the spiraling phase (Phase 2) operations sequences.

2.3 On-board autonomous guidance

The power limited onboard architectures yield to restrict real-time computations only to processes which outputs are used synchronously (e.g., the attitude and thrust direction need to be computed in real-time), and perform other computations asynchronously. The guidance function, for instance, is called asynchronously, once per orbit, to prepare the guidance profile for the following orbit. This guidance profile can then be interpolated, efficiently, in real-time, at the AOCS frequency.

We identified 3 major levels of autonomy and guidance modes:

- Manual: the guidance profile, **provided by the ground**, is interpolated in **time**, and attitude is expressed in inertial frame.
- Semi-autonomous: the guidance profile, **provided by the ground**, is interpolated in **orbital** position, and expressed in a local orbital frame. The current orbital anomaly shall be available in real-time for the interpolation of the guidance profile.
- Fully-autonomous: the guidance is **computed on-board**. We propose two approaches:
  - Close-loop: the algorithm computes the control to follow closely a reference trajectory. This adds some predictability to the operational timeline as the satellite is guaranteed to be in a box around the reference trajectory.
  - Open-loop: the algorithm computes the guidance to reach a given target. It adapts to any change. This poses more challenge to the operations as the trajectory is never known a priori.

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The autonomous guidance function for orbit raising is one of several functions needed to increase the autonomy level. Other algorithms can be implemented to improve transfer guidance autonomy, in the different phases:

- EOR guidance function with attitude constraints
- Deorbit guidance function
- Orbit phasing function
- On-board eclipse computation
- Autonomous collision avoidance
- Thrust estimation

2.4 Common satellite activities during spiraling phase

Spiraling phase is specific to each study case; however there are some common operational concepts and activities.

2.4.1 Satellite monitoring

Satellite monitoring will be done periodically. The objective is to get periodic satellite housekeeping data and health status assessment, satellite anomaly detection (e.g. thruster outage) or anomaly prevention thanks to trend analyses, and GNSS data, if available.

2.4.2 Satellite commanding

Satellite commanding is required for orbit control, housekeeping operations requested by satellite specialists to tune some parameters of their subsystems or to handle events not processed automatically on board, contingency mode (recovery actions following an anomaly occurrence, collision avoidance manoeuver not included in the EOR cycle plan).

2.4.3 Housekeeping operations

Housekeeping operations are required to support nominally the spiraling phase, and activities other than the ones already covered by the orbit control. In lower autonomy mode, the TT&C ground stations will be booked at a frequency dependant on the guidance autonomy level to support the upload of the manoeuver plan and guidance profile. In higher autonomy mode, however, there is no data upload and satellite monitoring TT&C pass are only implemented to run Housekeeping operations, when needed.

2.4.4 Impact of autonomy level

The autonomy level will mainly introduce differences in the length and frequency of the activities. We introduce different parameters to better describe the differences between the use cases:

- The frequency for orbit monitoring and thruster calibration

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- Guidance profile update and upload frequency. Eclipses event are also computed and feed into the guidance accordingly with the PPS and EPS management constraint.
- Orbit prediction frequency for eclipses prediction and conjunction management

2.5 Operational concepts

Operational concepts were derived for each study cases, for the different identified autonomy levels. The raising phase follows the same operational activities throughout all study cases:

- Manual and semi-autonomous operations require periodic ground activities, some of them can however be automatized.
- For mission requiring orbit phasing (LEO and MEO cases), thrust uncertainty shall be taken into account by reducing as much as possible the impact of propagated uncertainties and doing frequent thruster calibration.
- Mars spiraling-down transfer is particular as it shows a solar conjunction phase, where no communication can be established between satellite and Earth’s ground segment. Semi-autonomous guidance is an enabler to continue transfer during this phase and thus reduce overall transfer duration.

2.6 Contingency cases

Several contingency cases were considered:

- Launcher injection error: this error affects the timeline of station acquisition and potentially the transfer performance.
- GNSS degradation: a degradation of the navigation solution (used for semi and full autonomous guidance modes) makes the guidance modes inefficient and may force to go back to manual mode.
- GNSS failure: the FDIR will generally handle the failure.
- Satellite failure with no thrust interruption: this will be handled by the on-board FDIR, and this should not have immediate impact on the transfer.
- Satellite failure with thrust interruption: the on-board FDIR will manage and reconfigure on-board systems;
- Collision risk: during the transfer satellite ephemeris are broadcasted to collision warning services (e.g. EUSST: European space surveillance and tracking service). FDS will assess the risk, and if confirm apply a manoeuvre avoidance strategy (i.e. manoeuvre abort, dedicated manoeuvre).
- Ground segment failure outside manoeuvre upload: Ground segment failure has limited impact on the raising phase. Collision management shall be monitored closely.
- Ground segment failure during manoeuvre upload: A manoeuver plan shall cover a longer period than the nominal cycle duration. In manual mode, a new cycle shall be computed and upload.
- Communication failure at end of solar conjunction (Mars case): the uploaded guidance profile shall allow the powered transfer for a given time after the effective end of conjunction.

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2.7 Critical points

The complexity of the transfers, the novelty of some missions and the will to increase the level of autonomy introduce some new concepts and raise questions that need to be addressed. We have then identified several critical points that shall be analysed further with a feasibility study.

- *The different levels of autonomy* opens up the cycle duration, which however is also constrained, for the different identified cases of contingencies, by the required tracking and prediction performance. **What would be the optimal guidance cycle compatible with low OPEX and good transfer performance?**
- *Satellite tracking* where there are thrust execution errors and orbit determination uncertainty is affecting the orbit predictability. What would be the tracking frequency so that despite trajectory uncertainty, we still have correct ground antenna pointing during satellite passes?
- *Thruster failure can result in missing satellite passes and not having sufficient tracking and monitoring data for critical operations.* ***How can we efficiently find the satellite in case of missed pass*****?**
- *Collision avoidance management* becomes more complicated owing to the prediction task that now includes thruster uncertainty. Collision avoidance management impact significantly the usability of advanced autonomous modes. **How often shall we update tracking and prediction to assess efficiently collision risk?**
- *On board navigation* works very well for low altitudes, under the GNSS constellation altitude. **What would be the expected performance when going above the GNSS constellation, using secondary signal lobes?**
- *Communication occultation and visibilities* during the transfer pose some timeline challenge, but can also prevents continuing a transfer. **Can we apply autonomous guidance during communication blackouts?**

3 FEASIBILITY STUDY OF THE OPERATIONAL CONCEPTS OF THE STUDY CASES

3.1 General

The similarities between the study cases and their operational concepts allow following a thematic approach. We analyze then a set of features, common and particular to each study case, but also concentrate on the identified critical points.

During the analysis various uncertainties are introduced (thrust execution error, navigation solution dispersion) to perform realistic simulations.

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3.2 Orbit prediction, and satellite tracking

3.2.1 Impact of thrust uncertainty and Orbit determination on tracking

Orbit determination activity helps having an initial satellite orbit to propagate from, and to support tracking and prediction activities. Measures are taken from each ground station. The visibility duration per station was assessed to check whether these durations were compatible with fair to good orbit determination accuracy and, to determinate for which mission long duration campaigns or complementary measures may be necessary to improve the orbit determination solution.

The tracking activity consists in pointing the satellite during its pass above the station. Tracking error were simulated considering orbit determination and thrust dispersion. Orbit determination dispersion were used to estimate the position of the reference satellite. Thrust dispersion were used during propagation of the actual satellite. Depending on the antenna beam half width (e.g. 0.5 deg), the tracking period varies from 1.8 day (LEO) to 2.5 days (MEO and GEO), with 1% thrust dispersion.

3.2.2 Impact of eclipses

Thrust uncertainty can shift the eclipse entry/exit events and affect the satellite power balance. In the maneuver command, margin around eclipses entry/exit location shall be put to accommodate any dispersions. The margin value was assessed for all relevant study cases, both in time and orbit angular position. Around 2-5 minutes around the eclipses dates are required to cover all cases of thrust uncertainty.

3.3 Collision avoidance strategy

Collision avoidance management consists in creating sufficient separation with a secondary object to prevent any risk of collision. During the transfer, thrust interruption is an effective way to create separation. We considered the worst case scenario where planned thrust interruption occurs one or two orbits before the TCA with a secondary object.

3.4 Manual and semi-autonomous maximum cycle duration

Cycle duration for the different autonomy levels is an important aspect of operations as it determines timeline, workload and operational cost. Too long a cycle period will produce off-pointing that can result in going into safe-mode to prevent equipment damages (e.g. optical head blinding). In the current study, however we compute cycle duration evolution along the transfer, for different thrust uncertainty level and for a maximum transfer ΔV overcost.

Table 3-1 synthetizes the simulations and the identified guidance cycle duration intervals. It has to be noted that difference might be small in terms of days (which is generally a relevant unit for OPEX), but in terms of dynamics in can result in several orbits.

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Table 3-1 Synthesis of cycle duration for 1% maximum overcost

	Guidance mode	LEO	MEO	GTO
Maximum Cycle duration	Manual	**3.5 - 9 days**	**5 - 11 days**	**10 - 17 days**
	Semi-autonomous	**3.5 - 9 days**	**6 - 16 days**	**14 - 21 days**

3.5 GNSS availability for GTO transfer

Onboard navigation solution is a mandatory requirement for higher level of guidance autonomy. Navigation solution can be obtained through onboard GNSS receiver. We thus showed that a GNSS receiver can be used during a GTO to GEO EOR, despite rising above the GNSS constellation, using secondary lobes and all available GNSS constellations, namely Galileo, GPS and GLONASS. It is of benefit for the quality of the navigation solution. The GNSS signal blackouts are thus shorter. This simplifies short-term on-board propagation that would be used to provide a navigation solution for dead reckoning.

3.6 Semi-autonomous guidance during solar occultation (Mars spiraling case)

Low-fidelity on-board navigation is an enabler for using semi-autonomous guidance during long Earth occultation. We used eclipses dates as a mean to detect and compensate guidance execution error. It is simple, as it requires few tuning parameters, and it is robust; it is less sensitive to the accumulation of thrust magnitude/direction errors, so it produces the maximum apoapsis/periapsis altitude reduction. Using semi-autonomous guidance can thus reduce significantly the transfer duration.

3.7 Contingency: satellite failure with thrust interruption and tracking

When a satellite is lost, we have studied two strategies that can apply to any study cases:

- Search pattern. It is an active search process in the sky above the ground station. In most case, it does not add operational cost. Multiple stations are necessary for fast recovery.
- Waiting point strategy. It is a robust approach, but it needs to be applied systematically while failure cases are rare. It is thus a penalty that can increase OPEX (e.g. increase station location duration).

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4 GENERAL CONCLUSION

This study provides clues on the operational concepts to conduct multi revolution solar-electric propulsion transfers for mission. Analysis of critical points of operational concepts was conducted for various levels of autonomy.

The substantial impact of the level of autonomy on the ground operation workload has been analysed within the following subjects: Tracking frequency, Orbit determination frequency, Guidance cycle duration.

The key critical points stemming from the use of low-thrust propulsion identified throughout the study are:

- The management of collision. As long as the board has not as high a knowledge of the space debris environment as the ground, there exist a dependency between the ground and board. This dependency imposes tracking and monitoring frequency whichever the guidance autonomy level.
- The uncertainty owing to thrust execution and navigation error, whether for tracking in low level of autonomy, or for mirroring on-board guidance for highest level of autonomy.

4.1 WAY FORWARD

The study addresses the operational concepts for EOR. Their implementatibility is discussed when relevant. In some case, autonomy can be dealt with dedicated hardware:

- We have seen in the case of GTO to GEO transfer, the needs to have an on-board GNSS receiver qualified above the GNSS altitudes. Few GEO satellites or concepts (LION navigator) consider on-board GNSS receiver.
- Thrust uncertainty problems could be dealt with close loop hardware on the thrust acceleration. Methods and tools to measure on-board the thrust performance, and adapt the thruster functioning point to ensure the nominal guidance profile execution would simplified greatly operations.
- Autonomous navigation: such systems have already been implemented for small-body missions.
- Debris conjunction: a fully autonomous system would require satellite to have a direct interface with a trusted and accurate conjunction message provider, not necessarily ground-based.

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