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Astrodynamics Tools for Assessment Studies in a Concurrent Engineering Environment

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Abstract

Since 1999, in-house ESA assessment and pre-phase A studies are performed within the ESTEC Concurrent Design Facility (CDF). The application of concurrent engineering principles allows reducing study duration from an average of about 6 months to 6 weeks. To achieve such a drastic decrease in the duration of a study while keeping quality of work unchanged, new ways of working had to be implemented.

This is particularly true for Mission Analysis tasks, which are effort intensive, especially for complex scientific missions. This paper describes how astrodynamics tools are prepared to accomplish Mission Analysis tasks in a concurrent engineering environment.

Mission Analysis tasks are divided in three classes:

1. tasks, which can be easily solved by simple astrodynamics tools
2. tasks, which can be solved by dedicated software packages
3. tasks, which require development of new software

Tasks of class 1 are directly solved and integrated into the CDF Mission Analysis Model. This is a Microsoft-Excel workbook, which interacts with the corresponding models of other satellite systems (propulsion, power, communication, etc.). Simple methods (two-body relations, rocket equation, J2 secular perturbation, etc.) are coded

- in the spreadsheet language, or
- in Visual Basic for Application (VBA), the background language of Excel, or
- in FORTRAN modules integrated in a Dynamic Link Library (DLL) called by a VBA code.

Results are obtained instantaneously and, during a CDF session, any input parameter modification leads to updated results in real time.

Tasks of class 2 are solved with existing stand-alone software packages, usually coded in FORTRAN, running on workstations. Obtained results are integrated into the Model in the form of tables for processing and display. For tasks of class 3 a

software development effort is required. It is therefore important to isolate such tasks before start of the CDF sessions and to prepare corresponding software in advance. This allows being in a task class 2 situation at start of the CDF sessions.

To illustrate the fact that there are all the time new Mission Analysis challenges resulting from new space missions, in particular the new scientific missions, a short description of Mission Analysis tasks to be considered for project XEUS, an X-ray telescope in space, is given.

1 Working Environment

Modern days working environment has usually the three following characteristics:

1. Collective work: many people are working together in a large noisy room and can easily interact between themselves. A team spirit is automatically achieved but there is little room for quiet thinking.
2. Computer assistance: an abundant computing power is made available to the worker. Computers are used for everything; they are netted together wirelessly so that any information is accessible any time at any place.
3. Multitasking: a modern worker is required to master multitasking such as reading material, performing a calculation, reading and writing e-mail messages, answering the telephone and conversing with a visitor practically simultaneously, and this in any environment such as an airport waiting room, in an airplane or also at home.

Multitasking seems to be attractive because children love to practise it: it is not unusual to see them playing a computer game and surfing the internet while they simultaneously listen to rock music with an MP3 player. If they are interrupted by a cellular phone call, they do not feel at all bothered. This faculty of the young people make them fully prepared to the modern way of working awaiting them during their adult life.

2 Concurrent Engineering

Concurrent Engineering is a way to perform studies in a well organised working environment making full use of the three characteristics of modern working environment: collective work, computer assistance and multitasking.

Collective work is achieved by collecting a set of experts in a large room, ready to brainstorm and solve problem in real time. Each expert - there is one expert per "System" such as Power, Structure, Communication, Cost or Risk Analysis - has in front of him a computer attached to a server possessing various software tools and communication channels. Everything, which can help performing the work, is easily available. In front

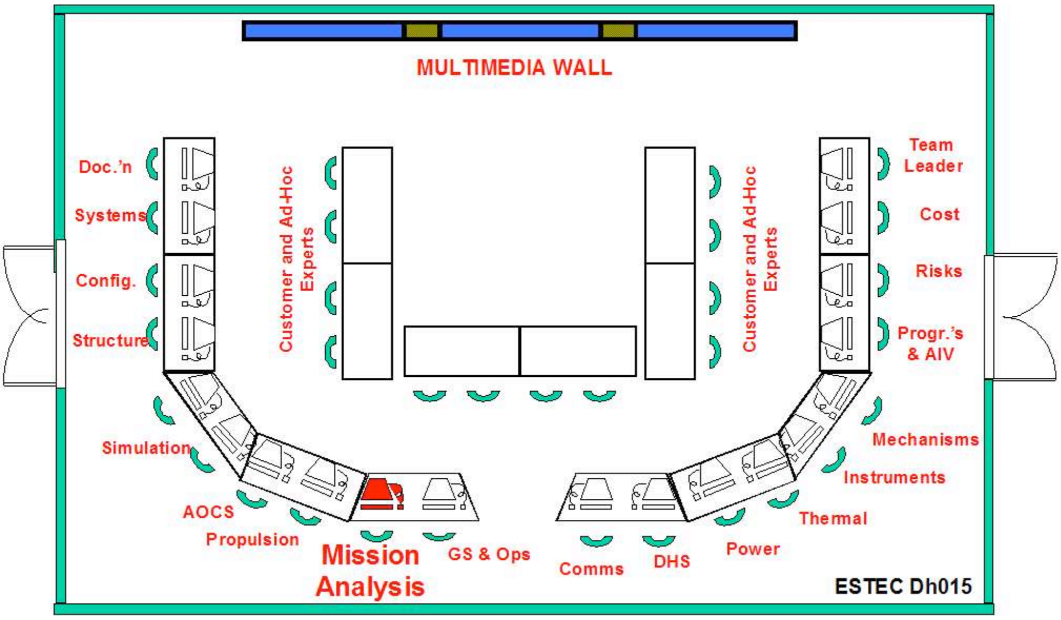

Figure 1.— ESA CDF arrangement at ESTEC.

of the experts a wall of screens allows showing presentations, documents, animations and video with off site participants located any place in the world. One of the screens is active and allows making drawings, which are stored as picture files. A Concurrent Engineering session is lead by a Team Leader. The "customer" for the study is also present in the middle of the room; he follows the sessions and intervenes when needed.

The experts follow the presentation and discussion, take notes, perform calculations, prepare a presentation and, if the topic discussed at the moment is of little interest to them, check their e-mail or work on something else. This is a true multitasking environment.

A study is performed along a certain number (typically 12) of 4-hour sessions, twice a week, and leads to a Final Presentation and a Final Report.

All documents are electronic and the main document is a set of spreadsheets - one per speciality - connected to a Data Exchange spreadsheet. This set of spreadsheets is the so-called Model representing all aspects of the object of the study, a space mission in our case.

Since 1999, ESA possesses such a Concurrent Design Facility (CDF) located at ESTEC. The CDF room arrangement is shown on Fig. 1 while a photographic snapshot of a session can be seen on Fig. 2.

Among other activities, the CDF allows efficiently performing Assessment Studies of space missions. Studies which used to take 6 months to be performed are now completed in six weeks. In some cases the output of such CDF studies has approached in some respects the output of the phase following an Assessment Study: the Phase A Study,

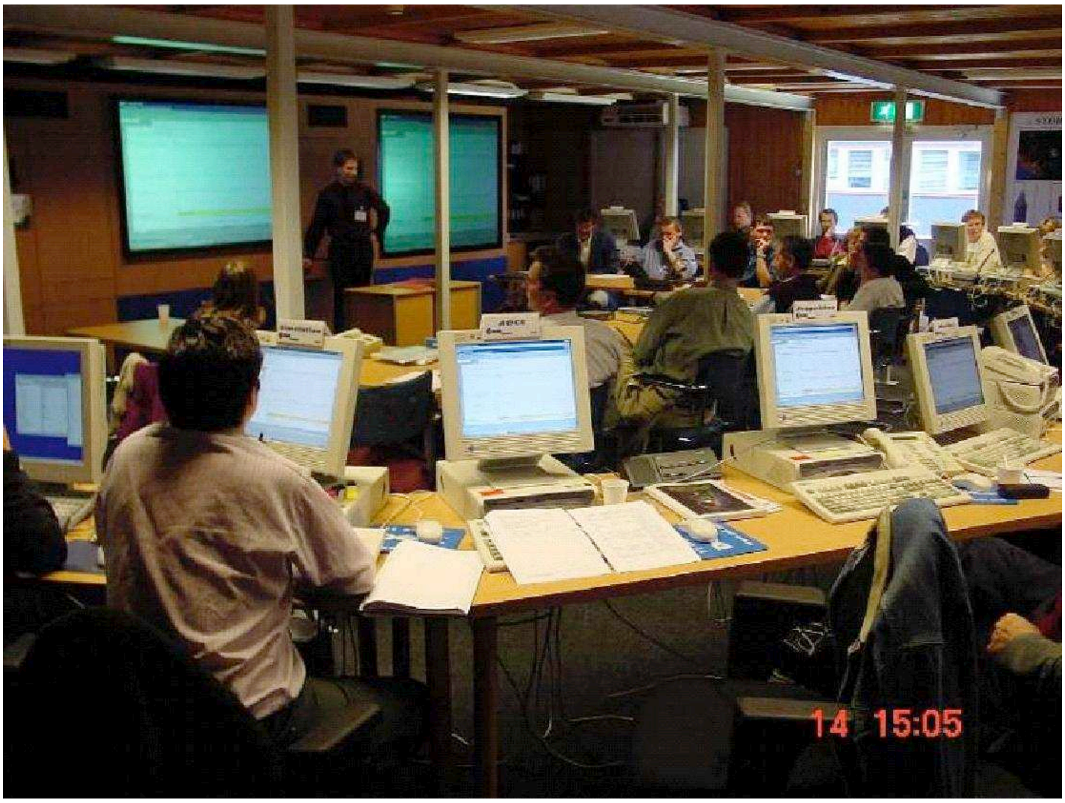

Figure 2.— Snapshot of a CDF session.

usually performed under contract by the industry.

The CDF software is presently based on Microsoft Office under Windows Operating System. The spreadsheets are Excel workbooks.

3 The Mission Analysis Workbook

Mission Analysis is one of the most important Systems in the CDF. Mission Analysis has a global aspect, as it interacts with most of the other Systems; in particular it provides data to other workbooks such as:

- Launcher's performance
- Velocity increments for orbit manoeuvres
- Eclipse and occultation profile
- Ground station coverage
- Trajectory parameters such as distance, velocities, angular values, etc.
- Mission timeline (list of events)

Such parameters have to be provided for all phases of the mission, such as

- Launch and Early Orbit Phase (LEOP)
- Operational Orbit acquisition
- Operational Phase
- End of Life operations

The parameters are obtained by performing astrodynamics calculations. This is done the following way.

4 Performing Calculations in the Mission Analysis Workbook

The Excel language allows performing spreadsheet functions. However, this language is rather cumbersome and insufficient for covering all mathematical operations. It can be used only for very simple calculations, such as applying elementary two-body relations.

Excel allows calling Visual Basic for Application (VBA) procedures. This is a far better language allowing real mathematical programming. Still, it does not offer all the commodities of a well developed high level language like FORTRAN or C. However, calculations such coordinate transformations and two-body + J2 relations can very well be programmed in VBA.

VBA allows calling high level language procedures if they are included in modules dynamically linked (DLL). This is the way to perform arbitrary complicated calculations, such as computing planetary ephemeris or ground station coverage.

Many parameters needed for designing a space mission are obtained by dedicated astrodynamics programs, not suitable to be incorporated into a spreadsheet. It is therefore more efficient to use the existing programs as such and to incorporate the obtained results into the Mission Analysis spreadsheet. Results are often output as tables, which can easily be imported in a spreadsheet. For graphical output, rather than using a standard graphic program, the graphical capabilities of Excel are used, allowing graphs to be contained in the spreadsheet and to be automatically updated when a new table is calculated.

However, the CDF environment imposes some constraints on the use of astrodynamics programs. This has resulted in dividing astrodynamics tools in three categories:

1. Fast tools allowing obtaining results in real time during a session. These are typically procedures programmed in Excel or VBA, calling possibly dynamically linked high level language modules, or external tools such as ORBIMAT and the Swingby Calculator. These external tools must have a well design Graphical User Interface (GUI) allowing an easy input/output of data. Such tools have to be used as such and do not allow any tailor making of input/output parameters or special calculation for particular purposes.

2. Tools allowing performing calculations between two sessions. Such tools may need some preparation and time to operate and are therefore not suitable to be used in real time during a session. However, no software development is required and a set of meaningful results can be obtained within a few hours at most. Examples of such tools are USOC, INTNAV and STK. These tools allow sometimes tailor making to some extend. In USOC for instance, output tables can be tailor- made and USOC library modules can be replaced by user developed modules.

3. Special application software. When no existing tool is able to perform the required calculation, a new piece of software is to be developed. The design, coding, testing and production cycle can usually not be performed within the short time available between sessions; therefore, this work has to be done before the start of the CDF sessions. This means that the requirement for the development of such software has to be known quite a while before the study start so that the mission analyst has time to develop and test the corresponding software. At start of the sessions, such software package should reach the level of a category 2 tool.

5 New Challenging Scientific Missions

Astrodynamics tools for space mission were developed since the sixties (and mostly coded in FORTRAN) and one could think that a large number of software packages are now available for taking care of all possible types of Mission Analysis calculations needed. Unfortunately, this is not the case; new missions are facing completely new problems, whose solution can only be obtained by developing new software packages.

New ESA scientific missions such as

- Coronograph in space (PROBA 3)
- Interferometry in space (Darwin)
- Very long focal telescope in space (XEUS)
- Detection of gravitational waves (LISA) are technologically very demanding. The corresponding spacecraft are located in exotic orbits such as
- halo or Lissajous orbits around one of the Earth-Sun libration point
- Earth trailing orbit

and they are usually not composed of one satellite but of several satellites flying in a precise formation. This means that the satellites, except one in the formation, are no more free flying but have to be constantly controlled.

As an example of the Mission Analysis challenge presented by the new ESA scientific missions, the case of XEUS is briefly shown now.

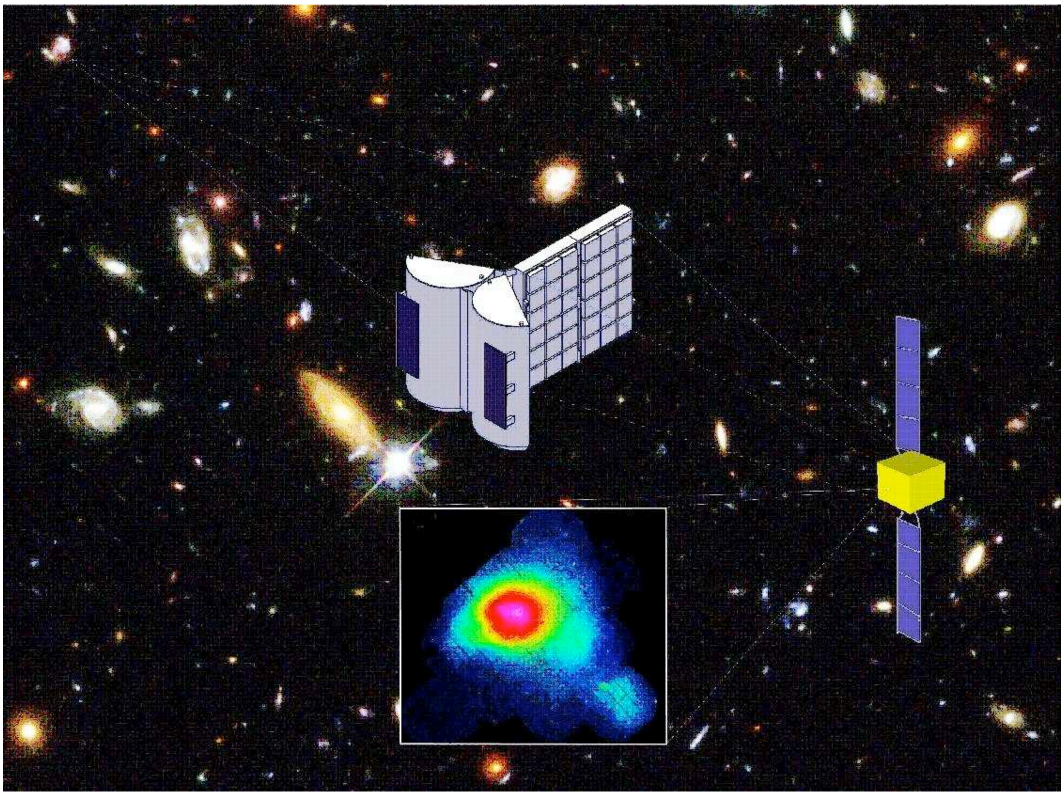

Figure 3.— The XEUS telescope in space: Mirror and Detector flying in formation.

6 The ESA XEUS Project

The XEUS (X-ray Evolving Universe Spectroscopy) project is an X-ray telescope in space, successor to XMM-Newton launched in December 1999. The satellite is composed of two parts: the Mirror and the Detector separated by a distance of 50-100 m. The two parts are therefore flying in formation (see Fig. 3).

Like the Hubble Space Telescope, this X-ray telescope was initially foreseen to be on a low Earth orbit in order to be serviced by the Space Shuttle. The orbital plane would have been selected close to the plane of the ISS orbit so that ISS astronauts could have performed maintenance and repair jobs.

Due the cancellation of Space Shuttle flights after 2010, the uncertainty of the future of the ISS and also the fact that a low Earth orbit is not ideal for astronomical observations, the idea of servicing the spacecraft was dropped and new target orbits for XEUS were contemplated. Indeed, on low Earth orbits high differential perturbations and high thermal stress on the spacecraft (due to passage in and out of eclipse every revolution) makes formation flight control difficult.

7 Selecting an Orbit for a Scientific Satellite

Selecting an orbit for a new project consists in

1. Looking at all possible terrestrial orbits and listing their characteristics (Table 5-1).
2. Qualifying (pro and contra) these orbits in terms of launch energy, ground station coverage, communication distance, eclipse profile, radiation and disturbance environment and orbit maintenance requirement. Table 5-2 summarizes such an analysis.
3. Assessing (good, OK or bad) their general properties (Table 5-3).

Based on such an analysis, the new orbit selected for XEUS is an Earth-Sun Libration Point Orbit (LPO) around L2.

Table 1.— Definition and characteristics of the various types of terrestrial orbits.

Abbreviation	Meaning	Definition and Characteristics
LEO	Low Earth Orbit	Nearly circular altitude below 2000 km
SSO	Sun Synchronous Orbit	Subclass of LEO: orbital plane rotates by 0.99727/day
REPEAT	Repeating ground trace Orbit	Repeats the ground coverage cycle
GTO	Geostationary Transfer Orbit	Ariane 5: 620x35786 km, i = 7, ω = 180
GEO	Geostationary Orbit Circular	h = 35786.4 km, i = 0
HEO	Highly Eccentric Orbit	Often high inclination and geosynchronous (12-, 16-, 18-, 24-, 36-, 48-, 72- or 96-h)
LPO	Libration (Lagrange) Point Orbit	Lissajous (small amplitude) or Halo (large amplitude)

8 XEUS on a Libration Point Orbit around L2

Numerous future space telescopes will be located on such LPO, in particular the James Webb Space Telescope, successor of the Hubble Space Telescope. Such orbits offer ideal conditions regarding to available observation directions (the two prohibited zones, toward the Sun and the Earth, are along the same direction) and offer a low gravitational field gradient, reducing the effort needed for formation flying control. In addition, there are orbits (halo orbits), which are never in eclipse.

The orbit selected for XEUS is a halo orbit around L2. Characteristics of such an orbit as well as the transfer from Earth are pictured on Fig. 4. The spacecraft composite will be launched as a whole by an Ariane 5 ECA launcher (estimated performance on LPO:

Table 2.— Pro and contra of the general classes of terrestrial orbits.

Orbit	Pro	Contra
LEO	Low launch energy Short communication distance	High disturbances (drag, potential, South Atlantic anomaly,) Frequent eclipses Short ground coverage periods ($\sim$ 8 mn/pas
SSO	Like LEO + Nearly-constant solar incidence on orbital plane No eclipse when $1382 < h < 3348$ km	Like LEO
REPEAT	Like LEO + Ground trace repeat after a number of days/orbits	Like LEO
GTO	Can be launched as an Ariane passenger for GEO commercial mission	Crosses low radiation belt at every revolutio Long eclipse periods (up to 2.2 h) Irregular coverage (between 0 and 10 h/rev.)
GEO	Complete coverage with one station with non-steerable dish	High injection requirement (1.5 km/s) Orbit maintenance (50 m/s per year) Orbit inside the radiation belt
HEO	Good and regular coverage (synchronicity) Eclipse reasonably short (launch window)	Orbit unstable (launch window) Large communication distance at apogee Orbit synchronicity maintenance (1 m/s per year)
LPO	Quiet environment No eclipse (Halo orbit) Constant distance from Earth and Sun	High launch energy requirement Orbit maintenance (0.2 m/s per year) Very large communication distance (up to 1.8 million km) Long transfer time (90-160 days)

Table 3.— Properties of the general classes of terrestrial orbits.

Parameter	LEO	GEO	HEO	LPO-Moon	LPO-Sun
Thermal environment	Bad	Bad	Bad	OK	Good
Radiation environmen	OK	Bad	Bad	Good	Good
Earth Occultation	Bad	OK	Bad	OK	Good
Eclipse	Bad	OK	Bad	OK	Good
Δ V injection	Good	Bad	Good	Good	Good
Δ V maintenance	Bad	Good	OK	Good	Good
Communication	Bad	Good	OK	OK	OK
Launch mass	Good	Bad	OK	OK	OK
Transfer duration	Good	Good	Good	OK	Bad
Operation load	Bad	Good	OK	OK	OK
Orbital lifetime	Bad	Good	Bad	Good	Good

6800 kg).

The requirement of being able to service the spacecraft was replaced with the requirement of having the possibility of replacing one of the parts of the system. If for instance the Detector spacecraft reveals to be defective or in need of a new component, a whole new Detector would be launched with a Soyuz launcher and flown in the vicinity of the Mirror. This resumes to performing a rendezvous with a spacecraft on a halo orbit. Is this possible? This is a new challenge in orbital mechanics.

9 Rendezvous with a Spacecraft on a Libration Point Orbit

The launch energy for bringing a spacecraft in the L2 region is sizably higher than for going to a low Earth orbit. In addition, a velocity increment is needed for insertion into the LPO. However, if the target orbit is a halo orbit and the insertion point is at the point on the orbit of maximum declination relative to the ecliptic, the insertion delta-V turns out to be vanishingly small. Outside this particular point, insertion delta-V requirement can be easily of several hundreds of m/s.

The orbital period on an Earth-Sun LPO is six months. Therefore, to perform a minimum insertion delta-V rendezvous with a spacecraft on a LPO is possible only twice per year. This is not compatible with the requirement of being able to replace the Detector any time when needed.

Is it possible to find other types of transfer to LPO leading to low insertion delta-V? This question is currently under study.

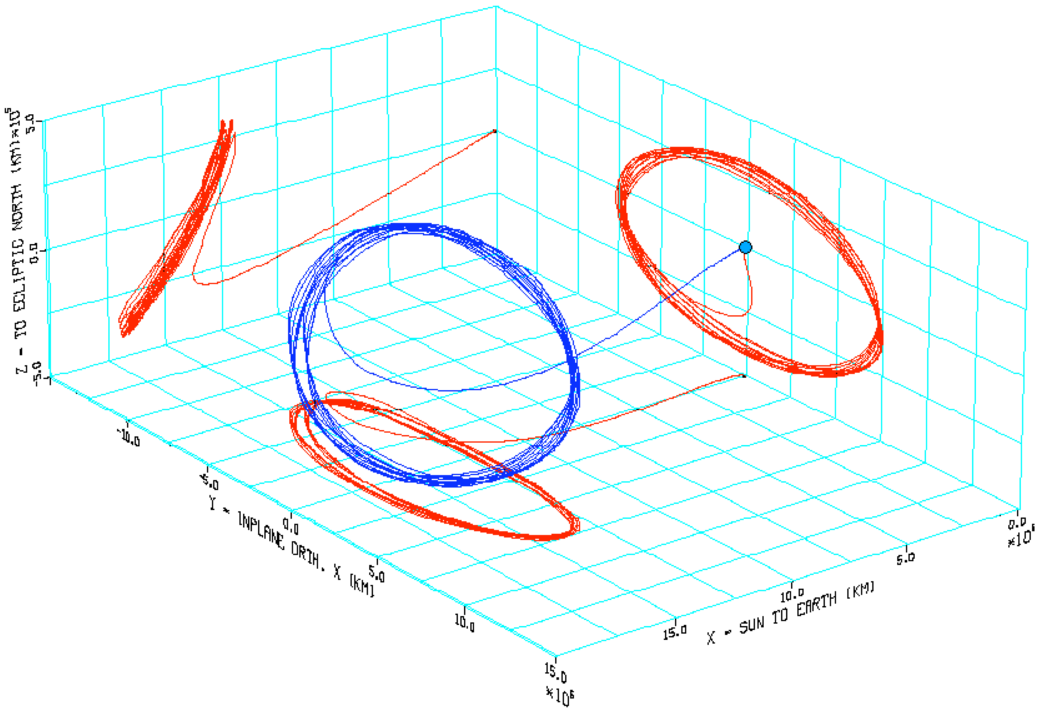

Figure 4.— The halo orbit around Sun-Earth L2 selected for XEUS.

10 Conclusion

Performing studies in a concurrent engineering environment require the Mission Analysis expert involved to have available

1. Simple astrodynamics tools directly usable in the Mission Analysis workbook for solving simple Mission Analysis problems such as calculation of Kepler orbits, possibly with J2 perturbation, coordinates transformation, calculation of angular parameters or rough estimation of launcher performance.
2. Easy to use astrodynamics tools for performing calculations in real time within a concurrent engineering session producing a tabular output, which can be copied into a worksheet. Example of such tools is ORBIMAT or the Swingby Calculator allowing calculating eclipse and coverage profiles or interplanetary transfers respectively.
3. Astrodynamics tools for performing more ambitious calculations between sessions. This should allow calculating launch windows, multiple body transfers, low-thrust transfers or reliable launcher performance.
4. Software, developed and tested prior to start of the sessions, for handling particular problems encountered in this study. Finally, one should add that, to be successful in his contribution, the expert should handle multitasking with ease.