FLIGHT DYNAMICS ANALYSIS AND OPERATIONAL SUPPORT FOR "CBERS"

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Abstract

Workstation based software package has been developed for Flight Dynamics analysis and spacecraft mission support for CBERS (China Brazil Earth Resources Satellite) mission. Flight dynamics analysis is the process of generating information related to the position and orientation of a spacecraft relative to a selected frame of reference, predicting mission critical events and monitoring on-board subsystems. Analysis consists of navigation and trajectory analysis, attitude analysis along with the acquisition and processing of data. In the past this activity was performed through groups of tasks and analysts acting in parallel on several types of computer platforms, which led to many operational difficulties. In this context an integrated approach along with visual interfaces to provide quick and near real time decision oriented flight dynamics software system is designed. The impetus of such design is initiated to meet the mission requirements of CBERS. Many mission analysis and post-flight performance of various subsystems can be represented through visual aids. One of the prominent and significant activities has been implemented for orbit maintenance of CBERS. Definitive orbit parameters are computed every day and are stacked in the history database along with necessary orbit parameters. The ground track shift with reference to nominal longitude and the deviations observed along with correlation of solar activity is represented through visual representation. This paper focuses the flight dynamics software system overview, process and details along with brief mathematical details of its components. Further the paper outlines the envisaged visual tools provided for operational ease and convenience, and an assessment of maneuver performance in real time through attitude monitoring and orbit event history. The software system acts as a convenient tool for post-flight analysis of orbit behavior and orbit control, on-board performance verification of some of the subsystems and attitude sensor monitoring. Details and capabilities of flight dynamics support system for CBERS is presented.

Key words: CBERS, Flight Dynamics Software, Visual Interface for Flight Dynamics.

Introduction

CBERS mission is an operational remote sensing mission, which demands high accuracy from the orbit determination and control. A substantial effort is being made to standardize and evaluate the flight dynamics software system to meet the mission specification. The implementation of the flight dynamics software system has commenced and shall be made available in its fully operational basic configuration during the initial in-orbit phase of CBERS. The flight dynamics software system, as it is now, has been supporting hitherto SCD satellite series. On the other hand, orbit maintenance and mission specific software elements have been developed in the new environment. The intended integrated software system with an approach towards object orientation and visual aids shall support the launch and early orbit phases of the mission and later cluster formation. The impetus of the shift in the paradigm of flight dynamics software has originated with the beginning of the operational satellite era and as a response to an effort to reduce the life cycle cost for existing and future spacecraft missions. It is also directed to reduce the number of man-hours for ground support and analysis. The planned design of integrated collection of the software packages for spacecraft flight dynamics analysis and mission support thus provide an interactive tool which can aid also post-flight analysis. One of the main tasks of the subsystem is to provide the predictions of the satellite positions. The spacecraft mission analysis software has analysis capabilities of orbit determination, orbit prediction and orbital event calculations along with attitude determination, on board subsystem performance verification and attitude sensor monitoring. In addition, the system accesses raw tracking data from one or more tracking stations in standard format protocol. The system has facilities for attitude data preprocessing and telemetry file accessing. Maneuver computation and performance evaluation has been provided with some of the graphic interfaces as a beginning for the flight dynamics integrated system. Till now the flight dynamics software system operations are being carried out on mainframe computers, which were shared with other disciplines. The extensive use of graphics and modern window-based man-machine interface is employed in order to increase the visual aids and reduce analysis time. This paper addresses the concept of the evolution of flight dynamics software system and establishes an approach towards object orientation.

Satellite orbit

CBERS is a remote sensing mission equipped to observe the Earth through various payloads. It is to be placed in a sun-synchronous near circular orbit to observe as much as possible the Earth's surface. For precise orbit computation and orbit control a higher orbit is desirable. On the other hand, a lower orbit is preferred for better ground resolution. However, in lower orbit the atmospheric drag makes precise orbit determination and ground track maintenance a crucial task and, in addition, orbit is prone to have rapid decay in presence of high solar activity. Trade-off studies were carried out in order to select the orbital radius and, as a consequence, an almost constant altitude of 780 km was selected as the optimal combination. Table 1 shows the characteristics of the selected CBERS orbit.

Table 1: Orbit characteristics of CBERS

Semi-major axis	a	7148 km	Sun-synchronous
Eccentricity	e	0.0011	Frozen eccentricity
Inclination	i	98.504°	Sun-synchronous
Equator crossing	H	10:30 h	Descending node
Perigee argument	ω	90°	Frozen perigee
Orbital period	$\boldsymbol{N}$	14 9/26	Orbits per day

At this altitude satellite moves at a velocity of around 7.6 km/s and completes 14 9/26 revolutions per day. An important aspect of CBERS orbit is that it is a repeat orbit which means that at regular intervals of exactly 26 days it shall fly over the same ground track. The true ground track will present a deviation from the reference ground track because of perturbations. The mission specifications envisage the ground track to be controlled within the specified limits as per Table 2.

Table 2: Orbit maintenance requirements

Equator crossing deviation	H	± 10 min
Ground track deviation	δ	± 10 km
Frozen perigee deviation	$\delta\omega$	± 10°

This is achieved by occasionally executing maintenance maneuvers, as described elsewhere[1]. It is also intended to maintain cluster of satellites in the future. This imposes additional orbit maneuver constraints to maintain the satellites. One should pursue the reduction of the combined repetitive cycle and maintain adequate phasing with proper orbit control maneuvers.

Flight dynamics software

Flight Dynamics analysis is the process of generating information related to the position and orientation of the spacecraft apart from predicting and generating mission critical events and monitoring on-board subsystems. When these analysis are executed in near time schedule it is referred to as mission support. Flight Dynamics analysis can be divided into four major categories: data acquisition and preprocessing, trajectory and navigation analysis, attitude analysis, and results re-formatting and delivery. Data acquisition and preprocessing deals with obtaining spacecraft data to formats compatible with analysis software. Trajectory and navigation analysis comprises orbit determination, orbit prediction and mission event prediction. Attitude analysis consists of attitude determination, onboard computer subsystem performance and verification, attitude sensor monitoring. The results are then reformatted and finally post-flight analysis follows. One of the main tasks of orbit determination is to provide the predictions of the satellite positions for the required time span. The ground stations need this information to be able to track the satellite within the accuracy limits, as given in Table 3, for operational orbit determination and predictions for CBERS.

Table 3: CBERS orbit determination specification errors

Error source	Determination error (m)	Prediction error (m) after 48 hours
Radial	25	30
Cross track	15	15
Along track	60	900

During the Launch and Early Orbit phase (LEOP) of CBERS, it is intended to have tracking support from 6 ground stations world widely separated. During orbit maintenance phase Cuiabá and Alcantara stations equipped with S-band tracking, TM and TC equipment, shall provide tracking data for orbit determination and control of spacecraft. The Flight Dynamics system operates off-line starting from satellite ranging and receiving telemetry data (consisting of attitude sensor data) at the control center, through mission history files. The orbit determination is performed every day using 48 hours of tracking data on sliding basis.

The current flight dynamics software[2] implemented to control the SCD series of satellites, as shows the schematic drawing of the system in Fig. 1, presents the following characteristics:

- Main frame based (Alpha-Digital server, Open-VMS)
- Fortran 77 coding
- Non user-friendly interfaces
- Restricted use of graphics
- Task oriented (one program for each task)
- Support for SCD1 and SCD2 missions
- Medium maintenance costs (software)
- Support to several ground stations

The contrast can be seen in the following envisaged Flight Dynamics system for CBERS in Fig. 2, as well as a list of desirable software requirements for CBERS:

- IBM-PC based
- Fortran 77 coding (numerical calculations)
- User-friendly interfaces (Visual Basic shell)
- Intensive use of graphics
- Object oriented (visual shell)
- Support for CBERS and cluster missions
- Reduced software maintenance costs
- Integrated platform (visual shell and orbit computations)

Orbit determination

Here the main computational tasks of the orbit determination subsystem are introduced in the order in which they are performed:

Tracking data retrieval: The tracking data from network stations are logged-on to the mission computer in the recall mode at the satellite control center. The orbit determination subsystem runs on a different mainframe computer and a dedicated task transfer the data between these computers. The program is used to retrieve automatically the data, which was transferred to the mission history files.

Tracking Data preprocessing: The data files are reformatted and as necessary the compression and certain standard corrections are applied. It also applies piece-wise polynomial fits to edit wild points. The software selects the processing of only the most recent data.

Orbit Determination: The central task in the subsystem is the precise orbit determination. The component uses a batch least squares algorithm to estimate the spacecraft orbit based on tracking measurements. The subsystem has an access for full geo-potential model, a ground station database, more accurate aerodynamic coefficients, and optimal control parameters. The orbit determination is processed once every day, whereas the tracking data preprocessing is executed more frequently to have a quick assessment of the quality of the incoming tracking data. The definitive orbital parameters are used for subsequent prediction.

Product generation: Once the orbit ephemeris file is generated, specific products containing flight dynamics information is needed for subsystems, external users, and payload processing. Some of the significant events are summarized below:

- Station predictions: files necessary for use in the ground stations, containing the visibility and target designation information as a function of time.
- Event files: orbital events such as eclipse conditions, ascending and descending node epochs, longitudes and times at equatorial crossings, etc.
- Scheduling files: orbit information data for planning and scheduling of mission operations.
- Orbit files: orbit, attitude and scene information file needed for generating data products. These tasks are intended to be invoked automatically through software to schedule the processing of software components sequentially.

Attitude determination

The attitude determination process comprises attitude sensor preprocessing, preliminary attitude determination and fine attitude determination. Attitude determination is the process of estimating the relationship between vectors measured in spacecraft fixed coordinate system as well as in a reference coordinate system. A measurement vector is the position of a known object quantity, such as Sun, as seen in a spacecraft coordinate system by an on-board sensor. Reference vectors are generated in the inertial coordinate frame for each measurement vector. These reference vectors are computed using environmental models, such as planetary ephemeris for the position of Sun and Earth and inertial geomagnetic reference field model for earth's magnetic field. The model includes algorithms for digital sun sensor data processing. For the CBERS case it is desired to have a special task of real time attitude monitoring, whose main objectives are:

- Monitor AOCS sensor telemetry
- Check the AOCS performance based on the post-flight on-ground attitude determination
- Detect eventual AOCS anomalies

Onboard subsystem performance verification

Onboard performance verification can include monitoring of the real time attitude parameters and control law performance. This is of great relevance when a maneuver is executed. To this end a Kalman filter processes the telemetry data flow in real time to yield the attitude estimates. Visually the results are shown and compared against the nominal expected attitude angles. Main telemetry information consists of data from gyros, Earth and sun sensors, orbit and attitude control thrusters activity, etc.

Orbit maintenance and ground track control

Since it is required that the CBERS ground track stay within ±10 km of the mean ground track, an accurate prediction of the ground track is required. The actual spacing ($\Delta\lambda$) between two successive descending nodes can be determined by:

$$\Delta\lambda_{\boldsymbol{A}} = \boldsymbol{P_A}\,(\dot{\theta} - \dot{\Omega}) \qquad (1)$$

where $\boldsymbol{P}_A$ is the actual nodal period, and $\dot{\theta}$ and $\dot{\Omega}$ are the Earth's rotation and nodal precession rate respectively. Because of drag and variation in orbital inclination due to lunar-solar gravity, $\boldsymbol{P}_A$ will change. Furthermore, $\dot{\Omega}$ also will change with varying inclination. Both effects must be accounted for in computing ground track deviation. Assuming that the drag and inclination variations are linear over each orbit, the nodal period after "*j*" orbits is

$$\boldsymbol{P_{Aj}} = \boldsymbol{P_{Aj-1}} + \delta\boldsymbol{P_{Dj}} + \left(\frac{\partial \boldsymbol{P}}{\partial \boldsymbol{i}}\right)\Delta\boldsymbol{i}_{\boldsymbol{j}} \qquad (2)$$

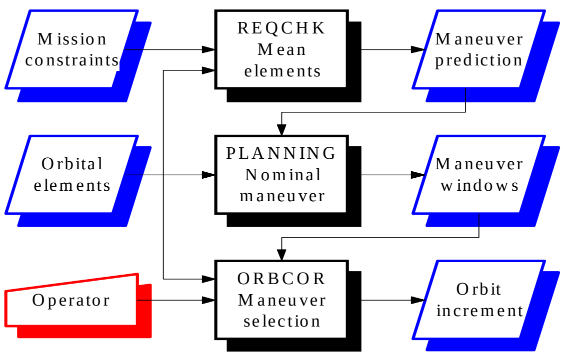
where $\boldsymbol{P}_{A\,j-1}$ is the nodal period in (*j-1*)-th orbit, $\delta\boldsymbol{P}_{Dj}$ is the nodal period change due to drag in the *j*-th orbit., Δi_j is the inclination change in the *j*-th orbit and[3]:

$$\left(\frac{\partial \boldsymbol{P}}{\partial \boldsymbol{i}}\right) = \left(\frac{2\pi}{\boldsymbol{n}}\right)\left[-12\,J_2\left(\frac{\boldsymbol{R_e}}{\boldsymbol{a}}\right)^2 \cos \boldsymbol{i}\,\sin \boldsymbol{i}\right] \qquad (3)$$

Once assumed that the variations are linear over the orbital period, the actual nodal period is computed. The change in node rate in combination with direct perturbation to Ω is computed, plus an indirect perturbation due to inclination variation. The indirect effect is dominated by the secular rate due to J_2. It is necessary to have precise computation of drop in semi-major axis due to drag. Accurate computation of density and generation of node and inclination histories over a length of period and the variation of ground track are essential. The precise ground track maintenance is carried out by using the (in-development) orbit maintenance software[1]. For that purpose the following new modules are envisaged [4]:

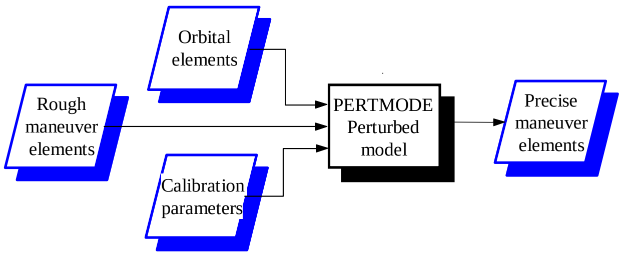
- Maneuver prediction and planning
- Maneuver optimization
- Maneuver evaluation

The schematic flow of the Maneuver prediction and planning software is shown below.

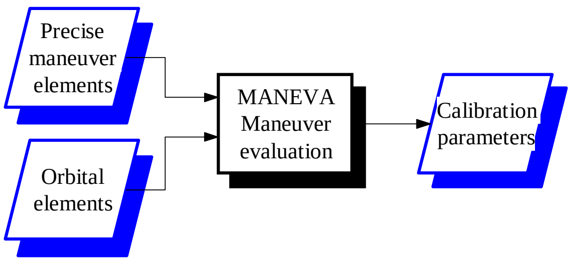


The module REQCHK checks future violations in mission requirements. To that end it uses analytical models and the given mission requirements. The module PLANNING performs nominal maneuver calculation, taking into account OD errors and uncertainty in $F_{10.7}$. The module ORBCOR selects the best maneuver windows as per operations requirements given the satellite position in the orbit.

The module MANOPT (maneuver optimization), as shown below, optimizes the predicted maneuver taking into account a perturbed orbit model, solution of a TPBVP using optimization models, and maneuver duration, thrust direction, misalignments and efficiency.



The module MANEVA (maneuver evaluation) shown below, compares the expected maneuver performance with the post-maneuver OD data, and estimates the thrust efficiency, misalignment and fuel consumption.



Finally, the integrated ground track maintenance and control system is depicted in Fig. 3.

Software architecture

The revolutionary changes in the hardware architecture are paralleled by changes of the similar significance in the software domain. The concept of the object orientation has become a powerful tool for cost effective software maintenance. It is intended to have advanced system functions coupled with object oriented analysis for the flight dynamics system in future missions. Any flight dynamics analyst with minimum learning effort can use the system functions. Secondly the de-coupling between support and application functions have increased the overall robustness of the system. It is for instance possible to code and test software and later on add graphical user interface (GUI) by fully non-intrusive mechanism. The option to process the software without graphic interface still remains the same. The libraries are maintained by means of shell and can be reusable within and between the projects, whereas facilities are self-contained programs or program packages for multi-project reutilization. Shells are suitable for implementation of software in recurrent terms concerning the overall task structure and interfaces, but with project specific algorithms. The introduction of shells aims at a higher degree of separation between mathematical and data processing function. This shall have a great deal of flexibility and the system will have significant exposure to operations.

The flight dynamics software was developed incorporating the precise trajectory generation based on Cowell's method and state of art force modeling needed for orbit keeping purposes. The system is now made flexible to be operated on many platforms like mainframe, workstation and Pentium-CPU systems. Efforts are underway to develop the system compatible for Graphical User Interface (GUI).

Mission planning phase

The flight dynamics software comprises the mission planning software, as one of its component. During the planning phase some of the activities which are initiated for planning purposes also sometimes serve as a most useful tool during in-orbit operations. One of the software elements being the world-referencing scheme designed to have the path and row pattern based on the nominal orbit. This serves as a reference grid during in-orbit operations. During initial phase of the mission, mission planning builds the payload operations for both in-orbit spacecraft characterization and data collection. The characterization identifies any pointing errors and jitter due to spacecraft motion, vibration and sensor alignment. The challenges to mission planning to provide such a wide variety of experiments, some within the window of opportunities, were solved largely by software tools developed in house.

Planning Software: Such software provides a set of tools to handle the large and varied applications and requirements. Visual Basic© was used to build the tools that generate orbital events. Visual basic© was chosen due to its capability to display a user-friendly graphic interface and broad interconnectivity. The orbit design and determination software was coded in compiled

Fortran, as it required more speed and memory than was available on a personal computer.

Data base organization: The operational convenience and standardization prompted to use conventional file conventions for the database organization based on the satellite dependent data base and independent data base viz. station coordinates, biases of the measurements, geophysical coefficients, etc. The other parameters are maneuver parameters, fuel availability, pressure bar, etc. It is intended to use Visual basic© to retrieve the information of the dynamic parameters, to create one page report complying with subsystem name, day of the year and time of execution of maneuver impulse time, estimated Δv for orbit correction, optimal firing angle and station visibility statistics, and spacecraft position and orientation at the time of impulse, along with many other parameters using history data base information coupled with orbit files.

Future developments

The integrated software approach for flight dynamics in the object-oriented design is a desirable option for the future mission. It is aimed at designing the software under the window-based environment or user-friendly environment with graphically oriented interface, the interface acting as a front end. The data processing function can be performed under the menu driven environment. The view menu invokes all graphical user interfaces. The cluster concept and orbit phasing, and orbit maintenance along with ground track drift monitoring, would be possible to be analyzed through visual aids.

Concluding remarks

Flight dynamics software system at INPE hitherto supported SCD series of satellites. With the beginning of the operational CBERS remote sensing mission, the accuracy requirements became stringent. The ground track has to be controlled in small dead band limits and this necessity prompted to make a conceptually new software design change. Orbit maintenance software was developed in the new environment. It is intended to have gradual change in the existing flight dynamics system to make it more user-friendly and with a thrust towards object oriented approach. Towards this a beginning of window based environment is designed and graphical user interfaces are being built. The existing software is augmented with Visual basic© shell to have visual aids for mission operation and to conduct post flight analysis.

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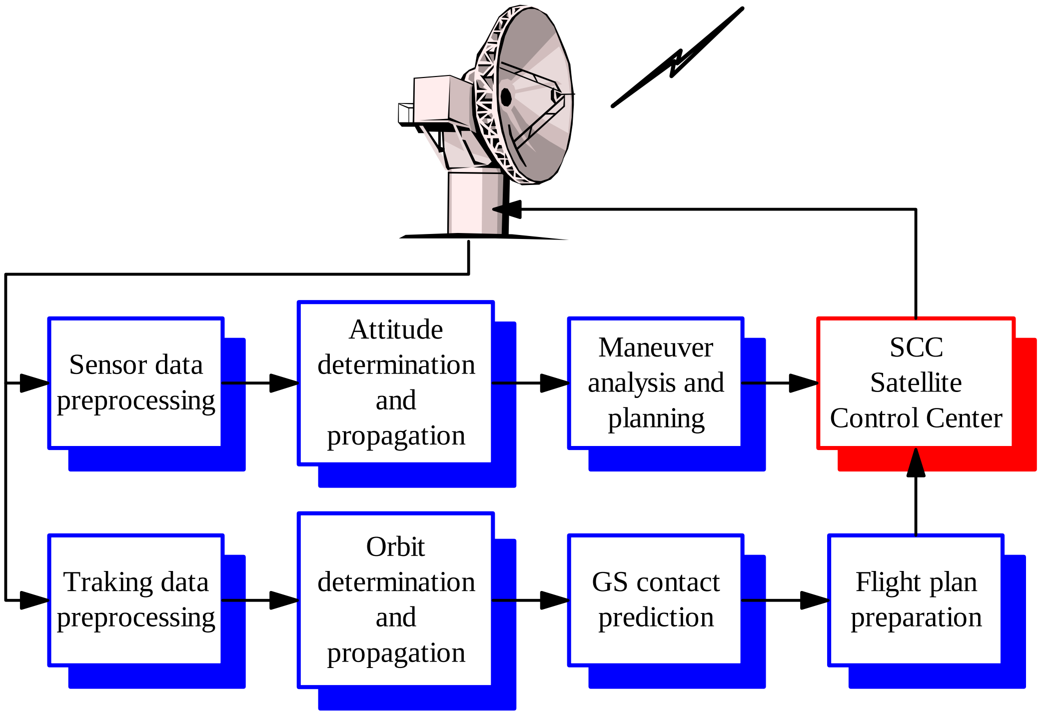

Figure 1: Flight dynamics system for SCD series

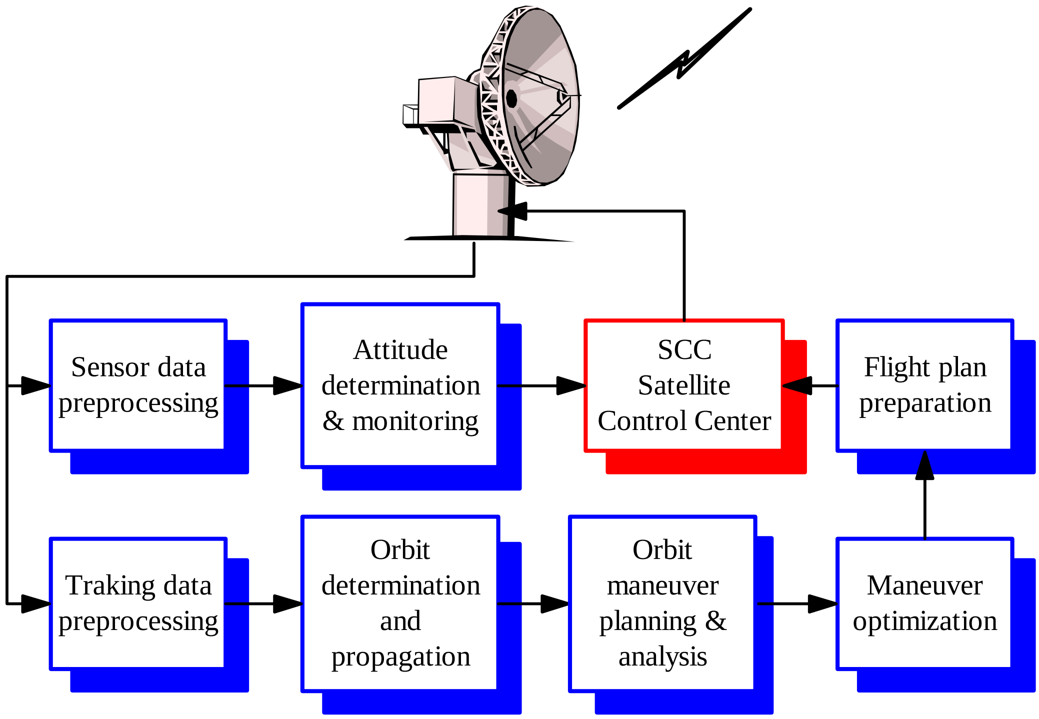

Figure 2: Envisaged Flight Dynamics system for CBERS

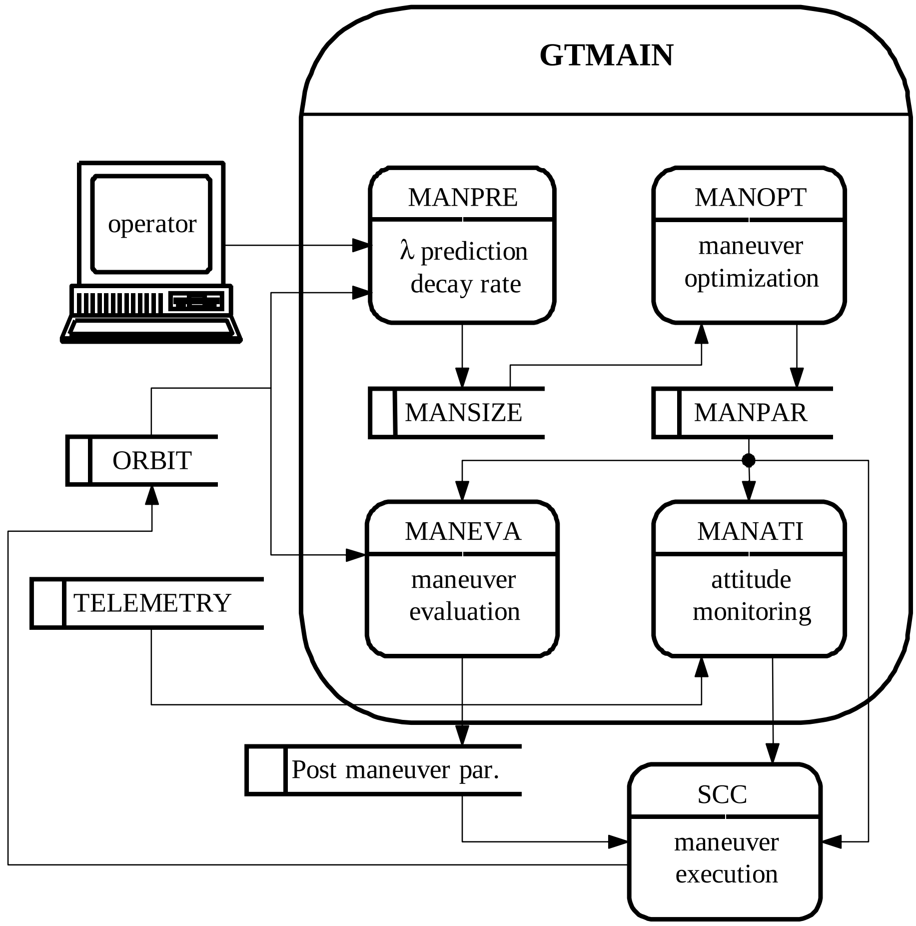

Figure 3: Schematic design of ground track maintenance and control for CBERS