SPACECRAFT FLIGHT DYNAMICS SUPPORT AT ESOC

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ABSTRACT

ESOC has been involved in preparing and supporting the operations of 17 spacecraft since 1967/68. The missions are characterised by various types of orbits, of attitude stabilisation and control, and of on-board and ground measurement instruments. Orbit and attitude state estimation and control are the primary tasks of operational flight dynamics support. This is based on dynamics and space environment modelling, mathematical tools and computer software facilities. The variety of tasks for the flight dynamics specialists includes presently the preparation for interplanetary flights and for the support of more complex spacecraft with increasing on-board processing autonomy.

Keywords : Flight Dynamics, Orbit, Attitude, Stabilization, Estimation, Optimisation, Modelling

1. INTRODUCTION

The purpose of this paper is to present the way flight dynamics support is realised at ESOC. This is done by firstly reviewing the spacecraft missions that have been supported; secondly by an outline of the specific characteristics of the related mathematical tools, the relevant space environment and of the spacecraft and ground system hardware components. Furthermore the computer software implemented is described emphasizing on multisatellite and system aspects and on quality control. Finally the totality of the flight dynamics support tasks is shown stressing the involvement of experienced specialists and identifying the requirements of the present and the future.

2. FLIGHT DYNAMICS CHARACTERISTICS OF THE PAST SPACECRAFT MISSIONS AND THOSE IN PREPARATION

Table 1 contains the characteristics of all spacecraft missions ESOC has been involved in. Five of them are not purely ESA originated :
ANS, the "Astronomical Netherlands Satellite" used ESOC as control centre with only a limited direct support;
ISEE-B is part of a NASA-ESA project in which the flight dynamics support is shared between GSFC and ESOC;
IUE is operated at Villafranca (Spain) for 8 hours per day utilising NASA software (only a few flight dynamics areas are covered by ESOC);
GOES was taken over from NOAA-NESS for one year of full support as part of the global weather experiment (GARP); and
FIREWHEEL was built by MPE (Max-Planck-Institut für Extraterrestrische Physik) but could not be supported due to the launcher failure (ARIANE L02).

Table 1 : List of Spacecraft supported

Name	Launch Date	Re-entry Date	End of useful mission	Mission Objectives	Comments
ESRO II	May 68	May 71		Cosmic rays, solar X-rays	First launch in 1967 failed
ESRO IA	Oct. 68	June 70		Auroral and polar cap phenomena, ionosphere	
HEOS I	Dec. 68	Oct. 75		Interplanetary medium, bow shock	
ESRO IB	Oct. 69	Nov. 69		as ESRO IA	Early reentry (rocket under performance)
HEOS II	Jan. 72	Aug. 75		Polar magnetosphere, interplanetary medium	
TD 1A	Mar. 72	Jan. 80	May 74	Astronomy (UV, X - and γ-rays)	
ESRO IV	Nov. 72	April 74		Neutralatmosphere, ionosphere, auroral particles	
ANS (NL)	Aug. 74	June 77	July 76	Astronomy (UV, x-rays)	
COS-B	Aug. 75	Jan. 86		Gamma-ray astronomy	
GEOS-1	April 77	Dec. 99+	July 78	Dynamics of Magnetosphere	Rescued from too low transfer orbit
ISEE-B	Oct. 77			Bow shock, magnetopause, neutral sheet	Rendez-vous with ISEE-A
METEOSAT	Nov. 77		(Nov.79)	Meteorology, earth images	Imaging failed after 2 years
IUE	Jan. 78			Astronomical Observatory (UV)	
OTS-2	May 78			Communications Test Satellite	First launch in 1977 failed
GEOS-2	July 78			as GEOS-1	
GOES-1 (US)	(Nov. 78)		(Dec.79)	Earth images	
FIRE-WHEEL	May 80			Magnetosphere, (Ba-, Li-Clouds)	ARIANE L02 failure

Five of these missions were affected by launcher failures : The first launch of ESRO II in 1967 failed due to malfunction of a SCOUT vehicle. ESRO IB re-entered 1 month after launch based on the underperformance of another SCOUT. GEOS-1 could not reach the planned geostationary orbit, separation of the Thor-Delta third stage from the spacecraft before firing caused a low "transfer orbit". OTS-1 fell into the ocean together with the Thord-Delta that had to be destroyed a few seconds after lift-off. And FIREWHEEL never reached an orbital position due to the explosion of ARIANE during the second test flight.

At present support for six orbiting spacecraft is given by ESOC, viz. COS-B, ISEE-B, METEOSAT, IUE, OTS-2, and GEOS-2. Preparations are continuing for the successors of the OTS project, i.e. MARECS and ECS, for a second flight of METEOSAT, the double launch of SIRIO-2 with MARECS-B, and for EXOSAT. All of these projects are planned to be launched by ARIANE within the next two years. Their characteristics are shown in Table 2.

Flight dynamics characteristics of a spacecraft mission are related to its orbit, to the mode of attitude stabilisation (rigid and flexible body) and to the control of orbital and attitude state. When classifying the missions from Tables 1 and 2 according to these characteristics one finds various types that can be distinguished. The Flight Dynamics support on ground is tightly related to these types and to a certain extent classifyable in an analogous way : The following three tables con-

Table 2 : List of Spacecraft to be launched

Name	Planned Launch Date	Mission Objectives	Comments
METEOSAT-2	June 81	Successor of METEOSAT	Identical Spacecraft
MARECS-A	Oct. 81	Maritime Communications Satellite	Spacecraft based on ECS platform
MARECS-B	Feb. 82	Maritime Communications Satellite	Spacecraft based on ECS platform
SIRIO-2	Feb. 82	Experimental Communications and Laser Station Synchronization Satellite	Launched together with MARECS-B
ECS-1	Apr. 82	European Communications Satellite	
EXOSAT	June 82	X-ray observatory	
ECS-2	May 83	European Communications Satellite	

Table 3 : Orbital Characteristics

Type of orbit	Perigee and Apogee ranges (km)	Inclination ranges	Spacecraft
Close earth	240 - 530 383 - 1530	polar sun-synchronous	ESRO II, ESRO IA, ESRO IB, ESRO IV TD-1A, ANS
Highly eccentric	180 - 35000 35000 - 240000	$26^{\circ} - 98^{\circ}$	HEOS I, HEOS II, COS-B, GEOS-1, ISEE-B, FIREWHEEL, EXOSAT
Geostationary Transfer	180 - 200 36000	$10^{\circ} - 28^{\circ}$	GEOS-1 (non-nominal) METEOSAT, OTS-2, GEOS-2, FIREWHEEL, METEOSAT-2, MARECS-A,B, SIRIO-2, ECS-1, 2
Geostationary (geosynchronous)	26000 - 36000 36000 - 45000	$\pm 28^{\circ}$	METEOSAT, IUE, OTS-2, GEOS-2 GOES-1, METEOSAT-2, MARECS-A, B, SIRIO-2, ECS-1, 2

Table 4 : Attitude Stabilization Characteristics

Type	Stabilization		Spacecraft
Passive	Geomagnetic Field : Hysteresis of permanent magnet (one axis)		ESRO IA, ESRO IB
	Spinning	rigid body	ESRO II, HEOS I, HEOS II, ESRO IV, COS-B, GOES-1, FIREWHEEL, SIRIO-2; OTS, MARECS and ECS in their transfer and drift orbit phases
		rigid body with movable parts	METEOSAT, METEOSAT-2
		rigid body with flexible parts (wire booms)	GEOS-1, ISEE-B GEOS-2
Active (3-axes stabilised)	Sun pointing, roll control with earth horizon detection (gyros and wheels)		TD-1A, ANS
	Earth pointing, (geostationary, one axis north) (wheels)		OTS-2, MARECS, ECS
	Arbitrary pointing (wheels, thruster limit cycling)		IUE, EXOSAT

Table 5 : Control Characteristics

Stabilisation	Type	Mode	Spacecraft
Spinning	Attitude	Magnetorquer	ESRO II, ESRO IV
		Thrusters (pulsed mode, continuous and pulsed for spin rate manoeuvres)	HEOS I, HEOS II, COS-B, GEOS-1, ISEE-B, METEOSAT, OTS-2, GEOS-2, GOES-1, METEOSAT-2, MARECS, SIRIO-2, ECS
	Orbit	Solid fuel motor	GEOS-1, METEOSAT, OTS-2, GEOS-2, FIREWHEEL, METEOSAT-2, MARECS, SIRIO-2, ECS
		Thrusters (continuous and pulsed mode)	GEOS-1, ISEE-B, METEOSAT, OTS-2, GEOS-2, GOES-1, METEOSAT-2, MARECS, SIRIO-2, ECS
3-axes stabilised	Attitude	Wheels	IUE
		Thrusters and gyroscopes	EXOSAT
	Orbit	Thrusters (continuous mode)	OTS-2, MARECS, ECS, EXOSAT

tain an overview about these types. No mention is made at this point of the ground and on-board hardware components which are part of the overall system. They will be treated in the following section.

3. THE MATHEMATICAL TOOLS

The operational flight dynamics support is based on a variety of mathematical tools that are employed for the solution of the characterised problems. Apart from the primary tasks - orbit and attitude state estimation and control - mathematical tools are needed for the modelling of the dynamics, the modelling of the space environment, and the modelling of sensing and controlling devices. This section contains an overview of the most frequently used tools as they are available at present.

For fully passive spacecraft (ESRO IA and IB are examples), estimation of the orbit and attitude state is the only and most important flight dynamics task. For more advanced spacecraft with attitude and orbit control (they may be called active spacecraft), estimation delivers the necessary information for mission planning (optimization) and manoeuvre preparation.

Table 6 contains estimation methods and their applications as being used, described in a global way without detailing the availability of different versions and the mode of operations.

As soon as spacecraft had to be supported for which the change of either attitude or orbit state played a role (this may be viewing requirements of experiments, orbital state keeping and orbital injection procedures), optimization methods had to be employed. They are used for minimization of fuel or time under given constraints for the reaching of a desired target. Table 7 contains information on the most commonly used optimization methods.

For both estimation and optimization the modelling of the underlying orbital and attitude dynamics is needed. This is also true for the actual preparation of the state change manoeuvres which may result from an optimization process (telecommand generation). Tightly related to the dynamics is the modelling of the space environment as far as it is generating, influencing and disturbing the spacecraft movement. Other elements of the space environment are used as references for sensing (and even controlling) mechanisms but as well have to be taken into account as unwanted disturbance factors. Table 8 and 9 contain information about the items mentioned, while table 10 gives an overview of all sensing and controlling devices that have been or are in use. The modelling of these is needed both in the operational software (partly simplified) and in the simulation and test software.

Table 6 : Estimation Methods

Method	Application
Differential Correction (weighted least squares) with bias estimation and modelling parameter improvement	Orbit Determination Attitude Determination for spinning spacecraft
Adaptive Kalman-Filter with restricted bias estimation and divergence detection	Attitude Determination for spinning spacecraft
Geometrical Methods (cone and plane intersections)	
Dynamic Methods (sensor measurement derivations)	
Refined Methods (Model parameter fitting(natural disturbances) over long time intervals)	Orbit Determination Attitude Determination for spinning spacecraft
Earth chord variation method	Attitude Determination for geostationary spacecraft (spin axis perpendicular to orbit plane)
Star-pattern recognition (Correlation and auto-correlation)	Attitude Determination for 3-axes stabilized scanners
Covariance Analysis	Orbit and Attitude Determination : Accuracy Estimation

Table 7 : Optimization Methods

Method	Application
Dynamic Programming Computer-specific Search Procedures	Observation Sequence Optimization under observability constraints
Discretized steepest descent and derivative-free gradient search (including penalty factors for constraints, covariance analysis and Monte-Carlo simulation)	Analytical, deterministic, worst-case and stochastic optimization for AMF (apogee motor firing)
Gradient projection method with linear constraints, parametric search for multi-impulse solutions (linear optimization problem)	Various strategies for station acquisition in NSO (near-synchronous orbit) taking into account all possible hardware and operational constraints
Search for permissable 2-impulse solutions, multiple-pulse optimization	Optimization of orbital rendez-vous (linear optimal control problem)
Constrained gradient search	Time shift manoeuvres planning
Target biasing, discretization methods	Low thrust problems

Table 8 : Dynamics Modelling

Dynamics	Model
Orbit generators including control manoeuvres and modelling of disturbances	Analytical representation Semi-analytical solution of the differential equations
Simulation of spacecraft dynamics (rotation) in free drift, with natural disturbances, and under active control with and without flexible appendices' modelling	Various numerical integration methods (single and multi-step methods with constant and variable step-size)

Table 9 : Space Environment Modelling	
Element	Characteristics
Ephemerides of Sun, Moon and Planets	JPL Planetary Ephemerides 96 implemented for on-line fast retrieval
Earth Rotation	Nutation, Precession, Polar Motion, Timing Standard
Earth Potential	GEM 9,10 (GEM6 used operationally)
Earth Albedo	
IR Radiance of Earth	NASA Model Refined BAC model
Geomagnetic Field	Inner and outer parts
Catalogues of Stars and other celestial objects	SAO, SKYMAP
Earth Stations Locations	Measured via TRANSIT
Atmosphere	Jacchia 71, MSIS (GSFC)
Ionosphere	BENT
Solar Radiation	
Gravity Gradient	
Magnetic Coupling	
Air Drag	

Table 10 : Modelling of Sensing and Controlling Devices		
	Type	Characteristics
Sensors	Sun	Analogue, digital
	Earth	IR (pencil and fan beam scanning) Albedo (fan beam scanning)
	Geomagnetic Field	Magnetometers
	Stars	Scanner, Tracker, Mapper
	Velocity and Acceleration	Accelerometer, gyros
	Radio Frequency	RF sensors
	Orbit Position and Earth Stations	Interferometer Tone Range Range Rate (Doppler) Antenna Angles
Actuators	Geomagnetic Field	Magnetocoils
	Thrusting Devices	Cold gas Hydrazine (catalytic) Solid fuel motors

4. THE COMPUTER SOFTWARE IMPLEMENTATION

Flight Dynamics Software has been and is implemented on a variety of computer systems. At present there are altogether 9 different systems. Their utilisation is shown in Table 11.

Based on this diversity, portability of the software plays an important role and is realised mainly by the establishment and maintenance of a library of basic software modules in FORTRAN.

The major part of the software is presently implemented on the CII 10070 being part of a multi-satellite support system (MSSS), a network of 6 SIEMENS 330 processors and 2 CII's. Embedded in an extension of the operating system, the "Task and Data Handling" subsystem, an integrated software and data system has been established for the support of geostationary missions. It includes the subsystems :

Table 11 : Computer Systems and Applications	
System	Application
CII 10070	Mainly for geostationary projects : orbit determination, attitude determination, manoeuvre and strategy optimisation, manoeuvre implementation and evaluation, data bases and system facilities. In addition for the development of EXOSAT software and study work
SYSTEMS 32/77	The successor of the CII dedicated to the operational support for the present and future projects (planned for full operations take-over by mid-1982)
IBM 370/145	Presently dedicated to the support for COS-B : orbit determination, attitude determination and control
ICL 2980	Dedicated for METEOSAT : reduced support for flight dynamics interfaces (actual support on CII 10070), to be exchanged
ICL 4/72	Used for general studies and the support of ISEE-B orbit and attitude control
CII HB 66	The successor of the ICL 4/72
SIGMA 9	Dedicated to IUE at Villafranca, Spain : Antenna steering, facilities for moon and comets' observation
MITRA 125	On-board computer for SPACELAB : attitude pointing algorithms for experiment operations
SIEMENS R30	Dedicated for the ECS project at Redu for the routine phases (orbit determination, station keeping, commanding and evaluation)

"Orbit Determination" containing all related functions such as tracking data preprocessing, orbit determination, orbit, station and antennae predictions, and ΔV manoeuvre evaluation

"Attitude Determination" including telemetry data pre-processing, spin-axis attitude determination and prediction, sensor coverage prediction, and in-flight calibration and evaluation

"Manoeuvre Support" covering all aspects of orbit and attitude manoeuvres : strategy optimisation (NSO Station Acquisition and SO Station Keeping), single burn optimisation (ABM firing), rhumb-angle attitude manoeuvres, thruster modelling and command generation, fuel budget management and manoeuvre evaluation.

In addition to these standard subsystems, various other functions are realised depending on the particular project requirements. They may be :

- Mission Planning and observation sequence optimisation
- Production of auxiliary data for on-line usage in the data processing area and for provision (e.g. on magnetic tape) to outside users (experimenters)
- Evaluation of spacecraft and mission performance for support of incentive scheme for the spacecraft constructor

The MSSS flight dynamics software system has been firstly used operationally in April 1977 (GEOS-1). Its software is built in such a way that only minimal changes or additions are necessary for the support of further geostationary missions (modular and parametrised). Via the Task and Data Handling subsystem possibilities exist for

- Near real-time attitude determination (maximum delay in the order of one telemetry format)
- Automatic and periodic starts of programs in routine phase

- Parallel support of several missions with priority setting for missions in critical phases (e.g. transfer and near synchronous orbit).

All input parameters are kept on disc files with interactive update possibilities. The common Spacecraft and mission parameters are stored centrally on the "General Data File" that exists for each mission.

Investment costs for this system (initially planned to support GEOS, OTS and METEOSAT) were rather high, in the order of magnitude of 60 manyears. Partly this is based on the limited resources and capabilities of the chosen computer system, partly on the effort spent for the implementation of a true multi-satellite system, fully integrated, centralised, standardised and consistent.

The further support given (GEOS-2, GOES-1) and the estimated investments for METEOSAT-2, MARECS and ECS, however, show the correctness of the approach: Minimal costs will quickly amortise the initial investments (e.g. the total investment for GOES-1 preparation including interface meetings, documentation, software production and testing was less than 1 manyear).

It is intended to expand the system such that it can - at least for the more standard tasks such as orbit determination - cope also with non-geostationary missions. This is feasible as the system was produced entirely in-house, such that enough knowledge and expertise is continuously available. The concept of "maintenance by improvement and modification" utilising knowledgeable staff is followed in most project-independent areas. This has paid off already, especially in cases of operational anomalies (quick modifications cover the new cases) and of requirement changes.

To ensure, however, the integrity of the software, especially when to be used in critical phases (transfer and near-synchronous orbits, e.g.) and in general, a "Quality Control" function is established. It is realised by an independent team who is responsible for developing the relevant test tools, establishing test plans and participation in and evaluation of tests. Together with system facilities (e.g. controlled registration of operational data files) the quality control function is a powerful management tool for mastering the responsibility vis-à-vis the readiness of the flight dynamics support for a particular mission or mission phase.

Table 12 : Flight Dynamics Support Tasks

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<u>Feasibility and Assessment Studies</u>
This concerns methods and algorithms as well as related problems in the spacecraft AOCS and ground station areas (e.g. estimation accuracy). These studies are performed in addition to those elsewhere in ESA and concentrate mainly on operational aspects.
<u>Consultancy</u>
On all questions related to flight dynamics which may arise at different levels and for various problems (mostly but not exclusively within ESA), the specialists are available for consultancy.
<u>Development of Computer Software</u>
This includes the standard tasks of design, production, testing, quality control and documentation of software for the implementation of algorithms, mathematical methods, related data bases, data interfaces and specific system facilities.
<u>Mission Planning and Operations Preparation</u>
Planning of flight dynamics mission sequences especially for the early orbit phase is performed by taking into account all operational constraints including the coverage of selected non-nominal cases. The result of this activity will finally be reflected as part of the Flight Operations Plan (FOP). In addition to this, other preparations for the operational support are performed. These include system tests and flight dynamics team training and participation in integrated system tests and simulations.
<u>Operations Support and Assessment of Results</u>
During critical phases of spacecraft operations (early orbit phase and special events in routine phase) the flight dynamics team is performing all related activities, such as operations of software and the assessment of results,used as criteria for the continuation of the sequence of events. A dedicated Flight Dynamics Control Room (FDCR) with all necessary facilities has been established for this purpose. During routine phase of a mission operations staff are handling the surveillence of the related operations.
<u>Evaluation of Mission and Software Performance</u>
This activity closes the circle and establishes the necessary experience for the performance of studies as pointed out at the top of this table. Both the performance of the mission (e.g. evolution of orbit and attitude, disturbances, spacecraft sensor and actuator characteristics, station location and tracking data assessment) and the software (e.g. accuracy of methods, adequacy of algorithms) are important items to keep the expertise and apply it to new tasks.

5. THE PRESENT AND FUTURE TASKS

Spacecraft Flight Dynamics Support at ESOC is realised within the Orbit Attitude Division. Seventeen specialists, in the orbit, attitude and software areas, supported at present by the same amount of staff from industry, perform the various tasks which constitute the totality of the support. These tasks are listed in Table 12.

The list covers in general the tasks that are being performed. At present, the division is occupied with the preparation for the next geostationary launch, METEOSAT-2 and APPLE (ISRO) with ARIANE L03, planned for 19th June 1981. The other launches to come, for which preparations have been started, are already mentioned in Section 2, Table 2. In parallel to the software development and preparations for the involved spacecraft, the transfer of the software facilities to a new computer system is under way. The first launch to be supported by this is the one after February 1982. In preparing for the conversion, standards have been established that combine those of the past with the new developments in the standardisation area (software engineering) in an optimum way for the particular environment of operational flight dynamics support. Further to this conversion, investments are at present put into the production of flight dynamics software which can be installed in dedicated station computers for the routine support of geostationary application satellites.

Related to ESA's future programme, three spacecraft projects are approved, viz. ISPM, GIOTTO and HIPPARCOS. They will require investments in the areas of interplanetary flight, of supporting advanced star sensors, and of support for more complex and autonomous on-board systems. In addition to these three projects, L-SAT (a large platform for communication satellites) is in preparation and initial studies for ERS (earth resources) are being conducted. Table 13 contains the characteristics of these new missions, identifying those items which need new investments in the flight dynamics area.

In addition to the projects mentioned in the above table, ESA is assessing other advanced scientific missions, the most demanding from the flight dynamics point of view being a Mars orbiter, a lunar orbiter, a libration point mission, observatories and an asteroid fly-by. Effort will also go towards large space structures for which rendez-vous and docking problems and flexible body dynamics are key items for the flight dynamics support.

Table 13 : Characteristics of ESA's New Missions

Name	Planned Launch Date	Mission Objectives	Characteristics
ISPM	1986	Exploration of the Sun's polar regions	Spinning Spacecraft, Earth Pointing with CONSCAN,interplanetary Flight (Jupiter swing-by), hydrazine thrusters, wire booms, autonomous recovery
GIOTTO	7/85 (fixed)	Investigation of comet Halley	Spinning spacecraft, de-spun antenna earth-pointing, ESA star mapper, interplanetary flight (Comet fly-by), hydrazine thrusters, perigee motor
HIPPARCOS	end 1986	Astrometry	Spinning in transfer orbit, 3-axes stabilised in geosynchronous orbit, star mapper, high accuracy pointing and estimation requirements
L-SAT	1985	Communications	3-axes stabilised in transfer and geostationary orbit, bi-liquid propellant system (used as well for injection)
ERS	1987	Earth resources (Ocean colour monitoring, sea surface temperature, synthetic aperture radar, altimeter, scatterometer)	3-axes stabilised based on SPOT-platform, fine attitude pointing with star sensor, near-earth orbit, high position estimation accuracy requirement (atmosphere)

It will be essential to prepare the support for the future missions in an economic way, by performing amendments to the existing facilities and investing for new requirements by utilising the expertise of experienced specialists, their continued availability being essential.

6. REFERENCES

Flight Dynamics Support at ESOC presents itself in a series of documents which cover the total spectrum of tasks being performed. These are :

1. OAD Working Papers
2. Flight Dynamics Reports
3. MSSS Flight Dynamics Facility
4. OAD Principles - A guide to the OAD Software Environment

Also Paper 10.3 of this Symposium "Quality Control for Mission-Critical Flight Dynamics Operations" (H. Müller and R. E. Münch) is relevant.