AN ADVANCED MODULAR FACILITY FOR ORBIT DETERMINATION OF ESA'S INTERPLANETARY MISSIONS

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***ABSTRACT** – The forthcoming ESA interplanetary missions ROSETTA, MARS EXPRESS and SMART-1 will present a number of diverse orbit determination challenges. These include planetary swing-bys and orbit insertions using conventional radiometric tracking methods, optical navigation with respect to small solar system bodies (ROSETTA), insertion into orbit around comet 46P/Wirtanen (ROSETTA) and low thrust navigation using solar electric propulsion (SMART-1). A single orbit determination program written to meet these disparate requirements would be unwieldy and complex. Ongoing improvements and enhancements would not be easy to perform and the software would be difficult for a user to appreciate fully since any given application would only be concerned with a small proportion of the program's capabilities. The alternative approach has been to create software modules to perform specific navigation functions. These modules are not tailored to individual projects and can be assembled by a user to provide a specific orbit determination application. The purpose of this paper is to demonstrate how the requirements have been met by the creation of an advanced modular facility for interplanetary navigation (AMFIN). The AMFIN software design allows a strong degree of flexibility both in terms of present application and in terms of its adaptability to meet future demands. In this paper it is not intended to include any discussion on specific mathematical models or techniques used. Emphasis is placed on the design at a modular level.*

KEYWORDS: ROSETTA, MARS EXPRESS, SMART-1, Interplanetary Orbit Determination, Software Design.

INTRODUCTION

GIOTTO [1], which flew past comet Halley in 1986, has been the European Space Agency's only interplanetary mission to date for which the Agency has had sole responsibility for the navigation. After a successful Halley encounter the mission was extended until 1992 for a rendezvous with comet Grigg-

Skellerup via an Earth gravity assist swing-by manoeuvre [2]. GIOTTO was very successful from both a scientific and a navigation point of view.

Currently ESA has three interplanetary missions planned to be launched in the near future. ROSETTA will rendezvous with the comet 46P/Wirtanen at a geocentric distance of approximately 5.3 AU (4.5 AU heliocentric) and then accompany the comet to its perihelion [3]. Mars EXPRESS (MEX) is to orbit Mars and deploy a lander called BEAGLE-2 onto its surface [4]. Finally, the Lunar mission SMART-1 will test an ion propulsion system [5,6]. More interplanetary missions are planned for the future. Planck and Herschel are to be launched in 2007 (destination Lissajous orbits around Lagrange Libration point L2 in the Earth-Sun system), and Bepi-Colombo, a Mercury orbiter to be launched around the end of the decade. Orbit determination software with wide ranging capabilities is required to meet the navigation requirements of these missions. The problem of finding a software design solution must be raised.

For many classes of Earth-orbiting spacecraft, the trajectories and tracking data observables can each be described by a single model. Hence, from the software point of view, only one orbit determination program is required, which nevertheless offers certain flexibility such as e.g. switching forces on and off. This applies for the currently flying ESA missions like XMM and CLUSTER 2, which are supported by the same core orbit determination program.

The deep space orbit determination software at JPL, ODP, is designed according to a more modular approach [7,8]. The system is broken down in such a way that each major function in the orbit determination process is performed by a stand-alone program, e.g. program PV for the trajectory propagation. ODP has evolved from its original form in 1962 into a multi-mission orbit determination tool today, having grown with time to cope with the always increasing demands of new upcoming interplanetary missions. The resulting properties of the program are its broad applicability and high complexity.

As indicated by Thurman [9], the design of the deep space orbit determination software at JPL has been accomplished using a primarily heuristic approach. That is the software design is mainly based on insights and guidelines derived from experience. Because of the complexity of the problems and the specialized functions to be performed, a great deal of expertise in the field of spacecraft navigation is required to design the software. ESA's interplanetary orbit determination software has been designed by drawing from the expertise gained from the development of the GIOTTO orbit determination system.

The desire to create software that has wide ranging capabilities to solve current problems which can also be adapted to provide orbit determination for future missions has been another important design issue. The software design approach has therefore had a strong element of what is referred to in [9] as a normative approach. That is the desire to adhere to design principles that are imposed by the software creators, namely adaptability and flexibility.

A compromise between the heuristic and normative approach has been chosen for the design of ESA's interplanetary orbit determination software. The GIOTTO orbit determination software and the expertise gained in its development were used to isolate the necessary individual tasks. Generalising and optimising the design of each task to maximise flexibility and adaptability results in a pool of modules which are not only usable within the orbit determination but throughout the entire spacecraft navigation system. For the purpose of orbit determination the modules are to be assembled by a main program as required. An orbit determination program can be built in this way for a particular mission or even for a particular mission scenario by choosing the appropriate 'off the shelf' modules.

This paper presents the design process of the Advanced Modular Facility for Interplanetary Navigation (AMFIN) and ESA's interplanetary orbit determination system. The scope of the paper is not intended to include any discussion on specific mathematical models or techniques used. Emphasis is placed on the design at a modular level. The software's application to the three near future missions ROSETTA, Mars EXPRESS, and SMART-1 is illustrated since the software for these missions is currently under development.

ORBIT DETERMINATION REQUIREMENTS FOR CURRENT MISSIONS

The ROSETTA mission requires orbit determination throughout a number of distinct phases. After the launch into its initial interplanetary orbit aboard ARIANE 5 there follow periods of up to 2 years of interplanetary cruise interrupted by a Mars and two Earth swing-bys. There are also asteroid fly-bys planned between the first and second Earth swing-bys (4979 Otawara) and after the second Earth swing by (140 Siwa). After comet detection a near comet drift phase and then comet approach phase occurs followed by the insertion into cometary orbit. The various science objectives, including comet mapping and deployment of a surface science package present further navigation demands until the end of the mission around 2013.

There are several crucial periods of navigation during the ROSETTA mission:

- The swing-by approaches demand accurate navigation. At the Mars swing-by a B-plane navigation error of 100 km in any direction would result in a Δv penalty of 60 m/s for the mission. This is due to the fact that any navigation errors must be corrected for immediately following the swing-by, which is effectively a direction changing manoeuvre for the first Earth swing-by three month later. The demands on the Earth swing-bys are less stringent since any errors can be optimally corrected for over the course of the rest of the mission [10].
- The asteroid fly-bys and the approach to the comet after detection require accurate relative body-spacecraft navigation. The required navigation is to be achieved by augmenting radiometric range and range-rate data of the spacecraft, with optical observations of the asteroid from the Earth and from the spacecraft itself. The spacecraft navigation software must be able to use various data types.
- Near comet navigation and the introduction of the spacecraft into the cometary environment presents a new set of navigation problems. Much more accurate relative spacecraft comet navigation is required including using images of cometary landmarks processed on ground.

The MEX spacecraft is launched by a Soyuz launcher with a Fregat upper stage. After insertion into the escape hyperbola towards Mars the mission consists of a 6-month cruise phase followed by a Mars approach phase and Martian orbit insertion. The BEAGLE-2 lander will be deployed 5 days before arrival at Mars. Routine orbit determination for the spacecraft is then required when in Martian orbit and to make manoeuvres whilst in orbit.

The key orbit determination requirements for MEX are:

- Mars approach navigation. The spacecraft must be accurately inserted into Martian orbit and the lander must be inserted into its correct approach trajectory.
- Relative orbit determination with respect to Mars required.

Finally, the SMART-1 spacecraft is deployed from ARIANE 5 into geostationary transfer orbit where it will then use its low thrust system (Solar Electric Primary Propulsion, SEPP) to first spiral out from the Earth and then in towards Lunar capture. There then follows a period of Lunar observation.

The important items for the SMART-1 orbit determination are:

- Low thrust propulsion system.
- Orbit Determination in Earth-Moon system required.

SOFTWARE REQUIREMENTS AND SOFTWARE DESIGN

In this section the design methodology for ESA's interplanetary orbit determination software is presented. The main component of this software is the collection of AMFIN modules. Both, the interplanetary orbit determination software and the AMFIN modules are coded in FORTRAN. It is worth briefly reviewing the design possibilities to illustrate why such a modular approach was chosen.

Some possible approaches to the interplanetary orbit determination software design are:

- A stand alone program for each mission or mission phase as required.
- An all embracing generic navigation program to be used for all missions and mission phases.
- A set of navigation libraries (modules) to be assembled into main programs as required.

The fact that there are many elements of orbit determination common to all the missions means that some form of generic approach is sensible. However an all embracing generic navigation program with a very high degree of complexity has the major drawback that it is so complex. Smaller programs are more manageable from a user point of view. Upgrading of an all embracing program or expanding functionality could be complicated.

In order to provide the broad functionality required without the necessity for complexity a set of navigation libraries (modules) have been developed. Throughout the design process an emphasis on adaptability of both individual modules and of the set of modules has been maintained.

The modules can be assembled by a user into a navigation application as required and can also be used for other purposes e.g. simulation software, orbit products software. They have been designed with clearly defined interfaces so that they can be assembled easily and individual modules can be interchanged easily.

As a result of this structure there is no fixed approach to orbit determination and no fixed set of approaches. A new navigation application can be created for each mission phase if desired by simply assembling the appropriate modules within a desired framework (even an all embracing generic navigation program could even be assembled from modules).

Basic Module Identification

In order to present the software design in a meaningful way it is intended to illustrate the software design process is some detail. As a starting point there is the question of what should be the basic functions the modules provide.

In Fig. 1 a basic flow diagram for an orbit determination program is shown. One can identify the main tasks required to assemble this program as follows:

- Spacecraft orbit and dynamic partial derivatives generation.
- Generating modelled observations and regression partial derivatives with respect to uncertain parameters.
- Estimation of uncertain parameters

This is by no means an exhaustive list of the tasks performed but can be used as an initial point from which the module design details can be derived. Other functions exist which may be performed by the main program or it may be more sensible to create a module to perform them.

Requirement Driven Evolution of Module Identification and Design

The design of AMFIN modules and of the AMFIN system as a whole has been driven by certain factors:

- Constraints imposed by mission navigation requirements
- Constraints imposed by adaptability requirements
- Constraints imposed by other requirements (e.g. portability of code, programming requirements)

The intention in this section is to describe how the design of the software evolved to meet the requirements.

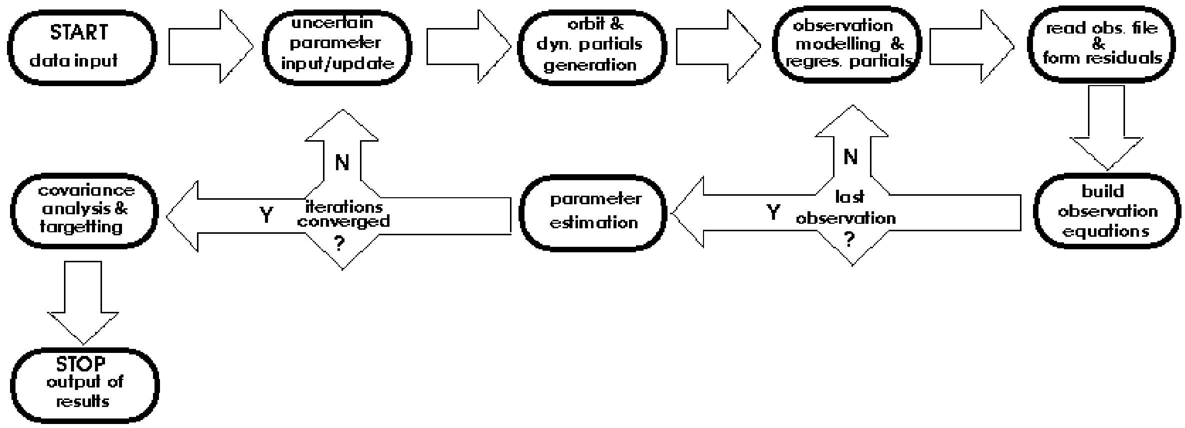

Fig. 1 Simplified flow diagram of an orbit determination program.

Constraints imposed by mission navigation requirements are usually demands that certain functionality be incorporated into the software. For example the demand that the software must be able to take all necessary dynamic models into account and treat the models' parameters as uncertain. Another example could be that the software must be able to incorporate a certain measurement type into the solution and be able to treat some parameters, which affect the measurement as uncertain. Other navigation requirements put specific demands on the software e.g. performing optical navigation with respect to a massive body requires that one can treat the body's state as a parameter which affects both the spacecraft dynamics and the measurement itself directly. In general these requirements are concrete demands.

Constraints imposed by adaptability requirements make demands that are usually of a more general nature. For examples the software should not be mission specific or the software should not have a fixed right hand side of the equations of motion but should allow a user to modify this to suit their purposes. These requirements tend to make rather more of an impact on the software design than the mission navigation requirements. They make demands of the design to ensure that the software is flexible.

The other requirements that arose are not related to either of the two previous sets. For example the requirement that the estimator module should have a very simple interface to allow it to be used completely independently of the other modules.

For the design and identification of modules the adaptability requirements imposed are of most interest. There follows a list of the requirements of this type:

- Uncertain parameter list flexibility. There should be no fixed list of uncertain parameters. A user should be able to assemble their own list according to mission and mission phase.
- Dynamic modelling flexibility. There should be no fixed list of dynamic models. A user should be able to assemble their own list according to mission and mission phase.
- Observation type flexibility. A user should be able to apply one or more observation types, and should be able to incorporate any new observation types as required.
- The software should not be mission specific. Any software relating to a specific mission should be external to the AMFIN modules.
- Basic functions, e.g. estimation method or integration technique should be replaceable
- The interfaces between AMFIN modules, and between AMFIN modules and a main program should be as clean and simple as possible. This is to facilitate assembling and adapting software.

Example Orbit and Dynamic Partial Derivatives Generation

The software design process can be viewed as the imposition of a series of requirements. In Fig. 2 the evolution of the modules concerned with the spacecraft orbit and dynamic partial derivative generation is given. This was earlier identified as a basic functional block.

If the restriction is introduced that basic functions should be replaceable then the numerical integration scheme (integrator) should be separate from the dynamic modelling allowing to interchange integration techniques whilst using the same right hand side (RHS) of the equations of motion and variational equations. Fig. 2.2 then gives the modular structure. Arrows indicate flow of information and give a dependence structure for the software.

The demand that the RHS should be constructed from a free choice of dynamic models indicates that these models should be available in a separate library. This produces further fragmentation of the modules (Fig. 2.3). The RHS module is split into a module DYNMOD containing all the dynamic models and a module RHS that assembles these models for use in the integrator. For each dynamic model the DYNMOD module supplies a contribution to the right hand side of the equations of motion (the spacecraft acceleration) and the variational equations in the form of a software element. The contribution to the variational equations consists of the partial derivatives of the spacecraft acceleration with respect to uncertain parameters that affect the trajectory of the spacecraft directly (dynamic parameters). It is a main characteristic of the DYNMOD module that the dynamic parameters to be treated as uncertain can be freely chosen and are not restricted to any fixed list. The chosen list of dynamic uncertain parameters is traced from their input down to the actual element of the DYNMOD module. This is controlled by a parameter book keeping system which is described below.

Spacecraft specific software is software which is non-generic, i.e. RHS which draws from the dynamic models library DYNMOD, or the software used to model the acceleration profile due to manoeuvres. If one specifies that spacecraft specific software must be external to the AMFIN structure one arrives at Fig. 2.4. Although the manoeuvre acceleration profile modelling is spacecraft dependent the manoeuvre

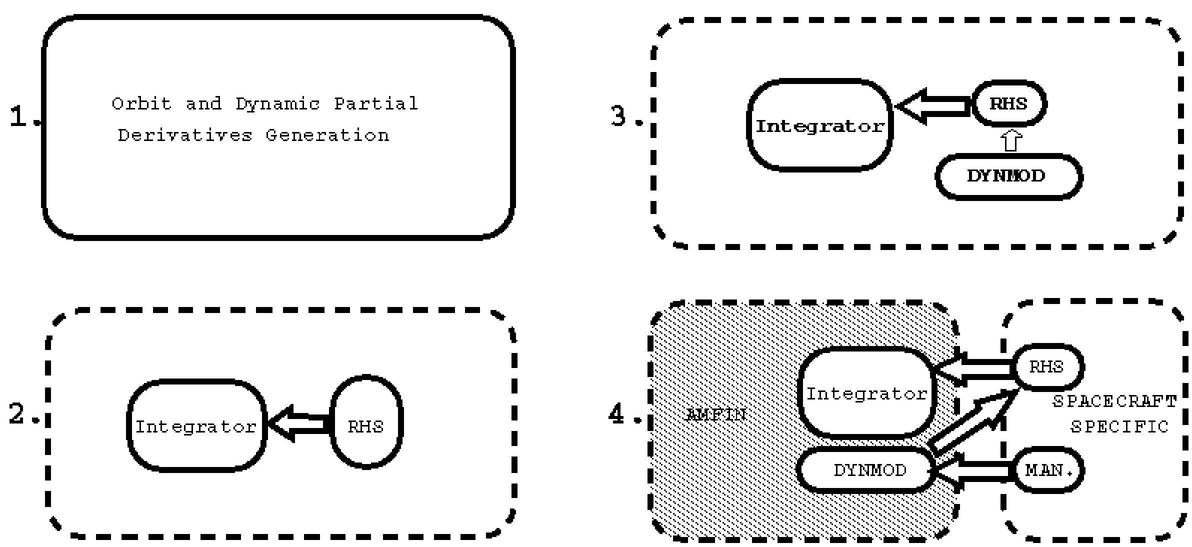

Fig. 2 Software design process of the spacecraft orbit and dynamic partial derivatives generation module. Arrows indicate main data flow.

calibration must be internal to AMFIN (DYNMOD) to allow the manoeuvre calibration parameters to be treated as AMFIN uncertain parameters. Thus one has a structure for the dynamic modelling software which satisfies the requirements imposed. As far as AMFIN is concerned the separation of integration and dynamic modelling has been established and the need for an external spacecraft specific software has been identified.

Example Observable Modelling

In Fig. 3 the evolution of the modules related to the modelling of the observables is displayed. This was identified earlier as a basic functional block.

The demand that the modelling of the observables should be mission independent requires that spacecraft specific data e.g. orbital and dynamic parameters of the spacecraft must be detached from the observable modelling modules. The modelling may even require specific dynamic data from more than one spacecraft or from a target body. This also needs to be considered as distinct from the modelling software. Fig. 3.2 gives then the desired modular structure.

One should be able to freely select the observable types relevant to an application. Furthermore individual observable modelling software should be replaceable by the user. This requires further modularization. The modelling software is split into modules, each of them modelling a specific set of observables e.g. a module for range and range-rate observables or a module for optical observables, Fig. 3.3. Each measurement module consists of a pool of routines specific to the particular observation type, e.g. light time solver, actual observable modelling, corrections to the observables, etc. nevertheless, one single high level routine defines the interface to the application programs.

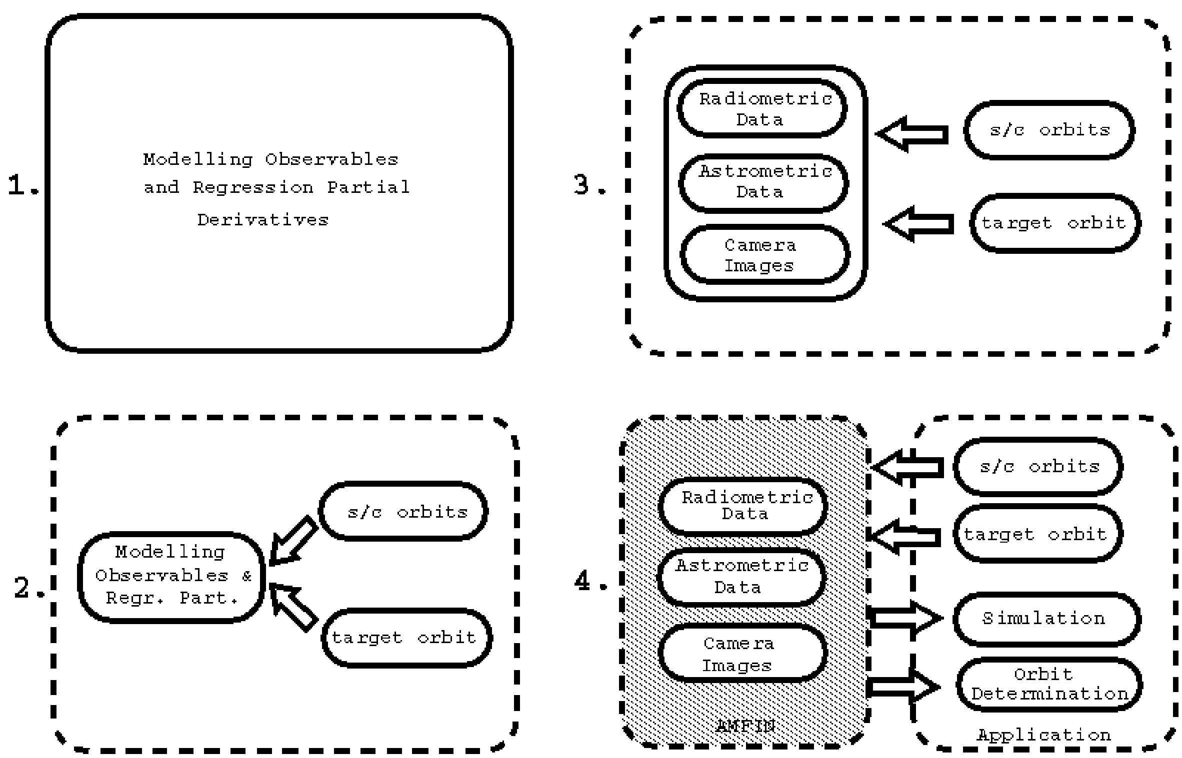

Fig. 3 Software design process of the observable modelling module. Arrows indicate main data flow.

A further task of the observable modelling modules is to provide partial derivatives of the observables with respect to uncertain parameters that affect the observables directly (measurement parameters) in order subsequently to construct the observations equation in an orbit determination application. The measurement parameters to be treated as uncertain can be freely chosen and are not restricted to any fixed list. The chosen list of measurement parameters that are treated as uncertain is traced from their input down to the actual observable modules. Again, this is controlled by a parameter book keeping system, which is detailed in the next section.

If one distinguishes between potential application software, e.g. an orbit determination program or an observable simulator and the measurement modules supplied by AMFIN, one finally arrives at the design as displayed in Fig. 3.4. The application software provides the orbital and dynamic data to the chosen AMFIN modules, which returns the desired modelled observable for further processing by the application program.

Example Parameter Book Keeping

Before the requirement is satisfied that the uncertain parameter list can be freely chosen, some form of AMFIN based uncertain parameter organising software is necessary. If a fixed list was sufficient one could perform this function within the application software and implicitly deal with the communications required between the distinct modules by knowledge of this fixed list. This is not sufficient and so it has been necessary to form a module called the parameter book keeping system (pbk system).

The uncertain parameters are input in a file along with information on how they are to be treated. They can be treated as solve-for or consider parameters and as bias parameters or process noise parameters. This information is processed by the pbk module and can then be used to order the subsequent treatment of the uncertain parameters. For example knowledge of which partial derivatives are required and the order in which they are to be output is communicated from the pbk module to the DYNMOD module and the measurement modelling modules. The result is that a user can set up an application specific input file based on an available library of uncertain parameters. They can also augment these libraries with new uncertain parameters if necessary. In addition an application only requires the computer memory for its specific input file. This is important if one considers that some aspects of the missions may require many uncertain parameters (e.g. MEX, Mars orbiting phase whilst treating the coefficients of the Mars gravity field as uncertain) and some only very few (ROSETTA during interplanetary cruise).

EXAMPLES OF AMFIN APPLICATIONS

This section gives two examples how AMFIN can be used within the orbit determination software to cope with nominal and optional navigation requirements for the specific mission scenario at hand.

MEX: Mars Approach and Orbit Insertion

For the nominal mission several specific items are required to ensure a safe approach and insertion of the spacecraft into Mars orbit.

The RHS module (Fig. 2) needs to accumulate the output of the following dynamic models which are specific to this scenario: the gravity field of Mars, the gravitational influence of Phobos and Deimos, the relativistic perturbative acceleration due to Mars, an eclipse model for the solar radiation pressure, and a facility to apply and calibrate manoeuvres. These models have been already developed as low level routines and can simply be assembled into a specific RHS module covering the Mars approach and orbit insertion.

In terms of dynamic parameters that can be treated as uncertain the coefficients of the Mars gravity field and the ephemeris of Mars are of particular interest. These are introduced to the parameter book keeping system and can be flagged as uncertain if desired. The corresponding DYNMOD modules have been set up to supply on request the required partial derivatives with respect to these parameters.

The full capability of the AMFIN system comes into light if new orbit determination requirements are raised after launch because the nominal mission trajectory cannot be met or other unforeseen scenarios arise.

If the propellant budget turns out not to be sufficient to reach the desired Martian orbit the apoapsis lowering manoeuvres can be replaced by performing aerobraking in the Martian atmosphere. The software offers an easy way to accommodate this situation. A dynamic module needs to be developed that computes the deceleration of the spacecraft due to air drag assuming a certain model of the Martian atmosphere. Partial derivatives of the deceleration with respect to parameters that are potentially uncertain, e.g. the atmospheric drag coefficient or other parameters related to the not very well known composition of the Martian atmosphere are furthermore calculated. This kind of module is relatively easy and straightforward to develop and after completion it simply needs to be plugged into the RHS module so that it can make use of the full capabilities of the orbit determination program without the necessity of further changes.

Present studies indicate that the Beagle-2 insertion navigation accuracy can only marginally be met based on classical 2-way range and range-rate data. Augmentation using ΔVLBI data [7] is being proposed. Again the main work to cope with this situation is the development of a ΔVLBI modelling module (Fig. 3). After completion this module can easily be inserted into the existing orbit determination program making use of its full capability, e.g. processing ΔVLBI observations and treating chosen measurement parameters as uncertain.

ROSETTA Asteroid Encounters

The ROSETTA mission asteroid fly-bys provide an interesting example of AMFIN software flexibility at an application level. During the approach to the asteroids 4979 Otawara and 140 Siwa it is intended to improve the estimate of the relative spacecraft asteroid state by supplementing ground based radiometric and astrometric data with spacecraft based optical images of the asteroid.

The orbit determination methodology to be used requires three separate orbit determination applications. The asteroid orbit is estimated using only astrometric asteroid measurements within a comet and asteroid orbit determination application. The main spacecraft orbit determination application uses only radiometric spacecraft observations. The output to these two estimations are then combined and the optical image data used to improve the relative state in a relative state orbit determination application. This method is preferred because it avoids the substantial extension of the main orbit determination program necessary to incorporate optical data as well as radiometric data in a single application [11].

From an AMFIN point of view the distinction between using a single application program or a pair of programs to perform the spacecraft orbit determination is irrelevant. The optical measurement module has been created alongside the radiometric measurement module and how these modules are incorporated into an orbit determination program or programs can be decided by the user. So whilst the current view is to treat the data sources separately this approach has had no impact whatsoever on the design of the modules. AMFIN can accommodate both data sources in a single application.

CONCLUSIONS

The software created for the forthcoming ESA interplanetary missions ROSETTA, Mars Express and Smart-1 has been designed with flexibility and adaptability in mind. Based on the programs used for navigating the GIOTTO spacecraft the software has been given a modular structure. The modular design has been driven by a set of clear requirements that have resulted in the Advanced Modular Facility for Interplanetary Navigation (AMFIN). Using AMFIN no fixed approach to the navigation problems that arise is necessary. The modules can easily be assembled into whatever navigation application seems appropriate to the user. This flexibility and adaptability has been achieved by carefully designing the modules, their interactions with each other and with a main program. The result is a navigation system that is easy to upgrade and can be augmented to address any developments that may arise in a mission. In addition the software can be easily developed to meet the needs of future missions.

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