MISSION PLANNING AND OPERATIONS FOR SMALL PAYLOADS
USING THE FLIGHT DESIGN SYSTEM

Bret Yetter
Barrios Technology, Inc.
Houston, Texas

Recent developments in the area of small satellites and small expendable launch vehicles have resulted in a need for mission planning and analysis tools and for supporting payload operations functions. Past experience in planning and replanning of Space Transportation System (STS) primary and secondary payloads has provided a basis for addressing small satellite projects. This paper presents a discussion of how the Flight Design System and related programs can be used for long range mission planning and near real time replanning to achieve small satellite payload objectives.

INTRODUCTION

The Flight Design System (FDS) has been used extensively for mission planning applications on Space Transportation System (STS) missions since the late 1970s. Originally developed and implemented at NASA Johnson Space Center, it was acquired by USAF Space Division in 1981 for long range mission planning in El Segundo, California\(^1\). FDS has also proven to be useful for near real time replanning applications and was installed for major payload replanning in Sunnyvale, California in 1984 at the Air Force Satellite Control Facility (Onizuka AFB). Space Division Detachment 2, Johnson Space Center acquired FDS in 1987 for planning and replanning of STS Secondary Payloads\(^2\). Fig. 1 shows the current network of FDS centers.

![Current FDS User Centers](image)

Fig. 1 Current FDS User Centers. Host machine is the Concurrent 3200 series minicomputer.
Although the primary uses of FDS have been for STS missions and payloads, its wide range of capabilities are useful for small, free flyer satellites, independent of the launch vehicle used. The remainder of this paper will present a summary of FDS capabilities which can be used for on orbit planning and replanning that may be applicable to small satellite programs.

FDS FUNCTIONAL OVERVIEW

The FDS consists of over 100 programs, or processors, a user Executive, and global and user specific databases. The system contains over 750,000 lines of source code, most of it ANSI FORTRAN '77 with some Assembler code. Each processor provides a primary function, with various user options, ranging from simple tasks, such as ground station coverage to more complex functions such as rendezvous/retrieval. The processors can be categorized into the functional groups shown in Fig. 2. FDS can be described as a simulation builder in that it allows the user to "string together" any sequence of functions and create an infinite number of unique simulations.

Fig. 2 The 100 FDS processors can be grouped in twelve functional areas.

A major strength of FDS is the commonality of many functions under the same data structures and editing formats. This feature provides easy data exchange between processors and allows an end-to-end mission plan to be constructed within a single computer system. An added benefit is the reduction in operator training time required to become proficient in the use of the system. Once a user learns the executive editor commands and the general format for processor inputs, this knowledge carries over into all the functional areas. The executive is the software interface between the user and the applications software. It provides a high level instruction set which allows the user to easily create, link, load, and execute the simulation.
An example of a simple mission analysis setup is shown in Fig. 3. This simulation was part of a feasibility study conducted to determine the applicability of FDS functions for a typical free flyer satellite, in this case the LACE satellite. The data shown represents simulation data used in the feasibility study. The executive commands are used to program or build a table that links the desired processor executions that are needed for a specific set of tasks. In this case, the functional areas of interest are state vector display, ground station acquisitions, ground traces, attitude and pointing data, view simulations, celestial sphere plots, and experiment timeline construction. Several of these functions will be explained in more detail in subsequent sections. A common trajectory ephemeris is used in each of these executions. Although not shown in this example, the trajectory generation can be included in the execution sequence if desired. This is especially useful in near-real time situations where vehicle state data is frequently being updated.

```
NRLDEMO -ST COMPLETE DATE/TIME TAG = 00/00/79 00/00/00 BARRIOS
EXECUTABLE
10, NO , "------------------------INITIALIZATION DATA------------------------"
20, NO , "------------------------STATE VECTOR--------------------------"
30, PE , SSVD
40, NO , "COMPUTE AOS AND LOS"
50, PE , STACN, STACN
60, PE , GTRACK, GTRACK
70, PE , GTRACK, GTZOOM
80, PE , ATLED, ATLED
90, PE , GAP, GAP
100, PE , VIEW, VIEW
110, PE , CELEST, CELEST
120, PE , ETP, ETP
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Fig. 3 A series of statements is linked together using the executive editor to automatically calculate orbital support data for the satellite simulation. Each line is a command to perform a processor with a particular function requested.

SPECIFIC FDS APPLICATIONS

A complete description of the entire functional capabilities of FDS is beyond the scope of this paper. The following sections will focus on several applications that may be of interest to the small payload mission planner.

Trajectory Design

FDS provides a range of propagator simulations depending on the speed and accuracy required. The most basic, conic solutions, are used for rough approximations at high speeds. The most common analytic propagator option used is the Analytic Ephemeris Generator (AEG) which provides accurate results for low earth orbit analysis with very fast computation times. The most accurate propagator available uses a precision numerical integration scheme. The integration method is a Runge-Kutta-Fehlberg Fifth Order method (RKF45), using a uniform, regular KS element set formulation. Although somewhat slower than the analytic solutions, the precision integrator is used when critical orbit
accuracies are required. This capability is used by NASA/JSC to generate the official planning simulation "supertape" which is used as input to the Crew Activity Plan (CAP), the STS Simulators, ground track maps, and other planning functions. All simulations in this category are 3 degree of freedom with constant ballistic coefficient for drag modelling. To complement the coasting options in the FDS trajectory design process, maneuver simulations are also available. Although the general purpose impulsive burn is the most common, a finite burn simulation is also used. Perturbation models for all simulation options include earth gravitation up to the 8th order and 8th degree, standard 1962 or Jacchia density model, solar and lunar gravitation effects, and solar radiation pressure.

Relative Motion Analysis

One particular area of interest to the small satellite user is the study of the separation and subsequent relative motion between the launch vehicle and the satellite. Since relative separation velocities are often very small for this class of payload, special care must be taken to fully understand the relative motion of the vehicles to avoid possible recontact. A high accuracy relative motion capability is available on FDS, which can perform six degree of freedom simulations and plots and view simulations of the results. Fig. 4 shows an example of an Orbiter centered relative motion plot after an OMS separation burn. Similar techniques were used for analysis performed on a ground radar calibration experiment payload for the Air Force in 1986. Several small calibration cannisters were scheduled to be deployed from the Shuttle on multiple orbits and acquired by ground radar equipment for calibration measurements. These FDS analyses determined the optimum ejection velocity and deploy times of the cannisters to allow maximum time for calibration.

Fig. 4 The Relative Motion and VIEW processors are used to analyze the separation of a payload from the Orbiter. Payload is shown as dots in left center of plot, depicting relative position to Orbiter.
Attitude and Pointing Analysis

The attitude and pointing processors on FDS provide several useful options to the small payload planner. First, any instrument, including its coordinate system, location on the vehicle, field of view, and gimbal limits, can be simulated. The General Attitude and Pointing (GAP) processor can then be used to determine pointing angle information, such as separation angles between instrument line of sight and celestial, ground, or moving targets, including sun, moon, earth. Second, a complete time history of vehicle attitudes can be generated using the Attitude Timeline Editor (ATLED) processor. These vehicle attitudes can be determined using various input schemes such as direct angular inputs (Local Vertical Local Horizontal, Mean of 1950 - inertial, Solar Inertial), vehicle body pointing vectors, dual line of sight pointing vectors, or various ground, celestial, or moving vehicle tracking modes. Examples of GAP and ATLED are shown in Figs. 5 and 6. These displays are the partial results of the commands given on lines 80 and 90 from the execution sequence in Fig. 3. To further aid the user, instrument views are available using the VIEW processor. This function is particularly useful in providing a visual verification of the digital data from the ATLED and GAP results. The example in Fig. 7 shows the results of statement 100 from Fig. 3, which is a graphic representation of the satellite instrument field of view. Backup pages for each picture are generated providing time tags and instrument specifications.

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**Table 1**

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Earth Angle</th>
<th>Celestial Angle</th>
<th>Celestial Separation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td>90.3</td>
<td>50.2</td>
<td>25.6</td>
</tr>
<tr>
<td>Moon</td>
<td>90.3</td>
<td>50.2</td>
<td>25.6</td>
</tr>
<tr>
<td>Sun</td>
<td>90.3</td>
<td>50.2</td>
<td>25.6</td>
</tr>
<tr>
<td>Moon</td>
<td>90.3</td>
<td>50.2</td>
<td>25.6</td>
</tr>
</tbody>
</table>

---

Fig. 5 One snapshot in a series depicting attitude data (top section) and pointing data (middle section) of two instruments on the satellite. The target section shows that the instrument "BODY" is tracking a ground target and is currently pointing at latitude 25.6 degrees and longitude 162.8 degrees.
Fig. 6 Five attitude events are listed, covering a span of 3 hours, 10 minutes. Attitude initialization mode is depicted, along with current attitude, in roll, pitch, yaw, and target type if mode is tracking. Digital Auto Pilot (DAP) rates and dead bands are given on far right.

<table>
<thead>
<tr>
<th>EVENT</th>
<th>TIME</th>
<th>COMMENT</th>
<th>TOE-</th>
<th>TOE-</th>
<th>CAT</th>
<th>OPION</th>
<th>TARGET/VECTOR</th>
<th>DAP RATE</th>
<th>DAP ATT</th>
<th>DEADBAND</th>
</tr>
</thead>
<tbody>
<tr>
<td>01:00</td>
<td>01:00</td>
<td>NET</td>
<td>INITIAL ATTITUDE</td>
<td>LULH</td>
<td>LULH</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>02:15</td>
<td>01:00</td>
<td>NET</td>
<td>MAUI TRACK</td>
<td>TRK</td>
<td>N50</td>
<td>54.020</td>
<td>0.000</td>
<td>372.000</td>
<td>65.070</td>
<td>0.500</td>
</tr>
<tr>
<td>02:15</td>
<td>01:00</td>
<td>NET</td>
<td>LOS MAUI</td>
<td>LULH</td>
<td>LULH</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>02:15</td>
<td>01:00</td>
<td>NET</td>
<td>MAUI TRACK 2</td>
<td>TRK</td>
<td>N50</td>
<td>62.030</td>
<td>0.000</td>
<td>292.000</td>
<td>65.070</td>
<td>0.500</td>
</tr>
<tr>
<td>02:15</td>
<td>01:00</td>
<td>NET</td>
<td>LULH</td>
<td>LULH</td>
<td>70.000</td>
<td>0.000</td>
<td>292.000</td>
<td>65.070</td>
<td>0.500</td>
<td>2.000</td>
</tr>
</tbody>
</table>

Fig. 7 Instrument Field of View is shown as circle located on earth horizon. Star background and earth terminator are labelled. Instrument gimbal limits are ± 45 degrees vertical, ± 50 degrees horizontal.
Experiment Timeline Analysis

The Experiment Timeline Processor (ETP) is used for Target of Opportunity analysis and for scheduling experiment operations. Fig. 8 shows an example ETP display. The eight lines near the bottom of the display are user specified opportunity bands which represent acquisition and loss times of certain targets of interest. The targets can be stars, planets, ground based point targets, area targets, or latitude crossings. For payloads with potentially conflicting experiment timelines, the ETP display shows the conflicting opportunities as well as lighting and radar station data, orbit count, attitude bands, and crew activities (if applicable), so the planner can quickly prioritize experiment data takes. This function is particularly useful for near real time replanning.

Fig. 8 The ETP provides a display which integrates many files from other FDS processors. The horizontal display allows the planner to make a quick assessment or potential experiment opportunities and conflicts. Future changes to ETP will allow a more flexible display.

Real Time Mission Operations

During actual mission operations, the planner desires up-to-date orbit information and the ability to quickly forecast upcoming opportunities, especially when orbit anomalies have occurred. As a response to this need, the FDS executive language has been used to develop mission modules, which are dedicated to the function and requirements of a particular payload or mission. The execution sequence in Fig. 3 is one of the basic components of the modules.
The modules are menu-driven for quick execution, and each contains a driver or master menu which allows the user to choose between several suboptions. This module concept has been used successfully on several major STS payloads and is currently being used to plan for many secondary experiments sponsored by the USAF on upcoming Shuttle flights. One such example is the Air Force Maui Optical Site Calibration Test (AMOS). The Driver Menu is shown in Fig. 9. Options 1, 2, and 3 provide trajectory file updating and manipulation. Options 4 - 7 provide station coverage data, lighting data, ground traces, and equator crossing times. Fig. 10 shows the result of choosing option 6, groundtracks. The concentric circles represent different elevation angles from Maui and are user specified, as are the requested orbits. The dotted line shows that a portion of the orbit 2 overpass occurs in orbital darkness. Finally, options 8 and 9 are used to manipulate display results and units. Fig. 11 shows a summary display of opportunities for orbits 2 and 3, including Time of Closest Approach (TCP), pass duration times for elevation angles between 25 and 40 degrees, and STS lighting conditions. This display has been customized using executive language commands. Using this capability, a new state vector can be received and propagated and new experiment opportunities determined in a matter of minutes.

***********************************************************************
AMOS TRAJECTORY SUPPORT TASK
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SPECIFY OPTION NUMBER:

0 - EXIT MODULE
1 - GET/SAVE TRAJECTORY
2 - CREATE/LIST A TRAJECTORY
3 - ASSIGN/CHANGE TIME TO CURRENT TRAJECTORY
4 - DISPLAY STATION CONTACT TIMES
5 - DISPLAY SUN RISE/SET TIMES
6 - DISPLAY GROUND TRACKS
7 - DISPLAY NODE CROSSING TIMES
8 - SUMMARY OUTPUT
9 - CHANGE PARAMETER DISPLAY UNIT

$NUMBER : 

Fig. 9 The main driver menu for the AMOS module provides options and brief explanations of the module functions.

CONCLUSION

The capabilities of the Flight Design System have been shown to be applicable to owners, operators, and planners of small payload and satellite programs. The references provide a more thorough listing of background material for the interested reader. Although the requirements for a new payload program may seem to impose high costs for FDS module set up, boilerplate menus and architectures have resulted in very responsive and immediate results. Due to the very expensive and valuable time on orbit of any payload, the initial expense of a comprehensive simulation as well as a real time replanning tool makes the use of a system such as FDS well worth consideration.
Fig. 10 AMOS closeup groundtrack data is displayed for orbits 2, 3, 4.

Fig. 11 Customized summary display of AMOS experiment opportunities for orbits 2 and 3.
REFERENCES


Resume'

Received Bachelors of Aerospace Engineering from Georgia Institute of Technology in 1981. During school, participated in cooperative education program at Johnson Space Center in Shuttle reentry analysis. Last 7 years in Mission Planning and Integration for USAF Space Division payloads on the STS. Most recent assignment as manager of Mission Planning and Flight Support Services at Barrios Technology, Houston, Texas.