MANNED SPACEFLIGHT TRAJECTORY OPEATIONS — THE DIFFERENCES

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ABSTRACT

This paper contrasts manned and unmanned flight dynamics operations for past and present United States spaceflight projects. A top-level review of current state-of-the-art capabilities for attitude determination, orbit determination, and orbit prediction is presented. Space Transportation System (STS, the Space Shuttle) flight dynamics operations are documented in detail, including ground and onboard attitude determination, attitude maintenance and prediction, ground and onboard orbit determination, orbit maintenance, and orbit prediction. Particular attention is given to operational aspects of manned spacecraft flight dynamics problems, and how these problems differ from those usually associated with unmanned projects.

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1. INTRODUCTION

Before delving into the paper itself the reader should be aware of both its contents and its limitations. The intent, as stated in the abstract, is to contrast manned and unmanned flight dynamics operations for United States spaceflight projects. Such a contrast requires the discussion of attitude and trajectory determination accuracies.

Accuracies, when quoted, are not intended as referenceable statements of United States or STS capabilities. Rather, they should be considered only as specific examples, since the length of this paper prohibits complete definitions of any generic situations to which the accuracies apply.

2. ACRONYMS

ASTP	Apollo Soyuz Test Project
BTB	Batch-to-Batch
COAS	Crew Optical Alignment Sight
DOD	Department of Defense
G	Gravitation Force
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
GSTDN	Ground Spaceflight Tracking and Data Network
IMU	Inertial Measurement Unit
km	Kilometers
MCC	Mission Control Center
NASA	National Aeronautics and Space Administration
NCC	Network Control Center
RM	Redundancy Management
SGLS	Space-Ground Link System
STS	Space Transportation System
TDRS	Tracking Data Relay Satellite
TDRSS	Tracking Data Relay Satellite System
VDT	Vehicle Data Table

3. DEFINITIONS

The following terms are defined in order to clarify the meanings of terminology used frequently throughout this paper.

3.1 Attitude Determination

The process of determining the orientation of a spacecraft relative to an identified reference frame by using independent data or observations, e.g., observations of star positions relative to the spacecraft to determine inertial orientation.

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3.2 Attitude Maintenance

The process of maintaining a current estimate of the orientation of a spacecraft relative to an identified reference frame, usually by extrapolation from an initial attitude determination point.

3.3 Attitude Control

The process of controlling the attitude of a spacecraft, e.g., causing the spacecraft to go to or remain in a planned orientation relative to an identified reference frame. The hardware aspects of attitude control are not dealt with in detail in this paper.

3.4 Flight Dynamics

Flight Dynamics is the engineering discipline which encompasses all the functions required to determine, maintain, predict, and control the attitude and trajectory of a spacecraft.

3.5 Orbit Determination

The process of determining the past position and velocity of a spacecraft relative to an identified reference frame by using independent observations, e.g., observations of the spacecraft by ground tracking stations. The determination can be made during the observations (real-time), after a group of observations (near-real-time), or at a later time (post flight). It should be noted that, in practice, parameters in addition to the spacecraft position and velocity, such as an atmospheric drag factor, are often solved for as part of the orbit determination solution.

3.6 Orbit Prediction

The process of predicting the future position and velocity of a spacecraft relative to an identified reference frame, usually by numerical integration of an initial orbit determination solution.

3.7 Orbit Maintenance

The process of using orbit prediction to maintain a current estimate of the position and velocity of a spacecraft relative to an identified reference frame.

4. MANNED VS. UNMANNED SPACEFLIGHT

To understand the way manned flight operations have evolved over the years it is necessary to understand some of the differences between manned and unmanned spaceflight and spacecraft. This paper presents some of the key issues which have direct effects on flight dynamics.

4.1 General Comments

4.1.1 Man-Rated Hardware, Software, and Procedures. Manned spaceflights, by their very definition, carry human beings as well as cargo. Thus, the penalties for errors can include loss of life as well as mission failure. As a result, all hardware, software, and procedures must be man-rated. This may imply testing which goes beyond that required for unmanned flights and/or higher success probabilities. Lead times can be longer, and costs higher. The pressure to update to the most current state-of-the-art capabilities may be tempered by cost and schedule considerations. The technology utilized for manned flights can thus lag behind that used for similar unmanned flights.

4.1.2 Crew Requirements. The presence of a human crew aboard a spacecraft creates many considerations which set these vehicles apart from their unmanned counterparts. Consumable resources such as water, air, and food must be provided. Crew living and sleeping requirements must be considered. A particular consideration which is of special interest to flight dynamics engineers is the generation of crew waste and methods of dealing with it. This subject will be addressed in more detail in Section 4.3 of this paper.

4.1.3 System Complexity. Manned spacecraft, because of the crew requirements noted above, are usually more complex than their unmanned counterparts. Because of this their design cycle may be years longer. The result has already been noted - the technology utilized for manned vehicles may lag behind that used for unmanned vehicles.

4.1.4 Flexibility. The observations noted in the previous paragraphs seem like an argument against manned spacecraft, and in fact are used by some for that purpose. They ignore, however, that aspect of manned spaceflight obtainable only from human beings-flexibility. Unmanned flights are severely limited by the imaginations of the personnel who, years before the actual flight, design the spacecraft and mission plans. The powers of the human brain, body, and senses to make observations, draw conclusions, refine flight plans as required, and evaluate and fix problems, are not available aboard the unmanned spacecraft. This situation tends to temper the long lead time arguments, since the human astronaut can observe, with no prior planning, unanticipated phenomena. Unmanned craft can usually observe only those things for which they were designed.

4.2 Attitude Determination, Maintenance, and Control

Although attitude determination techniques have remained rather stable throughout the history of spaceflight, there have been some significant differences between the details of the attitude maintenance and control approaches implemented for manned and unmanned programs. Unmanned programs have often used an attitude control technique in which one or more onboard star trackers remain locked onto known stars. Thus, attitude determination is, for all practical purposes, continuous. Attitude maintenance, as defined in this paper, is not required. This approach is encouraged by the relative stability of the attitude profiles of these flights, which remain in fixed attitudes for long periods of time. Manned programs, on the other hand, often involve very complicated attitude timelines, with frequent attitude changes.

The STS utilizes an attitude control approach in which an inertial reference platform is aligned, using star observations, several times daily. In between these attitude determinations the inertial platform is used as a reference for attitude maintenance. Primary error sources are the initial attitude determination itself and drifting of the inertial reference with time.

An earlier United States program, the Skylab Program, could be considered as man-tended rather than manned. Skylab was manned during part of its lifetime, but its attitude profile was stable, more like that of many unmanned vehicles. The Skylab attitude control system utilized sun and star trackers to perform a continuous autonomous attitude determination function. One problem encountered with the Skylab system is notable, and resulted from one of the unique aspects of manned vehicles previously discussed. Waste products dumped overboard were sometimes detected by the star tracker, resulting in false observations and invalid attitude determinations. Controllers on the ground had to monitor the system to guard against occurrences of this problem.

4.2.1 Ground Involvement in Attitude Control. Both manned and unmanned flights require significant levels of ground involvement in order to fly required attitude profiles. For manned spacecraft, however, that involvement has been more directed toward a backup role. United States astronauts normally command attitude maneuvers from the cockpit, flying a pre-planned attitude profile to accomplish mission objectives. Nominally, this profile is determined by flight design and planning personnel prior to liftoff. Deviations from the pre-planned profile may be required during flight operations to accommodate contingencies or to take advantage of inflight mission enhancement opportunities. Two examples of such deviations are noted below:

(a) A Flight plan change necessitated by a deployable payload failure which results in a one-rev-late or next-day deployment.

(b) A flight plan change desired to enhance mission scientific objectives by utilizing time saved due to early completion of other mission tasks.

For unmanned flights such deviations are usually more difficult. Changes to pre-mission plans may require commanded updates to onboard software. Onboard software for manned spacecraft, on the other hand, is usually more oriented toward manual onboard commands. Inflight changes require at least verbal requests from ground support personnel or at most the use of ground software to compute required attitudes. Manned spacecraft provide the flexibility to make the best use of available mission time, and onboard attitude control capabilities should be designed with this in mind.

4.2.2 Attitude Errors. Normally the dominant error source in an attitude control system such as that described above for manned spacecraft would be the drift of the reference platform between alignments. However, manned spacecraft present an additional problem, which often becomes the major source of error. Due to their size, manned spacecraft are subject to significant zero-G and thermal structural deformities. Cameras mounted in the experiment module of the Apollo spacecraft during lunar operations were misaligned by as much as one degree with respect to the reference platform when compared to their alignments as measured on the ground prior to launch. As a result, a highly accurate determination of the orientation of these instruments relative to either inertial space or the lunar surface was difficult or impossible. The lunar mapping camera avoided this problem by taking two simultaneous pictures, one of the lunar surface area to be mapped, the other of a reference star field. Since the two optical systems were mounted on the same fixed frame, their relative alignment could be measured almost perfectly. The star picture allowed a very accurate determination of the camera attitude independent of the spacecraft attitude, and thus removed the uncertainties due to spacecraft structural deformity. The design of any instrumentation system which requires a precise attitude reference should consider the use of such a spacecraft-independent attitude determination capability.

4.3 Orbit Determination

United States manned spacecraft have frequently presented an orbit determination problem not normally encountered when dealing with smaller unmanned craft. The Apollo spacecraft had an attitude control system which could be operated in several modes, only one of which used coupled jets to produce rotational accelerations. The uncoupled modes, used to accommodate various payload requirements, produced significant levels of translational thrusting, which were so unpredictable that they could not be modeled in ground trajectory computations. The spacecraft also had several vents which were used to dump the excess water created from fuel cell by-products and crew waste. This venting was also unmodeled.

As a result of these unmodeled forces the spacecraft trajectory was difficult both to determine and predict. Whereas unmanned trajectories could often be determined to accuracies of 100 meters or less, and predicted for hours or even days with only minimal degradation, the errors in estimates of the Apollo spacecraft trajectory often exceeded 1000 meters, and grew at rates which sometimes exceeded 10,000 meters per spacecraft orbit. The possibility of large errors in trajectory estimates required the development of new navigation procedures.

5. CURRENT STATE-OF-THE-ART

This section discusses current state-of-the-art in United States spacecraft flight dynamics. Statements made here are general, and are not intended to be applied to any specific mission or spacecraft. They are meant to provide a frame of reference for later discussions of STS capabilities. For the sake of brevity, a long discussion of the basis for the data is not provided. In many disciplines within the field of flight dynamics we find that true state-of-the-art technology is neither utilized nor practical for manned flights. For these disciplines this paper makes no attempt to carry the discussion beyond the state-of-the-art for manned flight. Guidance on obtaining reference documentation or points-of-contact for additional information on U.S. capabilities is available from the author on request.

5.1 Attitude Determination

Spacecraft orientation is almost always determined with respect to inertial space, with observations of sun and star positions relative to the spacecraft used for the determination. Onboard instrumentation to observe the positions is required.

Although attitude determination techniques have changed little since the initial flights of the United States Apollo program, the accuracy of the onboard instrumentation available for these determinations has increased significantly. We find, however, that manned spacecraft considerations, particularly spacecraft size (see paragraph 4.2.2) tend to dilute arguments for state-of-the-art attitude determination systems and sensors. Less expensive man-rated equipment is able to do the job required by U.S. manned programs, while payloads finding a need for higher accuracy attitude determination need to provide independent systems to avoid the problems created by structural deformity of large spacecraft.

5.2 Ground Tracking

The following sections describe briefly the networks currently being used by the United States to obtain spacecraft tracking data for United States manned programs. These same networks are also used for unmanned programs, although some vehicles requiring very high-fidelity trajectory information also use additional tracking support not used by the manned programs (see paragraph 5.5).

5.2.1 Direct Tracking. Direct tracking stations must be in line-of-sight view of a spacecraft in order to obtain tracking data. Two networks provide the direct data used to support United States manned space flights.

5.2.1.1 C-Band Tracking. C-band radar tracking stations utilize signals in the C-band frequency range for tracking. The characteristics of the C-band network used by the United States are described in the following paragraphs.

A majority of the C-band sites are military, but are available to civilian programs. The C-band tracking sites are concentrated in the continental United States and the Caribbean area. A few are located in other parts of the world. C-band sites are used exclusively for tracking. Telemetry and communications are not available through these networks.

C-band sites obtain range and angle observations. Range-rate data are available from some types of trackers, but are not used during the phases of STS flights discussed in this paper. The observation data may be obtained in one of two modes - beacon track or skin track. Beacon tracking utilizes a receiver/transmitter, or beacon, onboard the target spacecraft which receives the tracking signal, amplifies it, and retransmits it back to the tracking site. In the skin-track mode the signal is bounced off the target. The beacon-track mode is the preferred mode, since the required uplink signal strength is less, and the downlink signal strength is greater. In practice, however, skin-track is the prevailing mode. Most spacecraft prefer to avoid the weight and power requirements of the C-band beacon, since no C-band telemetry or command capability is available.

Table 1 compares the accuracy of C-band tracking observations with that of other types. Note that C-band accuracies compare favorably with other tracking types, although range-rate observations are not available.

TABLE 1 - COMPARISON OF TRACKING NETWORK OBSERVATION ACCURACIES
*CAPABILITY TO TRACK SMALL TARGETS MAY BE REDUCED

NETWORK TYPE	TRACKING TYPE	CHARACTERISTIC	OBSERVATION TYPE (DEG) ANGLE	(METERS) RANGE	(METERS/SEC) RANGE-RATE
DIRECT	C-BAND*	NOISE	0.010	5	-
	SKIN TRACK	BIAS	0.015	5	-
	C-BAND	NOISE	0.010	3	-
	BEACON TRACK	BIAS	0.010	10	-
	S-BAND	NOISE	0.010	3	.002
		BIAS	0.050	10	0
RELAY	S-BAND	NOISE	-	-	.003
(TDRSS)		BIAS	-	-	0

5.2.1.2 S-Band Tracking. S-band radar tracking stations utilize signals in the S-band frequency range for tracking. S-band radar tracking is used by most United States space programs.

Two S-band tracking networks are currently available to United States space programs. The Space-Ground Link System (SGLS) is a military system operated by the United States Department of Defense. It consists of seven tracking stations located throughout the world. Its only civilian use is for the STS program. The Ground Spacecraft Tracking and Data Network (GSTDN) is a civilian network, operated by the National Aeronautics and Space Administration (NASA), and comprised of 13 stations. The GSTDN supports almost all United States civilian programs. S-band skin tracking is not an option. Both telemetry and command are also available through S-band networks.

S-band sites obtain range, range-rate, and angle observations. Range-rate is obtained by measuring the frequency shift in the return signal caused by the Doppler effect.

Table 1 compares the accuracies of S-band tracking observations with those of other types.

5.2.2 Relay Tracking. The Tracking and Data Relay Satellite System (TDRSS) is currently being used, in conjunction with the GSTDN, as the primary tracking and communication network for the STS and several other major United States space programs.

The TDRSS is used to obtain relayed tracking observations of the Space Shuttle and other United States spacecraft. The TDRSS, in its planned configuration, will include three fully-functional satellites in various geosynchronous orbits communicating with a ground terminal located in White Sands, New Mexico, USA.

The current TDRSS network includes only a single satellite. This current satellite is not fully operational due to problems encountered during its launch in 1983. The next Tracking Data Relay Satellite (TDRS) will be launched by the next Space Shuttle flight, sometime in early 1988, with the third satellite launched within 6 months of the second. Nominal plans are for the use of only two satellites at any one time. Therefore, the TDRSS network should be fully operational by late 1988 or early 1989.

The TDRSS tracks target spacecraft by relaying a signal from the ground terminal through one of the TDRS to the target. A transponder on the target spacecraft receives the signal, amplifies it, and retransmits it back, usually to the same satellite, or in special circumstances to another of the TDRS, where it is relayed back to the ground terminal. The transmission from the ground terminal to the target spacecraft is referred to as the forward link. The transmission back to the ground terminal is referred to as the return link.

Observations obtained by using the same TDRS for both the forward and return link transmissions are referred to as 2-way. Observations obtained by using different TDRS for the forward and return link transmissions are referred to as hybrid. Ground terminal to TDRS transmissions are in the K-band frequency range. TDRS to target spacecraft transmissions may be in either or both the K-band or S-band range, depending on the requirements of the target spacecraft transponder.

The TDRSS has the capability of obtaining both range and Doppler shift observations. The STS program utilizes only Doppler observations, due to incompatibilities between the Space Shuttle transponder and the TDRSS ranging system.

Table 1 compares the accuracy of TDRSS relay tracking observations with that of other types. From a pure accuracy standpoint TDRSS observations compare favorably with those obtained from direct tracking networks. However, the information content of the data is not comparable. This will be discussed further in the following paragraph.

5.2.3 Geometry Considerations. When comparing the effectiveness of direct and relayed tracking, geometric considerations must be examined. Because of the length of the transmission paths for TDRSS tracking the information content of the data is not nearly as high as that of direct observations. A rule of thumb used by STS ground navigation personnel is that a single pass of TDRSS data, usually about 55-60 minutes in length, is roughly equivalent to a single 6-7 minute pass of ground direct data.

For the majority of unmanned spacecraft this difference in information content is not significant, since long periods of time are usually available for orbit determination. For manned flight, however, the difference can become a significant factor in planning for adequate navigation support.

5.3 Relative Tracking

The United States uses relative (spacecraft to spacecraft) observations for orbit determination only for rendezvous operations. Details on the use of relative tracking in the STS program are included in Section 6.3.3.

5.4 Global Positioning System

The Global Positioning System (GPS) is being developed by the United States Department of Defense (DOD) as a navigation system for eventual use by landcraft as well as aircraft and spacecraft. The system uses a constellation of up to 18 satellites. Each satellite will broadcast a unique signal. GPS receivers extract relative position and velocity information from these signals to determine their own position. Filtering of this position information can provide state vector estimates for spacecraft.

The GPS system is still in the development phase, so operational results are not yet available. Performance results from a preliminary constellation of six satellites indicate that position accuracies of 10 - 100 meters should be achievable. There are currently no funded plans to use GPS receivers on the Space Shuttle, but the United States Space Station will almost certainly utilize the system. Some consideration also has been given to using GPS for Space Station attitude determination by using position determinations from several receivers distributed over the station.

5.5 Orbit Determination

The variables associated with orbit determination accuracies are many. Primary error sources include one's models of atmospheric drag, the Earth's geopotential, atmospheric refraction of tracking signals, solar radiation pressure, and unmodeled spacecraft thrusting. When we attempt to address state-of-the-art accuracy numerous secondary error sources, such as tracking station locations, the Earth's polar motion, Earth rotation rate variations, and relativity effects, must be considered. Other factors, such as the response time required, must also be evaluated. In many cases the altitude of the spacecraft orbit is an important consideration, since the effects of several major error sources tend to decrease as altitude increases.

Achieved orbit determination accuracies vary significantly, of course, as the parameters noted above vary. Table 2 presents an overview of typical orbit determination accuracies from U.S. flights. The accuracies noted in line 10 were obtained using very accurate laser ranging data in a detailed postflight analysis which required over a year to complete. All other accuracies noted are typical of those obtained by the Mission Control Center (MCC) in near-real-time (lines 1, 2, 4, 5, 7, and 8) or by a medium fidelity post-flight analysis effort.

6. SPACE TRANSPORTATION SYSTEM

6.1 General Comments, Scope, and Limitations

The current United States manned program, the STS, is the reference for all comparisons and comments presented here. The STS flights are only one of several phases of the United States space program. Thus, statements and conclusions from this paper should not be applied generically to all United States programs.

6.2 Attitude Determination, Maintenance, and Control

6.2.1 Hardware Description. The STS attitude control system is built around a system of three Inertial Measurement Units (IMU's), each consisting of a stable member and a gyroscopic control system. The system is triply redundant in that any one of the IMU's is capable of controlling the spacecraft. Normally all three units are used by the onboard system. Redundancy Management (RM) software is responsible for determining the operational status of each unit, isolating a bad unit in the event of a failure, and identifying a dilemma in the case of a second failure. The orientations of the three stable members are skewed relative to one another to simplify the RM process.

The IMU's are aligned periodically, usually every eight to twelve hours, during the onorbit phases of the flight to minimize the effects of stable member drift. Two star trackers are available for these alignments. The availability of a manual optical alignment system, known as the Crew Optical Alignment Sight (COAS), creates a triple redundancy in the alignment capability. Virtually all of the alignment process is automated. The star trackers are automatic in their lock-on and tracking functions. The only constraints are that a star must be at least 3.0 in magnitude, and it must be in the onboard star catalogue. Onboard software determines whether a star is

TABLE 2
TYPICAL UNITED STATES ORBIT DETERMINATION ACCURACY

LINE	TYPE	ALTITUDE	RESPONSE TIME	PROPAGATION TIME	UNMODELED THRUSTING	1-SIGMA POSITION (METERS)
1	STS	175-700	5 MIN	NONE	YES	350
2	STS	175-700	5 MIN	2.25 HRS	YES	6000
3	STS	175-700	2-6 WEEKS	NONE	YES	100
4	UNMANNED	175-350	10 MIN	NONE	NO	100
5	UNMANNED	175-350	10 MIN	24 HRS	NO	300
6	UNMANNED	175-350	2-6 WEEKS	NONE	NO	50
7	UNMANNED	350-700	10 MIN	NONE	NO	50
8	UNMANNED	350-700	10 MIN	24 HRS	NO	200
9	UNMANNED	350-700	2-6 WEEKS	NONE	NO	25
10	UNMANNED	>1000	6 MONTHS	NONE	NO	<1

part of the catalogue, and therefore usable for alignments. Once this determination is made a series of measurements of the star position is obtained, converted to a unit vector, and stored for future use. Up to three such vectors are stored in a table. Subsequent vectors are evaluated by the onboard software to determine whether they improve the current alignment accuracy. When an alignment is desired the crew evaluates the star vector table. The onboard display includes information to aid the crew in evaluating the quality of the stored unit vectors. If the current unit vectors are adequate the crew queues the alignment. If not, the spacecraft is maneuvered to a pre-planned alignment attitude to obtain two additional unit vectors before the alignment is queued. Once the alignment has been queued the onboard software computes the torquing angles required to return the IMU stable members to their original orientations and executes the alignment.

During attitude maneuvers the onboard system is required to determine attitude rates. This determination is made by differentiating orientation information during the orbital phases of the flight. Rate gyros are used for this determination during the high-rate phases of ascent and entry.

6.2.2 Operations Overview. The following paragraphs describe the STS attitude dynamics systems from an operations standpoint, including the division of responsibility between man and machine, and ground and onboard.

Attitude determination for the Space Shuttle vehicle is purely an onboard function. Star trackers obtain the observations which are used to align the reference platform. Manual intervention is required, either by the astronauts or by ground controllers, to initiate and control the alignment process. Once commanded, however, the onboard computer takes care of all required processing. Some success has been achieved in automating the alignments, but the procedure works only when the spacecraft is already in an attitude which places acceptable stars in the star tracker field of view.

Once the reference platform is aligned, the attitude maintenance function, performed by the onboard computer, is completely autonomous. No interaction by astronauts or ground controllers is required.

Attitude control is performed by the onboard computer, but only upon ground, astronaut, or pre-programmed command. The nominal mode is for the astronauts to enter desired attitudes manually. The onboard system then maneuvers the spacecraft automatically. The astronauts also have the capability to override the computer and maneuver manually, but fuel usage in the manual mode is far higher, and the automatic mode is thus preferred.

6.2.3 Ground Functions. The primary role of ground controllers is to provide planning support for potential or required flight plan changes. The capability to support planning functions normally carried out by the mission planning team prior to a flight must be available to the real-time support team. This provides for the best use of the flexibility of manned flight, as well as the capability to deal with contingencies should they arise. The ground team is required to be particularly aware of flight-specific attitude constraints, such as payload sun limitations, which are not programmed into the onboard system.

6.3 Orbit Determination, Maintenance, and Prediction

6.3.1 Operations Overview. The following paragraphs present an overview of STS orbit determination operations, providing insight into the level of manual control exercised over various phases and the distribution of responsibilities between the ground and the onboard systems.

Orbit determination for the orbital phases of the STS program is primarily a ground function, with a notable exception during rendezvous operations. Ground operations are performed manually. The software is interactive, and has been designed for exceptionally quick response, but in all cases there is a human in the loop. On the other hand, the onboard software used during the final phase of rendezvous is highly automated. The astronauts are responsible for initializing the processing, for monitoring its progress, and for performing certain control functions, but no direct intervention in the processing is required.

An autonomous orbit determination processor has been designed for the MCC in Houston. This software will perform untended orbit determination for non-critical phases of STS flights, i.e. for about 60-75% of operational periods. The software is in the implementation phase, and has yet to be tested and approved for operational use. Further details on this system are available from the author.

Orbit maintenance for STS is a dual function, performed both on the ground and onboard the spacecraft. The ground function is man-tended. The software is designed to make the orbital parameters automatically available to users. Ground controllers monitor the quality of the ephemeris, and provide periodic updates as required.

The onboard system is an autonomous system, and will continue to provide current trajectory information for the duration of a flight. Because of the build-up of propagation errors periodic updates from the ground are required. Ground controllers monitor the onboard system around the clock to determine when to make these updates.

Orbit prediction is a ground responsibility, although the onboard system has some limited capabilities which are required for targeting for rendezvous and contingency operations. The ground orbit prediction function is essentially manual, although the orbit maintenance function makes available to users a short-term (up to 48 hours) prediction of the nominal spacecraft trajectory.

6.3.2 Ground Operations. All ground orbit determination for the STS program is performed in the MCC in Houston, Texas. The following paragraphs describe the ground operations process in detail.

Tracking data are returned from ground tracking networks via a worldwide network composed of geosynchronous satellites, ground communication lines, and data processing systems. The tracking data are transmitted from the tracking sites via either communication satellite systems or ground transmission lines. All data are sent first to the Goddard Space Flight Center (GSFC) in Greenbelt, Maryland. At GSFC the data are processed at the Network Control Center (NCC) and routed to the MCC. TDRSS relayed tracking data are transmitted from the TDRSS ground terminal at White Sands, New Mexico, via communication satellite directly to the MCC.

Tracking data arrive at the Houston MCC within a few seconds after their receipt at the tracking station. At the MCC tracking data are stored in batches. A batch contains all the data obtained from a single ground or TDRSS pass.

MCC software is driven by requirements much different from those which might typically be considered for unmanned flights. Response time and flexibility are of the utmost importance. Manned spacecraft trajectories are much less predictable than those of unmanned spacecraft. Thus, minimizing trajectory prediction intervals is important. Similarly, it is important to make the most of having people in the loop. Quick and efficient replanning capability is desirable.

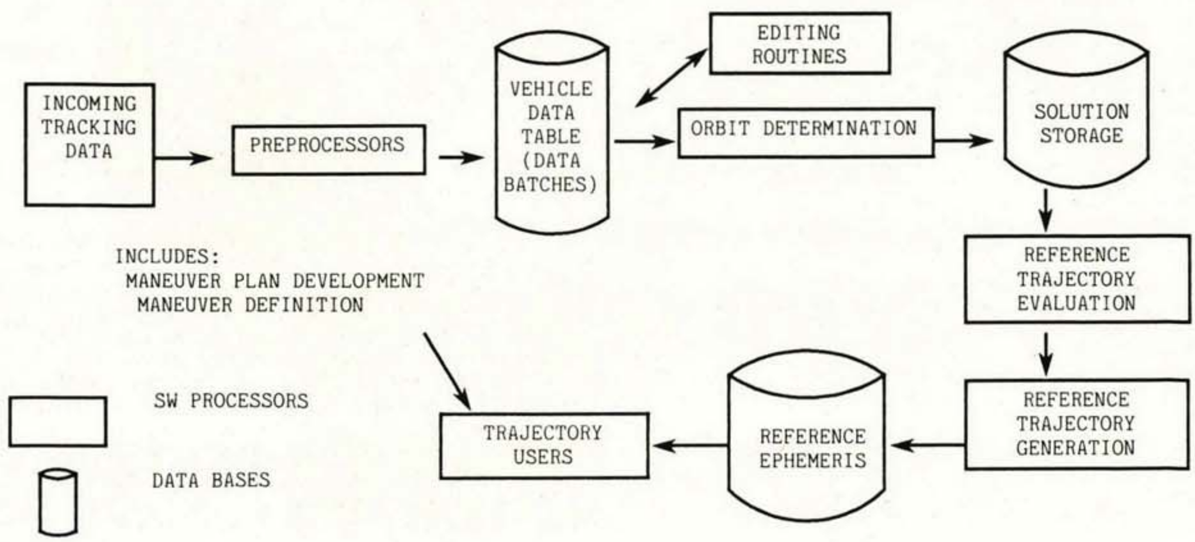
Figure 1 presents an overview of the major elements of the MCC trajectory software. The following paragraphs discuss each of the major processors and data bases.

The concept of a reference ephemeris is key to the integration of all MCC trajectory software. The reference ephemeris is a common data base accessed by all users requiring current or future predicted Space Shuttle trajectory and/or attitude information. It contains both an attitude and a trajectory timeline, and is often referred to simply as the ephemeris.

The attitude timeline contains the planned mission attitude profile. The timeline is updated as the mission progresses to reflect the as-flown timeline and changes in the flight plan. The timeline is accessed by any applications requiring attitude information. These include both payload users, who often require spacecraft pointing information to determine the line-of-sight of onboard instruments, and other MCC software processors, such as maneuver computation processors, which must determine the direction of translational thrusters, and the trajectory integrator, which requires attitude information to determine the effective vehicle frontal area for atmospheric drag computations. No attempt is made to profile the attitude during the execution of attitude maneuvers. Attitude changes are modeled as instantaneous in the attitude timeline.

The reference trajectory covers a specified interval of a flight, generally two or three days. It begins at or before current time, and extends forward into the upcoming phases of the flight. The length is variable, and is determined based upon the flight activities. The trajectory normally includes all planned and actual maneuvers during its time span.

FIGURE 1
MCC TRAJECTORY SOFTWARE OVERVIEW



The accuracy of the attitude and trajectory references cannot be easily defined. Their accuracy is dependent upon many variables. Some of the more important variables are the relationship to current time, the spacecraft activity, and the criticality of the mission phase. Users who require accurate reference trajectory information need to make their requirements known prior to flight so that the timeline can be optimized appropriately.

Tracking data are received at the MCC in raw digital format. Preprocessing software transforms the raw data into a form usable by the orbit determination program. This processing includes unpacking the digital data frames, evaluating the data validity flags included within the frames, discarding invalid data, converting the data to engineering units (the MCC uses English units, feet for range measurements, degrees for angles. Doppler shift observations are stored as counts of the number of cycles of frequency shift), performing certain gross credibility checks on the data, editing any bad observations, and storing all accepted data in batches.

As noted above, tracking data in the MCC are stored in batches, in a data base referred to as the Vehicle Data Table (VDT). The term batch as used in the MCC refers to a single pass of data from a single tracking station (for direct data) or satellite (for relay data). Each batch is assigned a unique number, and all subsequent accessing of tracking data, both by other software processors and manually, is by that number.

Two data editing techniques, one automatic and one manual, are available in the MCC. Either an entire batch of data or individual data points within a batch can be edited.

The automatic data editing processor operates on first and second differences of the tracking data residuals to identify discontinuities in the data. Points or groups of points which can be isolated as outliers are flagged as invalid. The process is very effective for detecting a few bad points, but is not able to identify systematic problems such as data biases.

The manual data editing processor permits the user to examine the tracking data residuals for a batch of data and manually identify individual points or the entire batch as invalid. The manual process is done interactively by the user. Complete editing of a batch of tracking data typically requires less than a minute.

The orbit determination process is a key element of trajectory operations. The following paragraphs describe the process from both a mathematical and an operational standpoint.

The MCC utilizes a weighted least-squares approach to orbit determination. The process is designed to satisfy two key requirements:

(a) Speed is required. Orbit solutions are often required within minutes of data receipt.

(b) Accuracy is required. The process must accurately accommodate the high level of unmodeled spacecraft thrusting typically exhibited by the Space Shuttle vehicle.

To satisfy the first requirement it is desirable to process as short an arc of data as possible and to minimize the number of elements of the solve-for solution vector. The second requirement demands that the solved-for solution at the end of the data arc accurately reflect the trajectory as modified by spacecraft thrusting.

To satisfy all requirements a modified weighted least-squares technique, which we refer to as batch-to-batch (BTB) processing, is used. With the MCC BTB processing technique a single batch of data is processed in each solution. Information from previous processing is available as an a priori covariance matrix, which is the output covariance from the previous solution. The user has the option of using the covariance directly or multiplying it by a user-controlled constant to downweight the previous data. This latter procedure is necessary when unmodeled spacecraft thrusting has occurred. Operational and mathematical details for this processing technique are available from the author.

Of the three data types available from the tracking networks (range, Doppler or range rate, and angles) only range and Doppler data are normally used. Angle data are validated and retained, since they are required when no a priori knowledge is available, but they are not processed in the normal BTB processing.

Three basic criteria are used for evaluating orbit solutions as they are generated by the BTB processor. The criteria currently in use have been developed from experience over a period of several years. They are discussed in detail in the following paragraphs.

In discussing the tracking data residuals we assume that the tracking data have already been validated, as discussed earlier in this section. For each data type commonly used in the MCC a maximum residual magnitude has been established. Each data type contained in the batch being processed is examined to determine whether the residuals for that batch meet the corresponding criterion. If one or more of the data types fails to satisfy its criterion, the solution is considered to be unacceptable.

When a BTB solution is computed by the MCC the processor automatically differences the new solution with the previous one and displays the changes in various elements of the orbit. Four key elements of the orbit - the semi-major axis, eccentricity, orbital inclination, and longitude of the ascending node - are monitored by the operator. As with the residuals discussed previously, a set of maximum changes have been established for each element based on past experience. These criteria would seem rather large to one used to dealing with unmanned spacecraft, since they must consider the unmodeled thrusting characteristics of the Space Shuttle vehicle. In practice, the criterion for a given element must be varied, depending upon the attitude control activity of the spacecraft during the past two hours. Greater numbers of attitude maneuvers mean that larger changes should be expected. If one or more of the orbital elements fails to satisfy its criterion the solution is considered unacceptable.

The BTB processor automatically displays the elements of the output covariance matrix for each solution. These elements are examined as part of the solution evaluation. It is desirable that the position and velocity uncertainties fall within a certain range. If the values are too small, the next solution, which uses this one as input, may be too constrained. If they are too large the current solution may not properly reflect the information from the previous data. The test is applied to two elements - the uncertainties in total position and total velocity. If either of these elements fails to satisfy its criterion the solution is considered unacceptable.

A BTB solution which fails one or more of the criteria discussed in the previous paragraphs may not indicate that a batch of data should be discarded, but rather that the optimum processing technique has not been used. The user in the MCC exercises a high degree of manual control over the orbit determination process, and may choose to either reprocess or discard the data. Reprocessing normally means manually increasing the uncertainties associated with previous data. This is frequently required because of the unmodeled thrusting characteristics of the Space Shuttle. If the users choose to reprocess, they may continue increasing the a priori covariance until an acceptable solution is achieved or until the maximum covariance limit is exceeded. If an acceptable solution cannot be achieved, the user must discard the solution or consciously elect to override the criteria and accept the best of the solutions obtained.

Output solutions from the BTB processing are automatically stored, in the form of state vectors and covariance matrices, in a data base. The user is allowed to compute multiple solutions for each batch of data, but only the latest solution is stored. Solutions for the last 50 batches processed are available. Additional data base storage for state vectors only (no covariance matrices) is available to the user by manual command. Once a state vector is stored it is available to the user by simply specifying the storage name rather than all components of the vector. This eliminates both time and the chance for input errors.

Once a new BTB solution has been computed, evaluated, and determined to be acceptable, the reference trajectory is evaluated to determine whether an update is required. The basis for this evaluation is a display which shows the difference between the new solution and the reference trajectory, in several reference frames, at a time near current time. The assumption in the evaluation process is that the new BTB solution represents the latest and best estimate of the current spacecraft orbit. Deviations between this new solution and the reference trajectory thus represent errors in that trajectory.

The criteria used to determine whether an update is required are not fixed, but rather depend upon the flight phase. Often, when a critical maneuver is approaching, the update is carried out regardless of the size of the differences in order that the best available solution be used for the maneuver. In other cases, where no critical activities are in progress, the differences may be allowed to grow to several kilometers before the update is completed.

All executed and planned spacecraft translational maneuvers are included in the reference trajectory. The maneuvers are computed by other MCC processors prior to the reference trajectory generation, and may require modification when a new trajectory is generated to maintain their planned target conditions.

The reference trajectory generation process updates not only the trajectory itself, but also various other related data bases which are required by multiple users, such as predicted ground station communication times and spacecraft sunrise-sunset times. The goal is to standardize as much of the commonly used data as possible and minimize computation time. The entire generation process requires as much as five minutes for a long trajectory.

6.3.3 Rendezvous Operations. Rendezvous has been the one exception to the rule that United States orbit determination has been ground-based.

During the terminal phases of a rendezvous the active rendezvous vehicle must know the position of its target relative to itself to, at worst, a few hundred meters. This requirement assumes that the crew can maneuver manually during final approach. For an unmanned approach the required accuracy is reduced to the one meter level. For our manned spacecraft we have never been able to guarantee the latter level of accuracy, due to the unmodeled thrusting discussed previously and to the frequent spacecraft maneuvers required to fly the rendezvous profile.

The approach used for past United States programs and for the STS program has been to use onboard determination of the relative state as the primary orbit determination capability. The initial estimates of the state vectors of both the active and passive vehicles are provided by the ground, based on ground tracking and processing. The active vehicle - the Space Shuttle - updates its estimate of its own position and velocity by processing observations of the target vehicle obtained from onboard instrumentation.

For the Space Shuttle vehicle onboard observations are obtained automatically by two instruments - a star tracker, which can track solar reflections from the target spacecraft at distances of up to 200 Kilometers (km), and rendezvous radar, which is used after the relative distance has closed to 50 km or less. A third instrument, the COAS, is available as a manual backup to the others for contingencies.

The observations are processed by the onboard computer using a Kalman filtering technique. The estimate of the target trajectory is held fixed throughout the process. Only the active vehicle trajectory is adjusted. Inertial accuracy is not critical to a successful completion of the rendezvous.

Throughout most of the rendezvous sequence Space Shuttle attitude control is maintained in the automatic mode, with the onboard computer commanding any required attitude maneuvers. An exception is the terminal phase of the rendezvous, where manual control is usually required for braking and station-keeping. Numerous tests and formal experiments have shown that fuel usage is far less in the automatic mode.

In all United States rendezvous operations to date the manned vehicle has been the active spacecraft. Currently, in the planning stages are several flights where the active role would be shared by both vehicles, but the final phases of the rendezvous would still follow the current scenario.

The subject of rendezvous accuracy is far too broad to cover in a paper of this type. Related information is available from the author on request.

The rendezvous scenario used by the STS is a three or four maneuver sequence, usually requiring six to eight hours to complete. This sequence assumes that the proper relationship between the two orbits has been established, either by launching into the required orbit, or by previous maneuvers. The first maneuver is a ground-targeted maneuver. All required orbit determination and maneuver computations are performed on the ground and the results uplinked to the spacecraft. All remaining maneuvers in the sequence are computed and executed by the onboard system, which becomes prime for the remainder of the rendezvous. Throughout this onboard phase of the rendezvous, the ground determines an independent estimate of the spacecraft position and velocity, and maintains a ground maneuver plan for rendezvous completion. This ground information is available for immediate uplink in the event of an onboard failure, and is used throughout the sequence to monitor the onboard performance.

6.4 Orbit Maintenance and Prediction. Spacecraft orbit maintenance and prediction depends upon some form of numerical integration of the equations of orbital motion and modelling of the physical forces which act on the spacecraft. Numerous options for performing this integration are available. For manned spacecraft the selection of numerical integration techniques and models has always been a trade-off between speed and accuracy. The capability to provide answers quickly has been equally or more important than the refinement of a high degree of accuracy. Because of this, the following paragraphs will not dwell on detailed technical descriptions of integration techniques or models, but rather on an overview of techniques and results.

6.4.1 Ground Operations. United States ground orbit maintenance and prediction techniques for manned flights have remained relatively unchanged throughout the Apollo, Skylab, ASTP, and Space Shuttle programs. An estimate of the spacecraft's future position, in the form of a series of predicted vectors, is always maintained in the Houston MCC. This series of vectors, referred to as the reference trajectory, or the ephemeris, was discussed in some detail in Section 6.3.2. The following paragraphs present additional details on the techniques and models used. Those desiring detailed references for any of the models discussed should contact the author.

The MCC uses an Encke integrator. The particular implementation chosen results in a step size of approximately 50-55 seconds in low Earth orbit.

The following paragraphs describe the major physical models employed by the MCC. These models have remained stable since the Apollo program, although values for various constants have, in many cases, been refined significantly.

The Earth's geopotential is modeled by a spherical harmonic expansion. Through the years this model has changed only in the degree and value of the terms included. For the STS program, the model used is seventh order. The values for the constants are from a higher order model developed by the Goddard Space Flight Center.

The STS Program uses the 1970 Jacchia model. Jacchia's original implementation of the model was modified to eliminate daily variations. The computation of the ballistic coefficient considers the variable frontal area due to spacecraft attitude changes.

Other models used by the MCC include the Fischer ellipsoid and perturbations due to the Moon and Sun. Certain well-known spacecraft thrusting is also modeled.

6.4.2 Onboard Operations. The Space Shuttle maintains its onboard estimate of position and velocity by integrating the results of orbit determination calculations, usually provided by the ground. Onboard integration techniques are similar to those used on the ground, but allow the inclusion of accelerometer information from onboard instruments. These data allow the onboard to more accurately maintain its estimate of position and velocity through planned translational maneuvers. Care is necessary in using the accelerometer information. Accelerometer biases can cause large errors over long integration periods. These are avoided by disabling the use of the accelerometer information except during periods of high thrusting.

6.5 Contingency Operations

Manned spaceflight can be a two-edged sword. The presence of the human crew offers great flexibility in dealing with contingencies, while creating a new array of systems for which failure is a possibility. The advent of reusable spacecraft has caused the positive aspects of manned flight to greatly outweigh the negative ones. The attempt here is to deal with this subject in a general sense, rather than discussing any particular contingency.

To make the best use of the advantages of manned flight, both to deal with contingencies and to make use of options which arise from mission flexibility, a high level of quick-response real-time mission planning capability is required. Many contingencies which would end the functional phase of unmanned flights can be dealt with and surmounted during manned flights. A replanning of the mission timeline, however, is almost always required. When unmanned operations can be replanned, the luxury of moving slowly and carefully on the effort is usually there. For manned flight, however, the time-in-orbit limitations make it mandatory that the replanning be completed as soon as possible. Response times of minutes to hours rather than days are usually required.

All of this boils down to two major considerations which should be addressed very early in the planning stages of a manned flight.

(a) A high level of quick-response planning capability should be available for use during the flight.

(b) Prior to a manned flight a significant level of effort, far more than would be necessary for unmanned flight, should be baselined for anticipating contingencies and planning for responses.

Emphasizing these two considerations prior to flying a manned spacecraft will allow for the best capability not only to deal with contingencies but to make use of the unique advantages of manned flight.

7. Manned Operational Considerations - A Summary

There are numerous constraints to STS operations which are unique to manned spaceflight. Many of these constraints have been discussed in this paper. The following list is a summary of what I see as the major problems and associated guidelines for manned spaceflight trajectory operations planning and design.

(a) Manned spacecraft will provide greater flexibility than unmanned. Plan the appropriate capabilities, both ground and onboard, to make use of this flexibility.

(b) Replanning will require quick response. Be sure that ground support capabilities are designed accordingly. Plan for expending a significant effort on premission contingency planning - anticipating contingencies and planning for responses.

(c) Unmodeled spacecraft thrusting will probably be a problem. Spacecraft and support system design should anticipate this. Flight planning should consider it.

(d) Spacecraft dumps of unwanted waste or consumables will create contamination and thrusting. Consider these problems in your planning and design.

(e) Zero-G and thermal structural deformities will make it difficult to achieve accurate pointing of onboard instruments. Consider carefully the requirements and design for any instrument requiring very high pointing accuracies.

(f) Attitude control system thrusting may have significant effects on your orbit determination capability. Analyze the attitude control system to determine these effects, and consider them in your premission planning.

Obviously there are many other differences between manned and unmanned flight dynamics, but I feel that the list above summarizes the major areas of concern. As a closing recommendation I caution you to anticipate the unanticipated. Many of the phenomena associated with manned flight are new to those whose experience is limited to unmanned programs. Do not let them catch you unprepared.