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SPACE SHUTTLE ORBIT DETERMINATION USING EMPIRICAL FORCE MODELING OF ATTITUDE MANEUVERS FOR THE GERMAN MOMS-02/D2 MISSION

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In the spring of 1993, the MOMS-02 (Modular Optoelectronic Multispectral Scanner) camera, as part of the second German Spacelab mission aboard STS-55, successfully took digital threefold stereo images of the surface of the Earth. While the mission is experimental in nature, its primary goals are to produce high quality maps and three-dimensional digital terrain models of the Earth's surface. Considerable improvement in the quality of the terrain model can be attained if information about the position and attitude of the camera is included during the adjustment of the image data.

One of the primary sources of error in the Shuttle's position is due to the significant attitude maneuvers conducted during the course of the mission. Various arcs, using actual Tracking and Data Relay Satellite (TDRSS) Doppler data of STS-55, were processed to determine how effectively empirical force modeling could be used to solve for the radial, transverse and normal components of the orbit perturbations caused by these routine maneuvers. Results are presented in terms of overlap-orbit differences in the three components. Comparisons of these differences, before and after the maneuvers are estimated, show that the quality of an orbit can be greatly enhanced with this technique, even if several maneuvers are present. Finally, a discussion is made of some of the difficulties encountered with this approach, and some ideas for future studies are presented.

INTRODUCTION

During the course of the second German Spacelab mission flown aboard the U. S. Space Shuttle in the spring of 1993, the MOMS-02/D2 camera performed digital

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mapping of the Earth's surface. The special characteristics of the camera combine high resolution panchromatic images for three-dimensional geometric information with multispectral images for thematic information. This experimental project has been funded by the German Federal Minister for Research and Technology (BMFT) with the aim of producing high quality maps, acquiring digital data for geographic databases and information systems, and generating digital terrain models with an accuracy of 5 m or better. To attain these accuracies in the terrain models, estimates of the camera's position and attitude during its operation must be introduced into the least squares adjustment of the image data. While it is not the intent of this paper to discuss the operation of the camera or of the mathematical modeling of the relevant phenomena, excellent explanations of these aspects can be found in (Ref. 1) and (Ref. 2). It is, however, the goal of this work to discuss the process by which position estimates of the Shuttle were established, and how these estimates can be improved by employing empirical forces to estimate the effects of routine attitude maneuvers.

The paper will begin by briefly reviewing the basic features of the primary on-orbit tracking system used during Shuttle missions: the Tracking and Data Relay Satellite System (TDRSS). This will help establish some perspective on one of the difficulties in estimating attitude maneuvers. This is followed by a summary of some of the key results from simulations performed in an earlier work (Ref. 10) to determine an appropriate dynamical model to be used for the processing of arcs. Then, a fairly detailed discussion is made regarding the effects and estimation process of the significant attitude maneuvers, which occur throughout the mission. Finally, a presentation of the quality of each orbit and the degree to which it was improved by estimating maneuvers is given.

TRACKING SYSTEM

The launch and subsequent deployment of TDRS-A from STS-6 (Space Transportation System) in April, 1983 established the first of five near-geostationary satellites making up the current TDRS System. The system was established by the National Aeronautics and Space Administration (NASA) as its fundamental means for relaying tracking, telemetry, voice and image data between a user-satellite and the ground. Nominally, two TDRSS satellites provide near-global coverage; but, due to the existence of only one ground terminal in White Sands, New Mexico, the use of additional satellites does not enhance the coverage. These two satellites, located at longitudes of 41° and 171° W, are always in view of the ground terminal and provide a link with the user-spacecraft for over 85% of the orbit. Fig. 1 shows the zone of exclusion for typical TDRSS users.

The Space Shuttle is equipped with S- and Ku-Band antennas for sending and receiving information via the TDRSS link. While this link provides for various forms of communication, the only tracking observable is a two-way Doppler signal. Fig. 2 shows the basic geometry of the TDRSS-user configuration and of the Doppler signal. A detailed explanation of the construction of the signal can be found in (Ref. 10), or, if an in-depth understanding of the entire TDRS System is sought, in (Ref. 8).

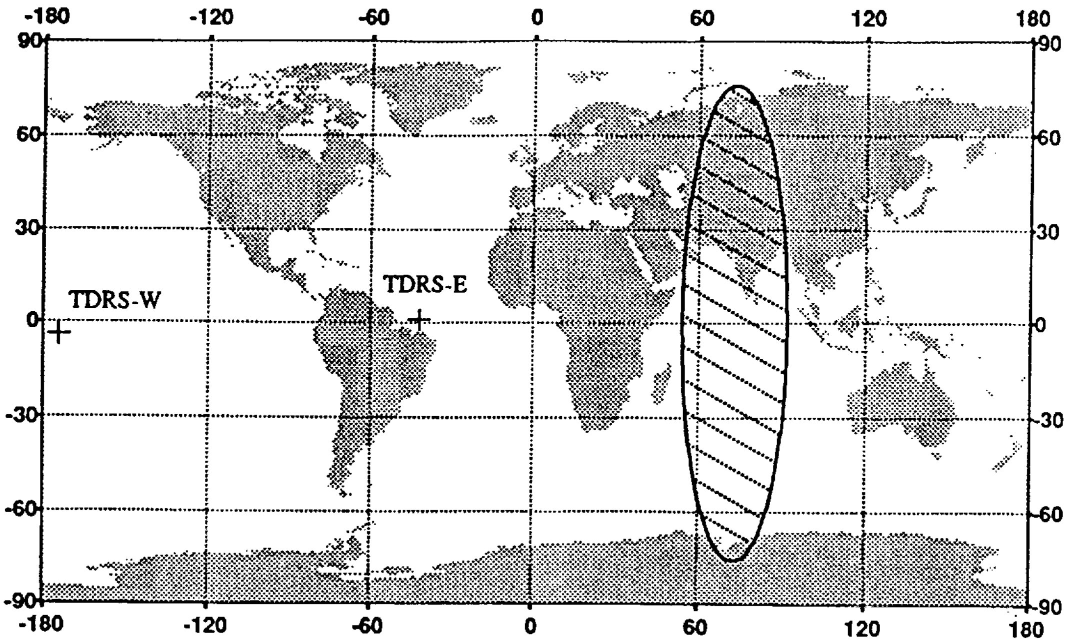

Fig. 1 Zone of Exclusion for TDRSS Users (200 km Altitude)

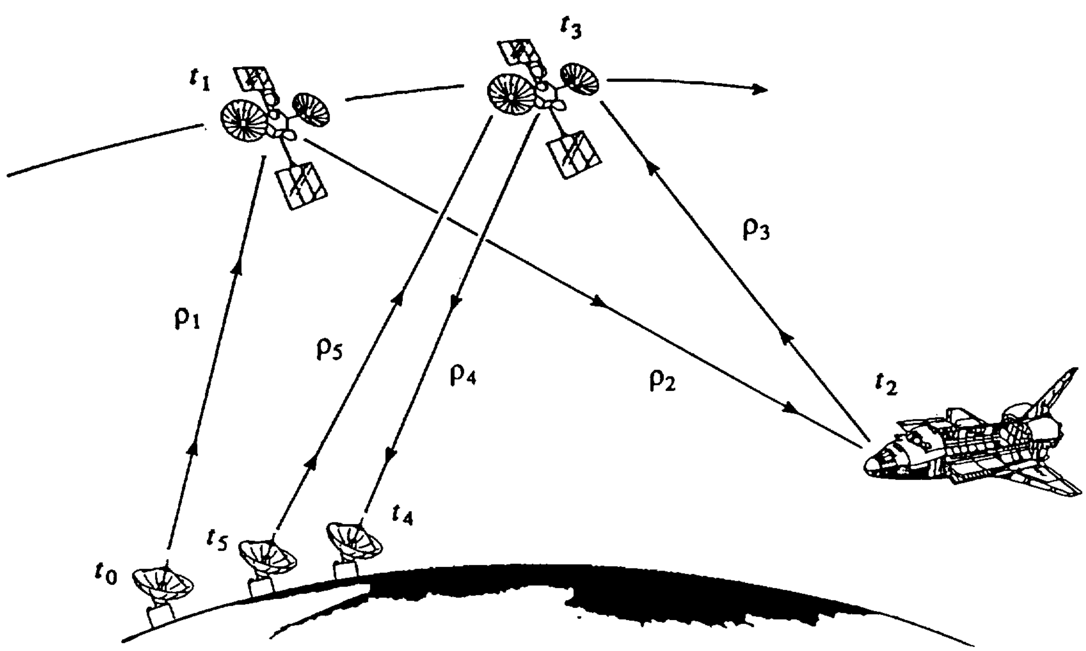

Fig. 2 TDRSS-Shuttle Tracking Geometry

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DYNAMICAL MODEL AND ORBIT PERTURBATIONS

One of the primary concerns in any analysis regarding orbit determination is to establish good mathematical models describing the response of the spacecraft to both natural and man-made forces. Any deficiencies in these models will be reflected in the comparison of the observed with the predicted behavior. Additionally, errors in the geometric and dynamic modeling of the observations, stochastic corruption of the signal and uncertainties in the model parameters will also degrade the quality of the orbit. The following sections briefly describe the dynamical force models used in this study, the degree to which these forces affect the motion of the Shuttle and the sources of any additional uncertainties in the model or observation type.

Dynamical Model

The forces which, in some reasonable way, affect the motion of the Shuttle can be separated into gravitational forces, surfaces forces and artificially-induced forces, such as maneuvers. Mathematically, the total force, $\mathbf{F}$, can be expressed simply as

$$\mathbf{F} = \mathbf{F}_G + \mathbf{F}_S + \mathbf{F}_M + \mathbf{F}_\varepsilon \tag{1}$$

where $\mathbf{F}_G$ comprises the forces which are gravitational in nature, such as the Earth's solid-body gravitational field, variations in that field due to solid Earth and ocean tides, and luni-solar and planetary perturbations; $\mathbf{F}_S$ represents the forces which act on the surface of the Shuttle, such as those due to the atmospheric effects of drag and lift and that of solar radiation; $\mathbf{F}_M$ consists of forces arising from orbit and attitude maneuvers; and $\mathbf{F}_\varepsilon$ encompasses all remaining forces, which are considered negligible in this study. Unlike the other forces, maneuvers do not occur continuously, but, clearly, only at selected times during the mission. While a detailed description of the mathematical modeling of each of these forces can be found in an earlier work (Ref. 10), a brief summary of the models and the degree to which the forces perturb the orbit will be given here, for the sake of clarity.

Perturbations due to the inhomogeneous mass distribution of the Earth are some of the most significant affecting the Shuttle orbit. The geopotential model used for the simulations and for the orbit determination of the Shuttle for the MOMS-02 mission is the JGM-1 (Joint Gravity Model) developed for use during the TOPEX/Poseidon mission. It has evolved from the GEM-T3 geopotential model (Ref. 5) and is one of the most complete developed to date, with harmonic coefficients up to degree and order 70.

The atmospheric effects of drag and lift also play a significant role on the behavior of the Shuttle. The model used in this investigation incorporates knowledge of the attitude of the Shuttle as a function of time and, thus, accounts for the variation of the surface area exposed to the relative wind. In this case, three primary surfaces, each oriented normal to one of the Shuttle body-fixed axes' unit vectors, were used. This technique was used to establish the effect of both drag and lift. The CIRA '86 (Ref. 4) model of the atmosphere, which relies on atmospheric data, solar flux values and indices of the geomagnetic activity, was the empirical model used to estimate the local density.

The remaining gravitational forces due to solid Earth and ocean tides, lunar, solar and planetary perturbations, and the surface force of solar radiation were shown to be below the levels of realistic Shuttle position determination (Ref. 10). Table 1, extracted from the same reference, shows the orbit perturbations on a 300 km Shuttle orbit over the course of three hours. In addition, the effect of the offset between the location of the Shuttle's S-Band antennas and its center of mass is given.

Table 1

RADIAL, TRANSVERSE AND NORMAL (RMS) ORBIT PERTURBATIONS

	orbit perturbation (m) for 3 hour arc lengths		
MODEL	r	τ	η
Ocean Tides	0.02	0.05	0.07
Earth Tides	0.04	0.07	0.25
Solar Radiation	0.01	0.05	0.06
Luni-solar and Planetary	0.14	0.28	1.05
Geopotential (50x50)	0.56	1.70	1.06
Geopotential (36x36)	0.55	1.27	2.31
Geopotential (8x8)	14.73	19.50	20.32
Antenna Offsets	0.53	3.59	2.81
Drag (spherical model) LVLH; C_D not est.	33.78	79.90	82.34
Drag (spherical model) LVLH; C_D est.	0.09	0.15	0.13
Drag (spherical model) IH; C_D not est.	12.94	31.88	32.86
Drag (spherical model) IH; C_D est.	8.76	18.96	9.56

It should be noted for clarity that these results were established by fitting an arc to simulated TDRSS Doppler data, with any given effect removed. The arc was then differenced with an arc that had been fit to the same data, but with all possible effects modeled.

Unmodeled Error Sources

The previous section discussed the modeling and orbit perturbations of forces which could be classified as gravitational or surface-dependent in nature. While several of these effects contributed non-negligible perturbations to the orbit, additional forces and error sources can produce comparable uncertainties, if left unmodeled.

In the case of a satellite-to-satellite tracking system such as TDRSS, one primary concern is of the quality to which the positions of these satellites can be estimated. Although these uncertainties will be naturally scaled down by the ratio of the tracking satellite's orbital radius to the user's orbital radius (Ref. 3), significant errors can still remain. It has been established that generated ephemerides of the TDRSS satellites, as performed at the Goddard Space Flight Center, possess errors of approximately 50 m (Ref. 9). Since the radii of TDRSS satellites are five to six times those of the Shuttle in low Earth orbit, these errors will manifest themselves as approximately 10 m errors in the position of the Shuttle. To incorporate these errors properly, it is necessary to perform a simultaneous solution for the positions of the TDRSS satellites and of the Shuttle, using a combination of TDRSS bilateration and Shuttle Doppler data. In this work, the TDRS positions were interpolated from an ephemeris in which data was available at 60 second intervals. It was assumed that there were no sources of error in the ephemeris.

Depending on the objective of any given mission, the Space Shuttle will perform fairly regular orbit and attitude adjustments. During the course of STS-55, two significant orbit burns or trim maneuvers were performed. Since these maneuvers tend to be so large that an arc is usually not fit directly through them, the modeling of their perturbations is not of primary concern. However, the same cannot be said for the attitude maneuvers. In most cases, their effect, or the effect of a series of routine maneuvers, will create perturbations considerably larger than any of the aforementioned effects, over a short arc. It is the modeling of these perturbations which is the major thrust of this work and the topic of the next section.

ESTIMATION OF ATTITUDE MANEUVERS

Description

Throughout the course of any mission, the Space Shuttle is in one of two types of attitude holds: those referred to as Local Vertical Local Horizontal holds (LVLH), in which the orientation of the vehicle is fixed relative to the surface of the Earth, and those referred to as Inertial Holds (IH), in which the spacecraft does not rotate with respect to the stars. Which hold is used at any given time, depends predominantly on the experiments which are being conducted, and which requirements, if any, these have placed on the orientation of the vehicle in space. However, usually both classes of holds will be required and, thus, significant maneuvers must be employed to rotate the spacecraft from one to the other. Since the Shuttle uses rockets and not momentum wheels to perform these maneuvers, and since the rockets are not aligned in such a way as to purely rotate the vehicle, each firing will contribute some degree of acceleration to the spacecraft, as a whole. The direction in which this acceleration occurs depends on a number of factors: which rockets are used, how long they fire and the initial and final orientation. Because the rockets are fixed to the body of the Shuttle, the overall perturbation on the orbit will be an integrated effect over the period of the burn, as a function of the vehicle's orientation during the maneuver. Clearly, if momentum wheels were used in the Shuttle, as is the case with most other satellites, the coupling between the orbit and the attitude would be reduced to that of natural dynamical coupling, which is completely negligible.

Neither the LVLH nor the IH configuration is very stable; drag, gravity gradient effects, and even crew activity tend to drive the vehicle away from these attitudes. As a consequence, fairly small but frequent attitude adjustment maneuvers are required to maintain any given hold. Typically, a deadband angle of about 2° is allowed for drift, but once this angle is exceeded, a small adjustment will be performed to correct the attitude. During the periods of the MOMS camera observation, this deadband angle was increased to 5° to maintain a more passive environment.

Both the large attitude maneuvers and the smaller control thrusting realignments can perturb the orbit to a non-negligible level, especially if they occur frequently. Typically, it is the cumulative effect of many unmodeled maneuvers that leads to large errors. Fig. 3 shows a typical timeline of the pitch angle of the Shuttle over a three hour span. The angle is given with respect to an inertial frame, so an IH configuration can be easily identified as periods during which the angle is, essentially, constant. The circles identify times when large attitude maneuvers occur, while control thrusting can be seen by the wave-like appearance during either of the two IH configurations.

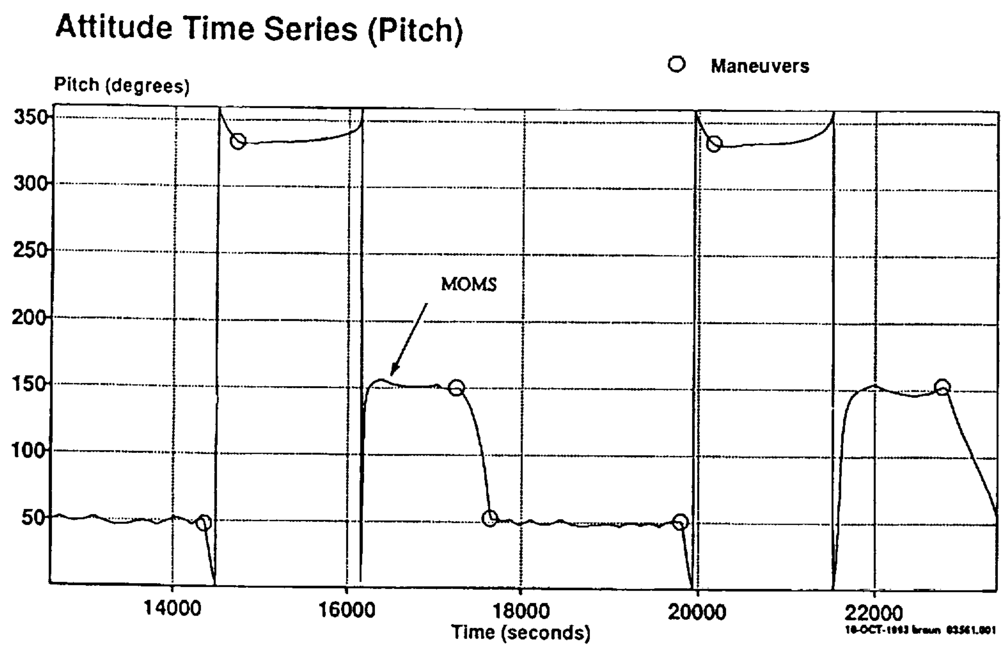

Fig. 3 Typical Shuttle Attitude Timeline (Pitch)

Any maneuver between an IH attitude and an LVLH hold consists of, firstly, an accelerative burn, followed by a period of a rapid change in the any given angle, and, secondly, a decelerative burn, once the new attitude is reached. This period can be identified as times when the slope of the angle is very high (the sudden jumps from 0° to 360° are of no relevance). Following each final braking maneuver, the Shuttle is then held in either an LVLH or an IH configuration for up to 30 minutes, before another significant maneuver occurs.

Approach

It will be seen in one of following sections that, because these attitude maneuvers are so highly coupled with the orbit, completely ignoring them will lead to errors of up to several hundred meters in the position after three hours. As a consequence, it was attempted to estimate some of the larger maneuvers by introducing so-called empirical forces during the isolated times of the burns.

Empirical forces act, essentially, as a mechanism by which unknown or unmodeled effects can be introduced into the model at any given time and acting over any given duration. In this case, they consist of three forces, one in each of the radial, transverse and normal (identical to the radial, along-track and cross-track) orbit directions. The magnitude of the force in any given direction can be established as an *a priori* value, if there is some knowledge of the phenomenon, or by simply estimating its value during the filtering process, if very little is known.

The technique used in this study was to isolate, from information of the as-flown attitude timeline and the actual time series of the pitch, yaw and roll angles of the Shuttle, the times at which each of the large attitude maneuvers between an IH configuration and an LVLH hold were conducted. Empirical force parameters were then estimated during the course of a maneuver, which, typically, lasts 10 to 15 seconds. As discussed earlier, each maneuver will contribute perturbations in each of the radial, transverse and normal directions, and any estimate of these, using this approach, will only yield an average value over the period of the burn. It was also found that a reasonable estimate of all three components was usually not possible, due to high correlations. Thus, since the energy required to perturb the orbit in the normal direction is considerably greater than that required to perturb it an equivalent amount in either the radial or transverse direction, it was always the case that the normal component of any given maneuver was not estimated. Even so, a good estimate of the transverse and radial components can also greatly improve the internal consistency of the orbit in the normal direction.

PROCESSING OF STS-55 ORBITS

Goals

Actual TDRSS Doppler tracking data from STS-55 were processed using the same force models discussed in the previous sections. Twelve arcs, each between two and a half and three hours in duration and centered around the brief period of operation of the MOMS camera, were selected for processing. Table 2 gives both the Shuttle and orbit parameters for the D2 mission; these are identical to those used during the simulations, the results of which were summarized in Table 1. It is the goal of this work to establish the best estimates possible for the position of the Shuttle during the operation of the camera, and, in doing so, assess the degree to which empirical force estimates of the significant maneuvers can be established.

Quality Assessment

In any batch or Kalman filtering technique, such as ones used in orbit determination, the theoretical accuracy of the estimates of the state is given by the state covariance. This, however, assumes that there exists a good understanding of the errors associated with the observations, the force models and the dynamic parameters.

Table 2

SHUTTLE AND ORBIT PARAMETERS OF THE SIMULATIONS

Semi-major axis	6678 km
Eccentricity	0.001
Inclination	28.5°
Shuttle mass	109090 kg
Shuttle cross-section	
(Bay doors open)	
Normal to u_x:	68.19 m^2
Normal to u_y:	222.60 m^2
Normal to u_z:	413.42 m^2
Reflectivity coefficient	
(nominal for all surfaces)	0.7
S-Band antenna x:	13.9 m
y:	3.39 m
z:	-1.76 m

If such error models are not known or if forces exist which are not well-modeled, as is the case with attitude maneuvers, then the covariance values will tend to be optimistic. As a consequence, another technique which is commonly used for assessing the quality of an orbit is to compare the arc with an overlapping arc generated with mostly independent tracking data (Ref. 6).

In this investigation, overlap arcs, similar in duration to the main arcs, were processed. The target overlap, in terms of the percentage of the main arc of which the secondary arc overlapped, was 25%; the number varied slightly, depending on the quality and supply of the tracking data and on the timing of the maneuvers. The quality of the orbit is then quantified as the root mean square (rms) of the radial, transverse and normal overlap differences.

Results

The results of processing 12 MOMS arcs are summarized in Table 3, where the improvements in the overlap values before and after maneuvers were estimated is given. For any given arc, the parameters estimated were the initial state, a combined scaling coefficient for lift and drag, and various radial and transverse empirical force values for the significant attitude maneuvers. Table 3 also shows the number of large maneuvers which existed in each of the main and overlap arcs. This, however, does not always directly correspond to the number of maneuvers estimated. This is the case for two primary reasons. Firstly, it is not always possible to estimate a maneuver if there is a poor supply of tracking data at the time of the burn. As mentioned earlier, there is a period over India, usually lasting about 10 minutes, for which there is no tracking data available. In addition, data is lost during the switch from one TDRS to another, often creating gaps of several minutes. If a maneuver occurs during or around the time of these gaps, it is very difficult to get a good estimate of its magnitude; any attempt will often corrupt estimates of the other maneuvers or simply degrade the quality of the orbit. The second reason it may not be possible to reliably estimate a maneuver is if it occurs near the end of an arc. Because there is not data beyond the end of the arc, the quality of the orbit tends to degrade in these areas. Any attempt to estimate maneuvers during these times will tend to yield magnitudes which are much too large, and overlap differences are likely to be too pessimistic. This is also very evident by the relative magnitudes of the estimated value for the maneuver and its uncertainty; clearly, the latter must be considerably smaller than the former if any confidence is to be placed on the estimate. Due to these shortcomings, only maneuvers which occurred during periods for which there was a good supply of tracking data and which were not near the ends of the arc were estimated. It is clear, however, from results in Table 3 that, even if a considerably large number of maneuvers is present, a significant improvement in the quality of the orbit can be made by carefully estimating their values.

Table 3

RADIAL, NORMAL AND TRANSVERSE (RMS) ORBIT OVERLAPS, BEFORE AND AFTER MANEUVER ESTIMATION

	Maneuvers		Rms Doppler Residual (Hz)		Rms Overlaps (r,η,τ) (m)	
Rev No.	Main	Overlap	Before	After	Before	After
9	6	6	1.52	0.83	88,201,186	15,23,18
10	6	6	0.92	0.79	88,201,186	15,23,18
11	8	6	1.29	0.84	120,268,289	38,67,21
12	6	6	0.80	0.77	48,107,96	17,49,25
14	4	6	1.14	0.81	153,178,337	40,73,61
75	4	2	1.18	1.04	82,48,110	14,32,31
82	4	3	0.88	0.82	23,155,160	35,45,20
91	4	2	1.30	0.85	54,23,121	52,39,62
97	6	4	0.88	0.86	42,120,80	17,53,31
105	6	0	0.92	0.86	120,134,119	40,43,56
115	4	4	0.93	0.87	96,51,107	10,15,16
146	6	3	0.81	0.71	121,154,256	15,47,46

This current discussion has, so far, said nothing of the frequent control thrustings that are needed to maintain an attitude hold. As was evident in Fig. 3, these occur every few minutes throughout the mission. There is very little hope of being able to estimate each of these maneuvers, as was done for the more significant burns, due to the frequency at which they are conducted. What tends to happen for small perturbations, particularly their along-track, or transverse, components, is that the scaling parameter for drag will absorb some of the errors. In fact, this term will assume the role of a junk parameter, and take on values which may not be realistic of a drag or lift coefficient. This was often seen to be the case here; but, in allowing the parameter to vary freely, i.e. without an *a priori* value, the overlaps differences could be modestly decreased.

CONCLUSIONS

Orbit Determination of the U.S. Space Shuttle during STS-55 was performed to assist in the processing of digital image data from the German MOMS-02 remote sensing camera on-board. Simulations from an earlier work (Ref. 10) have shown that the remaining unmodeled effects on the motion of the Shuttle are due to both attitude maneuver thrusting and attitude hold control thrusting; all other significant effects have been accounted for. In addition to the errors introduced due to the maneuvers, errors from uncertainties in the TDRSS satellite positions are at the 10 m level.

An attempt was made to absorb some of the most significant errors by estimating empirical force accelerations during many of the largest attitude maneuvers. Radial and transverse accelerations were estimated for up to six maneuvers during a three hour arc for 12 selected arcs during the mission. It was found that overlap differences could be greatly reduced in all cases, anywhere from two to 10 times, by estimating the maneuvers.

The primary difficulties in applying this technique are encountered if maneuvers occur during periods of poor or no tracking, and in areas near the beginning and end of the arc. It is also not feasible to estimate control thrusting maneuvers during attitude holds, due to the frequency at which they occur.

Clearly, if further significant improvements are to be made in Space Shuttle orbit determination, it will be necessary to completely model each maneuver that occurs. Since these attitude maneuvers couple the attitude with the orbit, this would require incorporating information about the instantaneous orientation of the Shuttle with knowledge of which rockets were used, their mean thrust values and the duration of each burn. Then, a numerical algorithm for determining the integrated effect of each burn as a function of orientation would have to be implemented into the orbit determination software, in order to establish the radial, transverse and normal orbit perturbation from each burn. Further improvements beyond this would need to focus on the quality of the TDRS position ephemerides.

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