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Operational Improvements of Long-Term Predicted Ephemerides of the Tracking and Data Relay Satellites (TDRSs)*

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Abstract

Tracking and Data Relay Satellite (TDRS) orbit determination and prediction are supported by the Flight Dynamics Facility (FDF) of the Goddard Space Flight Center (GSFC) Flight Dynamics Division (FDD). TDRS System (TDRSS)-user satellites require predicted TDRS ephemerides that are up to 10 weeks in length. Previously, long-term ephemerides generated by the FDF included predictions from the White Sands Complex (WSC), which plans and executes TDRS maneuvers. TDRSs typically have monthly stationkeeping maneuvers, and predicted postmaneuver state vectors are received from WSC up to a month in advance. This paper presents the results of an analysis performed in the FDF to investigate more accurate and economical long-term ephemerides for the TDRSs.

As a result of this analysis, two new methods for generating long-term TDRS ephemeris predictions have been implemented by the FDF. The Center-of-Box (COB) method models a TDRS as fixed at the center of its stationkeeping box. Using this method, long-term ephemeris updates are made semiannually instead of weekly. The impulse method is used to model more maneuvers. The impulse method yields better short-term accuracy than the COB method, especially for larger stationkeeping boxes. The accuracy of the impulse method depends primarily on the accuracy of maneuver date forecasting.

Introduction

The Flight Dynamics Facility (FDF) of the Goddard Space Flight Center (GSFC) Flight Dynamics Division (FDD) provides many Tracking Data Relay Satellite (TDRS) and TDRS System (TDRSS)-user ephemeris products, both short-term and long-term, every month to numerous users. Short-term products generally have spans of less than 2 weeks, while products greater than 2 weeks in length are considered long-term products. The recipients of these products include several spacecraft Payload Operations Control Centers (POCCs), the Space Network (SN), the Ground Network (GN), and the science community.

The support provided by the FDF includes the TDRS planning and scheduling products for many TDRSS-user spacecraft. Prior to the launch of the Hubble Space Telescope (HST) in 1990, there were no strict accuracy requirements for long-term TDRS products. The merged ephemeris method used at the time involved merging predicted ephemerides generated from FDF definitive solutions with those generated from the White Sands Complex (WSC) predicted postmaneuver vectors. WSC provides these predicted postmaneuver vectors about 30 days in advance, which was adequate for the long-term ephemerides generated at that time. With the launch of HST, however, the FDF was levied with its first tight long-term accuracy requirement (see Reference 1).

In response to these new requirements, the FDF performed an analysis to find an accurate, more cost-effective method to generate these long-term TDRS products. Two methods were identified: the Center-of-Box (COB) method and the impulse-modeled method. This paper gives an overview of the TDRS System, describes the two new methods for generating long-term TDRS ephemerides, and presents their applications to current and future missions.

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The TDRS System (TDRSS)

TDRSS currently consists of a constellation of five TDRSs, a central command center in White Sands, New Mexico, called the White Sands Complex (WSC), and several auxiliary transponders. Five TDRSs in geostationary orbits have been deployed since 1983. Each TDRS actively tracks lower Earth-orbiting satellites and provides a primary link for their telemetry and command. The locations of the five TDRSs are distributed from 41 degrees west longitude to 275 degrees west longitude. TDRS-4 (TDRS-East) is currently in the eastern-most position at 41 degrees west longitude, TDRS-5 (TDRS-West) is at 174 degrees west longitude, TDRS-6 (TDRS-Stored) is at 46 degrees west longitude, TDRS-3 (TDRS-Spare) is at 171 degrees west longitude, and TDRS-1 is at 275 degrees west longitude. TDRS-3 and TDRS-5 mutually support and complement each other in the TDRS-West position, and TDRS-6 and TDRS-4 mutually support and complement each other in the TDRS-East position. These four TDRSs are all within direct view from WSC. TDRS-1 was moved to its 275-degrees-west location to provide additional real-time communications for the Compton Gamma Ray Observatory (GRO) spacecraft, which suffered a failure of its onboard tape recorders. This relocation allows 100-percent coverage for GRO in conjunction with TDRS-East and TDRS-West. A new ground terminal for the GRO Remote Terminal System (GRTS) was built for TDRS-1 at Canberra, Australia.

Around 1989, the National Aeronautics and Space Administration (NASA) entered upon a contract to provide C-band communication services for commercial satellites. The contract requires two TDRSs be maintained within ± 0.1-degree limits in both latitude and longitude to assure that their signals do not interfere with other commercial satellites. Currently, TDRS-West and TDRS-East are maintained within these 0.1-degree stationkeeping boxes. TDRS-1, TDRS-3, and TDRS-6 are maintained within ± 0.5-degree stationkeeping boxes in longitude only. The 0.1-degree stationkeeping box corresponds to a ± 70-kilometer box, with the half-diagonal of the box equal to 100 kilometers (see Figure 1). The 0.5-degree stationkeeping box corresponds to a ± 370-kilometer longitudinal 'box" with no latitude constraint. The geopotential induces a longitudinal (east-west) drift that is dependent on the longitude of the TDRS relative to the geoidal stable points. Inclination changes are caused by the gravitational forces of the Moon and the Sun (see Reference 2).

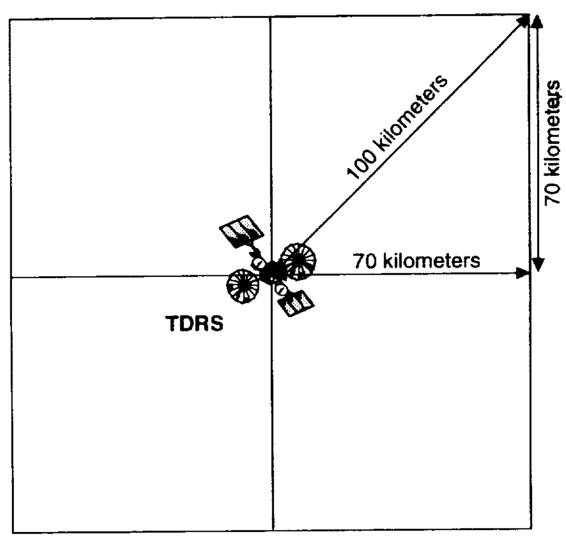

Figure 1. TDRS 0.1-Degree Stationkeeping Box

Each TDRS undergoes periodic stationkeeping maneuvers to maintain it in its individual stationkeeping box. The maneuver planning is the responsibility of WSC personnel, who rely on the FDF for daily and postmaneuver orbit determination support. North-south (N/S) stationkeeping maneuvers are required to maintain the orbit within the latitudinal constraint, and east-west (E/W) stationkeeping maneuvers are required to meet the longitudinal constraint. The 0.1-degree boxes require frequent maneuvers, approximately every 15 to 40 days, while the 0.5-degree boxes require less frequent maneuvers, approximately every 70–90 days. Table 1 summarizes these characteristics for each TDRS.

Table 1. Current Operational TDRSs (as of March, 1995)

TDRS	Location	Name	Inclination (degrees)	Stationkeeping Box Size (± degree) Longitude	Latitude	Days Between Maneuvers
1	275° west	Zone of exclusion	8.2	0.5	n/a	90
3	171° west	Spare	1.5	0.5	n/a	70
4	41° west	East	< 0.1	0.1	0.1	15
5	174.3° west	West	< 0.1	0.1	0.1	15
6	46° west	Stored	1.5	0.5	n/a	70

COB Method

The COB method refers to the satellite being modeled as fixed at the center of its stationkeeping box. This method is ideal for spacecraft that are maintained within a strict orbital constraint of a 0.1-degree stationkeeping box, such as TDRS-4 and TDRS-5. Such spacecraft may have their position approximated at the center of their stationkeeping box, thereby alleviating the need to model maneuvers. The error associated with this method is strictly the box size.

COB-modeled ephemerides are proposed for long-term predictions of TDRS positions but in general were not intended to replace short-term ephemeris products needed for acquisition. Although the idea behind COB allows for the use of the same vector to estimate the TDRS position over time, most FDF customers require an ephemeris representation of a specific format. Due to ephemeris requirements, these ephemerides are currently generated by propagating the COB vector using a point-mass Earth model. Theoretically, COB ephemerides would never need updating. Within the FDF, these ephemerides are updated semiannually to limit file lengths.

Standard COB modeling includes no perturbation forces and maintains the same longitude over several months for geostationary orbits. The main perturbation forces neglected in the COB method are the nonspherical geopotential terms, the solar-lunar gravitational potentials, and solar radiation.

Two variations of the standard COB method are the ***offset*** COB method and the ***inclined*** COB method. The offset COB method is effectively the same as the COB method, except that an offset is applied to the position used to generate the COB ephemeris. The stationkeeping box stays the same, the position that is used is just offset from the official center of the box. This method could be used if a spacecraft were being maintained in an area offset from the official center of its nominal stationkeeping box. Although this scenario may not be known ahead of time, historical data would show if the comparisons of long-term ephemerides with definitive solutions were biased east or west of the nominal COB. In such cases, a long-term offset of COB would be recommended to reduce observed errors between the definitive solutions and the COB ephemerides.

Temporary offsets may also be applied. If a TDRS maneuver were to exceed its box after a maneuver, a temporary offset could be applied. As the TDRS drifted back towards its center, this offset could then be removed. In practice, however, this offset can be applied until the next update of the ephemeris. For example, HST currently has a requirement to update the COB ephemeris when the definitive comparison exceeds 130 kilometers. In November 1994, the definitive comparison indicated that the TDRS had exceeded its stationkeeping box by a small amount. In this case, a temporary offset of 0.01 degree east of its nominal center was applied.

The inclined COB method is an alternative COB method for spacecraft that are not restricted in inclination. For example, the inclination of TDRS-1 is currently 8.2 degrees and will increase over time to a maximum inclination of 14 degrees, after which it will slowly decrease again (Reference 3). This inclination growth is caused by solar and lunar gravitation. Use of the COB method in these situations requires the application of forces in addition to those due to a point-mass Earth. Modeling the solar and lunar gravity for inclination variation and the J_2 (zonal) geopotential term for orbital precession increases the propagation accuracy.

Figure 2 gives an example of the accuracy of an inclined COB ephemeris for a TDRS maintained in a 0.2-degree stationkeeping box. Although the boxes mentioned within this paper are restricted to an 0.1-degree and 0.5-degree box, the example illustrates that the errors associated with the COB method are equal to the box size. In the case of an 0.2-degree box, the errors should not exceed 200 kilometers (km).

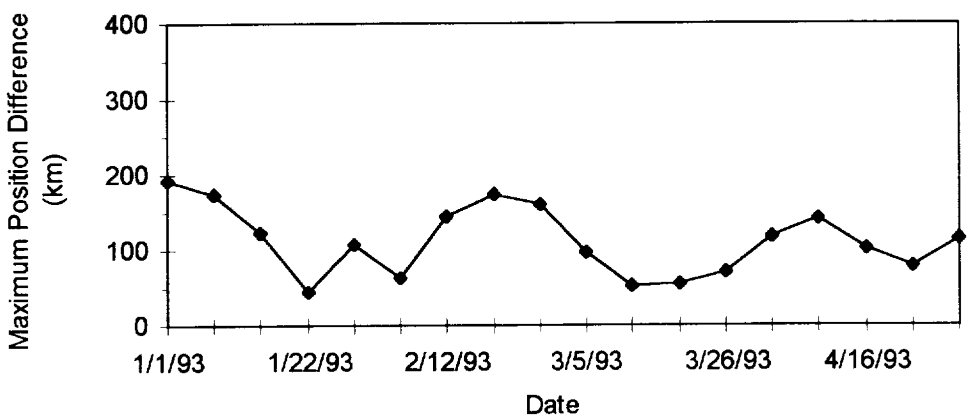

Figure 2. TDRS-1 Inclined COB for a 0.2-Degree Box (January 1, 1993, to April 30, 1993)

Currently within the FDF, only the standard COB method has been implemented (for TDRS-East and TDRS-West). This has reduced the delivery schedule of TDRS-East and TDRS-West long-term product deliveries from a total of eight per week to eight every 6 months. The other three operational TDRSs have tighter accuracy requirements than COB modeling allows for their larger stationkeeping box size. For these TDRSs, the impulse method is used.

Impulse Method

Unlike the COB methods, the impulse method involves actually modeling TDRS maneuvers in the computation of ephemerides. For simplicity, these maneuvers are modeled impulsively rather than as finite burns. Using the standard geopotential model, the operational state vector is propagated with a ΔV applied on the maneuver dates predicted by the FDF after the last maneuver date announced by WSC. The instantaneous ΔV magnitudes are computed from the needed change in the drift rate, and the longitude drift table assures that the TDRS remains within its box. This method should results in the TDRS drifting back and forth parabolically from one edge of its box to the other, without leaving the box (Reference 4).

The impulse method is best suited for TDRSs that have infrequent maneuvers, such as those with a 0.5-degree stationkeeping box. Since N/S maneuvers are large and significantly disrupt E/W maneuver forecasts, an error of a few days in the maneuver forecast (which is hard to avoid with N/S maneuvers) would induce a 100-kilometer error for a 0.1-degree stationkeeping box. Therefore, impulse modeling is recommended only for E/W maneuvers in these large stationkeeping boxes. All TDRSs maintained within 0.5-degree boxes are not subject to inclination restraints and, therefore, are not subject to N/S maneuvers.

The impulse method is currently used for long-term modeling of ephemerides for TDRS-1, TDRS-3, and TDRS-6. These ephemerides are 14 weeks in length and are updated once per month in the FDF. On average, the errors associated with these ephemerides over a 7-week span are under 100 kilometers. The largest errors have occurred when changes to maneuver dates have occurred. For example, the FDF predicted maneuver date for a TDRS-1 maneuver in December of 1994 was within 1 day of the first announced maneuver date. The announced date was then changed by 6 days, resulting in errors over 200 kilometers. Figure 3 illustrates this example. The graph depicts the definitive comparisons of the TDRS-1 impulse-modeled ephemeris over a 14-week span. The "inaccurate" December maneuver was first modeled in the TDRS-1 long-term ephemeris generated in September and was subsequently modeled in the updates performed in October and November. The three spikes in Figure 3 represent the error associated with the original maneuver date as seen in the September, October, and November updates. The solid black line represents the TDRS-1 accuracy requirements of 40-kilometers between ephemeris updates (every 4 or 5 weeks) and 100-kilometers for the following 6 weeks.

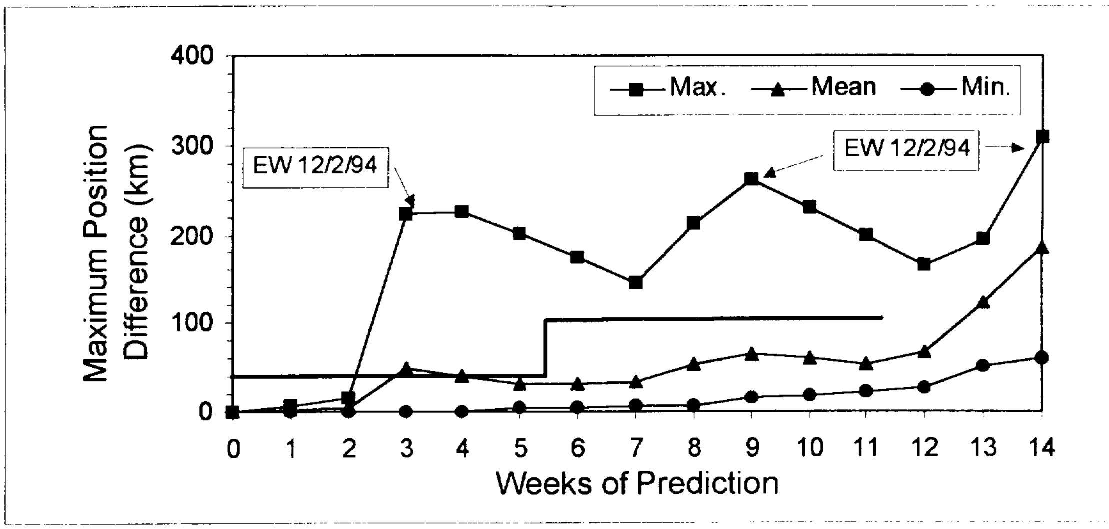

Figure 3. TDRS-1 Long-Term Accuracy Using Impulse Method (August 11, 1994, to February 23, 1995)

It should be noted that these results are based on only 6 months of operational data. Although the effects of mismodeled maneuvers is noticeable, the number of maneuver date changes since August, 1994 may not accurately represent the true frequency of maneuver date changes. The new Second TDRS Ground Terminal (STGT) was undergoing testing with the TDRSs throughout the summer of 1994 and into the fall. In addition, the transition of TDRS control from the original White Sands Ground Terminal (WSGT) to STGT was performed in December. These situations required adjustments to planned maneuver dates to minimize interference with the transition activities on the ground. It is expected that the mean error after 3 weeks of prediction will decrease as more data become available.

COB Application to Current and Future Missions

Although the primary use of the COB method is for generating long-term predictions of TDRS positions, it can also be used for the short-term prediction by onboard computers (OBCs).

TDRSS-user satellites need to know both their own position and the position of any TDRS that tracks them or with which they communicate, so they can pass information through them. Certain user satellites require files to be uplinked to provide this information. This information can be provided in numerous ways. Some older satellites, such as the Upper Atmosphere Research Satellite (UARS), have limited computing power and, therefore, require a compact representation of the ephemeris that can be uplinked to the satellite efficiently and can be easily converted back into a usable form. This compact representation is based on a truncated Fourier series plus residuals. Other satellites with more data storage could have actual ephemerides uplinked to the spacecraft. For those with more computing capabilities, such as the soon-to-be-launched X-Ray Timing Explorer (XTE), a state vector could be uplinked to the spacecraft for propagation by the OBC. This method is the most efficient from an operations standpoint because only a vector is supplied, not an ephemeris or a Fourier representation. However, onboard propagation of the vector requires more extensive computing power. In the past, these methods typically were based on short-term ephemerides, requiring frequent updates.

An alternative to these methods is the use of the COB modeling for the TDRS representation for those missions that don't require short-term accuracies of under 130 kilometers for TDRS-East and TDRS-West. Depending on the OBC configuration, either COB ephemerides or COB state vectors could be delivered to a spacecraft project. For those OBC's propagating an ephemeris, vectors would be uplinked to the spacecraft and propagated by the OBC. Both methods would reduce the number of products to be delivered to the project and the need for postmaneuver updates. Ephemerides would be updated semi-annually and the COB state vectors would require updates only if a TDRS were repositioned.

As mentioned above, implementation of the use of COB in this manner is dependent on the spacecraft's required TDRS position accuracy. For example, the Tropical Rainfall Measurement Mission (TRMM) spacecraft, currently scheduled for launch in 1997, has tentatively agreed to a 0.5-degree requirement for absolute position accuracy for all TDRSs. The TRMM project will received standard COB ephemerides for TDRS-East and TDRS-West and inclined COB ephemerides for the other TDRSs. Vectors will be uplinked to the spacecraft and propagated for several hours by the OBC using a point-mass Earth model. The X-ray Timing Explorer (XTE) spacecraft, scheduled for launch later this summer, has not settled on a TDRS requirement. However, its OBC can have specific modeling for each TDRS. Therefore, COB ephemerides could be used for the 0.1-degree box TDRSs and the impulse method used for the 0.5-degree box TDRSs. The XTE project has been advised of the advantages with COB modeling, but their initial proposals were at the 47-kilometer level position accuracy at 14 days, which is too small for the COB method to satisfy.

The HST provides a good illustration of the benefits of COB modeling. Unlike other spacecraft that use short-term ephemerides for their OBC uplinks and long-term ephemerides for planning, HST uses the long-term TDRS ephemerides for both functions. Shortly after HST was launched in April 1990, the 7-week TDRS ephemerides required for TDRS-East, TDRS-West, and TDRS-Spare were increased to 10 weeks in length. The TDRS position accuracy requirements at that time were 5 kilometers at 10 days, 100 kilometers at 3 weeks, and 310 kilometers at 10 weeks. Although the COB method would have satisfied the 3-week requirement, it would not have met the 10-day requirement.

In an effort to move to COB modeling, two alternatives were proposed to the HST project: (1) relaxing the 10-day, 3σ requirement from 5 kilometers to 200 kilometers or (2) delivering two ephemerides instead of one. In the second option, an operational short-term ephemeris would be delivered in addition to the COB ephemeris. The advantages would have been improved long-term accuracy and easy generation of products. However, the disadvantages would have been additional transmissions (twice as many per TDRS) and reduced convenience. There would also have been increased short-term errors soon after TDRS maneuvers.

Early discussions with the HST project indicated a preference for one ephemeris per TDRS. Further analysis by the HST project revealed that their total error would be smaller using a less accurate, smooth COB ephemeris compared with a more accurate merged ephemeris (see Reference 5). The discontinuities of merged-method ephemerides induced errors of up to 200 kilometers in the HST project's adaptation of the FDF ephemerides. In contrast, the project's adaptation of a COB-ephemeris induced new errors of only 0.02 kilometer. Therefore, a 130-kilometer TDRS accuracy requirement was agreed upon for COB generated ephemerides. For TDRS-Spare, the impulse method was recommended, and its requirements became 100 kilometers for the first 6 weeks and 400 kilometers for the last 8 weeks. The COB method reduced the maximum onboard errors for HST from 200 kilometers for TDRS maneuvers to 130 kilometers over all spans. In addition, because there is less overlap in COB deliveries, total storage space was reduced by a factor of eight for the project's TDRS ephemerides.

Conclusions and Recommendations

This paper has presented two alternative methods for generating TDRS long-term ephemerides: the COB method and the impulse method. The COB method maintains the TDRS position within the center of its stationkeeping box with an error that is strictly the box size. The impulse method provides a potentially more accurate model of the TDRS position by modeling TDRS maneuvers in computing the long-term ephemerides. However, just a 1-day error in maneuver forecasting can induce large errors in the ephemeris.

Based on this analysis, the question arises as to how to determine which method to use in a particular situation. The primary consideration in this determination is that the maximum error of the COB method is equal to the functional stationkeeping box size for the spacecraft. For a 0.1-degree box, the nominal maximum error is equal to 100 kilometers. However, due to occasional excursion beyond the 0.1-degree box, the maximum error currently guaranteed by the FDF is 130 kilometers. It is recommended that spacecraft with TDRS position accuracy requirements less than 130 kilometers use another method. The nominal maximum error for a 0.5-degree box is equal to 370 kilometers. In general, the COB method is recommended for 0.1-degree stationkeeping boxes, because these satellites are more tightly controlled. For nonequatorial satellites, the inclined COB method is recommended.

If more accuracy is required, the impulse modeling method has proven to be accurate because individual maneuvers are modeled. However, changes to the maneuver schedule or off-nominal maneuvers require updates to these ephemerides. In addition, 1-day errors in the modeling of large E/W maneuvers can induce errors of up to 70 kilometers. Since 0.1-degree stationkeeping boxes require N/S maneuvers, there is an even greater chance for large errors with this method. Therefore, the impulse modeling method is recommended for TDRSs with larger stationkeeping boxes that only perform E/W maneuvers.

In conclusion, the methods presented in this paper are intended to provide cost savings and accuracy improvements for both future and current users. Careful consideration of long-term TDRS accuracy requirements and alternative methods of attaining these accuracies can open up possibilities for cost and resource savings.

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