TRACKING AND DATA RELAY SATELLITE (TDRS) ORBIT ESTIMATION USING AN EXTENDED KALMAN FILTER[Ψ]

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ABSTRACT

Alternatives to the Tracking and Data Relay Satellite (TDRS) orbit estimation procedure were studied to develop a technique that both produces more reliable results and is more amenable to automation than the prior procedure. The Earth Observing System (EOS) Terra mission has TDRS ephemeris prediction 3σ requirements of 75 meters in position and 5.5 millimeters per second in velocity over a 1.5-day prediction span. Meeting these requirements sometimes required reruns of the prior orbit determination (OD) process, with manual editing of tracking data to get an acceptable solution.

After a study of the available alternatives, the Flight Dynamics Facility (FDF) began using the Real–Time Orbit Determination (RTOD®) Kalman filter program for operational support of TDRSs in February 2007. This extended Kalman filter (EKF) is used for daily support, including within hours after most thrusting, to estimate the spacecraft position, velocity, and solar radiation coefficient of reflectivity (C_R). The tracking data used are from the Bilateration Ranging Transponder System (BRTS), selected TDRS System (TDRSS) User satellite tracking data, and Telemetry, Tracking, and Command (TT&C) data.

Degraded filter results right after maneuvers and some momentum unloads provided incentive for a hybrid OD technique. The results of combining EKF strengths with the Goddard Trajectory Determination System (GTDS) Differential Correction (DC) program batch-least-squares solutions, as recommended in a 2005 paper on the chain–bias technique, are also presented.

1. INTRODUCTION

This paper discusses a continuation of the work described in Reference 1, documenting the continued progress toward the two goals of meeting the 75–meter (3σ) predicted accuracy requirement for Tracking and Data Relay Satellites (TDRSs) in support of the

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Earth Observing System (EOS) Terra mission, and the continued progress toward increased automation of the daily OD solutions.

The Flight Dynamics Facility (FDF) at the Goddard Space Flight Center (GSFC) currently uses two software systems for orbit determination/estimation (OD) of the TDRSs. One is the Goddard Trajectory Determination System (GTDS) Differential Correction (DC) program, which was developed within the GSFC and which obtains batch-least-squares solutions. The second is the Real–Time Orbit Determination (RTOD®) system, which implements an Extended Kalman filter (EKF). RTOD® is a commercial product currently marketed and supported by Northrop Grumman.

The background section of this paper discusses a description of the OD techniques and a review of prior performance. More recent results of the EKF are then discussed, along with coincident changes. The operational results obtained from applying the EKF are presented, followed by an overview of operational automation advances, and concluding with a summary and recommendations.

2. BACKGROUND

In 2005, studies were completed to improve the accuracy of TDRS OD and the ability to automate this process through improved analytic and numeric techniques and tools (Reference 1). Since the completion of those studies, which are summarized in this section, efforts have continued to assess and improve the TDRS OD process to address. This paper is a follow-on study to Reference 1, which describes TDRS OD techniques with increased accuracy and automation potential relative to the prior GTDS Single–Bias (SB) technique. The two newer OD techniques detailed in Reference 1 are an enhanced technique modeling the biases in equipment chains and the EKF. Each of the three techniques is summarized below.

Most TDRSs and Space–to–Ground–Link Terminals (SGLTs) at the White Sands Complex (WSC) have three different service type and antenna combinations that may be used. These are the S-band SA 1 (SSA1) service (with chains A and B), the S-Band SA 2 (SSA2) service (with chains A and B), and the MA service (with chains 1 to 6). For TDRS–3 and –10, the GTDS methods also use TT&C tracking data. Since Reference 1 was written, we have learned that Forward and Return chains need not be identical for SA, which potentially doubles the possible number of SA chains from four to eight. The MA forward link also has a backup, which potentially doubles the possible number of MA chains from six to twelve. The prior operational GTDS technique, the GTDS SB, estimates or applies one composite range bias for all chains of BRTS data taken through the same SGLT.

The enhancement to the GTDS DC, the Chain–Bias (CB) technique, assigns hybrid station indices depending on which Single Access (SA) or Multiple Access (MA) service and chain are recorded at the tracking station for Bilateration Ranging Transponder System (BRTS) events.

The EKF was the third technique evaluated for TDRS OD. Because an EKF updates the estimates of all solve-for parameters at each observation, it possesses an inherent capability to determine time–dependent biases. The FDF installation of the EKF does not assign a separate bias to each service type and chain. For the period reported here, the EKF was configured to solve for range biases for each BRTS transponder, to model the transponder delay in range data. The BRTS transponder biases are treated as Gauss-Markov parameters and the supplied BRTS transponder delay establishes the a priori range bias. The estimated bias then floats from this value based on the bias uncertainty model and the tracking data received. Because this bias is intended to model the BRTS transponder delay, all service types and chains for any TDRS supported by that BRTS are modeled within it.

Presently, the EKF technique provides operational FDF support for the EOS Aqua and Aura missions. The FDF implementation of the EKF performs simultaneous state estimation for a constellation of satellites. The current implementation includes eleven satellites: the five operational TDRSs and six TDRSS User satellites [Aqua, Aura, Terra, the Hubble Space Telescope (HST), the Rossi X–Ray Timing Explorer (RXTE), and the Tropical Rainfall Measurement Mission (TRMM)]. The EKF configuration uses BRTS range and Doppler, TT&C range, Ground Network (GN) Doppler, and TDRSS User range and Doppler tracking data in its state update. The EKF potentially provides advantages over GTDS by dynamically estimating drag, solar radiation coefficient of reflectivity (C_R), and observation biases, and by providing the capability to use all TDRSS User data in TDRS OD.

Both the EKF and the GTDS CB were seen to have advantages over the prior technique. The tentative choice of the GTDS CB for the automation process was made. The comparison of the three techniques has continued beyond that of the initial study, and the results of this follow-up work are presented throughout the remainder of this paper.

3. RECENT EKF RESULTS

Evaluation of results collected in more recent analysis showed significantly improved performance of the EKF as compared with the GTDS CB technique. Table 1 displays both the GTDS CB and the EKF results for all operational TDRSs for daily cases in the first 8 months of 2006, excluding solution arcs over thrust periods for GTDS CB.

Table 1. Predicted Ephemeris Accuracy for 1.5 Days
January 2006 to August 2006

Techniques	GTDS CB	EKF
# of cases	1044	796
# of cases over 75 meters	9	3
Normalized "over 75 meters" Failures per Case	0.009	0.004
Failure Rate Percentage (%)	0.862	0.377

The results suggested that the EKF would meet the Terra requirements near the 3σ level (a failure rate of 0.27%). This improvement is coincident with and is attributed to four factors:

1. A decrease in solar activity from September 2005 to August 2006 allows more accurate OD using the EKF constellation.

2. A shorter compare span (1.5 days instead of 2 days) seemed to help EKF more than it helped GTDS. This change was done to exactly match the Terra requirement span.
3. Three satellite-missions [the Earth Radiation Budget Satellite (ERBS), the Upper Atmosphere Research Satellite (UARS), and the Ocean Topographic Experiment (TOPEX/POSEIDON)] were removed from the EKF simultaneous-solution processing, as their active mission phases terminated. The estimation of the first two had worse accuracies than many spacecraft in the filter because of their highly drag–perturbed orbits.
4. Ephemeris generation was changed from the EKF smoothed ephemeris to a GTDS propagator.

Because of this marked improvement in accuracy and the relative ease for automation with the EKF, the EKF was implemented as the prime FDF system for routine TDRS OD on February 20, 2007. The EKF solution vectors are propagated to yield ephemerides with future maneuvers and momentum unloads (MUs) modeled as impulses. These ephemerides also serve as reference data for comparisons.

Table 2 and Figures 1 through 5 present the predicted accuracies of the EKF solutions for periods of normal, nonmaneuver support, for February through June 2007. The EKF can be seen as having a good success rate, with three times out of 521 when the 75–meter requirement was exceeded. This failure rate was 0.576%.

Table 2. Predicted Ephemeris Accuracy for 1.5 Days in 2007

	TDRS-3	**TDRS-4**	**TDRS-5**	**TDRS-6**	**TDRS-10**
Mean (km)	0.0174	0.0273	0.0209	0.0140	0.0250
Standard Deviation (km)	0.0150	0.0180	0.0090	0.0085	0.0152
Maximum Value (km)	0.0740	0.0904	0.0586	0.0479	0.0713
# of Cases	105	105	106	104	101
# of Cases over 75 meters	0	3	0	0	0
Failure Rate Percentage (%)	0	2.86	0	0	0

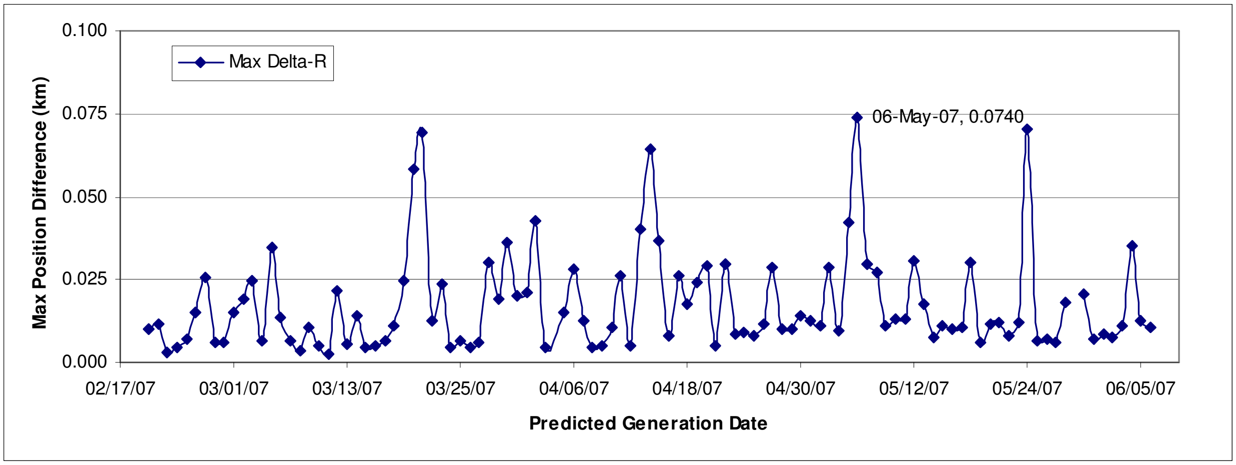

Figure 1. TDRS-3 Predicted Accuracy for 1.5–days

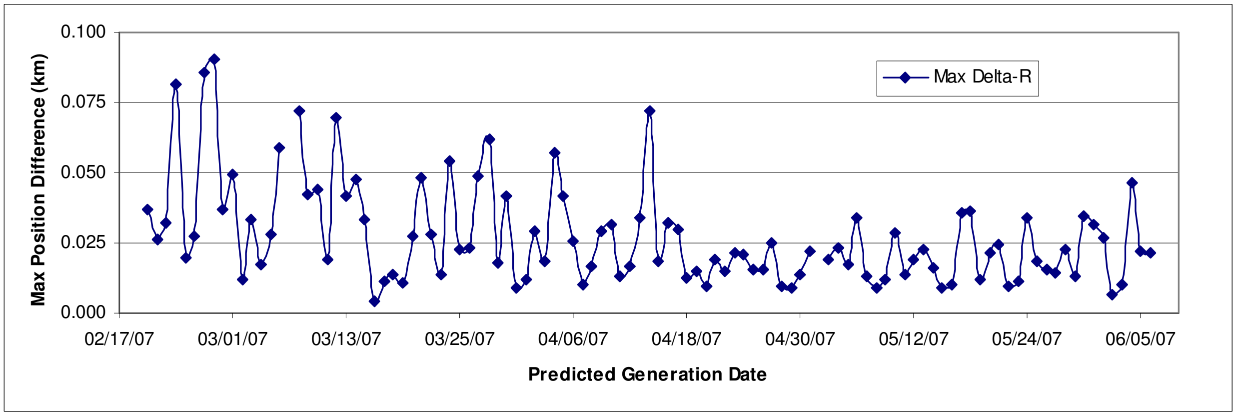

Figure 2. TDRS-4 Predicted Accuracy for 1.5–days

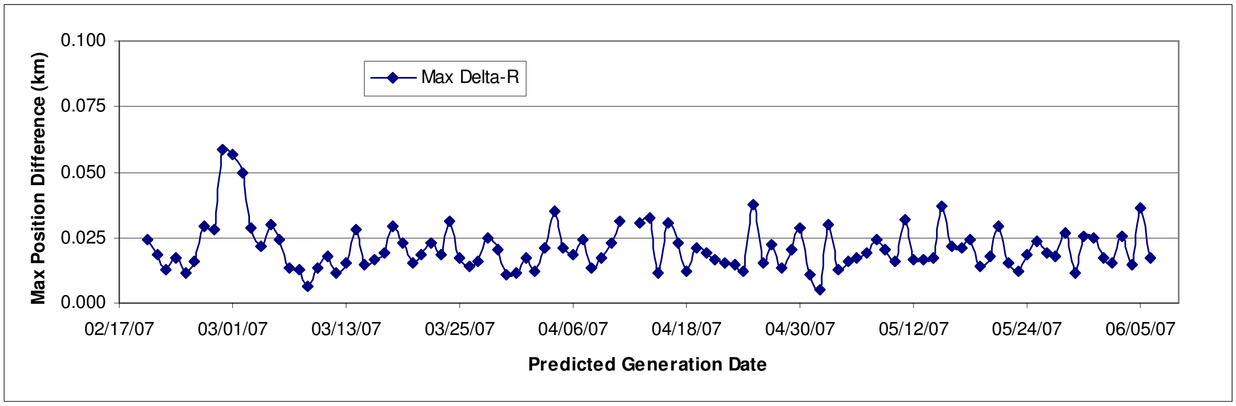

Figure 3. TDRS-5 Predicted Accuracy for 1.5–days

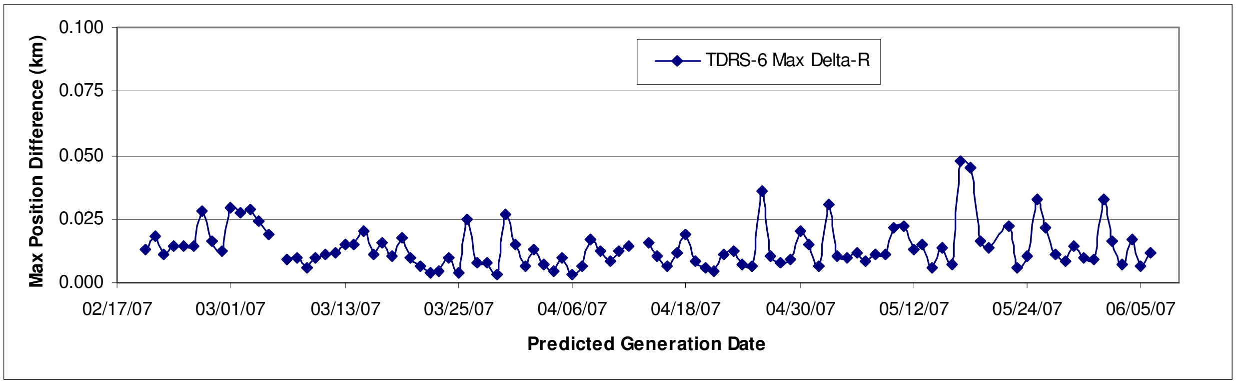

Figure 4. TDRS-6 Predicted Accuracy for 1.5–days

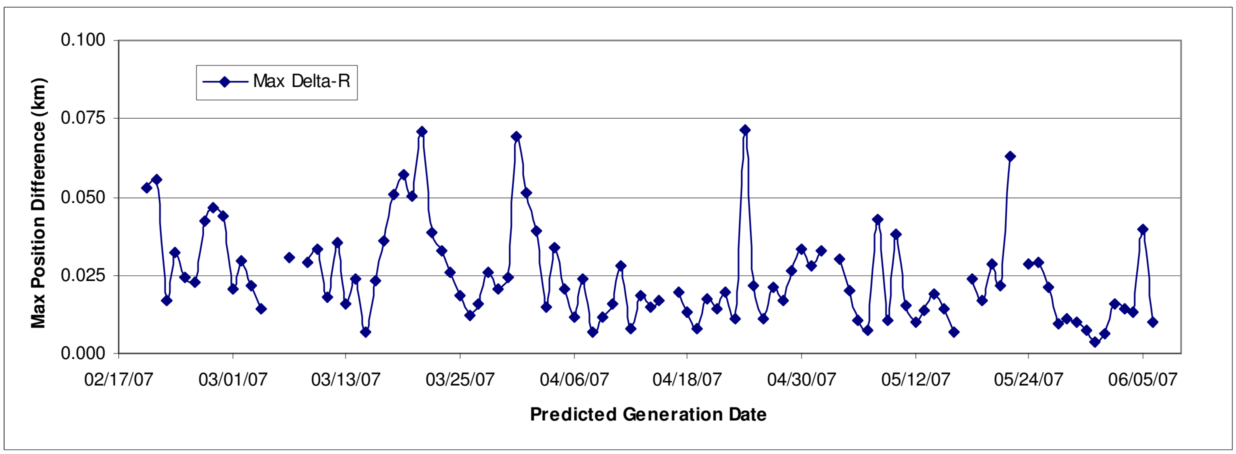

Figure 5. TDRS-10 Predicted Accuracy for 1.5–days

When the EKF process is not expected to reliably accommodate maneuvers or MUs, GTDS is used. An MU within 2 hours of the normal solution run time automatically triggers the use of the GTDS CB. For stationkeeping maneuvers within 11 to 16 hours of 1300 Greenwich Mean Time (GMT), the default EKF epoch time, the GTDS SB alternative is used for all five operational TDRSs. Further automation work is described in the next section.

4. AUTOMATION

As experience was gained in using the EKF, enhancements were made to the automated TDRS daily production process. In particular, added quality assurance (QA) tests were implemented to guard against problems from thrusting or range bias shifts. These tolerances must be passed before an automated delivery occurs. An operational engage-disengage option was also added to prevent degraded, EKF deliveries to the Terra Project. This option keys on both the elapsed time since the last thrusting event and the type of thrusting. If thrusting was too recent, a skip or nonoperational condition is enabled, which makes the GTDS solution prime. Additional adjustments were made to ephemeris comparison tolerances to prevent unnecessary interruption to automated Terra deliveries; some of those tolerances were either re-categorized as warnings (non-failures) or relaxed and augmented with warnings.

Reducing manual intervention and allowing cost savings are continual incentives for increased automation. Weekend labor reduction or elimination is an added benefit. The logic flow for daily automated deliveries is shown in Figure 6. After the automation begins, a check for a recent maneuver or MU is done. If thrusting was too recent, GTDS will be used for the delivery if its QA checks pass. If there was no recent thrusting, the EKF will be used for the delivery if its QA checks pass. Once a delivery is done, analysts are notified by pager and/or email.

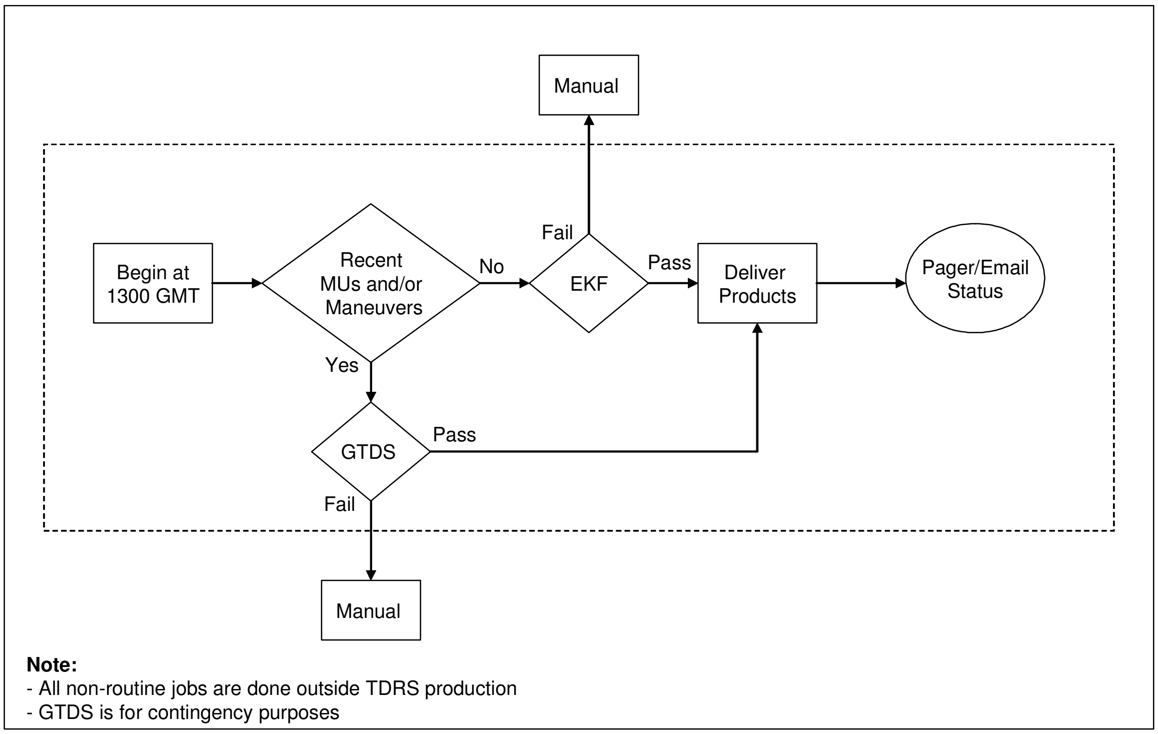

Figure 6. Process Flow of TDRS Automation

Based on empirical results, limits were established on the use of EKF in general and during special circumstances following MUs or maneuvers. Required threshold criteria are used in monitoring the acceptable percentage of data used by the EKF, which would have avoided at least two of the three high TDRS–4 comparisons in Figure 2. Had that been done, the failure rate would have been no more than 1 case in 521, or 0.19%, which is within the 3σ requirement. For the first day after stationkeeping maneuvers, manual intervention is currently necessary.

Beginning in April 2007, Figure 7 shows the progress of the TDRS automation for Terra deliveries. The percentage of daily Terra deliveries that were made automatically for Terra is displayed by month. The July automation rate was 65%. Maneuvers are expected to limit the current automation success rate to 80 or 90%. Full autonomous daily support, including unattended weekend support, began on June 12, 2007.

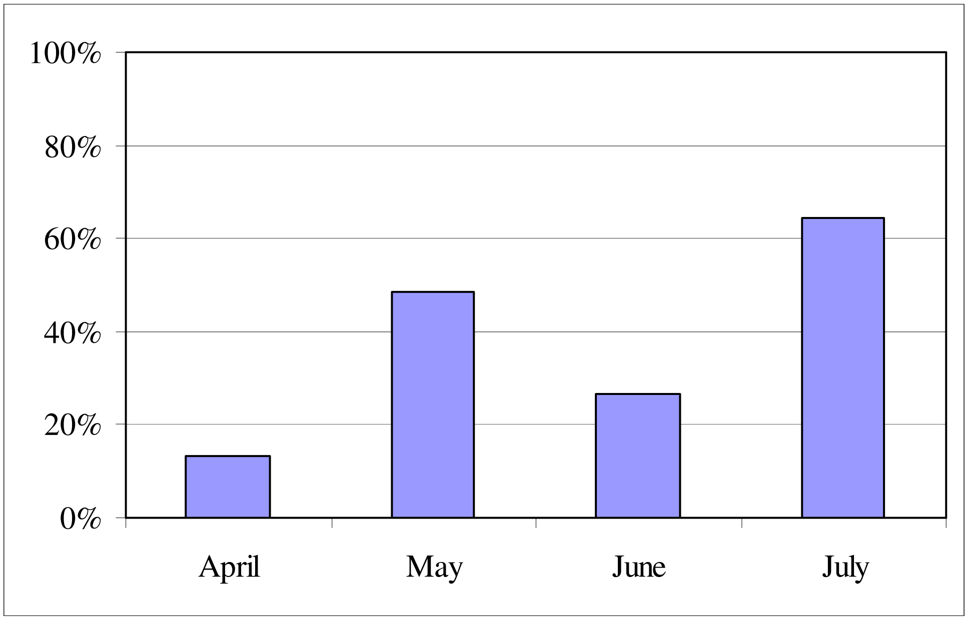

Figure 7. Percentage of Autonomous TDRS Deliveries for Terra since April 2007

Work continues to increase the efficiency, the accuracy, and the robustness of the automated process.

5. SUMMARY AND RECOMMENDATIONS

The EKF technique was chosen for the automation of TDRS support because of the relative ease for automation of the EKF. The EKF was implemented as the prime FDF system for routine TDRS OD on February 20, 2007. Automated deliveries to Terra became predominant in July 2007. Except for the first day after stationkeeping maneuvers, fully autonomous daily support has been in use since June 12, 2007.

The automated process will continue to be refined as experience is gained in its use. One consideration is to investigate further the procedures and techniques applied during periods of TDRS orbit perturbation, principally the maneuvers and momentum unloads. Momentum unload modeling may improve with recalibration based on more accurate OD with the EKF. Another investigation might be on improving the solar radiation pressure modeling in the filter, as the GTDS modeling is seen to be more responsive.

The decline of the 11–year solar cycle was coincident with the improvement of the EKF performance. A natural question is how the EKF will be affected by the next maximum of the 11–year solar cycle, when there will be increasing variations in the solar flux and geomagnetic indices, which will directly affect TDRSS User OD.

The results presented here show that the accuracies achieved by the automated operational support procedures, combining the strengths of both the EKF and GTDS, can meet the TDRS accuracy requirement of 75 meters, 3σ. The automation also has the additional benefit of reducing the needs for both manual processing and weekend labor.

6. REFERENCES

1. K. Dang, D. Ward, S. Slojkowski, J. Dunham, and M. Blizzard, *Tracking And Data Relay Satellite (TDRS) Orbit Determination Using Chain-Dependent Range Biases*, 2005 Flight Mechanics Symposium, Greenbelt, Maryland, October 18–20, 2005, NASA/CP–2005–212789, Session 4, Paper No. 4.