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Orbit Determination and Navigation of the Time History of Events and Macroscale Interactions during Substorms (THEMIS)[1]

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Abstract

This paper provides an overview of the launch and early orbit activities performed by the NASA Goddard Space Flight Center's (GSFC) Flight Dynamics Facility (FDF) in support of five probes comprising the Time History of Events and Macroscale Interactions during Substorms (THEMIS) spacecraft. The FDF was tasked to support THEMIS in a limited capacity providing backup orbit determination support for validation purposes for all five THEMIS probes during launch plus 30 days in coordination with University of California Berkeley Flight Dynamics Center (UCB/FDC)[2]. The FDF's orbit determination responsibilities were originally planned to be as a backup to the UCB/FDC for validation purposes only. However, various challenges early on in the mission and a Spacecraft Emergency declared thirty hours after launch placed the FDF team in the role of providing the orbit solutions that enabled contact with each of the probes and the eventual termination of the Spacecraft Emergency. This paper details the challenges and various techniques used by the GSFC FDF team to successfully perform orbit determination for all five THEMIS probes during the early mission. In addition, actual THEMIS orbit determination results are presented spanning the launch and early orbit mission phase. Lastly, this paper enumerates lessons learned from the THEMIS mission, as well as demonstrates the broad range of resources and capabilities within the FDF for supporting critical launch and early orbit navigation activities, especially challenging for constellation missions.

1 Introduction

As the primary provider of flight dynamics services, the THEMIS FDC, which is collocated with the Mission Operations Center (MOC) at the University of California at Berkeley (UCB), is responsible for performing orbit determination (OD) using the Goddard Trajectory Determination System (GTDS) through the entire mission and providing all acquisition data to the supporting ground stations. As backup to UCB/FDC, the Flight Dynamics Facility (FDF) located at NASA Goddard Space Flight Center (GSFC) was tasked to provide backup OD using GTDS for the first 30 days of the mission and again during the Ascent Phase beginning in September 2007 for approximately 70 days. Therefore, the FDF team had a limited role in the navigation support for THEMIS. Orbit determination solutions and predictions are required for the support of onboard attitude processing, reduction of scientific measurements, detailed maneuver planning, as well as generation of antenna acquisition data.

The spacecraft were successfully launched on 2007-02-17 23:01 UTC on a Delta-II 7925 launch vehicle from Cape Canaveral Air Force Station (CCAFS). After launch, all five THEMIS probes were inserted into a parking orbit around the Earth. Several small perigee raising maneuvers were nominally planned to occur within the first few weeks after launch. The spacecraft were planned to remain in the parking orbit until September of 2007, when the ascent phase is to begin.

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[2] National Aeronautics and Space Administration (NASA), Goddard Space Flight Center (GSFC), *FDF-28-012 THEMIS MOU Between GSFC FDF and UCB FDC2.doc*, January 2007.

This paper provides an overview of the launch and early orbit activities performed by the FDF in support of the five THEMIS probes. Although the FDF's orbit determination responsibilities were originally planned to be as a backup to the UCB/FDC for validation purposes only, various challenges early in the mission and a Spacecraft Emergency declared 30 hours after launch placed the FDF team in a role of providing the orbit solutions that enabled contact with each of the probes and the eventual termination of the Spacecraft Emergency. This paper details the challenges and various techniques used by the GSFC FDF team to successfully perform orbit determination for all five of the THEMIS probes during the early mission. In addition, actual THEMIS orbit determination results are presented spanning the launch and early orbit mission phase. Lastly, this paper discusses THEMIS lessons learned, as well as the strength and breadth of FDF services and resources for supporting critical launch and early orbit navigation activities. A number of important lessons learned are identified throughout the paper and summarized in the conclusion.

Section 2, Overview, provides pre-mission information regarding the THEMIS mission and anticipated FDF THEMIS support. This section includes a discussion of the nominal mission, the nominal orbit including pre-mission force modeling, nominal tracking assets, and anticipated challenges. Section 3, Launch Support, describes actual launch and early support from launch day through termination of Spacecraft Emergency. The content of this section includes: a summary of launch; a description of early orbit support including contingencies; and Spacecraft Emergency recovery including managing tracking asset configuration issues and FDF orbit analysis of spacecraft separation vector. Section 4, Additional Early Orbit Challenges and Orbit Determination, details tribulations encountered after the Spacecraft Emergency, which impacted orbit determination, and how FDF managed to cope with these difficulties in THEMIS mission support. Finally, Section 5, Conclusions, summarizes a number of the important lessons learned from FDF's support of the THEMIS mission as enumerated throughout the paper, and discusses the broad range of resources and capabilities within the FDF for supporting critical launch and early orbit navigation activities, especially challenging for constellation missions.

2 Overview

Section 2, Overview, provides pre-mission information regarding the THEMIS mission and anticipated FDF THEMIS support. This section includes a discussion of the nominal mission, the nominal orbit including pre-mission force modeling, the nominal tracking assets, and finally anticipated challenges.

2.1 Mission

THEMIS is a NASA-funded Medium Explorer mission (MIDEX) managed by the Explorers Program Office at GSFC in Greenbelt, Maryland. The THEMIS mission consists of five space probes, THEMIS A through THEMIS E, in elliptical low-inclination, high-Earth orbits and 20 Ground Based Observatories (GBO) deployed in Canada and Alaska. The five probes carry an identical suite of science instruments to measure electric and magnetic fields, as well as the distribution of plasma particles to study phenomena in the magneto tail of the Earth leading to the aurora. Each satellite includes a fluxgate magnetometer (FGM), an electrostatic analyzer (ESA), a solid state telescope (SST), a search coil magnetometer (SCM), and an electric field instrument (EFI). Every 4 days, the satellites will line up along the Earth's magnetic tail, allowing them to track disturbances. The satellite data will be combined with the observations of the aurora from the network of GBOs across the Arctic Circle.

THEMIS mission objectives are to measure the time history of auroral breakup, current disruption, and lobe flux reconnection at the substorm meridian. In addition, ground based observatories will locate auroral onset to 0.5^{o} in longitude. THEMIS provides answers to critical questions about the origin and phenomenology of solar and Earth magnetospheric interaction, the resultant electrical substorms, effects on space weather, disruptions in ground power grids, and effects on communications. These conditions affect the operation of other space satellites and the lives of humans in the sub-auroral regions on Earth. The mission primary objectives are as follows:

a. Establish when and where substorms start.
b. Determine how the individual substorm components interact macroscopically.
c. Determine how substorms power the aurora.

d. Identify how the substorm instability couples dynamically to local current disruption modes.

2.2 Orbit

After launch, all five THEMIS probes were inserted into a parking orbit around the Earth. Several small perigee raising maneuvers were nominally planned during the first 2 weeks after launch; otherwise the spacecraft remain in the assigned parking orbit until September of 2007. At this time, large apogee raising maneuvers will occur for each spacecraft, with the last maneuver scheduled to be completed sometime during a November 2007 time frame. Figure 1 illustrates the orbit regimes that will be targeted in order to conduct mission science. Every 4 days, the satellites will line up along the Earth's magnetic tail enabling THEMIS to track disturbances. The prime observing season extends from late fall through early winter.

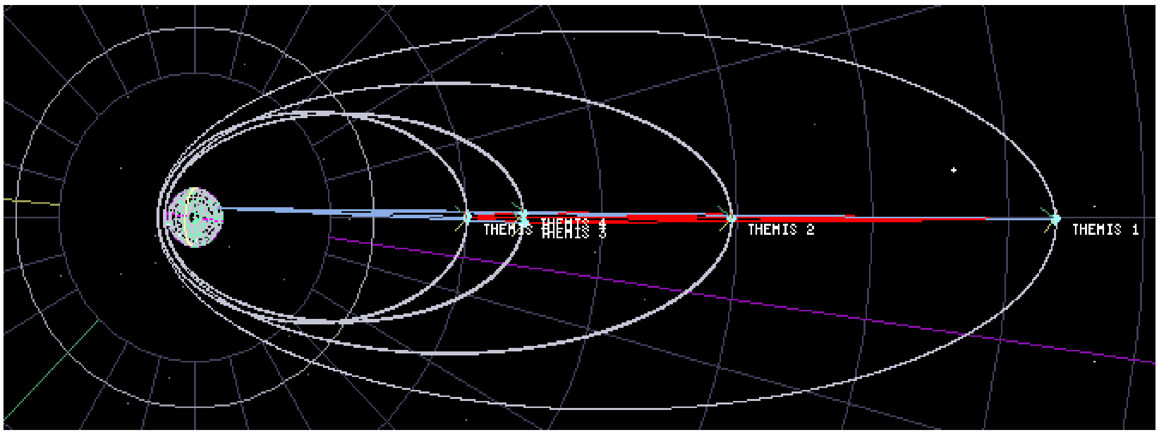

Figure 1. THEMIS Mission Science Orbit

Table 1 displays the estimated apogee, perigee, and inclination in Earth radii and degrees for the nominal THEMIS science orbits for each probe. THEMIS probe number 1 will reside farthest away from the Earth, with the higher number probes being placed in orbits closer to the planet. THEMIS probe numbers 3 and 4 will have the same approximate apogee and perigee. They will remain in their assigned orbits for two observing seasons or approximately 2 years, at which time they will begin maneuvers allowing them to re-enter the atmosphere.

Table 1. Science Orbit Information for THEMIS Probes

Probe	Apogee (R_e)	Perigee (R_e)	Period (days)	Inclination (deg)
P1	31.645	1.500	4.03	7.0°
P2	19.770	1.168	2.02	7.0°
P3	12.019	1.200	1.02	9.0°
P4	12.019	1.200	1.02	9.0°
P5	10.042	1.350	0.81	9.0°
Launch Insertion (All)	12.1	1.05	1.01	9.5°

Both FDF and UCB/FDC used GTDS as the orbit determination system. The basic force modeling parameters included in the THEMIS orbit solutions[3] are as follows:

[3] National Aeronautics and Space Administration (NASA), Goddard Space Flight Center (GSFC), *FDF-28-012 THEMIS MOU Between GSFC FDF and UCB FDC2.doc*, January 2007

- True of date
- JR Atmospheric Model
- 50 x 50 JGM-2
- 30 second integration step size
- Sun and Moon perturbations
- Atmospheric drag applied and solved-for
- Solar radiation pressure applied
- Polar motion correction applied
- Tide motion correction applied
- Spacecraft mass at launch
- Dry mass: 78.9983 kg
- Fuel mass: 49.0017 kg
- Total mass: 128.0000 kg
- Spacecraft cross-sectional area: 6.175×10^{-7} km^2

2.3 Tracking

Tracking support for the five THEMIS spacecraft is provided by the NASA's Ground Network (GN) antennas, including the Wallops Flight Facility (WFF), Merritt Island (MIL), and Santiago, Chile (AGO) tracking stations. Although not a part of the GN, both the Berkeley Ground Station (BGS) and the Hartebeesthoek Ground Station (HBK), in South Africa, also provide THEMIS tracking services, with BGS being the prime THEMIS Mission antenna.

Supporting GN stations transfer tracking data to the FDF and the UCB/FDC MOC via post-pass File Transfer Protocol (FTP). The THEMIS supporting ground stations collect and provide two-way Doppler tracking data measurements and, when available, angle tracking measurements. FDF and UCB/FDC use the tracking data to perform orbit estimation.

2.4 Anticipated Challenges

Constellation management is always a challenge, especially during the critical launch and early orbit mission phase. As stated, THEMIS is a constellation mission comprised of five identical, yet separate spacecraft probes. All five probes were launched on and deployed from one Delta II launch vehicle. The Delta payload/probe carrier was designed such that THEMIS A was deployed in the velocity direction, while the remaining probes, THEMIS B through THEMIS E, were arranged around the carrier's circumference and deployed radially. There was no guidance telemetry at payload separation and the probe carrier was spinning. The Delta Acquisition Assistance Message (AAM) for THEMIS was generated after the 2nd stage "piloted" burn, using telemetry from the first two stages with the nominal 3rd stage performance added and propagated to payload separation. Unfortunately, the Delta AAM did not model residual thrusting or the spinning of the probe carrier. Thus there was no definitive separation state knowledge for any of the probes. The only distinction that could be made was that THEMIS A was to be released 3 seconds prior to THEMIS B through THEMIS E. Having only one spacecraft separation vector for all five probes introduced error into the critical launch day orbit determination process. However, any difference was estimated to be below the expected propagation error and any uncertainty of the last known state.

An obvious flight dynamics challenge was managing all five probes simultaneously, particularly in their launch and early orbit phase. Also, all five probes shared identical transponders with identical frequencies, and thus the potential of misidentified tracking data. Fortunately, these risks were never realized.

FDF was only tasked to validate HBK's ability to track and provide useable coherent Doppler tracking data. The ground station's tracking data had not been certified to any level of accuracy or quality prior to launch. UCB/FDC independently verified and accepted the HBK tracking data quality and accuracy.

3 Launch Support

Section 3, Launch Support describes actual launch and early support from launch day through termination of Spacecraft Emergency. The content of this section includes: a summary of launch; a description of early orbit support including contingencies and activities and analysis critical to THEMIS Spacecraft Emergency recovery as related to orbit determination performed by the FDF including managing tracking asset configuration issues and FDF orbit analysis of spacecraft separation vector.

3.1 Launch Summary

THEMIS was successfully launched on Friday, 2007-02-17 23:01:00 UTC. The Delta II ascent to orbit was nominal with THEMIS A separation occurring at 2007-02-18 00:14:14 UTC followed by THEMIS B through THEMIS E at 2007-02-18 00:14:17 UTC. The Tracking and Data Relay Satellite System (TDRSS) was scheduled to monitor the separation event, but no tracking data was provided since the TDRSS event was scheduled as a WDISC service, which provides telemetry and command data only. There were no problems noted during the TDRSS contact or the BGS contacts that immediately followed. The Delta Acquisition Assistance Message (AAM) state vector compared well with the predicted nominal launch, and UCB/FDC decided not to update the network acquisition data.

3.2 Early Orbit Support

The Delta AAM state vector compared well with the pre-launch nominal; therefore, UCB/FDC decided not to update the network acquisition data. However, subsequent orbit solutions for all five probes indicated that the launch vehicle performance placed the THEMIS spacecraft 63.9% low on the achieved orbital period compared to the allowable launch vehicle dispersions. The launch vehicle dispersions allowance for the THEMIS orbit were 1999 +/- 180 minutes for the orbital period, perigee altitude dispersions of 435 +/- 6 km, and inclination dispersions of 16 +/- 0.5°. With such a large spread in orbital period permitted, the resultant orbit could produce extremely large instantaneous position errors compared to the mission nominal. Comparisons between the Delta AAM and pre-launch nominal could not identify the error in the Delta AAM vector since it was a modeled propagation of a nominal 3rd stage performance. The launch vehicle performance translated into a 2-hour difference between the actual spacecraft period and the Delta AAM modeled separation state with the actual period being 31.4 hours versus the 33.3 hour period modeled in the Delta AAM vector. See Table 2 for a comparison between the AAM separation state and that computed by FDF. This underperformance error in the Delta AAM state, which was used as the *a priori* state in the orbit determination process for all five probes, had an impact on critical early orbit determination and contributed to the THEMIS early mission difficulties.

Table 2. Comparison of the Delta AAM and the FDF Determined States

Parameter	AAM Values	FDF Values	Differences
Epoch (UTC)	2007-02-18 00:14:08.414	2007-02-18 00:14:08.414	0
X (km)	6484.8464	6485.26514941607	-0.418749
Y (km)	-3998.9338	-4007.03639711802	7.14302
Z (km)	-23.620889	-22.9429770845846	-0.677912
Vx (km/s)	7.3560188	7.34595828420958	0.0100605
Vy (km/s)	6.0284782	6.00830459333473	0.0201736
Vz (km/s)	2.5693697	2.57353917501606	-0.00416948
Osculating period (min)	1999.526	1884.305	115.221
Osculating perigee altitude (km)	435.306	436.618	-1.31436

Osculating inclination (deg)	16.004	16.037	-0.033

Another contributing error was a spacecraft RF anomaly[4] causing significantly weaker down link signal strength than expected, which was aggravated by less than ideal antenna to ground orientations. Since all five probes shared identical RF designs, they all suffered from this RF communication anomaly. The on-board RF anomaly was further compounded by the apparent link margin problems observed with certain antennas tracking the THEMIS probes around apogee. The WFF 11-meter (11m) antenna experienced extreme difficulty acquiring the very weak THEMIS downlink. The on-board spacecraft RF anomaly coupled with the poor spacecraft antenna geometry with respect to the supporting ground stations and the link margin problems all resulted in very little useable coherent UTDF Doppler tracking data being collected during the critical initial orbit phase immediately following spacecraft separation. With the large errors in the propagated Delta AAM vector coupled with sparse coherent Doppler tracking data, initial orbit determination and estimation was extremely difficult for THEMIS A, B, and E and nearly impossible for THEMIS C and D. Without orbital estimation results, there were no antenna acquisition data updates available on launch day based on orbit determination.

The actual insertion orbit quickly diverged from that which was modeled in the pre launch nominal acquisition data. In conjunction with the on-board RF anomaly, communication difficulties quickly escalated and eventually resulted in negative acquisitions, loss of communications with all probes, and ultimately in declaring a Spacecraft Emergency on 2007-02-19 04:30 UTC, only 30 hours after launch.

The majority of early mission passes on the THEMIS probes did not result in a successful acquisition of signal. The stations often then shifted to manual track, sweeping the antennas for a “hit” on the spacecraft. Tracking data from these contacts had to be used very judiciously, as all the resultant measurements were not good except for a couple, as the antenna was in effect on program track, with no RF from the spacecraft. In order to use this data, it was necessary for orbit determination analysts to talk to the ground station to determine if the antenna operator got any “hit” or contacts on the spacecraft during the sweep.

Although GN UTDF Doppler data was the only expected tracking data type prior to launch, angle tracking data from various supporting GN sites was absolutely critical during the first few days after launch for orbit determination and Spacecraft Emergency recovery. Of the certified THEMIS GN sites, only Wallops (WFF), Merritt Island (MIL), and Santiago (AGO) have the capability to provide angle tracking measurements. With the RF and link margin issues, angle tracking data came into FDF flagged invalid because there was a low signal to noise ratio, which prevented the validity trigger in the antenna system, hence all of the tracking data was marked invalid from launch on for THEMIS. FDF evaluated the invalid angle data and determined that although the measurements were invalid, the angle tracking was useable. In order to use the invalid angle tracking data in the orbit solutions, FDF had to manually configure the orbit system to override the validity flag, which was crucial in getting the solutions that enabled communication with the THEMIS probes.

Over the first few days after THEMIS launch, using the initial Wallops pass, with data flagged as invalid from THEMIS A, FDF was able to generate and provide the best initial post-launch orbit solution that was used to update the station acquisition data re-establishing communication with all five probes and terminating the Spacecraft Emergency. This solution was built from a couple of manual track hits on THEMIS A, as well as the first contact right after separation from BGS. This solution was crucial to recovery of all the mission orbits due to the quickly evolving Spacecraft Emergency. It was only by boot-strapping this initial solution for THEMIS A using the Wallops angle data, that good orbit solutions were achievable for THEMIS B through THEMIS E.

3.3 Spacecraft Emergency Recovery

The following subsections detail activities and analysis critical to THEMIS Spacecraft Emergency recovery as related to orbit determination performed by the FDF. The activities and analysis include managing

[4] UCB THEMIS Status Briefing & COMM Anomaly Tiger Team

configuration issues from various tracking assets, as well as Delta AAM orbit state comparisons with FDF orbit solutions.

3.3.1 HBK Facility Configuration

In an attempt to improve communication with the probes using antennas with greater link margins, the HBK facility began their support using uplinks and downlinks from the 10-meter antenna. Due to the troubled downlinks, the station attempted multiple configurations, eventually settling on a dual configuration consisting of a 6-meter transmit antenna and a 12-meter receive antenna. However, the tracking data from this HBK dual configuration was not properly labeled, as the UTDF tracking data from these events still used the antenna identifiers of the 10-meter antenna, as this was the expected nominal antenna validated for THEMIS support by UCB/FDC. In order to correctly process and use the HBK 6-meter/12-meter antenna tracking data, FDF had to manipulate the tracking data and overwrite the transmit and receive antenna identification codes. The 6-meter/12-meter antenna configuration was a new antenna for FDF and not included in the station files used by the FDF or UCB/FDC orbit ground systems. In order to correctly process and use the HBK 6-meter/12-meter tracking data, FDF had to manually configure the orbit determination system to correctly recognize the tracking station and use the correct station geodetic information. FDF reset this data to be the proper stations by overwriting the transmit and receive sites on the Oracle SQL database used to store the raw data.

Since the HBK 6-meter/12-meter was a previously unused antenna configuration, FDF first had to quickly research and analyze the geodetics for this antenna to ensure proper performance while under this Spacecraft Emergency, a process that is generally performed with multi-station tracking with known references for comparisons. This process was repeatedly necessary for the constellation of THEMIS spacecraft through the early mission support. Existing lines of communication between FDF and various elements of the tracking networks was crucial to verifying the HBK configurations used for each pass.

Unfortunately, UCB/FDC had no convenient means of properly overwriting and processing this tracking data. FDF extracted the reprocessed data from its Oracle database, converted it to 60-byte sequential GTDS input tracking data files[5], and sent this data to UCB/FDC. FDF provided consultation on how to manually configure orbit systems to use correct station geodetic information.

3.3.2 DSN Configuration

Orbit determination was originally planned to be based exclusively on two-way NASA Ground Network (GN) Universal Tracking Data Format (UTDF) Doppler tracking data. Spacecraft RF link margin issues and problems with antenna patterns during the early orbit mission phase led the FDF team to recommend additional support from the NASA Deep Space Network (DSN) after the THEMIS Spacecraft Emergency was issued. Therefore, although the GN antennas were the primary source of tracking data for THEMIS, DSN tracking data supplemented the GN data and was critical to early orbit estimation. Since DSN was not configured to support THEMIS, DSN sent all the THEMIS tracking data identified as TDRS-10 or as ChipSat, satellites they had supported before. This required FDF to perform data overrides for all of the DSN tracking data, as well. Again, a laborious and intensive project while supporting five probes.

Since UCB/FDC was not configured for DSN support, no network interface existed between UCB/FDC and the DSN. FDF generated and delivered to the DSN acquisition data to enable the antenna support for UCB/FDC since the capability did not exist. Also, UCB/FDC could not command THEMIS nor receive DSN telemetry or tracking data. There were a number of issues related to the DSN not being configured for supporting THEMIS that impacted FDF support. DSN was able to track only in a 3-way mode when another one of the THEMIS certified GN sites were tracking simultaneously. In order to properly process and use the DSN and simultaneous GN tracking data, FDF had to manipulate the data to add in 3-way overrides to the appropriate tracking measurements. Since in the majority of cases the data had already been accumulated, the data had to be replayed to reset the 3-way overrides to the data, or the data had to be

[5] The generalized 60-byte record format serves as a uniform medium for passing metric tracking data with standardized units as input to GTDS. National Aeronautics and Space Administration (NASA), Goddard Space Flight Center (GSFC), *60-Byte Data Format Definition*

directly manipulated to be the correct configuration. Again, this was laborious for five spacecraft throughout the support. Since GN Doppler UTDF tracking data was the only expected data type that UCB/FDC expected to receive prior to launch, the UCB/FDC orbit system was only configured to support this data type. DSN provided valuable angle data, as well as TRK-2-34 Doppler data types during THEMIS support. In order for UCB/FDC to be able to process and use the DSN tracking data correctly, FDF provided 60-byte sequential input tracking data file to UCB/FDC and consultation on how to setup and use this tracking data type in GTDS.

3.4 Delta AAM Orbit State Analysis

Table 3 presents the Delta AAM separation state, as well as the FDF orbit solutions for the probes during the early orbit support period. Solutions for THEMIS A and THEMIS B were created on the first day from the manual track data based on a few data points. When this data was later used by UCB/FDC to feed the GN acquisition data instead of using the UCB/FDC data, acquisition was successful for the probes, which enabled the successful recovery of communication, which led to further determination of the probes orbit parameters and continued launch and early orbit operations onboard the spacecraft.

Table 3. THEMIS Probe Osculating Perigee Altitude and Orbital Periods

Probe	ULA AAM		20070218 FDF*		20070219 FDF*		20070220 FDF**	
	Osculating Perigee (km)	Period (min)	Osculating Perigee (km)	Period (min)	Osculating Perigee (km)	Period (min)	Osculating Perigee (km)	Period (min)
A	435	1999	303	1867	609	1868	477	1870
B	435	1999	316	1886			480	1869
C	435	1999					475	1862
D	435	1999					480	1868
E	435	1999					480	1875

* Limited data

** Well-determined solutions

Table 4 demonstrates the configuration of the five probes as THEMIS came out of Spacecraft Emergency based on the FDF definitive solution (2007-02-18 00:14:00 – 2007-02-21 00:00:00 UTC) orbit estimation.

Table 4. FDF THEMIS Brouwer Mean Orbit

Epoch: 2007-02-20 00:00:00 UTC
(Based on definitive data from 2007-02-18 00:14:00 – 2007-02-21 00:00:00 UTC)

Spacecraft	Perigee (km)	Apogee (km)	Inclination (deg)
THEMIS A	476	87339	16.008
THEMIS B	479	87316	16.003
THEMIS C	474	87078	15.991
THEMIS D	478	87297	15.990
THEMIS E	478	87540	16.019

Using THEMIS C as an example, Figure 2 displays a comparison of the component position differences of the predicted nominal launch insertion, whereas Figure 3 highlights just the along-track position difference (the Delta AAM state was close to the predicted nominal). As can be seen in these figures, the position differences were on the order of 10,000 km on average in the first couple of days to as much as 50,000 km near perigee. The large orbital period dispersions led to the positions diverging rapidly during the support period.

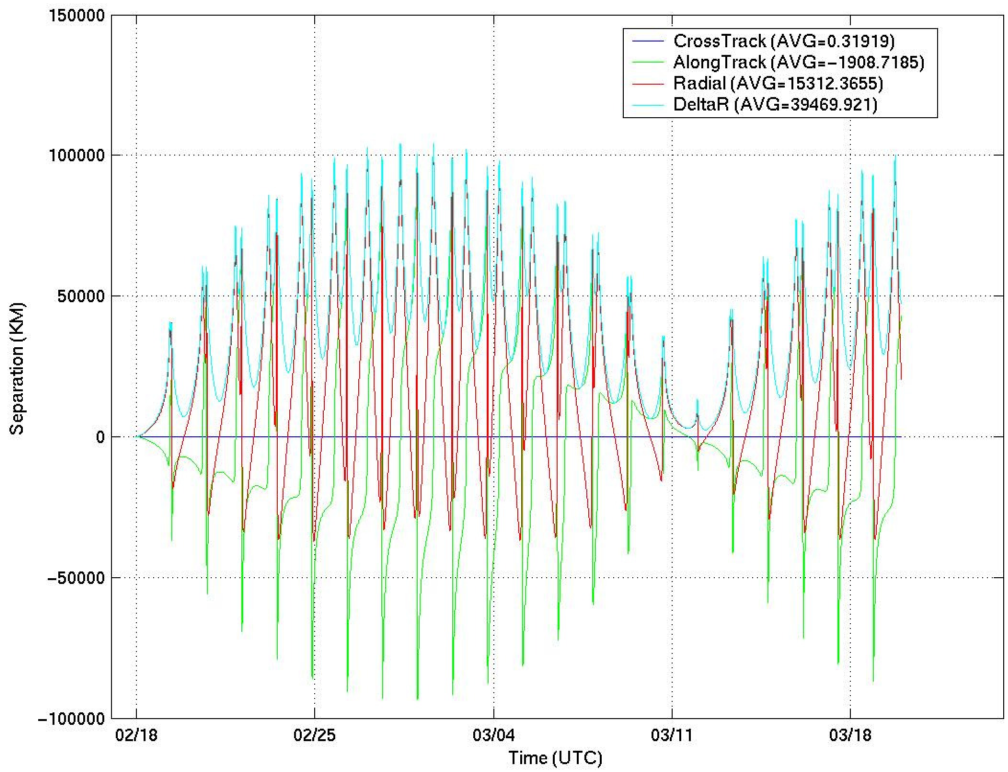

Figure 2. FDF THEMIS C Orbit vs. Predicted Nominal Launch Separation

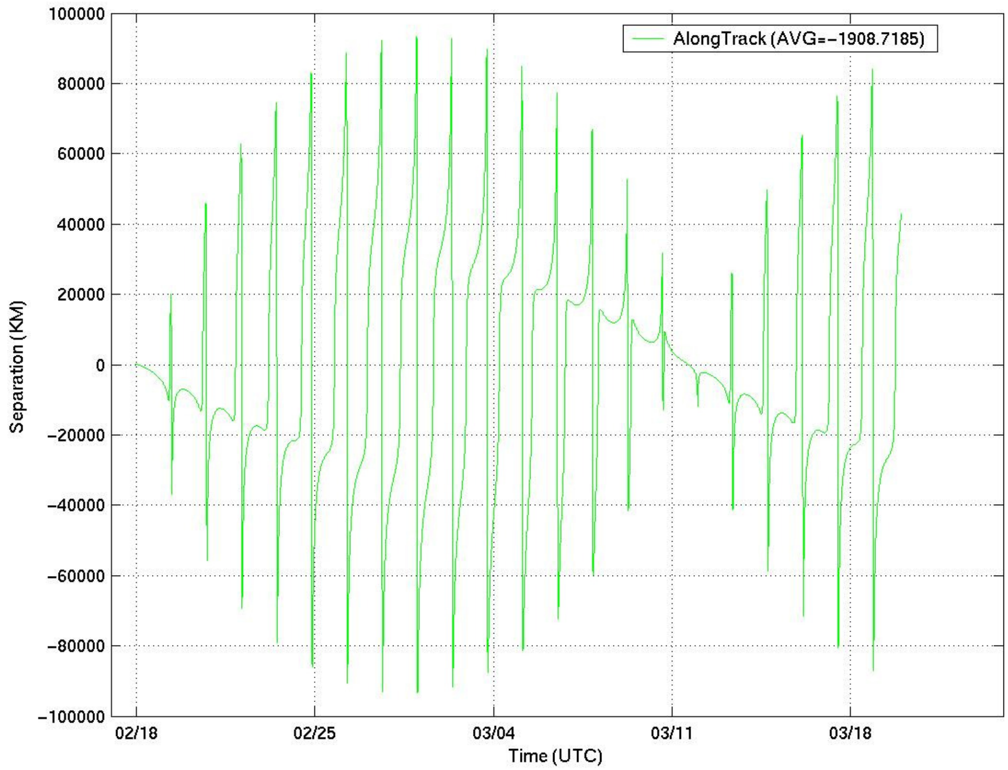

Figure 3. FDF THEMIS C Orbit vs. Predicted Nominal Launch Along Track Separation

THEMIS A was expected to be the lead spacecraft since it was to be ejected first from the launch vehicle in the forward velocity direction. As seen in Figure 4, THEMIS C quickly became the leading spacecraft.

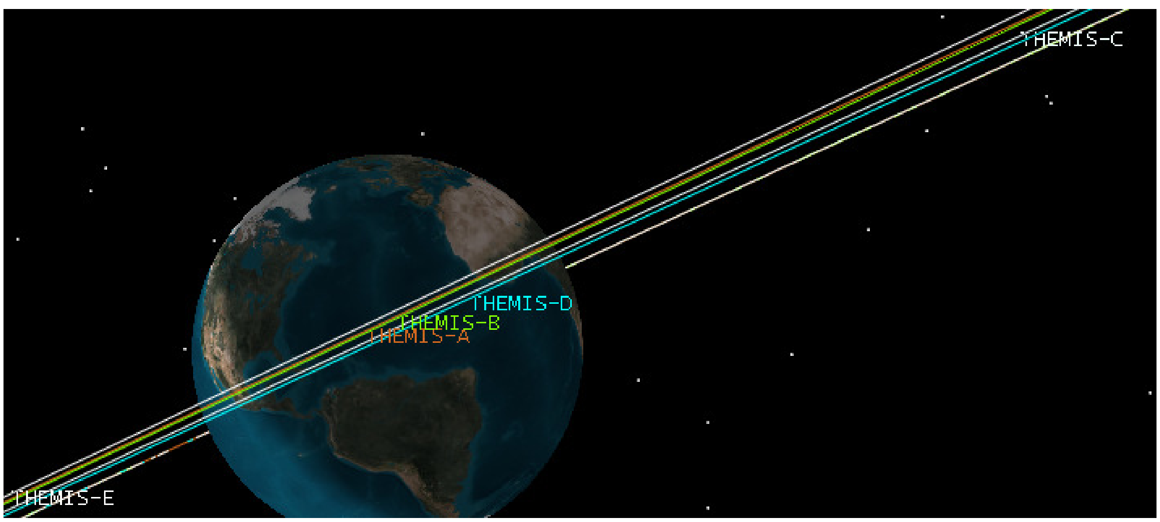

Figure 4. THEMIS Probe Position

Since THEMIS C was ejected with the lowest perigee, it essentially moved into the leading position on the first orbit. The relative separation of the spacecraft during early orbit was a significant issue. Since it was assumed that THEMIS A would be leading, it was assumed that the trailing spacecraft acquisition will be enabled from the acquisition of THEMIS A. The deployment sequence and possible permutations may not have been properly studied or evaluated for evaluation of acquisition complexities. Table 5 summarizes THEMIS C's separation, as the leading spacecraft, from the remaining constellation. Figure 5 below shows the actual separation of THEMIS C to THEMIS A, based on reconstructed definitive ephemeris data. It is evident that THEMIS C overtakes THEMIS A and remains the leading spacecraft. Figure 6 shows the separation of THEMIS C to THEMIS E, the trailing spacecraft.

Table 5. FDF THEMIS Spacecraft Separation Summary

Epoch: 2007-02-20 00:00:00 UTC
(Based on definitive data from 2007-02-18 00:14:00 – 2007-02-21 00:00:00 UTC)

Spacecraft Comparison	Position RMS (KM)	Radial RMS (KM)	Along Track RMS (KM)	Position Maximum (KM)	Radial Maximum (KM)	Along Track Maximum (KM)
C vs. A	1792	1319	1213	8794	5937	-8101
C vs. B	1656	1211	1130	8146	5352	-7489
C vs. D	1517	1111	1033	7521	4747	-6866
C vs. E	3158	2436	2010	14531	12636	-12684

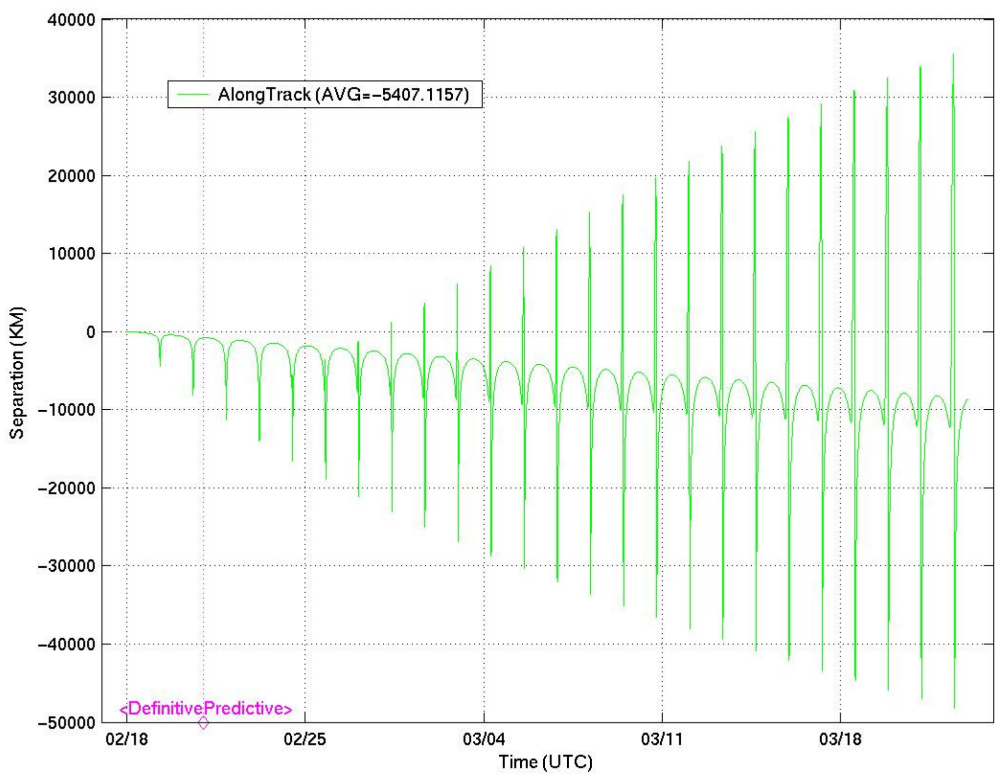

Figure 5. FDF THEMIS C Orbit vs. FDF THEMIS A Orbit Along Track Separation

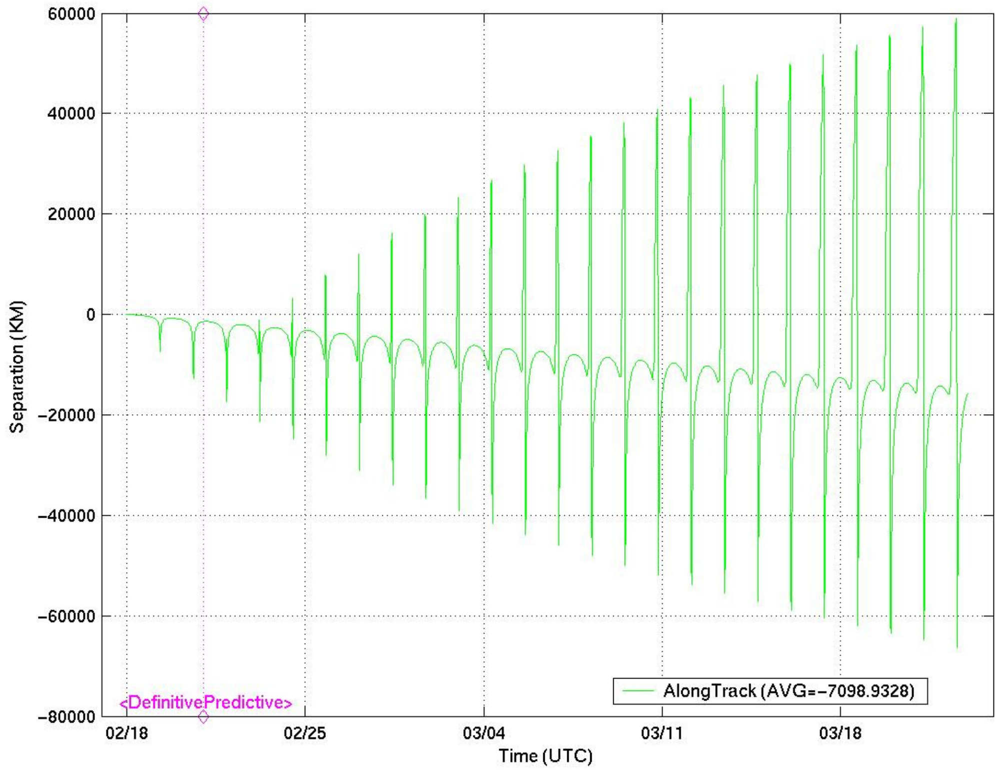

Figure 6. FDF THEMIS C Orbit vs. FDF THEMIS E Orbit Along Track Separation

Also evident from Figures 5 and 6 is that the relative separation of the spacecraft varied widely over the course of an orbit with emphasis on the separation divergence experienced through perigee as well as the trending average separation. As each spacecraft approached perigee, one by one each spacecraft rapidly accelerated, creating a rapid separation of several thousand kilometers, mostly down range. Then the spacecraft quickly regrouped closer together after exiting perigee. However, the passage through perigee evolves with each orbit so that the spacecraft separation continues to evolve. In just 1 week after launch, the total separation of THEMIS A and THEMIS C was 2000 km on average, with peaks well over 6000 km. These translate into acquisition differences of 10 minutes at perigee and over 30 minutes for the rest of the orbit.

4 Additional Early Orbit Challenges and Orbit Determination

Section 4, Additional Early Orbit Challenges and Orbit Determination, details tribulations encountered after the Spacecraft Emergency, which impacted orbit determination and how FDF managed to cope with these difficulties in THEMIS mission support.

After recovery from the Spacecraft Emergency, various challenges continued to hamper orbit determination and prediction for THEMIS. The spacecraft RF anomaly and the link margin issues and poor spacecraft orientation with respect to the supporting ground stations continued to produce very little tracking data for updating orbit solutions. Large differences in the comparisons between consecutive solutions were noted, seemingly due to a number of issues including too little tracking data, attitude thrusting not being modeled in orbit determination, and the orbit estimation integration step size.

FDF evaluated various integration methods to optimize orbit propagation during different portions of the orbit. The parking orbit was approximately 475 km x 87,000 km. Finding the original fixed 30 second integration step size to be inadequate, FDF tested a few different integration techniques to apply to THEMIS including:

1. Reduce integration step size to a smaller fixed interval. FDF tried 1-second to 5-second intervals, but there were significant performance issues when attempting fixed integration using step sizes of 2 seconds or less.
2. Vary integration step size with respect to altitude/semi-major axis. Used 2 seconds for all altitudes less than 1000 km, 5 seconds for 1000 km-5000 km, and 5 minutes to integrate portions of orbit above 5000 km altitude. This technique was useful for generating definitive ephemerides, but not predicted ephemerides.
3. Enable orbit system to determine and vary integration step size over the orbit automatically. This technique did not yield results refined enough as the minimum step size was only 20 seconds.

After evaluating the various methods above, FDF selected a combination of these as the best operational approach taking both orbit accuracy and system performance into account. A time regularized integrator, as described in option 3, was used while attempting quick assessments and preliminary orbit solutions. Once the orbit solution had been optimized, a fixed 5 second interval integrator would then be used to reprocess the solution and to generate operational ephemerides. The tracking arcs used for orbit solutions spanned approximately 2-3 days to include at most two perigee passages, where dynamics are high. However, the minimal tracking schedule often required longer data arcs to accumulate sufficient tracking at the expense of including additional perigee passages.

The nominal force model as described in Section 2, Overview, Orbit, was used as a starting point. FDF changed the integration step size to optimize integration of the orbit around apogee and perigee as discussed above. Since the issue of very little tracking data plagued early orbit estimation for THEMIS, atmospheric drag was not typically solved for unless there was enough tracking data to estimate C_D (coefficient of drag) correctly. Attempts to estimate C_D often yielded unrealistic values.

Assuming data arcs spanning 5.5 days or more, OD covariance analysis demonstrated that one ground station can support basic OD functions[6] Due to the extenuating circumstances experienced during THEMIS early orbit, the assumed ideal conditions were never met. Maximum data arc lengths peaked at only 4 days with a median length of 2.5 days due to the amount of useable tracking data available. When possible, OD performed from tracking data from multiple ground stations covering spans on the order of 5 days produced predictive ephemeris comparisons less than 1km. Fewer tracking stations and shorter arc lengths often resulted in predictive ephemeris comparisons of hundreds of kilometers.

5 Conclusions

Section 5, Conclusions, summarizes a number of the important lessons learned from FDF's support of the THEMIS mission as enumerated throughout the paper, and discusses the broad range of resources and capabilities within the FDF for supporting critical launch and early orbit navigation activities, especially challenging for constellation missions.

This paper provides an overview of the launch and early orbit activities performed by the FDF in support of THEMIS. The FDF was tasked to support THEMIS in a limited capacity providing backup orbit determination support for validation purposes for all five THEMIS probes during launch plus 30 days in coordination with UCB/FDC[7]. However, various challenges early on in the mission and a Spacecraft Emergency declared thirty hours after launch placed the FDF team in the role of providing the orbit

[6] University of California at Berkeley (UCB), Flight Dynamics Center (FDC), *THEMIS_FDFOR*, July 2006
[7] National Aeronautics and Space Administration (NASA), Goddard Space Flight Center (GSFC), *FDF-28-012 THEMIS MOU Between GSFC FDF and UCB FDC2.doc*, January 2007.

solutions that enabled contact with each of the probes and the eventual termination of the Spacecraft Emergency. A number of important lessons learned are identified throughout the paper and summarized in this section.

Contingency planning and extensive resources are strengths of the FDF. Drawing on experiences of launching and supporting hundreds of spacecraft missions, the FDF has built tools that permit data manipulation for contingencies and have the capability of using more than 23 data types to expand the possibilities of supporting new missions and aid in the recovery of spacecraft during spacecraft emergencies. FDF personnel analytical capabilities and experience also supply needed assistance during these endeavors.

For missions that have large possible launch dispersions, even a slight difference from nominal, could produce situations that will rapidly degrade into contingency situations. The best posture for these situations is to be prepared before launch to work with the launch dispersion cases quickly. Further, using launch vehicle inertial guidance data can be risky, especially when the final stages are only modeled. The best situation is to ensure that the launch vehicle data is available from all stages, a process that can be a mission criterion for the launch planning. Better yet is to ensure that the launch vehicle is tracked by ground antennas with tracking data to enable an independent verification of the separation state. This technique is often used for FDF-supported missions. Used in combination with a spectrum of possible dispersion data, the data will quickly yield the correct launch information for the new missions.

One of the primary objectives that FDF personnel use in planning launch and early orbit support is to build into the scenario the capability to use as many data types as possible due to possible contingencies with any one or more data types. In the past, FDF has put together launch and early orbit schedules that included as many as five different data types. In one instance as many as three of these data types were not available for various reasons. Hence it is better to be prepared for such contingencies during these critical few hours following launch. The fewer data types at launch, the greater the risk.

The prime consideration during an early orbit period is to determine the newly launched mission's orbit as quickly as possible, to prevent the outcome of poor acquisition and communications, as happened in this complicated support for the THEMIS mission. The THEMIS situation was also greatly exacerbated by the simultaneous support of five spacecraft, which also constrained the possible tracking contacts dedicated to any of the spacecraft.

Recognition that greater resources and planning will prevent far greater expenditures to recover the mission from Spacecraft Emergency or other anomalous situations will result in a savings in the long run and may prevent an irrecoverable loss.

THEMIS has been successfully recovered from its Spacecraft Emergency. Unfortunately the THEMIS mission is still affected by its RF condition. FDF continued to support UCB/FDC through launch plus 60 days, an extension from the original launch plus 30 day support plan. After the post-launch 60-day support period, FDF support subsided to a proficiency level of only one orbit solution per probe per month. FDF will resume a more dedicated support posture for THEMIS when the probes begin their Ascent Phase to reach their nominal science orbits for the first observing season planned for late fall through early winter of 2007.