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Orbit Determination (OD) Error Analysis Results for the Triana Sun-Earth L1 Libration Point Mission and for the Fourier Kelvin Stellar Ineterferometer (FKSI) Sun-Earth L2 Libration Point Mission Concept

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The Triana spacecraft was designed to be launched by the Space Shuttle. The nominal Triana mission orbit will be a Sun-Earth L1 libration point orbit. Using the NASA Goddard Space Flight Center's Orbit Determination Error Analysis System (ODEAS), orbit determination (OD) error analysis results are presented for all phases of the Triana mission from the first correction maneuver through approximately launch plus 6 months. Results are also presented for the science data collection phase of the Fourier Kelvin Stellar Interferometer Sun-Earth L2 libration point mission concept with momentum unloading thrust perturbations during the tracking arc. The Triana analysis includes extensive analysis of an initial short arc orbit determination solution and results using both Deep Space Network (DSN) and commercial Universal Space Network (USN) statistics. These results could be utilized in support of future Sun-Earth libration point missions.

INTRODUCTION

Triana is a mission dedicated to helping scientists construct more accurate models of Earth's climate and answering a key Earth Science question, how solar radiation affects climate. Triana has the following science objectives:

- Make the first direct measurements of the radiant power emitted by the whole Sun-lit side of the Earth to increase our understanding of how much of the Sun's energy is absorbed in the atmosphere and improve our understanding of global climate.
- Observe the vegetation canopy structure and evolution to monitor the health of the Earth's vegetation.
- Measure ozone and cloud coverage to study their affect on the amount of UV radiation that reaches the ground.
- Measure global aerosol optical thickness to increase our knowledge of how pollution, generated by both human and natural causes, affects the Earth.
- Improve our understanding of the characteristics of the solar wind and magnetic field and provide an early warning system for communication satellites and ground based systems susceptible to solar-related disturbances.

Triana was designed to be launched by the Space Shuttle. In a Space Shuttle launch scenario Triana, attached to a solid rocket motor (SRM), would be deployed by the Space Shuttle in low-Earth orbit. From low-Earth orbit the SRM transfer trajectory insertion (TTI) burn will increase the velocity of Triana by approximately 3.17 km/s sending the spacecraft on a transfer trajectory to its mission orbit, a Sun-Earth L1 libration point (Lissajous) orbit. The Triana Project decided to use a direct trajectory after consideration of radiation, shadow, and trajectory design issues. The Lissajous orbit insertion (LOI) maneuver of approximately 170 m/s will occur on the Sun side of L1 approximately 6 months after launch and will reduce the maximum Sun-Earth-Vehicle (SEV) angle. Following L1 Lissajous orbit insertion (LOI) the Sun-Earth-Vehicle (SEV) angle will nominally be maintained between 4.0 and 15.0 degrees for a period of 2-5 years after LOI, the duration of the nominal Triana mission. See Figure 1 for a graphic representation of a nominal Triana trajectory from Ecliptic North; the (blue) nearly circular portion of Figure 1 is the orbit of the Moon.

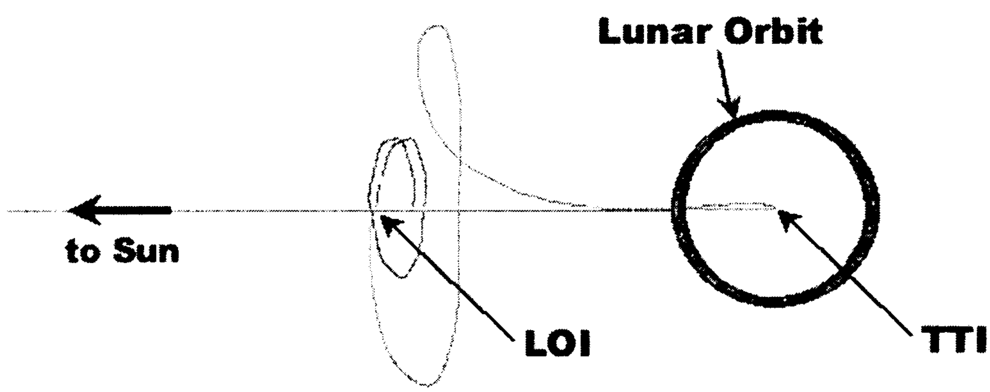

Figure 1: Sample Triana trajectory Viewed from Ecliptic North

Triana Project personnel felt it was very desirable to have deployment opportunities on 2 sets of 2 consecutive deployment orbits on either side of a 10 hour troubleshooting period for a Space Shuttle launch. However, Triana Project personnel felt it was acceptable, if necessary, to abandon the 10 hour troubleshooting period leaving deployment opportunities on 2 consecutive orbits only. For worst case analysis purposes it was assumed Triana deployment could occur over a 16 orbit period maximum. This range of deployment orbits means TTI could potentially occur over a large range of longitudes, approximately 180 degrees for a 16 orbit range of deployments.

In March 2001 it was decided to place Triana in storage. However, the orbit determination error analysis results presented in this paper could be useful to future Sun-Earth libration point missions.

In addition to the Triana results, orbit determination error analysis results are presented for the Fourier Kelvin Stellar Interferometer mission concept. The FKSI mission orbit is a large amplitude Sun-Earth L2 libration point orbit (with a maximum L2-Earth-vehicle angle of approximately 35.0 degrees). In this FKSI analysis the effect of small momentum unloading thrust perturbations is included.

TRIANA ORBIT DETERMINATION (OD) ERROR ANALYSIS RESULTS

The trajectory case which follows was the nominal trajectory case until the March 2001 decision to place Triana in storage and was used for the analysis results presented in this paper unless noted otherwise. For this nominal trajectory case the Space Shuttle's Triana deployment orbit was 150 nautical miles (277.8 km) altitude and nearly circular with an inclination of 28.5 degrees. Transfer Trajectory Insertion (TTI) was to occur on 4/21/2002 at a longitude of 50.19 degrees East with a delta v from LEO of approximately 3.17 km/sec. Lissajous Orbit Insertion (LOI) was to occur on 11/9/2002 requiring a delta v of approximately 166 m/sec. Finite maneuver analysis was performed for the Triana upper stage, a solid rocket motor with an approximately 83 second TTI burn. However, for the purposes of this analysis, impulsive TTI maneuvers were used.

After the March 2001 decision, limited additional analysis was performed using a different trajectory case which assumed a Space Shuttle deployment. Details concerning that different trajectory case follow. For this nominal trajectory case the Space Shuttle's Triana deployment orbit was 215 nautical miles (398.2 km) altitude and nearly circular with an inclination of 57.0 degrees. For this nominal trajectory case Transfer Trajectory Insertion (TTI) was to occur on 7/1/2004 with a delta v from LEO of approximately 3.14 km/sec, and Lissajous Orbit Insertion (LOI) was to occur on 1/16/2005 and required a delta v of approximately 189 m/sec.

NASA Goddard Space Flight Center's (GSFC's) Orbit Determination Error Analysis System (ODEAS) was used to perform a covariance analysis for different phases of the Triana mission. The ODEAS force model includes a 70 x 70 JGM-2 potential model, solar radiation pressure, and lunar and solar gravity. The 3 sigma uncertainty of force model, measurement model, and measurement parameters recommended in reference 3 (Schanzle) were used for this analysis. The position and velocity error results presented in this paper are 3 sigma errors. The nominal 4/21/2002 TTI trajectory was used for the analysis unless otherwise noted. The solar radiation pressure force coefficient (Cr) was not solved for in the pre-MCC1 analysis. Cr was solved for in the post-MCC1 analysis unless otherwise noted. The Triana area to mass ratio used in the analysis was 0.01 square meters per kg. Momentum unloading will be required no more frequently than every 3 weeks for the Triana spacecraft, but the goal is for momentum unloading to occur no more frequently than every 3 months. Because the maximum tracking arc modeled in this OD error analysis was 21 days, the effect of momentum unloading thrust perturbations was not included.

It was assumed Triana would be supported by a combination of Deep Space Network (DSN) and commercial Universal Space Network (USN) tracking stations. The 3 DSN station locations used in the analysis were Goldstone, Madrid, and Canberra. The 4 USN station locations used in the analysis were Alaska, Hawaii, Santiago (Chile), and Perth (Australia). Therefore, a total of 7 DSN and USN stations were available to support Triana.

DSN ODEAS range and range rate parameters used are consistent with the DSN 26 and 34 meter statistics documented in reference 3 (Schanzle); these parameters were determined in part using extensive data received from these tracking systems in support of operational space missions. The DSN ODEAS range noise and bias parameters were 3.0 and 15.0 meters respectively, and the DSN ODEAS range rate noise and bias parameters were 1.0 mm/sec and zero respectively. Documented USN accuracy requirements for support of Triana are 100 meters in range and 8.0 mm/sec for range rate, and these parameters were used as the USN ODEAS range and range rate parameters. The Triana/USN tracking campaign was not completed prior to Triana being placed in storage, so no statistical database was available to refine the USN parameters used in ODEAS. The minimum elevation constraint observed was 7.0 degrees unless otherwise noted, and it was assumed coherent S-band 2-way range and range rate tracking data was used for the arcs specified unless noted otherwise. ODEAS was run assuming batch mode orbit determination.

Table 1 summarizes the Triana DSN and USN support requirements. As a new tracking network, the USN stations were to be subjected to certification testing prior to Triana launch. This planned testing was suspended when it was decided in March 2001 to place Triana in storage. Premission analysis and testing indicated the DSN 26 and 34 meter stations would have the capability of providing simultaneous telemetry, tracking (range rate and range data) and command (TT&C) support of the Triana spacecraft. The simultaneous TT&C capability is very desirable for critical early mission support. At the time of the March 2001 decision to place Triana in storage it was unclear whether or not the USN stations would have the capability of providing simultaneous telemetry, tracking (range rate and range data) and command (TT&C) support of the Triana spacecraft.

Mission Phase	Tracking Requirements
TTI to TTI+6 hours	All DSN 26 meter stations with a view will be scheduled for continuous support as prime. USN stations will be scheduled as backup. A USN station may be prime for first contact, depending on TTI longitude/DSN visibility.
TTI+6 to TTI+72 hours	DSN 26 and/or 34 meter stations will be scheduled as prime, and continuous support will be requested. USN stations will be backup.
TTI+72 to TTI+144 hours	At least 4 hours per day of range and range rate data will be provided by USN stations in alternating hemispheres (North, South). At least 2 hours per day of range and range rate data will be provided by DSN stations in alternating hemispheres.
TTI+144 hours to LOI+6 weeks	At least 4 hours per day of range and range rate data will be provided by USN stations in alternating hemispheres (North, South). DSN will be backup in the event of problems
After LOI+6 weeks	16 hours of range rate and 20 minutes of range data per day will be provided by USN stations in alternating hemispheres.

Table 1: Triana DSN and USN Support Requirements

For analysis of pre-MCC1 orbit determination, it was assumed that the tracking data arc would end at TTI+6 hours and that MCC1 would begin at TTI+9 hours. The TTI+9 hour point was the earliest it was deemed reasonable to begin MCC1, which could begin as late as TTI+24 hours in the event of small upper stage errors. The TTI+9 hour MCC1 scenario was the worst case pre-MCC1 orbit determination scenario. Prior to the start of an unperturbed arc of pre-MCC1 tracking data Triana would complete solar array deployment and Sun acquisition and complete the thruster functional tests. Analysis indicated this unperturbed pre-MCC1 tracking arc would begin between approximately TTI+25 and TTI+60 minutes.

A series of mid-course correction (MCC) maneuvers and LOI correction maneuvers (LOIC) will nominally be required to correct errors in the Triana state. The primary error sources for the first MCC maneuver (MCC1) are the upper stage performance and attitude. The primary error sources for the MCC2, MCC3, LOIC1, and LOIC2 maneuvers below are the Triana propulsion system performance and attitude. A summary of the Triana maneuver schedule used for this analysis follows:
TTI: Transfer trajectory insertion
TTI+9.0 hours: MCC1 start
TTI+41.0 hours: MCC2 start
TTI+69.0 hours: MCC3 start
TTI+201.5 days (nominally): LOI
LOI+14 days: LOI correction maneuver 1 (LOIC1)
LOI+28 days: LOIC2
LOI+42 days: LOIC3
The pre-MCC2, MCC3, LOIC1, and LOIC2 maneuvers will require orbit determination with relatively short arcs of tracking data in the cases analyzed above. Operationally small maneuvers would be delayed to allow for longer arcs of tracking data and more accurate pre-maneuver orbit determination, as noted above for MCC1. Between MCC3 and LOI correction maneuver frequency is expected to be every 21 days or more. After the LOI corrections in the nominal mission orbit, stationkeeping maneuver frequency is expected to be every 3 months or more.

TRIANA PRE-MCC1 ORBIT DETERMINATION ERROR ANALYSIS RESULTS

As noted earlier, Triana TTI could occur over a potentially large range of longitudes with a Space Shuttle deployment. Analysis was performed using the nominal TTI trajectories and a utility which used an orbit generator to generate the nominal trajectory and which rotated the nominal post-TTI trajectory in an Earth-fixed (rotating) coordinate system through a range of TTI longitudes (0-360.0 degree in 10.0 degree increments for this analysis) and computed ground station visibility for each case. In testing, the effect of the assumptions above on ground station visibility was minimal compared with actual nominal TTI states propagated with a full force model over the period of interest (through TTI+720 minutes). TTI longitude changes by approximately 23.0 degrees (West) per orbit in the baseline case (with inclination of 28.5 degrees, altitude of 150 nmi). There were no gaps in coverage after initial acquisition of signal (AOS) for the first 3 of the 7 DSN/USN stations with a view by TTI+360.0 minutes in the cases analyzed.

Table 2 indicates the range of Triana TTI longitudes corresponding to Triana Visibility by 1 of 7 DSN/USN Stations by TTI+25 Minutes with AOS assumed to occur at 7.0 degrees. Table 3 indicates the range of Triana TTI longitudes corresponding to Triana Visibility by 3 of 7 DSN/USN Stations by TTI+360 Minutes with AOS assumed to occur at 7.0 degrees and with pass maximum elevation (MAXEL) no less than 11.0 degrees to insure sufficient measurements are available for orbit determination from all of the stations.

TTI Epoch (YYYYMMDD)	Inclination (deg)	Altitude (nmi)	TTI TOD Declination (deg)	TTI Longitudes (deg, East)
20020421	28.5	150.0	-9.39	0.0-280.0, 330.0-360.0
20020522	28.5	150.0	-15.33	0.0-280.0, 330.0-360.0
20020824	28.5	150.0	-0.76	0.0-270.0, 340.0-360.0
20021008	28.5	150.0	17.37	0.0-270.0, 350.0-360.0
20030103	28.5	150.0	28.26	0.0-320.0, 340.0-360.0
20040701	57.0	215.0	-13.89	0.0-290.0, 320.0-350.0

Table 2: Range of Triana TTI longitudes corresponding to Triana Visibility by 1 of 7 DSN/USN Stations by TTI+25 Minutes (AOS Elevation=7.0 degrees)

TTI Epoch (YYYYMMDD)	Inclination (deg)	Altitude (nmi)	TTI TOD Declination (deg)	TTI Longitudes (deg, East)
20020421	28.5	150.0	-9.39	40.0-240.0, 300.0, 330.0-350.0
20020522	28.5	150.0	-15.33	40.0-250.0, 340.0-360.0
20020824	28.5	150.0	-0.76	40.0-240.0, 300.0, 330.0-340.0
20021008	28.5	150.0	17.37	60.0-210.0, 300.0-330.0
20030103	28.5	150.0	28.26	50.0-200.0, 230.0-240.0, 300.0-320.0
20040701	57.0	215.0	-13.89	30.0-230.0, 270.0-290.0, 310.0-340.0

Table 3: Range of Triana TTI longitudes corresponding to Triana Visibility by 3 of 7 DSN/USN Stations by TTI+360 Minutes (AOS Elevation=7.0 degrees, MAXEL 11.0 degrees or greater)

For the 4/21/2002 TTI case (i=28.5 degrees), two trajectory cases were analyzed with TTI longitudes of 10.0 and 190.0 degrees East respectively using the method used for the post-TTI visibility DSN/USN analysis. A change in TTI epoch of approximately 12 hours results in a change in TTI longitude of approximately 180 degrees.

For the case with TTI longitude of 10.0 degrees the following stations were first three stations with a view with their respective approximate AOS times: Perth (TTI+14 minutes), Canberra (TTI+20 minutes), Madrid (TTI+385 minutes). In this case the first two stations with a view are in relatively close proximity (both in Australia).

For the case with TTI longitude of 190.0 degrees the following stations were first three stations with a view with their respective approximate AOS times: Santiago (TTI+13 minutes), Goldstone (TTI+100 minutes), Hawaii (TTI+240 minutes). In this case AOS for the second station does not occur until relatively long after TTI compared with other TTI longitudes.

Using both DSN and USN tracking data the TTI+540 minute OD solution errors were approximately 2.0-3.0 km in position and 4.5-6.5 cm/sec in velocity. Tables 4 and 5 document the pre-MCC1 OD error analysis results (3 sigma position and velocity errors at TTI+9 hours) using 1 measurement per 10 seconds of coherent 2-way range and range rate tracking data for TTI longitudes of 10.0 and 190.0 degrees respectively. In tables 4 and 5 the DSN statistics specified earlier are used for DSN stations, and the USN statistics specified earlier are used for USN stations.

Tracking Stations	Elapsed Time (minutes from TTI)	Position Error (m, 3 sigma) (TTI+540 minutes)	Velocity Error (cm/sec, 3 sigma) (TTI+540 minutes)
Canberra Perth	20.0-140.0 141.0-300.0	7142.6	15.312
Canberra Perth	60.0-140.0 141-300.0	8491.4	19.775
Canberra Perth	60.0-210.0 211.0-360.0	7601.1	17.942
Canberra Perth Canberra Madrid	60.0-140.0 141.0-300.0 201.0-375.0 385.0-450.0	3126.1	6.5159
Canberra Madrid	60.0-375.0 385.0-450.0	376.98	1.0068

Table 4: Pre MCC1 3 Sigma OD Position and Velocity Errors at TTI+9 Hours for Various Tracking Scenarios with a TTI Longitude of 10.0 Degrees

Tracking Stations	Elapsed Time (minutes from TTI)	Position Error (m, 3 sigma) (TTI+9 hours)	Velocity Error (cm/sec, 3 sigma) (TTI+9 hours)
Santaigo Goldstone	20.0-134.0 135.0-300.0	7986.3	18.539
Santaigo Goldstone	60.0-210.0 211.0-360.0	4445.0	10.398
Santaigo Goldstone Hawaii	60.0-100.0 101.0-240.0 241.0-360.0	1963.7	4.5263
Goldstone Canberra	100.0-460.0 461.0-540.0	335.23	0.97202

Table 5: Pre-MCC1 3 Sigma OD Position and Velocity Errors at TTI+9 Hours for Various Tracking Scenarios with a TTI Longitude of 190.0 Degrees

In two station tracking scenarios where the start of tracking was delayed from TTI+20 to TTI+30 minutes there did not appear to be a significant decrease in the probability of convergence. However, in two station cases where the start of tracking was delayed from TTI+20 to TTI+60 minutes there did appear to be a significant decrease in the probability of convergence.

In cases where tracking did not begin until TTI+60 minutes the addition of tracking data from a third station appeared to significantly strengthen the orbit solution and increase the probability of convergence.

Nominally operational orbit determination solutions will be generated successively using data from the first station with a view (including angle data nominally for the single station solution), from the first two stations with a view, and finally from the first three stations with a view.

It is obviously desirable for the spacecraft to be in view of a ground station as soon after TTI as possible to allow for the start of TT&C support. If MCC1 is to be performed at TTI+9 hours, it is desirable for three stations to have a view of the spacecraft by the end of the tracking data arc, which is assumed to end at TTI+6 hours in this case.

TRIANA POST-MCC1 ORBIT DETERMINATION ERROR ANALYSIS RESULTS

The pre-MCC2 orbit determination error analysis was performed using the nominal 4/21/2002 TTI case (i=28.5 degrees) with a TTI longitude of 50.19 degrees East with a tracking data arc starting at TTI+17 hours and ending at 2-3 hours prior to MCC2 start at TTI+41 hours. It appears continuous or nearly continuous tracking data is desirable to increase the probability of convergence. Using continuous DSN tracking data the orbit determination (OD) errors were approximately 0.8 km in position and 1.4 cm/sec in velocity. Table 6 documents the pre-MCC2 OD error analysis results (3 sigma position and velocity errors at TTI+41 hours) using coherent 2-way range and range rate tracking data.

Tracking Stations	Elapsed Time (minutes from TTI)	Measurement Frequency (seconds per measurement) (R=range) (RR=range rate)	Measurement Statistics	Position Error (m, 3 sigma) (TTI+41 hours)	Velocity Error (cm/sec, 3 sigma) (TTI+41 hours)
Goldstone Canberra Madrid	0.0-420.0 421.0-990.0 991.0-1260.0	10	DSN	838.0	1.4044
Goldstone Canberra Madrid	0.0-420.0 421.0-990.0 991.0-1260.0	R=60 RR=10	DSN	832.81	1.3886
Goldstone Canberra Madrid	0.0-420.0 421.0-990.0 991.0-1260.0	R=60 RR=10	DSN	879.12	1.4462
Goldstone Canberra Madrid	0.0-420.0 421.0-990.0 991.0-1260.0	10	USN	2883.6	1.7665
Santiago Hawaii Perth Santiago	0.0-360.0 361.0-720.0 721.0-1140.0 1260.0-1320.0	10	USN	4170.3	5.8776

Table 6: Pre-MCC2 3 Sigma Position and Velocity Errors at TTI+41 Hours for Various Tracking Scenarios

The pre-MCC3 OD analysis was performed using the nominal 4/21/2002 TTI case (i=28.5 degrees) with a tracking data arc starting at TTI+45 hours and ending 2-3 hours prior to the start of MCC3 at TTI+69 hours. With nearly continuous DSN tracking data from 3 DSN stations (Canberra, Goldstone, Madrid), using DSN statistics, 1/10 sec range rate, 1/60 sec range, and a 1260 minute tracking data arc, the 3 sigma position and velocity errors 1440 minutes after the start of the arc (TTI+69 hours) were 1398.5 meters and 1.8207 cm/sec.

The post-MCC3 OD error analysis was performed using the nominal 4/21/2002 TTI case (i=28.5 degrees) with a tracking data arc starting at TTI+72 hours and ending 4320 minutes (3 days elapsed time, TTI+144 hours) to 4440 minutes (3 days, 2 hours elapsed time) later. With 240 minutes tracking per day from alternating DSN stations (Canberra, Goldstone), using DSN statistics, 1/10 sec range rate, 1/60 sec range, and a 4440 minute tracking data arc, the 3 sigma position and velocity errors 4440 minutes after the start of the arc were 4173.6 meters and 2.7783 cm/sec. With 240 minutes tracking per day from alternating USN stations (Hawaii, Santaigo), using USN statistics, 1/10 sec range rate, 1/10 sec range, and a 4320 minute tracking data arc, the 3 sigma position and velocity errors 4440 minutes after the start of the arc were 8992.7 meters and 1.4528 cm/sec.

The OD error analysis starting at TTI+40 days was performed using the nominal 4/21/2002 TTI case (i=28.5 degrees) with a tracking data arc starting at TTI+40 days and ending 7 days later. With 240 minutes tracking per day from alternating USN stations (Hawaii, Santiago), using USN statistics, 1/10 sec range rate, 1/10 sec range, and a 7 day (10080 minute) tracking data arc, the 3 sigma position and velocity errors 10080 minutes after the start of the arc were 21571. meters and 0.97647 cm/sec. OD errors could probably be reduced using the additional USN range rate data which will be available per the TTI+70 day results which follow. In addition, OD errors could probably be reduced with a longer tracking data arc.

The OD error analysis starting at TTI+70 days was performed using the nominal 20020421 TTI case (i=28.5 degrees) with a tracking data arc starting at TTI+70 days and ending 7 days later. With 240 minutes tracking per day from alternating USN stations (Hawaii, Santiago), using USN statistics, 1/10 sec range rate, 1/10 sec range, and a 7 day (10080 minute) tracking data arc, the 3 sigma position and velocity errors 10080 minutes after the start of the arc were 20877. meters and 1.2332 cm/sec. Using DSN statistics for the case above the the 3 sigma position and velocity errors 10080 minutes after the start of the arc were 4300.9 meters and 0.48475 cm/sec. With 240 minutes range per day from alternating USN stations (Hawaii, Santiago) and all available range rate data, using USN statistics, 1/10 sec range rate, 1/10 sec range, and a 7 day (10080 minute) tracking data arc, the 3 sigma position and velocity errors 10080 minutes after the start of the arc were 9890.1 meters and 0.45441 cm/sec. OD errors could probably be reduced with a longer tracking arc.

The post-LOI OD error analysis was performed using the nominal 20020421 TTI case (I=28.5 degrees) with a tracking data arc starting at LOI+13 hours and ending 14 days later with intensive post-maneuver tracking. With 240 minutes tracking per day from alternating USN stations (Hawaii, Perth), using USN statistics, 1/10 sec range rate, 1/10 sec range, and a 14 day (20160 minute) tracking data arc, the 3 sigma position and velocity errors 20160 minutes after the start of the arc were 22385. meters and 0.31987 cm/sec. With 240 minutes range per day from alternating USN stations (Hawaii, Santiago) and extensive range rate data, using USN statistics, 1/10 sec range rate, 1/10 sec range, and a 14 day (20160 minute) tracking data arc, the 3 sigma position and velocity errors 20160 minutes after the start of the arc were 14322. meters and 0.14206 cm/sec.

For the nominal post-LOI OD error analysis an earlier post-TTI trajectory case was used. There were two passes per day from USN stations in the Northern and Southern hemispheres using USN statistics. There were 10 minutes of range data per station per day (20 minutes total per day) and approximately 360 minutes of range rate data per station per day (720 minutes total per day). A 21 day tracking data arc was used. The maximum 3 sigma definitive position and velocity errors were 5735.9 meters and 0.20107 cm/sec. The four week predicted position error was well under the 50.0 km requirement for all cases run.

TRIANA ORBIT DETERMINATION ERROR ANALYSIS CONCLUSIONS

Because of the potential for a start of coherent tracking as late as TTI+60 minutes, the TTI longitude should be chosen such that 3 of 7 DSN/USN stations have a view by TTI+360 minutes if possible (elevation of 11.0 degrees by TTI+360 minutes) assuming an arc of tracking data ending as early as TTI+360 minutes could be used to plan the first mid-course correction maneuver in a worst case scenario. The use of USN tracking data typically increases the orbit determination errors compared with solutions using DSN tracking data. The addition of the extensive USN range rate data available for Triana as a result of continuous USN telemetry support will decrease the orbit determination errors. The effect of the orbit determination errors on pre-stationkeeping correction maneuvers is small compared with the effect of propulsion system and attitude errors whether USN or DSN statistics are used, which is consistent with analysis done in support of previous missions. The post-LOI orbit determination errors using a long tracking data arc of USN tracking data are comparable to those predicted using only DSN tracking data for other missions and future mission studies. In the post-LOI mission orbit, the definitive and 4 week predicted Triana ephemeris accuracy requirement is 50 kilometers in position. The orbit determination error analysis performed indicates meeting these requirements should not be a problem. The ephemeris accuracy requirements for maneuver planning had not yet been formally defined at the time Triana was placed in storage. The requirements would be expected to be roughly equivalent to the accuracy predicted by the OD error analysis. Preliminary analysis indicates OD errors like those seen in the analysis will not significantly affect the Triana delta v requirements or result in unreasonable correction maneuver frequency, and these are the issues which would drive the definition of the requirements. Per reference 9 orbit determination error analysis results obtained using ODEAS for the Microwave Anisotropy Probe (MAP), a Sun-Earth L2 libration point mission, were consistent with orbit determination experience. Per reference 10, the orbit determination error analysis results presented for the Triana nominal post-LOI scenario are consistent with MAP orbit determination experience.

ORBIT DETERMINATION ERROR ANALYSIS FOR THE FOURIER-KELVIN STELLAR INTERFEROMETER MISSION CONCEPT WITH MOMENTUM UNLOADING THRUST PERTURBATIONS

An orbit determination error analysis was performed for the Fourier Kelvin Stellar Interferometer. This mission has a large amplitude Sun-Earth L2 libration point orbit (with a maximum L2-Earth-vehicle angle of approximately 35.0 degrees). In this analysis the effect of small momentum unloading thrust perturbations on the mission orbit is included.

As was the case with the Triana analysis, NASA Goddard Space Flight Center's (GSFC's) Orbit Determination Error Analysis System (ODEAS) was used to perform covariance analysis. The 3 sigma uncertainty of force model parameters recommended in reference 3 (Schanzle) was used for this analysis. As previously noted, the position and velocity error results presented in this paper are 3 sigma errors. The solar radiation pressure force coefficient (Cr) was solved for in this analysis. The spacecraft area to mass ratio used in this analysis was 0.0458 square meters per kg. DSN ODEAS range and range rate parameters used are consistent with the DSN 26 and 34 meter statistics documented in reference 3 (Schanzle); these parameters were determined in part using extensive data received from these tracking systems in support of operational space missions. The DSN ODEAS range noise and bias parameters were 3.0 and 15.0 meters respectively, and the DSN ODEAS range rate noise and bias parameters were 1.0 mm/sec and zero respectively. A 21 day arc of tracking data was used, and there was one 75 minute DSN pass every 1.5 days, alternating between Goldstone and Canberra. The minimum elevation constraint observed was 7.0 degrees. In the first case no momentum unloading thrust perturbation was included. With no momentum unloading thrust perturbations, the maximum 3 sigma position and velocity errors over the 21 day definitive arc were 1.9965 km and 0.0856 cm/sec respectively. In the second case momentum unloading thrust perturbations were included. Nominally, the thrusters used for momentum unloading would produce pure torque and no delta v perturbations. In this analysis momentum unloading events occurred every 3.5 days with a 3 sigma delta v (error) of 0.23 mm/sec. With momentum unloading thrust perturbations, the maximum 3 sigma position and velocity errors over the 21 day definitive arc were 13.239 km and 1.6109 cm/sec respectively.

FOURIER-KELVIN STELLAR INTERFEROMETER MISSION CONCEPT ORBIT DETERMINATION ERROR ANALYSIS CONCLUSIONS

The increase in the definitive position and velocity errors resulting from the momentum unloading thrust perturbation is significant. These errors would increase the magnitude of stationkeeping maneuvers done after a specified duration or would increase the frequency of stationkeeping maneuvers to keep the stationkeeping delta v below a specified value. An increase in stationkeeping maneuver frequency was not a significant impact to the FKSI mission. However, an increase in stationkeeping maneuver frequency is a potentially significant issue for future missions, especially missions where extended periods between stationkeeping maneuvers are desirable. Efforts should be made to design the spacecraft so that momentum unloading thrust perturbations do not occur over the required minimum arc of tracking data (approximately 21 days for a libration point orbit with a conservative tracking schedule) if possible. If momentum unloading thrust perturbations must occur over the required minimum arc of tracking data and if the impact of the momentum unloading thrust perturbations on orbit determination is unacceptably large, the addition of instrumentation to measure the effect of these thrust perturbations would have to be considered. For spacecraft with large area to mass ratios and variable solar radiation pressure force profiles, it may be necessary to improve the solar radiation pressure force model used for orbit determination.

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