REAL-TIME ESTIMATION OF COMETS TRAJECTORY

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Abstract

Real-time trajectory estimation technology provides valuable information about the motion of a spacecraft. In critical phases such as rendezvous and docking, de-orbit and re-entry, this technology is necessary for tracking and control of spacecraft from the Earth. NASDA's existing operational system for estimating trajectory is only for free-flight satellites and is executed in batch process mode. Thus, NASDA has developed a new trajectory estimation program capable of estimation in real-time for a satellite undergoing thrust acceleration. NASDA conducted experiments to verify the performance of the program with the Engineering Test Satellite VI(ETS-VI) in 1994, as well as with the Communications and Broadcasting Engineering Test satellite (COMETS) in March and May 1998. The accuracy of real-time estimation of semi-major axis is about 14 km during the second apogee engine firing that caused the change of 318 km. This paper presents the results of the real-time trajectory estimation experiments with the COMETS, including the result of a post-analysis.

***Key words**:* Real-time Estimation, Trajectory Estimation, COMETS.

Introduction

Real-time trajectory estimation technology provides valuable information about the motion of a spacecraft. In critical phases such as apogee engine firing (AEF), rendezvous and docking, de-orbit and re-entry and so on, this technology is necessary for tracking and control of spacecraft from the Earth.

The existing operational system for estimating trajectories of National Space Development Agency of Japan(NASDA), called NOCS (NASDA Orbit Computing System), is only for free-flight satellites and is executed in batch process mode[1]. Thus, it was necessary to develop a new system of real-time trajectory estimation for use in the case of a satellite undergoing thrust acceleration.

The Real Time Trajectory Estimation Program (RTEP) was developed as NASDA's experimental system of estimating a satellite's trajectory and thrust acceleration based on the Extended Kalman filter using Range and Doppler data. The range and Doppler data are external observation data that completely differ from the on-board equipment data of thruster thermometer, acceleration sensor, earth/sun sensor and so on. So, it is possible to monitor the motion of the spacecraft from a dynamic point of view in situations such as the trouble in the onboard sensor. The RTEP has two execution modes, one is for ground network and the other for space network. The RTEP for ground network is able to utilize 2 or 3 way Doppler data from three domestic stations and one foreign station such as NASA's Deep Space Network (DSN). This mode is originally designed for monitoring AEF from geostationary transfer orbit to geostationary orbit. It is necessary to obtain Doppler data simultaneously at more than three stations in order to estimate trajectory and thrust acceleration of a spacecraft. The RTEP for space network utilizes satellite-to-satellite ranging data via a data relay satellite. The details of the modeling and filter algorithms of the RTEP are described in Ogawa et al.(1995)[2] and Sawabe et al.(1998)[3].

RTEP Experiments Overview

NASDA used the RTEP for the first time to monitor the trajectory of the Engineering Test Satellite VI (ETS-VI) during its AEF phase in 1994. Even though the ETS-VI developed a relatively low thrust acceleration due to trouble in the apogee engine, the algorithms used in the RTEP and the usefulness of real-time trajectory estimation for space operations was verified[2].

As the next step, NASDA planned to perform experiments with the Communications and Broadcasting Engineering Test Satellite (COMETS) and its user satellite, in order to verify the real-time trajectory estimation function for the COMETS itself with comparatively large acceleration during its AEF phases, and for its user satellites using satellite-to-satellite ranging data[4].

On February 21, 1998, the COMETS was launched from the Tanegashima Space Center by the H-II Launch Vehicle Flight No. 5. The COMETS failed to achieve the scheduled geostationary transfer orbit, but was injected into an orbit at apogee altitude of 1902 km, perigee altitude of 247 km, inclination of 30 degrees. This mishap took place because the duration of the second firing of the launch vehicle's second stage rocket was shorter than originally planned. From March to May 1998, a perigee-up maneuver and apogee-up maneuvers were performed by a 1700 N liquid apogee engine in order to put the COMETS into a recurrent orbit (9 revolutions per 2days). During these perigee-up and apogee-up maneuvers, hereafter referred to as "AEF," the real-time trajectory estimation experiments were executed[3,5].

The Schedule of the COMETS Real-Time Trajectory Estimation Experiment

In view of the achieved non-nominal injection orbit, investigations were undertaken to find an operational orbit that would allow as many of the planned experiments as possible to be carried out, within the limits of the available on-board fuel. As a result, the COMETS target orbit was selected to be a highly eccentric orbit at apogee altitude of 17700 km, perigee altitude of 500 km, inclination of 30 degrees[6]. The first AEF was performed at the apogee to increase the perigee altitude for reducing the atmospheric drag, and six more AEFs were performed near the perigee to increase the apogee altitude. Each of AEFs consists of the pre-burn by two 50 N thrusters and the main-burn by a 1700 N liquid propellant engine. Real-time trajectory estimation experiments using the RTEP were performed during the AEFs when simultaneous Doppler measurements were available at NASDA's three ground stations, that is, at Katsuura (KTCS), Masuda (MTCS) and Okinawa (OTCS). The time sequence of AEFs and Doppler measurements is shown in Table 1.

From this table, we can see the second AEF is the only case that Doppler data of the COMETS was obtained throughout the AEF phase. As mentioned above, the operational orbit determination system NOCS is applicable only to a non-maneuvering spacecraft, and is able to calculate the COMETS orbit before and after AEF. Therefore, only the RTEP result during second AEF can be compared with the NOCS result.

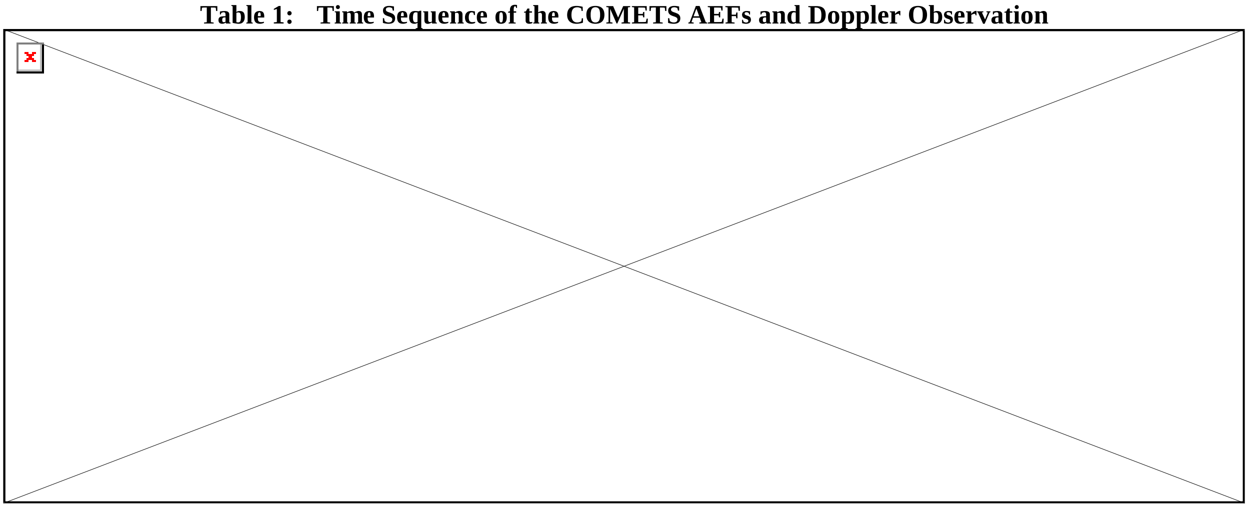
The second AEF of COMETS

During the second AEF phase, OTCS and MTCS could obtain Doppler data of the COMETS from the beginning of the AEF, but KTCS could not observe the COMETS. Figure 1 is the trajectory of the COMETS, that indicates the second AEF by thick line.

The AEF attitude is maintained automatically over the AEF interval by an on-board attitude control sub-system, and its yaw axis and the direction of increment velocity are the same. On the second AEF planning, yaw axis was intended to be taken in the direction whose east longitude was 314.56 degrees, north latitude was 18.76 degrees (nominal AEF attitude).

According to the orbit determined by the NOCS after the second AEF, the AEF yielded incremental velocity of 134.39m/s and incremental semi-major axis of 318 km.

Table 1: Time Sequence of the COMETS AEFs and Doppler Observation



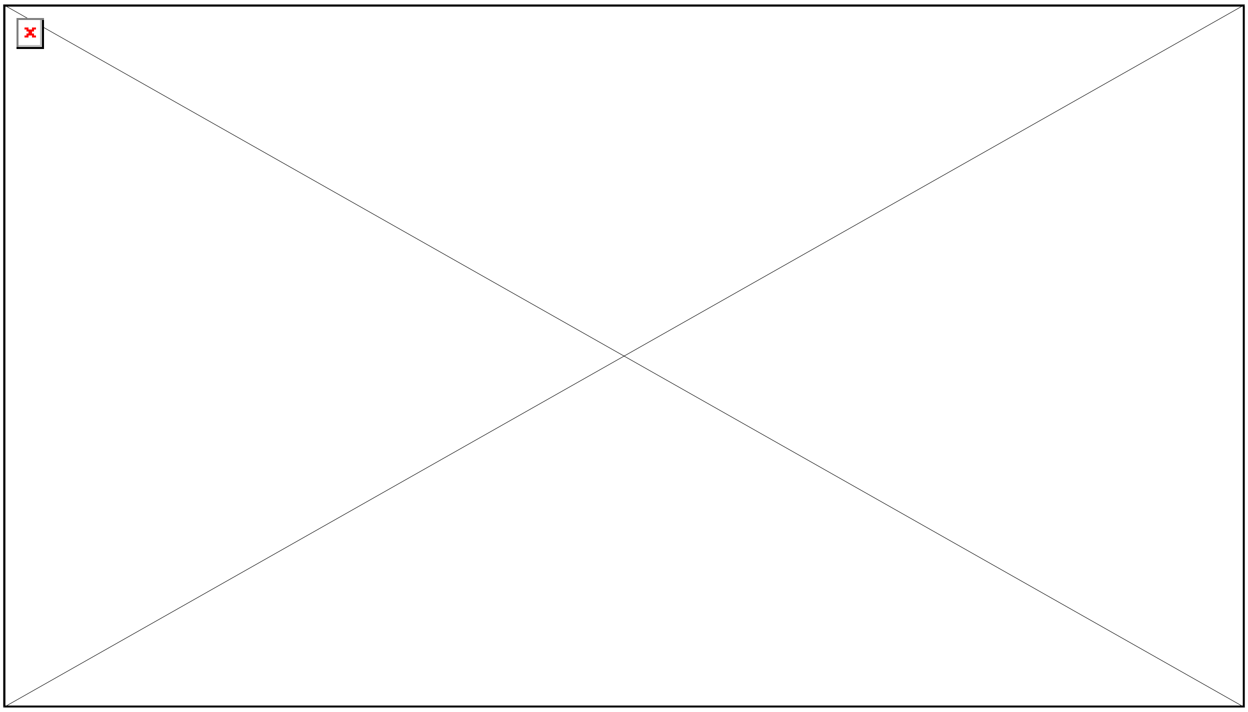


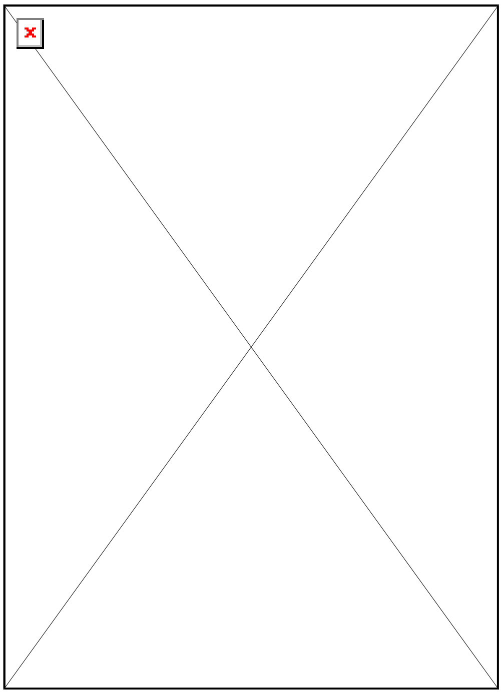
Figure 1: The COMETS trajectory before and after the second AEF (Thick like indicates the second AEF)

Conditions for the RTEP

The initial conditions for estimations during the second AEF are shown in Table 2. This includes update interval of the filter, sampling interval of measurements and so on, as well as the initial orbit parameters and their a priori uncertainty. These parameters were optimized and specified in the preliminary analysis. The update interval of filter and sampling interval of measurements are the same, one second. The initial orbit parameter applied to the COMETS state at epoch t = 0, namely, the AEF start time, was determined and propagated by the operational NOCS using the previous tracking data.

The residual tolerance parameter was not set, in order to use all the data. In the case that only two stations could observe the spacecraft at the start time of the estimation, like as the second AEF of COMETS, the filter would converge abnormally with the data from two stations during the first period of the AEF. Therefore, when the third station begins to be obtain the data, there is a danger of rejecting all the data from the third station, if residual tolerance parameter is set.

Table 2: Initial conditions for real time trajectory estimation



RTEP Estimation Results

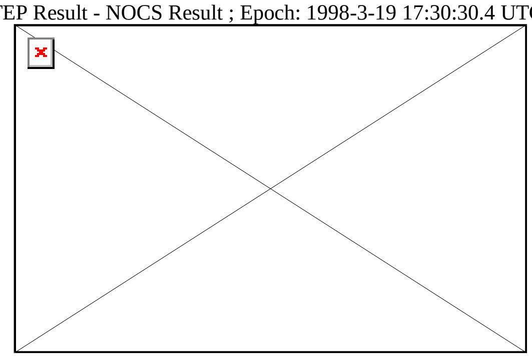
During the second AEF phase, the real-time estimation started at the same time the AEF started where OTCS and MTCS obtained Doppler data, but KTCS could not observe the COMETS.

Table 3 shows a comparison of the orbital element estimated by the RTEP with that determined by the NOCS at epoch of about 40 seconds after the end of the second AEF, and 3σ estimated by the RTEP. The NOCS results were derived by using full perturbation force model and sufficient ranging data over several revolutions, which were obtained at foreign ground stations and domestic stations after the end of the AEF. Difference of eccentricity and inclination are small, and difference of semi-major axis of -14.06 km for its change of 318 km by the second AEF is sufficient for monitoring the maneuver. Figure 2 and 3 show the difference between the nominal attitude and the estimated AEF increment velocity (ΔV) direction in longitude, and in latitude with the lapse of time past the AEF start time, respectively. Figure 4 and Figure 5 show the increment velocity and semi-major axis respectively, estimated by the RTEP on real-time basis, and simulated value based on the COMETS orbit determined by the NOCS.

The Figures 2 through 5 show that estimation from only two stations' Doppler data could not converge and led to noticeable error, but estimation from three stations, after the start of KTCS observation, could converge. The estimation of the AEF attitude converged to the nominal attitude approximately one minute after the start of KTCS observation, and estimated ΔV and semi-major axis increased straight to the nominal value after AEF. The standard deviation (σ) of estimated semi-major axis decreased discontinuously just after KTCS observation started and dropped at a level of 3 km at the AEF end time, and at a level of 2km at 40 seconds after the AEF.

Table 3: Difference between the RTEP Results and the NOCS Results

(RTEP Result - NOCS Result ; Epoch: 1998-3-19 17:30:30.4 UTC)



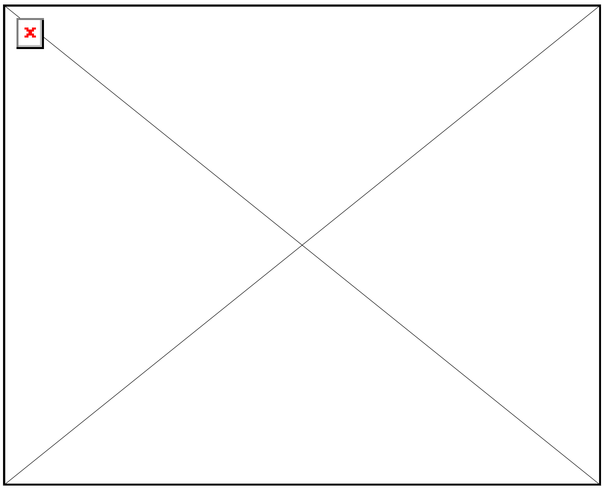


Figure 2: Estimated AEF ΔV direction in longitude

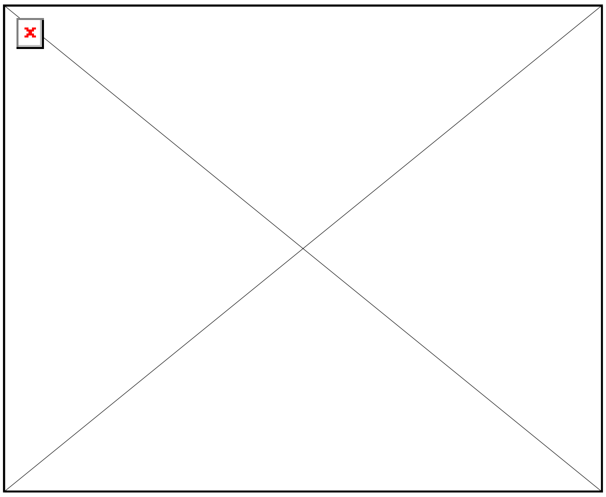


Figure 3: Estimated AEF ΔV direction in latitude

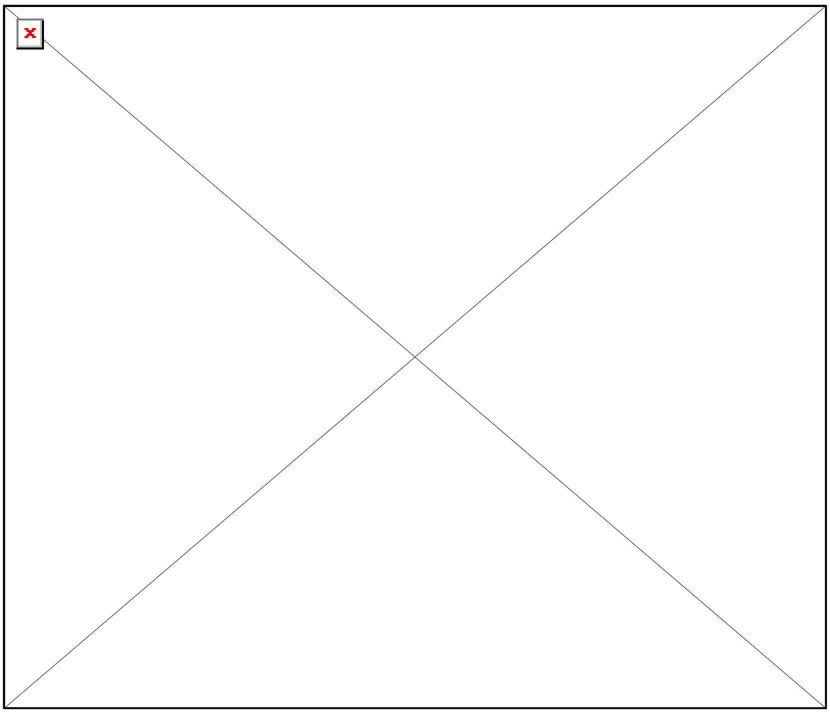


Figure 4: Estimated increment velocity

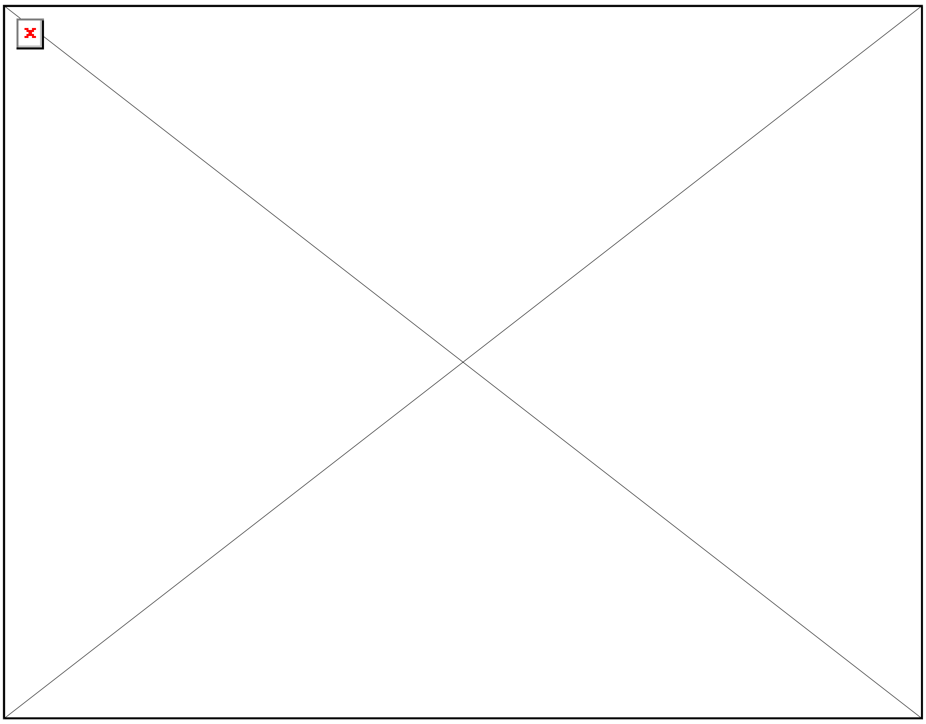


Figure 5: Estimated semi-major axis and standard deviation

Post Analysis by RTEP

The difference between the results of the NOCS and the real-time results of the RTEP is greater than 3σ estimated by the RTEP. One of the causes may be the influence of estimating with data only from two stations. In addition, there were lack of data of OTCS and KTCS up to 20%, due to fluctuation of data transmission delay (see Figure 6). Those lack data ware logged by the RTEP, but not used for filter process.

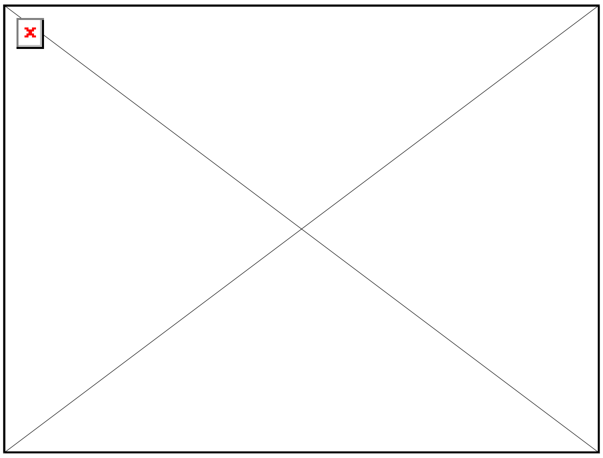
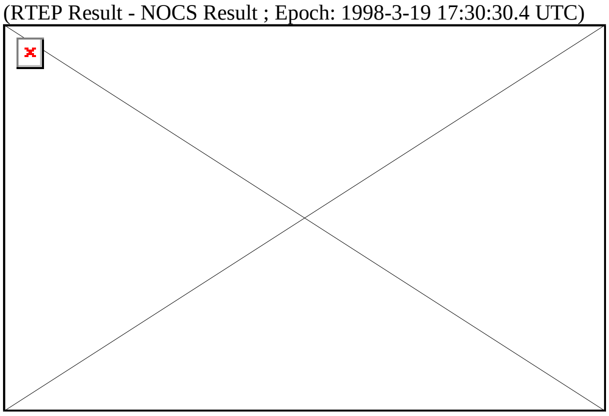


Figure 6: The example of data lack

Post analysis was performed assuming that the all the Doppler data were used for the real-time trajectory estimation by the RTEP. The difference between the results of the NOCS and that of the RTEP decreased to 2.3σ (see the right column of Table 4). Figure 7 through 10 show the results that were estimated by the RTEP using all the logged data.

Table 4: The improvement of the RTEP accuracy

(RTEP Result - NOCS Result ; Epoch: 1998-3-19 17:30:30.4 UTC)



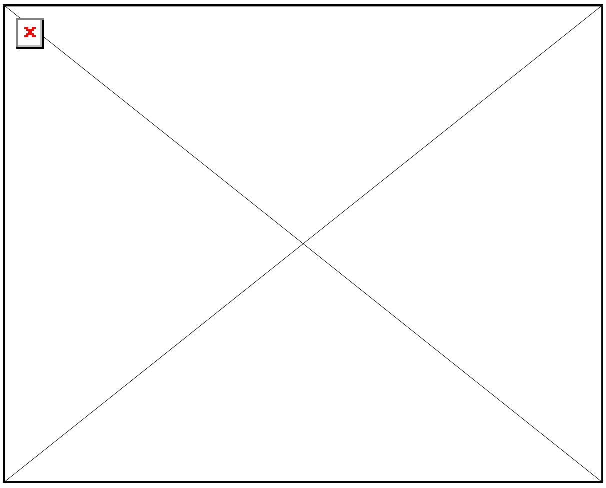


Figure 7: Post analyzed AEF ΔV direction in longitude

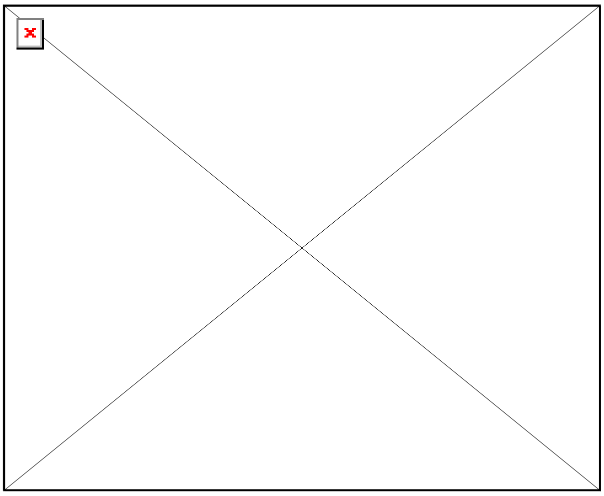


Figure 8: Post analyzed AEF ΔV direction in latitude

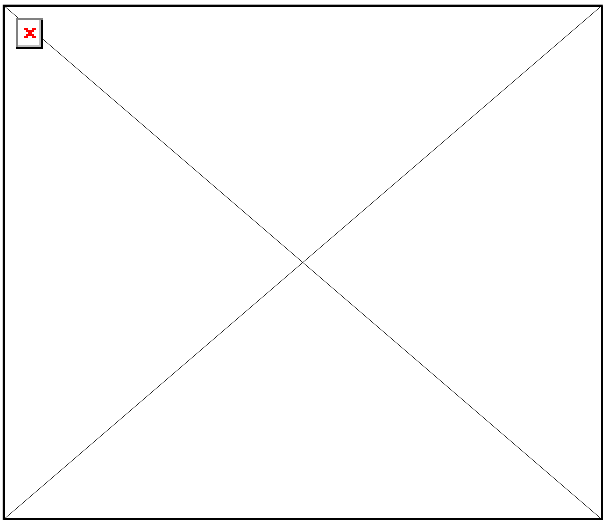


Figure 9: Post analyzed increment velocity

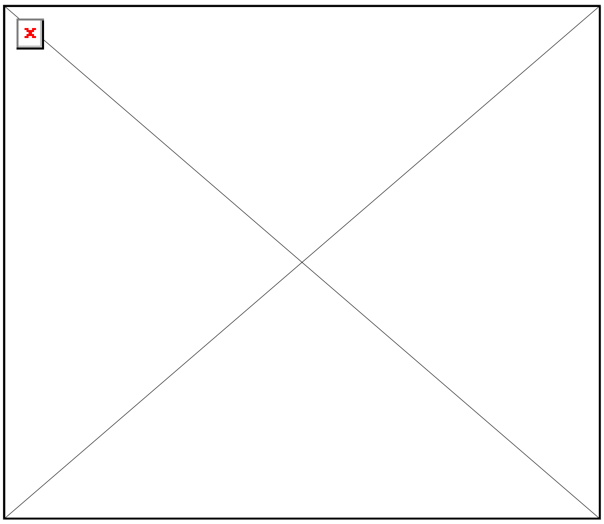


Figure 10: Post analyzed semi-major axis and standard deviation

Conclusions

In these experiments, we prove that the Real Time Trajectory Estimation Program(RTEP) for ground network has a capability of estimating attitude and trajectory during an apogee engine firing(AEF) on a real-time basis. During the second AEF of the COMETS that caused the increment of 318 km in semi-major axis, the accuracy of real-time estimation of semi-major axis is about 14 km, that is sufficient for tracking and operating a satellite. Post analysis showed that the accuracy may become better by improving the data interface. Of course, the estimation accuracy depends upon the geometry of ground stations and the spacecraft.

Furthermore, we can say that real-time trajectory estimation by the RTEP is quite useful and effective against an emergency in spacecraft operations. If a maneuver is not performed nominally, we would stop the maneuver halfway according to the RTEP estimated results and plan additional maneuver immediately, and also generate quickly antenna prediction data from the RTEP estimated orbital parameters and track the satellite.

We would like to utilize this function for critical phases of the early spacecraft operations with liquid apogee engine, such as the Data Relay Test Satellite (DRTS), NASDA's relay satellite next after the COMETS. We would like to verify the function of the RTEP for space network with user spacecraft of the DRTS.

In order to control a spacecraft from the ground successfully, it is a necessity to monitor its orbit and attitude on a real-time basis. In future space activities, such as rendezvous and docking, de-orbit and re-entry and space-based positioning missions that will become standard for future NASDA's missions, real-time operation is growing more important. Eventually, real-time trajectory estimation and monitoring will be necessary for these missions. We believe that the RTEP technology will meet these requirements.

References

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