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# Midcourse Space Experiment Precision Ephemeris

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**The Midcourse Space Experiment satellite, hosting a suite of state-of-the-art sensors, was launched into an 898-km altitude, nearly sun-synchronous orbit in April 1996. One of the primary tasks of the space surveillance principal investigator team was to evaluate the utility of the Midcourse Space Experiment sensors in performing space surveillance tasks. A critical issue in assessing the sensors' performance is the metric accuracy of their observations, which depends on the ephemeris accuracy of the satellite. In particular, to support the accuracy requirements of the Space-Based Visible, the primary space surveillance sensor onboard the satellite, the ephemeris accuracy goal was set at 15 m (1 sigma). There are two issues that had to be addressed in meeting this ephemeris accuracy goal: 1) the quantity and quality of the tracking data and 2) the dynamic modeling of the satellite's motion. The tracking of the satellite was performed by the U.S. Air Force Space Ground Link System of S-band radars, while Lincoln Laboratory's Millstone Hill radar in Westford, Massachusetts provided tracking data that were used to independently assess orbit accuracy. The most difficult aspect of the dynamic modeling of the satellite's motion was due to the effect of anomalous accelerations from cryogen gas venting. Results are presented that show the 15-m ephemeris accuracy goal has been met and exceeded.**

## I. Introduction

THE Midcourse Space Experiment (MSX) satellite, hosting a suite of state-of-the-art sensors was launched into an 898-km altitude, nearly sun-synchronous orbit in April 1996. The satellite was originally funded and managed entirely by the Ballistic Missile Defense Organization (BMDO) to address critical phenomenological and functional issues related to ballistic missile defense and to demonstrate space-based space surveillance. The principal sensor used for the space surveillance demonstration was the Space-Based Visible (SBV), designed and operated by Massachusetts Institute of Technology (MIT) Lincoln Laboratory. The SBV represents the first space-based platform for space surveillance.[1]

The objective of space surveillance is to create and maintain current information on all manufactured objects in Earth's orbit. This includes the tracking of resident space objects (RSOs) for catalog maintenance and augmentation and status monitoring. The SBV has acquired both metric and photometric observations of RSOs, consisting of active and inactive payloads, rocket bodies, and orbital debris. In addition, the Space Infrared Imaging Telescope III (SPIRIT III) was used by the space surveillance principal investigator (SPI) Team to gather infrared observations of RSOs. These data are currently being analyzed by the SPI team to demonstrate their utility in space surveillance.

A primary requirement on all sensors used for space surveillance is that their metric accuracy be adequate to support the various requirements of the Space Surveillance Network (SSN). The SBV has demonstrated the capability of collecting precise metric observations on targets that are detectable and within its field of view. This process has been demonstrated in experiments that were performed to characterize and calibrate the metric accuracy of the SBV by observing targets in stressing (lit Earthlimb) and nonstressing (celestial) backgrounds.

The calibration experiments have determined the metric accuracy and precision of the SBV sensor, determined biases for metric data products, and established the metric errors associated with the SBV boresight, the spacecraft jitter and attitude drift, the observation timetag, the MSX ephemeris, and the streak endpoint determination on the focal plane.[2] In a prelaunch study, the SBV satellite observations were estimated to be accurate to 4 arc-s (1 sigma). This is, in fact, the demonstrated accuracy of the SBV.[2] Because the accuracy of the MSX ephemeris could limit the quality of the sensor's performance, it was established that the contribution of the ephemeris error to the 4-arc-s budget could be no larger than 1.3 arc-s. To translate the 1.3-arc-s constraint into an MSX-position-error constraint, the most stressing scenario for SBV was considered. If SBV were viewing an object at a range of only 2500 km, a position error for MSX of 15 m would contribute 1.3 arc-s to the SBV error budget. Through this reasoning, the ephemeris accuracy goal for the MSX satellite was set at 15 m (three-dimensional rms).

The ephemeris accuracy goal was considered difficult because of the limited tracking data available and because of the continuous venting of cryogen gas from the spacecraft. To reduce the instrumentation noise of the SPIRIT III sensor to an acceptable level during its 10 months of operation, it was necessary to maintain the focal plane at a temperature of about 8 K. This was accomplished through the use of a hydrogen cryostat system that was designed to absorb much of the radiant energy encountered by the sensor. In doing so, a block of solid hydrogen sublimated, and the gas was vented to the rear of the spacecraft. This venting created a thrust that had to be modeled if high-precision position estimates of the satellite were to be obtained. In principle, if the thrust were entirely in the along-track direction, it could have produced an along-track perturbation of 30 km/day. To model this anomalous thrusting rigorously, a model requiring the continual mass flow rate of hydrogen would have been needed to establish the exhaust velocity and pressure of the vented gas. In addition, spacecraft attitude data would have been needed to determine the direction of the thrust. As will be discussed, the need for such a completely rigorous flow model, however, was circumvented.

This paper discusses the relevant aspects of the orbit determination of the MSX satellite: the procedures used to routinely generate and assess the quality of the MSX ephemeris and the modeling of the forces acting on the satellite. There are three phases of MSX operations that are discussed. The first was the so-called cryogen phase, coinciding with the first 10 months of operation. The second phase commenced after the depletion of cryogen for the SPIRIT III, with SBV continuing to be used to demonstrate space-based space surveillance. This second phase ran from March 1997 through September 1997. The third phase began in October 1997 and continues to the present, as the SBV serves as a contributing sensor to the SSN. In this role, the sensor is used to gather observations on RSOs for 8 h per day, whereas the remaining 16 h are used for

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health and status monitoring of the spacecraft and to allow the vehicle to cool down and recharge its batteries. For more information on SBV, Ref. 3 provides a comprehensive review of its development and operations.

## II. Ephemeris Generation Overview

Two primary goals were originally set for the MSX-ephemeris-generation process. The first goal was to establish a quick-look, preliminary and predicted ephemeris for the satellite, to support SBV and SPIRIT III experiment mission planning and operations.[4] The second goal was that, as all required input data types for the ephemeris generation are finalized and modeling reviewed, a final or definitive MSX ephemeris that meets the 15-m accuracy specification be generated.

To meet the first goal, the following data types are automatically collected on a daily basis: 1) tracking data, in the form of range measurements, through one of the two onboard transponders; 2) transponder switch information; 3) geophysical data for the drag model; and 4) Earth orientation data from the U.S. Naval Observatory. Once these data are acquired, a procedure automatically performs an orbit fit, generates the satellite ephemeris, assesses orbit quality, and distributes the ephemeris to the users. This process is still in operation today, in support of contributing sensor operations with U.S. Air Force (USAF) Space Command.

The quick-look, preliminary ephemeris generally meets the 15-m accuracy goal specified for the final or definitive ephemeris, but two additional steps were taken to ensure that the goal be met. The first was the inclusion of onboard attitude data needed for the cryogen-thrusting model. Without accurate attitude data, the direction of the thrust vector associated with the venting would have been poorly modeled. As it was, reliance on the nominal park-mode pointing and predicted attitude information was required for the preliminary ephemeris because it generally took a few days to collect the onboard attitude data from the telemetry. The second step needed to assure the highest quality ephemeris was to monitor, on a weekly basis, the volume, consistency, calibration, and quality of the tracking data. This aspect of the processing is discussed subsequently.

During the cryogen phase, the delay in generating the definitive ephemeris was one week, at which time it was made available to the MSX community. At that time, SBV was in its proof-of-concept phase and this extended timeline for establishing the definitive ephemeris was generally sufficient. With current postcryogen operations of SBV as a USAF contributing sensor, there is a 24-h turnaround for SBV measurements, and because the tracking data are not available until the end of a day, it is necessary to use the predicted ephemeris. The tracking data are still monitored regularly, daily for quality and weekly for calibration. All available onboard attitude data are still collected and used for the modeling of the radiation pressure, although this is probably an unnecessary refinement. With the completion of these steps, definitive ephemerides are still computed, but supplied only upon request.

## III. Data

### A. Tracking Data

The primary tracking data for orbit determination was chosen to be that from the USAF Space Ground Link System (SGLS) radars. A global positioning system (GPS) receiver on MSX was proposed by the SPI, but was rejected due to weight and power considerations. Note that in the late 1980s, when the MSX was in its design phase, the GPS constellation was incomplete, and the satellite receiver technology was still being refined. The use of SSN sensors to track MSX was also suggested, but this, too, was rejected, due to the excessive demand expected on the SSN resources. Tracking data are, however, obtained roughly once every 7–10 days from the SSN's Millstone radar. These radar data are used primarily to evaluate the SGLS tracking data and the orbits derived from them.

The SGLS network is primarily used for S-band satellite communications, but metric tracking data are also obtained for routine orbit maintenance of a variety of USAF space assets. Measurements of range and range rate are obtained with the coherent S-band transponders on MSX, as well as the azimuth and elevation angles. However, the angle data are not used in the orbit-determination process for MSX. The precision of the SGLS data is 6 m in range and 3 cm/s in range rate. The measurement biases can be determined to a few meters in range; the range rate should be unbiased.[5] A comprehensive study of the SGLS data was made prior to launch, using types of satellites comparable to MSX. This study was conducted to understand how to use these data, to investigate calibration issues, and to ensure that the network could be used to meet the orbit accuracy goals for MSX.[5]

The SGLS network provides up to 11 metric tracks of data per day for MSX, from eight globally distributed stations. From April 1996 to July 1997, these data were collected at the Test Support Complex (TSC) in Sunnyvale, California, and transmitted to the Applied Physics Laboratory (APL) at Johns Hopkins University near Baltimore, Maryland, and then, finally, to MIT Lincoln Laboratory in Lexington, Massachusetts. From August 1997 until November 1998 the tracking data had been collected at the Research, Development, Testing and Evaluation Support Complex in Albuquerque, New Mexico. From December 1998 to the present day, these data are being received from the 1st Space Operations Squadron, which is part of the 50th Space Wing, at Schriever Air Force Base near Colorado Springs, Colorado.

The SGLS range data have a nominal sensor and transponder bias correction applied. On-going monitoring of range residuals is performed to ensure the best possible calibration of the SGLS data for MSX. With regard to refraction corrections, the measurements have tropospheric corrections applied to them, but none are applied for the ionosphere. MSX initially was flying during a period of very low solar activity, but this is now increasing. Some of the resulting ionospheric error is absorbed by the range bias. Various ionosphere models are currently being investigated to correct for its contribution to the range error.

### B. Attitude Data

Attitude data have been used for the modeling of the solar radiation pressure force and, during SPIRIT III operation, for the cryogen thrusting. The attitude data give both the park-mode orientation and the pointing of MSX when it is maneuvered for data collection events (DCEs). Park mode is defined in such a way as to minimize the amount of direct, radiant energy that would enter the SPIRIT III sensor. The park mode also maintains one face (with antennas) of the satellite toward the Earth and another (with solar panels) normal to the sun. This is accomplished by first pointing the satellite in a radial direction, then rotating it about its boresight axis, until the sunshade blocks the sun. Finally, the solar panels are rotated about their support axis so as to maximize their power gain. To maintain park-mode, MSX must be continuously reoriented in inertial space. Under current operations, MSX maneuvers frequently during the 8 h of SBV space surveillance operations, but is in park mode most of the other 16 h.

Two different sets of attitude information have been available for orbit determination. The attitude history buffer on MSX holds quaternions and timetags at 100-s intervals for roughly five orbits, at which time it is downloaded. This attitude information is decommutated from the telemetry and, as mentioned, generally takes a few days to be completely collected. During the cryogen phase, the predicted attitude quaternions for the planned surveillance events were obtained from APL and combined with the predicted park-mode quaternions. Early on, the predicted attitude data were invaluable for sorting out various issues regarding the proper use of the onboard attitude data.

### C. Transponder Data

MSX has two S-band transponders onboard. Each is used according to the orientation of the vehicle. A SGLS contact schedule provides daily information specifying which transponder is being used. At the present, and as best as has been determined, the transponder biases are assumed identical, although this could change in the future.

### D. SGLS Network Calibration

An important aspect of achieving the required orbit accuracy is to have well-calibrated data from the SGLS network. Historically, the range biases of the sensors within the SGLS network have been determined using the postfit measurement residuals of the data from orbits fit for a variety of satellites. (Efforts using S-band tracking of GPS satellites and high-precision orbits derived externally have also been used to provide SGLS station calibration.) The use of the residuals derived from the orbit fits still remains a primary means of monitoring the sensor range biases for the MSX orbit computation. One can, in principle, begin to disentangle the transponder and sensor range bias from the uncorrected ionosphere mean range error by using nighttime, high elevation, and range-rate data only and then by analyzing the residuals of the range measurements with the resulting orbit. Generally though, there are not enough tracks available and so the range data are also used in the orbit fits, albeit in a somewhat incestuous way, to determine the range biases. Having computed more than 3 years of MSX orbits using the SGLS tracking data, a history has been kept of the calibration of the SGLS station biases in the range measurement. Nominal corrections are determined, as needed, and compared with those that have been independently determined using data from other satellites that are tracked by the SGLS network. Monitoring of SGLS data has shown that some of these biases to drift or otherwise change with time.[5]

## IV. Summary of Dynamic Models for MSX

The MSX ephemerides are computed with a high-precision orbit computation program DYNAMO. The gravity field in DYNAMO is JGM-3, and a 40 × 40 field is used. The Mass-Spectrometer-Incoherent-Scatter (MSIS) atmosphere (COSPAR International Reference Atmosphere 1986) is used to model the drag on the satellite. A scale factor is used with the drag model as a free parameter in each orbit estimation to consider any model deficiencies over the fit interval. Solid Earth and ocean tides are modeled, as well as Earth albedo and luni–solar third-body perturbations.

To consider solar radiation pressure, a simple model for the MSX satellite was developed. This models MSX as six main body surfaces and two solar panel surfaces. In addition, the model specifies the total mass of the satellite and the area of each surface, as well as their specular and diffuse reflectance properties. When available, the model uses onboard attitude quaternions to identify the vehicle's orientation. Otherwise, it is assumed that the MSX is in park mode and uses an attitude pointing law identical to that used for GPS satellites.

As will be discussed in the next section, extensive analysis and simulation studies prior to launch[6] showed that the cryogen venting could be simply modeled as a continuous thrust, the direction of which could be established using the satellite attitude. It was also seen that a simultaneous estimate of a thrust scale factor and a drag factor for each orbit-fit span could absorb the thrust effect to well below 2 m, with low correlation between the two estimated parameters.

## V. Cryogen Venting Modeling

As mentioned earlier, the SPIRIT III sensor on MSX was cryogenically cooled to reduce, to an acceptable level, the noise produced by the infrared emission of the sensor itself. This was accomplished by providing a substantial heat sink with which to draw away any unwanted radiant energy that may enter the sensor. A block of solid para-hydrogen that sublimated in the process of absorbing the heat provided for the heat sink. After passing through various portions of the cryostat to absorb more energy, the waste hydrogen gas was vented to the rear of the spacecraft and out into space, creating a small but continuous thrust on the vehicle.

Prior to launch, the cryogen venting was considered to be a major problem for achieving the desired 15-m position accuracy for MSX. Considerable study and simulation were undertaken at Lockheed Missiles and Space in Palo Alto, California and at the Space Dynamics Laboratory at Utah State University to understand the flow of the hydrogen gas through the cryostat and the vent line. This theory was built upon in Ref. 6, where a model for the compressible, viscous flow of the hydrogen gas down the vent line was developed. This model, which will be discussed, helped in understanding the magnitude of the cryogen thrust and how its effect could be treated to reduce the orbit errors associated with it.

The thrust $T$, produced by the venting of the hydrogen, can be expressed simply by the relation

$$T = \dot{m}u_e + (p_e - p_a)A_e \tag{1}$$

where $\dot{m}$ is the mass flow rate of the hydrogen gas; $u_e$ is the velocity of the flow at the exit plane of the vent line; $p_e$ is the pressure of the flow at the exit plane; $p_a$ is the ambient pressure of space, taken to be zero; and $A_e$ is the cross-sectional area of the exit plane, which is known by design. By applying the appropriate theory for the flow of the gas at the exit plane, and with the proper assumptions and conditions, good estimates of $u_e$ and $p_e$ could be obtained. The flow of hydrogen gas was assumed to be compressible, viscous, adiabatic, and reversible. The flow was also designed to choke at the exit plane of the vent line. Based on these assumptions, compressible flow theory[7] was used to establish expressions for $u_e$ and $p_e$ (Ref. 6). The remaining parameter in Eq. (1) is $\dot{m}$, or the rate at which hydrogen gas was vented from the cryostat. This was the only quantity in the model that was to be derived from actual measurements on the spacecraft.

Before launch, simulations were performed in which the mass flow rate was characterized and modeled under various MSX data collection scenarios and, hence, heating of the SPIRIT III telescope. The simulations used realistic DCE scheduling for heating of the SPIRIT III telescope, the compressible flow model just described, a realistic representation of the mass flow rate corresponding to the DCEs, and attitude quaternions to represent the orientation of the spacecraft. These simulations yielded an understanding of the hydrogen venting and the resultant thrust; in particular, they revealed the way in which cryogen model errors could be absorbed using various orbital parameters or scale factors.

This study proved to be even more critical inasmuch as it became evident later in the process that on-orbit measurements of the mass flow rate required in Eq. (1) would not be made frequently enough for them to be effective in the flow model. Fortunately, the simulations showed that, even with insufficient sampling of the mass flow rate, the cryogen thrust effect could be simply modeled by assuming a constant thrust along the vent line. In fact, this approach required no actual flow rate data, and hence, the compressible flow model would not be needed. In addition to a constant thrust, predicted in ground simulations to be about 300 dyne, a scale factor was estimated as a free parameter over each orbit-fit span. Because the actual value of the thrust varied in magnitude, depending on heating conditions, and because the thrust was not known exactly, a free parameter would allow for variations about the 300-dyne estimate. In addition, a drag scale factor was estimated simultaneously with the thrust scale factor. This was to absorb errors associated with the atmospheric drag. Although simulations indicated that the thrust and drag scale factors were not highly correlated, and given the orientation typically assumed by the vehicle, it is possible that along-track errors not absorbed by the thrust scale factor were absorbed by the drag scale factor. The opposite statement would also be true.

The simulation study showed that the thrust effect would be less than 200-m along track after three days, given the type of routine operations expected with MSX. It was seen that a considerable part of the thrust was projected normal to the orbit, and a normal thrust is tantamount to changing the inclination. Orbit inclination changes require a significant amount of energy to achieve any appreciable effect. The simulation also showed that the cryogen thrust could be modeled down to below 2 m for short arcs of 2 and 3 days; in practice 2-day arcs are computed. Also, it was seen in the simulations and in practice that the thrust and drag solve-for parameters not only have low correlation but that, in fact, the use of the drag solve-for parameter permitted better recovery of the thrust parameter. During the actual cryogen operation it was seen that, if these scale factors had not been used, errors as large as 200 m would have existed in the orbits, as measured by the accuracy criteria discussed in the next section. Finally, the simulations were further validated as they predicted that the block of solid hydrogen would not last the originally expected 18 months but only 12 months or less. In actuality, the cryogen lasted 10 months.

A detailed study of the cryogen venting during flight was not possible because, as mentioned earlier, the hydrogen gas flow rate was gathered too infrequently to be of any use. It was seen, though, over the course of the 10 months of cryogen venting that a mean value of 322 dyne (with a sigma of 25 dyne) was recovered in the orbit estimation. Also, a negative drag factor was consistently recovered, indicating that this scale factor was drawing up an acceleration component that the cryogen thrust scale factor could not.

## VI. Measure of Orbit Accuracy

A number of measures are used to evaluate the day-to-day ephemeris quality. The conventional technique of overlapping subsequent orbits provides a measure of consistency and a fairly good indication of accuracy. Postfit residuals of the SGLS data are examined for systematic errors, biases, data precision, and an acceptance level of data from each SGLS site. To provide an external measure, the Millstone radar data is not used in combination with the SGLS data in the orbit fit, but is only used to monitor the SGLS data and the orbits derived from them. The Millstone radar range is accurate to 5 m or better, as is established through weekly calibration with laser ranging satellites. These radar range measurements can be compared with the SGLS-derived orbits, and the residuals provide a direct measure of the orbit accuracy over part of the orbit. Orbits can also be computed exclusively from the radar data, and the SGLS data can be compared with these orbits to check for timing or other errors. Finally, both the cryogen thrust and the drag solve-for parameters are checked for realism and consistency. The cryogen thrust scale factor was expected to adjust the nominal average hydrogen mass flow rate and depended on the surveillance activity, especially that of the SPIRIT III sensor. In addition to absorbing errors associated with the mismodeling of the atmosphere, the drag scale factor performed an important role by absorbing along-track cryogen thrust effects that were not absorbed by the thrust scale factor.

The Millstone radar range data make a good external measure of orbit accuracy because of the radar's signal processing and calibration that results in highly accurate range measurements. Its signal processing approach interpolates range gates for range measurements. As a consequence, its range-measurement accuracy approaches the theoretical limit, which is on the order of 2 m for a tracking bandwidth of 1 MHz and an integrated signal-to-noise ratio of 30 dB, typical for the Millstone radar. The calibration is achieved through routine monitoring of the range and angle biases and with the use of the best-available troposphere model and a real-time map of the ionosphere over the Millstone radar. The Millstone range and angle biases are examined daily by comparing them with high-accuracy orbits of laser ranging satellites. The satellites typically used in this calibration process are the Japanese EGP, Starlette, LAGEOS I and II, and two Russian Etalons. The laser ranging data are obtained weekly from NASA Goddard Space Flight Center near Washington, D.C., and are used to establish high-accuracy orbits on these satellites. This permits a review of Millstone measurements taken to that time, and a predicted orbit is used for daily monitoring until the next week. The laser range data are the quick-look normal point data, which may not have the final calibration applied, but which are still expected to have an accuracy from 10 to 50 cm. Analysis of the orbit accuracy that DYNAMO can achieve with the laser data is about 1 m, for these satellites. With this level of orbit accuracy, the Millstone range bias can be determined to 1 m or so.[8] With regard to considering the error in the Millstone measurements due to tropospheric and ionospheric refraction, a model described by Refs. 9 and 10 is used for the troposphere, with input from a weather station at the site. In addition, a real-time Kalman filter model is used for the ionosphere, with input from a dual-band GPS receiver available every 3 s (Ref. 11). Figure 1 shows the orbit accuracy assessment during the cryogen phase of the MSX mission, as based on the residuals between the Millstone Hill radar range measurements and the SGLS-determined orbit for MSX. The residuals are generally better than 15 m, with a mean of 1 m and a sigma of 6 m.

To provide the estimate of orbit accuracy from the overlap analysis, the MSX definitive orbit fits are designed so that they span

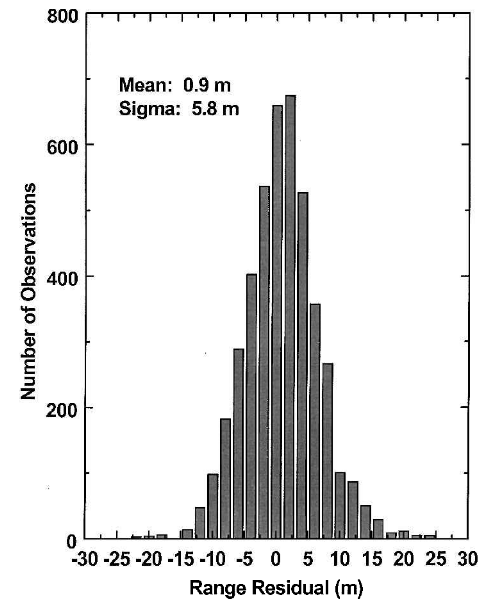


**Fig. 1 Millstone range measurement residuals computed with orbits determined from SGLS tracking data from day 28 of 1996 to day 56 of 1997.**

2.25 days. The ending 0.25 day of one orbit fit will just overlap the first 0.25 day of an orbit fit that starts two days later. All orbit fits are, therefore, compared with those orbit fits starting two days before and two days after. From the 2.25-day orbit fits, state vector ephemerides are generated in an inertial reference frame at 900-s intervals over the common period for both overlapping orbits. The method then differences the state vectors at each common epoch. Another, physically intuitive, way of characterizing these differences is to convert the differences in $x$, $y$, and $z$ to differences in the radial, cross-track, and along-track directions with respect to the orbit. The radial direction is along a vector from the center of the Earth to the satellite position, the along-track direction is along the velocity vector, and the cross-track direction is perpendicular to these two and measures the orbit differences in terms of the out-of-plane component of the orbit. These orbits are computed and then summarized, statistically, using a standard rms of their differences. As a measure of accuracy for each orbit, this rms difference is divided by two, with the assumption that the orbit differences are contributed equally from errors in each orbit. Figure 2 shows a histogram of this measure of orbit accuracy during the cryogen phase, as expressed in radial, cross-track, and along-track directions. The along-track error is typically the most significant. As a measure of accuracy, these results again indicate that the orbits are well within the 15-m goal (1-sigma rms).

Figures 1 and 2 show results for the definitive ephemerides during the cryogen phase. The accuracy goals have been more easily met during the postcryogen period for both the definitive and quick-look ephemerides. Of interest, as well, is the prediction accuracy of the orbits. Specifically, a prediction up to a day and a half is made available to provide the USAF Space Command immediate use of the SBV data.

The prediction accuracy is assessed by propagating the ephemeris backward by one and a half days and by overlapping it with the preliminary ephemeris that was previously generated. For this comparison, the previous preliminary ephemeris is considered to be truth and the rms differences of the overlaps are not divided by two as described earlier. The rms statistics of this prediction accuracy assessment over a one-year period are 3 m in radial, 13 m in cross-track, and 24 m in along-track directions. This orbit accuracy is generally satisfactory because SBV is most often looking at targets farther than 2500 km. Clearly, the more distant the target object is located from the MSX, the less the position error contributes to the error of the SBV measurements. If necessary, the 15-m preliminary ephemeris can be used when it is available a day later.

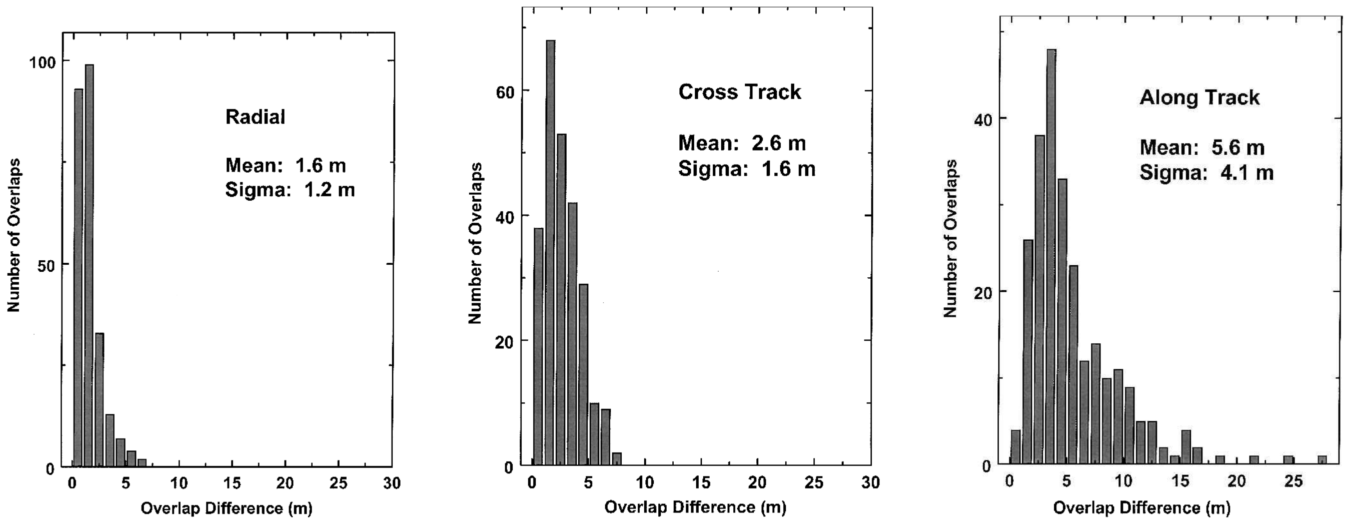


**Fig. 2 Orbits fit from day 28 of 1996 to day 56 of 1997, rms difference divided by two of 0.25-day overlap.**

## VII. Conclusions

Both the SBV and the SPIRIT aboard the MSX satellite have successfully demonstrated space-based space surveillance. To support the accuracy goals of these instruments, an orbit procedure has been presented that yields a satellite ephemeris accurate to 7 m (three-dimensional rms).

The accuracy goal has been met and exceeded with a final ephemeris that is delayed to consider additional refinements in the calibration of the tracking data and in modeling of the satellite orientation. It is also generally met with a quick-look ephemeris that is delayed 1 day to collect all tracking data.

The ephemeris must be computed every day for the lifetime of the SBV instrument, which is now a USAF contributing sensor. Therefore, the methods described here, from collecting the available tracking data to posting the ephemeris and quality assessment for users, have been completely automated.

The aspect of the dynamic modeling for the satellite's motion that was considered to be difficult prior to launch was that of the thrusting due to cryogen venting of hydrogen gas. Extensive prelaunch study and simulation showed that this could actually be treated simply by considering the thrust to be constant and pointed in the direction provided by attitude data and scaled with two free parameters for each orbit estimation. Results presented show that this method worked extremely well during the cryogen phase of the satellite mission.

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