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Metric Accuracy Improvements of Space-Based Visible Using Spacecraft Attitude Drift Corrections

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The Midcourse Space Experiment satellite, sponsored by the Ballistic Missile Defense Organization, was launched in April 1996 into an 898-km altitude, near sun-synchronous orbit. One of the principal sensors onboard the spacecraft is the Space-Based Visible, a visible-band, electro-optical camera designed to perform the first technical and functional demonstration of space-based space surveillance. The principal task of the Space-Based Visible is to gather metric and photometric information on a wide variety of resident space objects. To assess the metric performance of the sensor, routine on-orbit metric calibration is performed. In addition, a complete independent error assessment was made using actual flight data. The goal of producing 4-arc-s (1-sigma) observations of resident space objects was set during design, and results show that this goal is being met. A method is presented that improves the metric observations of resident space objects to better than 2-arc-s (1-sigma) by estimating the drift of the spacecraft attitude during staring events and removing the effect from the observations. Compensating for this error source brings into agreement the results of on-orbit calibration and the independent error assessment.

Introduction

THE Midcourse Space Experiment (MSX) is funded and managed by the Ballistic Missile Defense Organization (BMDO) with the goal of addressing fundamental phenomenological and functional issues associated with ballistic missile defense and space-based space surveillance. Visible-band, long-wavelength infrared and ultraviolet sensors have been successfully used to gather high-quality data on strategic ballistic missile targets, resident space objects (RSO), and terrestrial, earthlimb, and celestial backgrounds, over a wide range of the spectrum.

One of the principal sensors onboard MSX is the Space-Based Visible (SBV), a visible-band electro-optical camera designed to conduct technical and functional demonstrations in support of space-based space surveillance. The SBV represents the first space-based space surveillance sensor and is transitioning from that of an experimental sensor, as part of a principal investigator effort, to a contributing sensor within U.S. Air Force Space Command's Space Surveillance Network.[1] In addition, the experience with SBV offers a wealth of knowledge for the proposed Space-Based Infrared System-Low, the future objective system for space surveillance.

Designed at the Massachusetts Institute of Technology, Lincoln Laboratory, the SBV's principal role is to gather metric and photometric information on a wide variety of RSOs. Routine on-orbit metric calibration is conducted to assess the metric performance of the sensor. This is accomplished by observing satellites for which the positions are well established and comparing these known positions with SBV-observed positions. During the design phase of the SBV program, the goal of producing 4-arc-s (1-sigma) metric observations of RSOs was set. This 4-arc-s error budget comprises a wide variety of error sources ranging from the estimated position of the sensor on-orbit to systematic uncertainties within the established star catalogs. Although on-orbit metric calibration is the only true method of determining the metric performance of the SBV, an independent error assessment was made using actual flight data.[2] This was performed by isolating each error source within the error budget and quantifying its effect on the SBV observation.

This paper will present a technique for further reducing the errors in the observations of RSOs by addressing the unexpected error source of spacecraft attitude drift. This error is introduced into an observation when SBV is gathering data during a sidereal stare, the sensor's fundamental mode of operation. Whereas it was originally assumed that this would be an insignificant contribution to the SBV error budget, it was discovered through analysis of SBV calibration data that the drift associated with the spacecraft attitude was contributing significantly to the 4-arc-s budget. However, unlike with a number of the other error sources, this could be addressed with an improved algorithm.

Before presenting the analysis associated with the spacecraft drift, the paper will briefly describe SBV data processing and summarize the findings of the on-orbit error assessment and metric calibration. It was the comparison of the calibration results with the independent error assessment that precipitated this analysis of the drift. For extensive discussions on SBV's performance and its contribution to space surveillance, the reader is referred to Refs. 1–5.

SBV Data Processing

The SBV performs data collection in, most commonly, a staring mode. In this mode, light from stellar sources, the cosmic background and any diffuse or specular reflection of an RSO within the field of view (FOV) will be detected on the focal plane. The light is gathered on the detector for a variety of integration periods, depending on the type of data collection. An image gathered over one integration period is referred to as a frame. One raw or unprocessed frame of SBV data appears as a star field on a dark background, and, if an RSO is in the FOV, a short streak of illuminated pixels. Typically, a streak taken over one frame is not long enough to distinguish it from a stellar point source. As a consequence, it is necessary to superimpose multiple frames to produce an image that can be effectively processed.

A collection of frames, or frameset, typically consists of between 8 and 16 frames. The process of establishing an observation (right ascension and declination) of an RSO entails first determining the precise pointing of the boresight of the sensor in an inertial frame, then determining the position of the beginning and endpoints of that streak on the focal plane. Once these focal plane positions are known, they can then be transformed into right ascension and declination. Finally, the position of the observing platform must be established to support the angular measurements. For a detailed discussion of the processing of SBV image data, the reader is referred to Ref. 3.

Metric Errors Sources

Error sources that exist within the SBV metric error budget can be catagorized in four broad groups: 1) boresight pointing, which is influenced by star catalog errors, spacecraft attitude drift and jitter, and

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star centroiding and optical distortion; 2) observation timing errors; 3) MSX ephemeris errors; and 4) streak endpoint (SEP) determination errors. The total SBV error budget is determined by assuming that the error sources due to the MSX ephemeris, the satellite clock used for tagging the observations, the determination of the sensor boresight and the determination of the streak endpoints are independent. With this assumption, the total error can be expressed by

$$\sigma^2 = \sigma^2_{\text{ephemeris}} + \sigma^2_{\text{timing}} + \sigma^2_{\text{boresight}} + \sigma^2_{\text{SEP}} + \sigma^2_{\text{unknown}}$$

where the errors due to unknowns will become clear when a comparison of the error budget is made with on-orbit calibration. In fact, it was this comparison that revealed the error source that is the principal topic of this paper.

Inasmuch as it is not the purpose of this paper to discuss in detail each of the sources of error in the SBV error budget, the reader is referred to Ref. 2. However, results from Ref. 2 showed that the prelaunch error budget anticipated metric performance at about 3 arc-s. These values were determined based on observations taken by an SBV-grade charge-coupled device (CCD) located at the Lincoln Laboratory Experimental Test Site in Socorro, New Mexico in 1991 and also based on simulations.[2] In much the same way as was performed in the ground tests described earlier, the actual error budget for SBV was determined during the first 6 months of on-orbit operations. The results of this study revealed that actual metric performance could be expected at slightly better than the 2-arc-s level, a reduction of 50% over the 4-arc-s goal set during design.

Whereas an independent assessment of the SBV errors is of tremendous value to the understanding of the sensor's performance, the only true test of the quality of the observations is through routine calibration using known references. This was performed routinely on-orbit using laser calibration objects and GLONASS satellites and is now being performed using global positioning system (GPS) satellites. Results, both from the early part of the mission[2] and those compiled since launch,[5] place the quality of the residuals at the 4-arc-s level, but not at the level of either the pre- or postlaunch error assessments. It was this discrepency that motivated the search for an unknown error source that would explain the difference.

Spacecraft Attitude Drift

It was speculated during the error analysis studies that, although spacecraft attitude drift and periodic motion did not factor directly into the SBV error budget, they did influence the ability to perform centroiding of a star detection on the focal plane. However, in searching for the 2-arc-s discrepency between the estimated error budget and calibration performance, it was identified that this assumption was not completely true. It seemed that spacecraft attitude drift was, in fact, large enough to affect the SEP process, thus limiting the metric accuracy of the sensor to the 4-arc-s goal. Figure 1 shows a typical time series of the difference of the right ascension (RA), declination (DEC), and roll from the boresight pointing of the initial frame for a 16-frame frameset. It can be seen from Fig. 1 that the spacecraft drift during this period of data collection approached several arcseconds in both RA and DEC. As mentioned earlier, it was assumed that, when the spacecraft was in a sidereal stare, the spacecraft attitude drift would have a negligible contribution to the SEP determination process. However, with the evidence shown in Fig. 1, clearly this assumption is violated. Note that, whereas the roll angle appears to vary to a much larger degree than do the RA and DEC, this is only an artifact of the poor sensitivity of SBV to this direction of motion and should not be concluded to be the actual roll behavior.

Note that variations in the SBV boresight could be attributed to effects other than spacecraft attitude drift. Alignment changes between SBV and the MSX bus or variations within the sensor itself could create similar behavior in SBV's boresight. However, it was discovered during this study that it was possible to remove significant portions of the drift by locking the solar panels of the MSX. As is the case with most spacecraft, motors are used to adjust the solar panels so that they remain oriented toward the sun. These adjustments cause reaction on the bus of the spacecraft. It was found that, by locking the motors during SBV data collection, it was possible to remove most of the drift effect. It is for this reason and because SBV has an athermal design, significantly reducing the likelihood that changes are occuring within the sensor, that the detected changes in the SBV boresight were attributed to spacecraft attitude drift and not to the other aforementioned causes.

SBV Observation Errors from Spacecraft Attitude Drift

A study was undertaken to quantify the contribution of spacecraft attitude drift to the error budget. This was performed by identifying a group of framesets taken by SBV for which the data were gathered for varying levels of drift; 13 such cases were chosen, with drifts ranging from as little as 0.001 arc-s/s to as large as 4.0 arc-s/s. The drift rates were estimated by first determining the pointing of SBV, which is done by comparing star detections on the focal plane with those same stars from a star catalog for each frame of data. Figure 2 shows a typical time series of the RA and DEC of SBV pointing, as determined by this star-matching process, along with the error bars associated with each data point. These errors are determined based on the quality of the star-match residuals and the number of stars matched to determine the pointing solution. To estimate the drift, a linear function was fit to the RA and DEC, independently, and an estimate of the slope and an uncertainty of that estimate were determined. The values of these estimates are also shown in Fig. 2. It was found, for obvious reasons, that in cases for which the drift was nearly zero, the uncertainty in the estimate was considerably larger than the estimate itself and, therefore, the rate was indistinguishable from zero. Table 1 shows the estimated rate in RA, ω_α, and in DEC, ω_δ, for each of the 13 cases, using this technique. Once the rates are

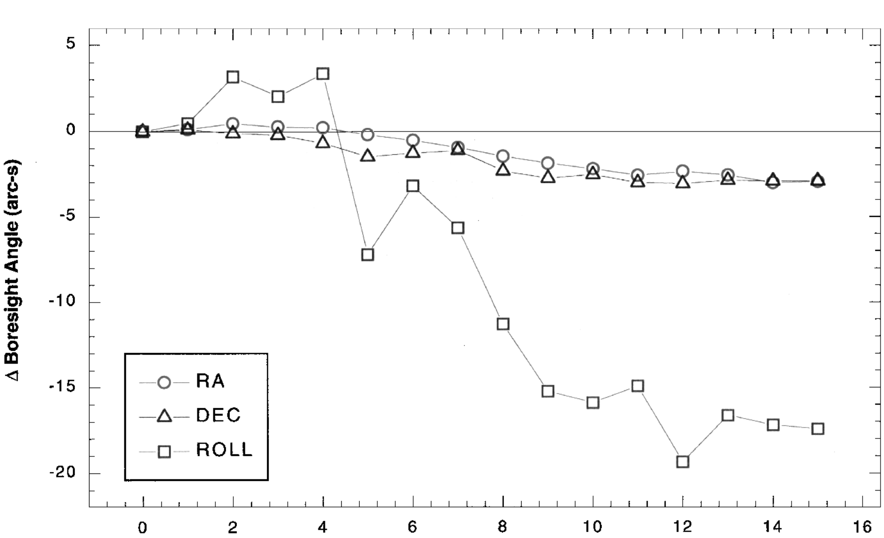

Fig. 1 MSX spacecraft drift.

determined, the effect of this rate on the RA α and the DEC δ of the SEPs can be determined by

$$\Delta\alpha_{\text{drift}} = \omega_\alpha \times \tau, \qquad \Delta\delta_{\text{drift}} = \omega_\delta \times \tau$$

where τ is the time span of the frameset. This term represents a correction to the observations that were originally determined with the assumption that drift was not present.

To assess the validity of the hypothesis that drift is causing a corruption of the observations, it is first necessary to quantify the quality of the observation before any correction for drift has been made. For each of the 13 cases, this was determined by comparing the RA and DEC, as determined by SBV, with those same angles, as determined through the metric calibration technique described earlier. Therefore, for each case, an independent angular position was determined for each of the target satellites in Table 1 and was differenced with the SBV observation of that target at that same time.

Table 1 Spacecraft drift assessment

Satellite	ω_α, ″/s	$\Delta\alpha_{\text{res}}$, ″	ε_α, ″	ω_δ, ″/s,	$\Delta\delta_{\text{res}}$, ″	ε_δ, ″
GPS	0.01	1.1	1.3	0.19	−2.5	0.5
TDF	0.22	−2.5	1.0	−0.19	3.3	0.3
GPS	−0.43	6.1	−0.8	−0.28	4.3	−0.2
SATCOM	0.02	0.0	0.3	0.01	0.4	0.5
GSTAR	0.001	−2.1	−2.1	0.05	−0.3	0.4
GPS	−0.88	13.7	−0.4	1.17	−16.6	2.1
JCSAT	−0.09	1.8	0.4	0.38	−7.5	−1.4
COSMOS RB	0.01	0.0	0.2	−0.94	15.8	0.8
GSTAR	−0.09	0.0	−1.4	0.64	−6.4	3.8
GORIZONT RB	0.33	−6.5	−1.2	−0.20	6.1	2.9
JCSAT	0.23	−4.6	−0.9	0.60	−10.1	−0.5
GORIZONT RB	0.16	−1.5	1.1	−0.15	2.5	0.1
GPS	1.2	−29.1	−9.9	−4.0	40.6	−23.4

″ = arc-s

The residuals are listed for RA as $\Delta\alpha_{\text{res}}$ and for DEC as $\Delta\delta_{\text{res}}$. These values represent the metric performance of SBV, prior to the application any drift correction. Clearly, the goal is to apply a correction to the observation such that these residuals are reduced in absolute magnitude, and, ultimately, if drift is the remaining unknown error source, are reduced to the 2-arc-s level found in the postlaunch error budget.

To apply the correction properly, it is important to realize that both the direction of the spacecraft drift and the direction of the target relative to SBV are important. With this in mind, it can be shown, in general, that the residual error, ε is given by

$$\varepsilon_\alpha = \Delta\alpha_{\text{res}} + \Delta\alpha_{\text{drift}} = \Delta\alpha_{\text{res}} + \omega_\alpha \times \tau$$

$$\varepsilon_\delta = \Delta\delta_{\text{res}} + \Delta\delta_{\text{drift}} = \Delta\delta_{\text{res}} + \omega_\delta \times \tau$$

The results, after the corrections have been made, are also given in Table 1, with the mean and standard deviations given in Table 2. It is clear from these results that significant improvements to the observations can be made by introducing a correction for spacecraft drift. The rms error improved from 3.3 arc-s in RA to 1.0 arc-s after the correction was applied, and from 4.4 arc-s in DEC to 1.6 arc-s. This gives an rss error on the angular position of 1.9 arc-s for the entire 13 events, after excluding 3-sigma outliers. This value for the metric performance of SBV now agrees well with the postlaunch error budget of better than 2 arc-s. This same information has been shown in Figs. 3 and 4 as histograms. Figures 3 and 4 display clearly

Table 2 Mean error and standard deviations of residuals before and after drift correction

Parameter	$\Delta\alpha_{\text{res}}$, ″	ε_α, ″	$\Delta\delta_{\text{res}}$, ″	ε_δ, ″
m	−0.75	−0.21	−0.01	0.78
σ	3.19	1.04	4.43	1.41

″ = arc-s

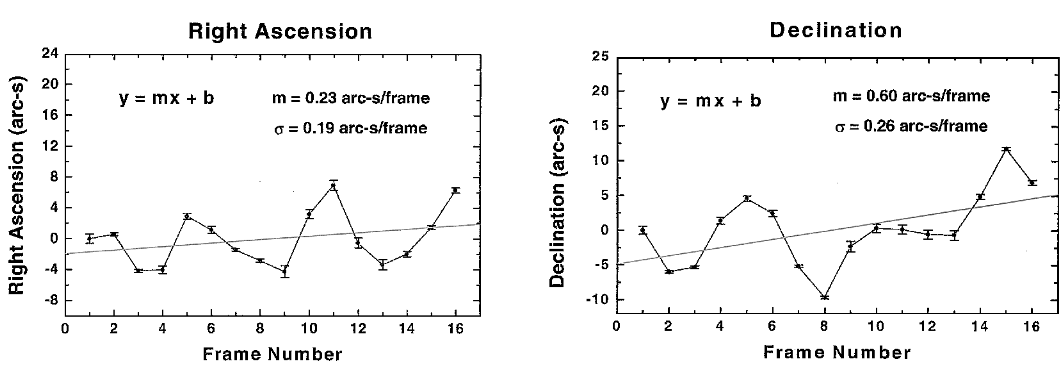

Fig. 2 Time series of SBV pointing.

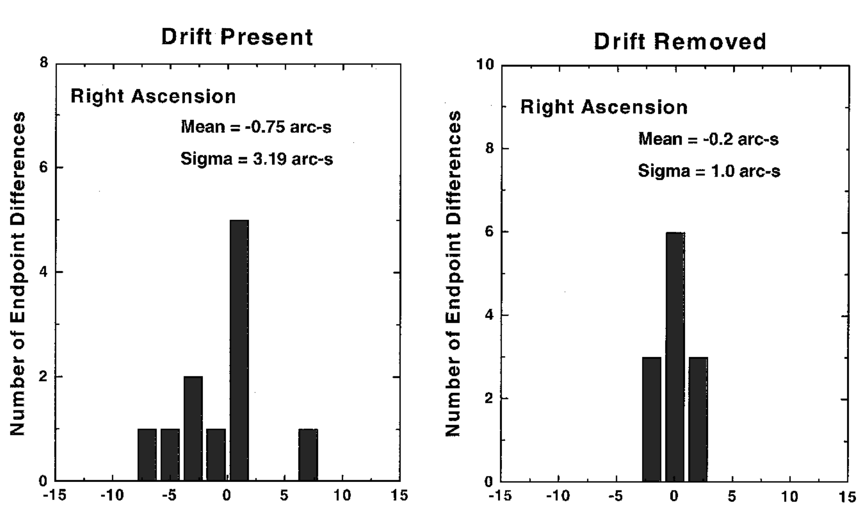

Fig. 3 Errors in RA before and after correction for drift.

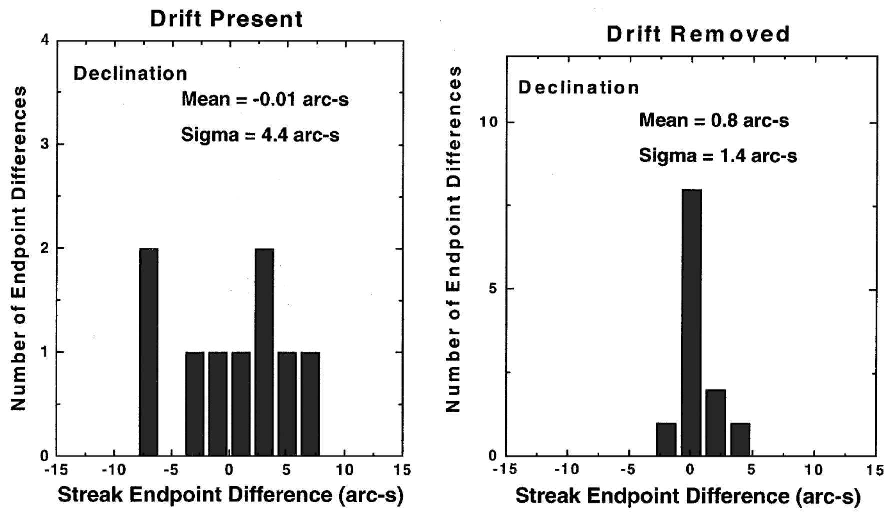

Fig. 4 Errors in DEC before and after correction for drift.

that, prior to correcting the observations, little clear statistical structure existed in the data, whereas, after the correction had been made, a Gaussian-like distribution was evident.

It is clear from these results that spacecraft drift plays a significant role in explaining the difference between the on-orbit calibration results of SBV and the postlaunch independent error analysis of the sensor. At least to within a few tenths of an arc-s, the results are consistent. Futher comparisons between the independent error budget and calibration results are still warranted, to completely eliminate any discrepencies. Recently, calibration of SBV uses GPS satellites, for which highly accurate ephemerides from the Jet Propulsion Laboratory are routinely available. This will allow for nearly error-free reference orbits with which to compare SBV results, thus allowing for more refined analysis.

Conclusions

It has been discovered in this work that spacecraft drift is the metric error source that accounts for the discrepency between the SBV's theoretical error budget and the sensor's performance indicated by on-orbit calibration. It was successfully identified that, with the proper modeling of the effect of drift on the SEP determination process, the metric performance of the SBV could be improved by at least 50%, to reach the 2-arc-s level. As was shown in this paper, this correction can be made by estimating the drift of the spacecraft using a linear fit to SBV pointing data.

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