Image Stacking Method Application for Low Earth Orbit Faint Objects

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ABSTRACT

The Earth orbit has been contaminated by artificial objects for decades. Therefore, Space Situational Awareness (SSA) is one of the most important actions for safe and sustainable space development and its utilizations. Orbital objects tracking and maintaining their catalog is the fundament of the activities. To improve the effectiveness of SSA activities, objects tracking capability should be enhanced in terms of applicable size limitation. This paper proposes a collaborative observation method consists of space-based sensors and ground observatories. The proposed method aims to discover and track faint objects in Low Earth Orbit (LEO) by ground observatories using initial orbit estimation result provided by space-based sensors. This follow-up observation is based on an assumption that signal amplification using the image stacking method developed by Japan Aerospace Exploration Agency (JAXA) can be applied to faint LEO objects. However, the applicability of this method is confirmed only for objects in geostationary orbit. Therefore this paper assesses the feasibility of faint LEO object detection using the image stacking method. This paper concluded that the image stacking method based on the space-based observation is applicable for ground observations of LEO objects. And it is also concluded that the proposed ground observatories are able to observe objects smaller than 1 – 5 cm by single 1 m telescope with the image stacking method.

1. INTRODUCTION

The Earth orbital environment has been fouled by debris for decades. And this is one of the major threats for safe and sustainable space development and its utilizations. There are two types of countermeasures against debris collision risks that the spacecraft can take. One is the protection using properly designed structure and the other is the collision avoidance operation based on the debris tracking database. Applicable debris sizes of these countermeasures are clearly distinguished. The minimum size of the current orbital database being opened to the public is approximately 10 cm in Low Earth Orbit (LEO)[1]. And the maximum tolerable collide object’s size is approximately 1 cm for International Space Station [2] which should have maximum security precautions among present spacecraft. These applicable size limitations indicate importance of tracking capability for objects smaller than 10 cm. The LEO objects are mainly observed by ground facilities such as optical telescopes and radars. The atmosphere degrades these facilities’ sensitivity and fixed-on-surface condition affects the effectiveness of observations badly. Therefore space-based sensors are a potential solution for small object tracking and there are several examples; Small Orbital Debris Detection, Acquisition and Tracking (SODDAT) of the United States [3], Canada’s Sapphire satellite [4] and AsteroidFinder of Germany[5]. However, our previous study found that LEO-to-LEO observation method is not suitable for follow-up observation [6]. This paper proposes a collaborative observation method between a space-based sensor and ground observatories to enable small object detections and follow-up observations. The proposed method stands on an assumption that the ground observatories can detect small, i.e. faint, LEO objects by applying a signal amplification measure called the image stacking method with an orbit estimation result from the space-based sensor.

This paper contains following topics. The brief overview of the collaborative observation method proposed in this paper is summarized in the section 2. The section 3 consists of three sub-sections. The section 3.1 describes the sensitivity analysis that assesses how small object in LEO can be detected by a telescope using the image stacking method. And next sub-section, 3.2, evaluates an applicability of the image stacking method by observation simulation. The section 3.3 confirms appeared trends in the section 3.2 by an observation experiment.

2. COLLABORATIVE OBSERVATION BETWEEN GROUND-BASED OBSERVATORIES AND SPACE-BASED SENSORS

Object tracking capability improvement is one of the effective countermeasures for orbital environment pollution. This paper proposes collaborative operation of LEO space-based sensors for LEO small object detection and ground observatories for follow-up observations. Space-based sensors can observe orbital object without atmospheric extinction and, dusk and dawn effect hence these sensors have superiority in sensitivity and efficiency. Here the orbit of the space-based sensor is considered to conduct effective detections.

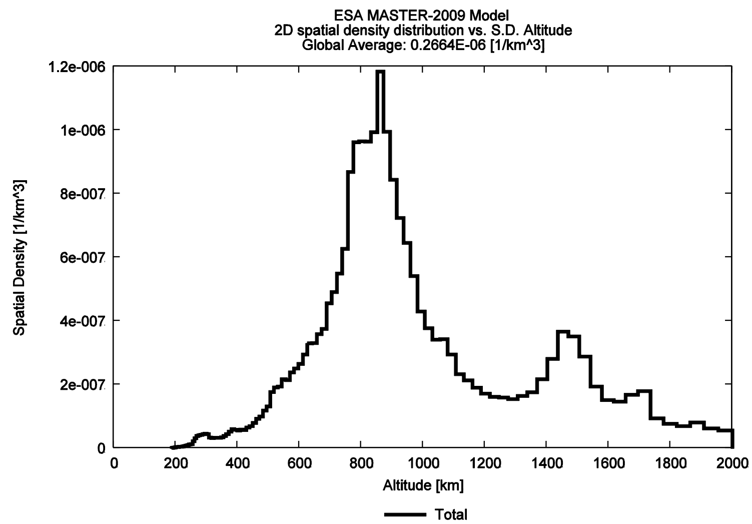

Fig. 1. Small (1 – 10 cm) object spatial density as a function of altitude according to MASTER-2009

Fig. 1 shows the spatial density of small objects in LEO and this result indicates object accumulation around altitude 800 km. Our previous study concluded that a space-based sensor located in altitude 800 km SSO can detect approximately 10 % of LEO small objects in four years [6]. Yet the study also concluded the difficulty of periodic detection by a space-based sensor because the sensor's orbit was designed to enable sweep observation. Since the object database should be updated frequently to keep enough tracking accuracy, collaborative observation method between a space-based sensor and ground observatories is proposed. If an apparent trajectory of an LEO faint object is predicted using primary observation data given by a space-based sensor, ground observatories can potentially detect the faint object. Because the signal amplification method named "image stacking method" is theoretically applicable for predicted apparent trajectories.

The image stacking method used time series images and superimposes stirred images based on the apparent motion prediction. When the apparent motion is properly predicted and images are stacked correctly, a faint object appears as a bright point. The image stacking method has been tested and applied only to geostationary orbit (GEO) objects [7]. The objects in GEO have a limited variety of orbital elements in comparison to LEO objects, therefore it is relatively easy to predict apparent motion without primary observation data. To apply the method to faint objects in LEO, their apparent motions need to be predicted. The collaborative observation method proposed in this paper uses the space-based sensor's observation result to predict the apparent motion in the ground observatories.

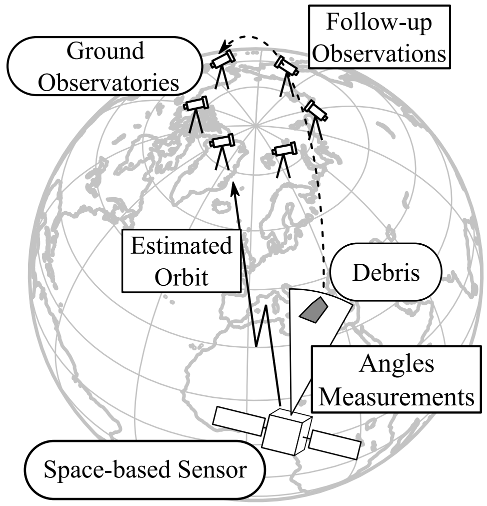

Fig. 2. The concept of the collaborative observation for low Earth orbit objects using a space-based sensor and ground observatories.

Fig. 2 illustrates the concept of the collaborative observation method for faint LEO objects. This method aims to detect small LEO objects by space-based sensors which are being faint from the ground and conduct follow-up observation by ground observatories, and enable such objects to be tracked. The space-based sensor is assumed to equip optical sensors as angles measurement instruments. Therefore the space-based sensor’s injection orbit should be Sun-synchronous orbit (SSO) due to its homeostatic sunlight environment. The detectable objects in proposed space-based sensor also are around SSO. The ground observatories should be placed in high latitude to observe SSO objects effectively. Low latitude observatories’ SSO object detection capability is limited in terms of Local Time of the Ascending Node (LTAN) as just after dusk and before dawn because objects come over the observatories around midnights are not illuminated by the Sun. Nevertheless, the observing efficiency of high latitude observatories would be strongly affected by seasonal effect such as nights with midnight sun in summertime. Therefore ground observatories in collaborative observation method should be located both Polar Regions at least. With these ground observatories, the method has a wide range of observable LTAN in SSO objects.

3. FOLLOW-UP OBSERVATION FEASIBILITY STUDY USING SPACE-BASED PRELIMINAL DETECTION

3.1 Sensitivity Analysis for Ground-based Observatories

The goal of the proposed observation method is to track LEO objects smaller than 10 cm in size. Thus the ground observatories should be designed to have enough sensitivity in size. It is assumed that the observatories consist of optical telescopes and CMOS sensors. The detectable size of ground-based optical observation is mainly determined by elevation angle and target's apparent velocity in pixels. The elevation angle affects air-mass [8] and relative distance to the target, and the other affect incident photon per pixel and exposure time.

Table 1. Assumed specifications of ground observatories

Aperture	1000 mm
Focal length	1500 mm
Sensor diagonal size	278 mm
Pixel number	1264 × 1264
FOV	7.73° × 7.73°
Resolution	22 arcsec
Readout noise	2.5 e-
Dark current	0.007 e-/pixel/sec
Quantum efficiency	0.53 @ 500 nm
Read-out time	21 msec
Signal to noise ratio criterion	2
Altitude	1800 m
Season	Winter

Assumptions in the optical telescope, CMOS sensor and facility are described in Table 1. The optical device is composed of large sized CMOS sensor and 1 m aperture telescope. The CMOS sensor's diagonal reaches current typical silicon wafer size limitation. And the noise characteristics are based on Andor's scientific CMOS (sCMOS) sensor specifications [9]. As shown in Table 1, the required Signal to Noise Ratio (SNR) is very low value, 2. This paper assumes that faint object detection with such low SNR can be enabled by signal amplification using the image stacking method.

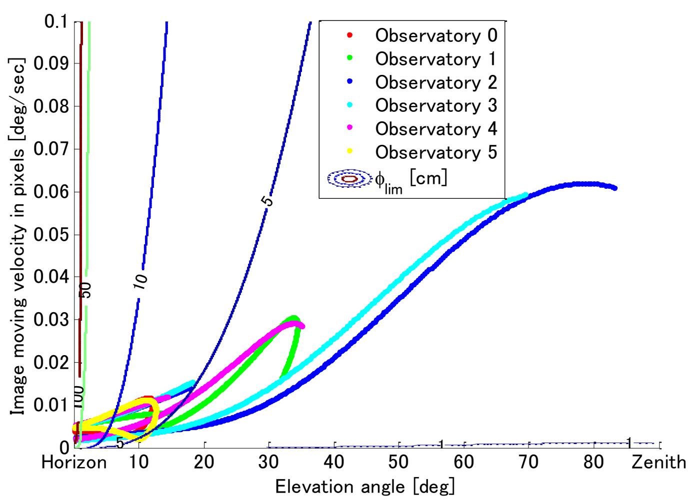

Fig. 3. Contour lines represent the detection limit diameter of sphere target as a function of elevation angle and image moving velocity. Plotted points represent simulated apparent trajectories in tracking observation based on preliminary estimated orbit.

The detectable size limitation is analyzed as a function of elevation angle and apparent velocity in pixels as shown in Fig.3. The contour lines in Fig. 3 represent the observable diameter of spherical objects with albedo 0.13 [10] under $\pi/2$ solar phase angle (i.e. Half-moon) assumption. It is found that moving slowly objects at high elevation angles have an advantage in observable size because such objects can be exposed long with relatively thin air-mass. And it can be concluded that these ground facilities have the potential detection capability for objects smaller than 5 cm.

3.2 Follow-up Observability

This paper proposes a collaborative observation method using space-based sensors and ground observatories. In the method, a first observation of a target on a ground observatory requires preliminary estimated target's orbit to predict apparent motion. Such first observations are the basis of follow-up observation of target objects therefore feasibility study of this collaboration part is very important. The space-based observation simulator is developed to conduct virtual observation and assess preliminary orbit estimation accuracy. It is presumed that a single satellite with optical sensors is used in the space-based observation phase thus preliminary orbit estimation is based on angles-only algorithm. And the target's orbit is taken as almost circular in the algorithm because it is predictable that the space-based observations are very short arc condition. Error assumptions in angle measurements, the satellite's position and the velocity are follows; 0.01 degrees (0.36 arcsec), 30 cm and 42 cm/sec [6].

Table 2. Sample results of preliminary orbit estimation using space-based observation

	Target	Estimated	Difference
Semi-major axis: a	7385.47 [km]	7202.50	-182.97
Eccentricity: e	0.0092	0.0011	N/A
Inclination: i	100.00 [deg]	99.59	-0.42
Right ascension of the ascending node: Ω	5.95 [deg]	5.58	-0.37
Argument of perigee: ω	353.68 [deg]	133.76	-219.92
True anomaly: f	55.30 [deg]	274.09	218.79

The preliminary estimated orbital elements of a sample target are shown in Table 2. This result indicates that orbit estimation based on angles-only space-based observation is relatively good at orbital plane determination. On the other hand, an approximately 200 km error occurred in the estimated semi-major axis. This error in semi-major axis is one of the most dominant factors in the follow-up observation capability assessment because this error appears in ground observations as apparent altitude and image moving velocity differences.

Here, the ground observatories are assumed as being located around the polar region to observe highly inclined objects during winter and summer. However the sample observation is assumed to occur in January, i.e. winter in northern hemisphere, contributions of the observatories around the South Polar Region are negligible. Therefore, only the observatories around the North Polar Region are considered here. The observatories' locations are arranged in a concentric pattern at north latitude 79 degrees with 60 degrees difference in longitude, respectively. In this arrangement, the reference point (Observatory 0) is the Ny-Alesund ground station, Norway.

When the target and observer satellite are located around SSO, the region most likely to have observation events should be above the equator. In this region, both orbits can be overlapped and have slow relative velocity if their ascending nodes are in proper relationship. Thus the sample target is assumed to be observed by the space-based sensor approximately quarter period before North Pole passing. And this assumption stands on ideal conditions in on-board computing power and communication link.

To assess the follow-up observation capability, the apparent motions in the tracking observations are simulated in each ground observatory. And the apparent motion simulation results are plotted in Fig. 3 as scatter points as a function of elevation angle and image moving velocity in pixels. The results in apparent motion simulation and sensitivity analysis indicate 4 of 6 observatories can detect objects smaller than 5 cm with SNR 2. And all the observatories can observe objects smaller than 10 cm with SNR 2. This SNR criterion is based on the assumption that signal amplification using the image stacking method is applicable for LEO objects. Therefore the method's applicability should be evaluated.

The applicability evaluation of this amplification method comes down to linearity and uniformity analysis of apparent motions. If an apparent motion can be treated as linear and uniform motion in adequate time, an object can be detected. Here the adequate time is defined by required exposure, read-out time and number of images. The required number of pictures to detect an object with SNR 2 is assumed as 32 according to Yanagisawa, T. (pers.

comm. 2013). If a distance between target's position in pixels and predicted pixel under linear and uniform motion assumption at the adequate time after observation beginning is smaller than 1 pixel, it can be concluded that the motion is reasonably linear and uniform.

$$V_{x_j} = \left(\frac{\Delta X}{\Delta t}\right)_j = \frac{X_j - X_{j-1}}{t_j - t_{j-1}} \qquad j = M+1 \cdots N \tag{1}$$

$$a_{x_k} = \left(\frac{\Delta V_x}{\Delta t}\right)_k = \frac{V_{x_k} - V_{x_{k-1}}}{t_k - t_{k-1}} \qquad k = M+2 \cdots N \tag{2}$$

$$\Delta P_{x_k} = a_{x_k} \times \Delta t_k^2 \tag{3}$$

To calculate the pixel distance at end of observations, pixel velocity and acceleration along X axis are defined as shown in Eq. (1) and (2). And the pixel distance along the X axis is calculated as Eq. (3). The pixel velocity, acceleration and distance along Y axis are also calculated in the same way. And total pixel distance is the square root of the sum of both distances' squares. In these equations, frames between numbers M and N are available pictures. .

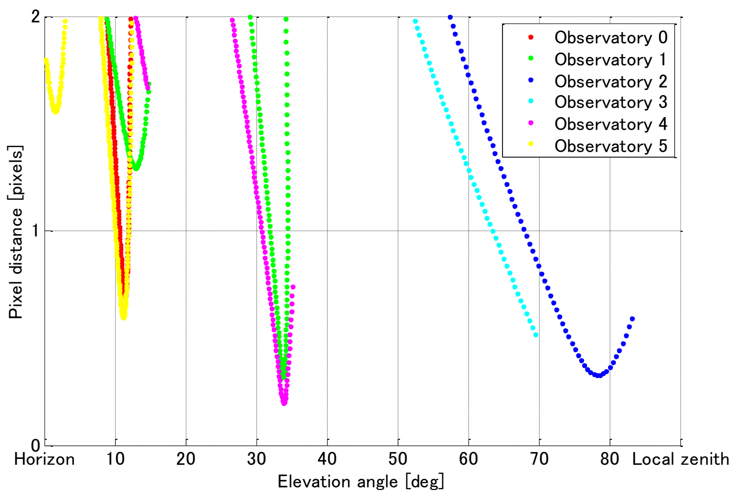

Fig. 4. Each scatter point represents the pixel distance at 32 frames after each observation moment.

Fig. 4 shows calculated results in the pixel distance for each ground observatory. The scatter points in Fig. 4 are the assumed beginning frames of 32 images, respectively. In this calculation, exposure time of 32 frames is assumed to optimal exposure of beginning frame. Here, optimal exposure means the longest duration to keep the target in single pixel therefore this value depends on the image moving velocity in pixels.

The results presented in Fig. 4 indicates that signal amplification using the image stacking method is applicable around local peaks of elevation angle at each ground observatory. Especially, observatory 1-4 can potentially detect smaller than 5 cm objects in LEO with the method. Because these four facilities' observations near the peak elevation angle satisfy 5 cm detection threshold in Fig. 3 and pixel distance criterion shown in Fig. 4. And another trend of the pixel distance is found in Fig. 4 that the pixel distances have other local minimal values around the low elevation angle region while these values do not satisfy the pixel distance criterion. The observations around the peak elevation are suitable for the image stacking method because their apparent velocities in pixels change rates are relatively small in comparison to observations other elevation angles. On the other hand, the observations in the low elevation angles also have an advantage in image moving velocity compare to observations in rising elevation region. However such slow apparent velocity and thick air-mass in the low elevation angles make their optimal exposure time long. Thus their required time to take 32 images is longer than observations at the peak elevations and this long required time makes the pixel distance large.

3.3 Tracking Observation Experiment

We conducted tracking observation experiment for LEO objects based on error contained orbit information to evaluate applicability of the image stacking method. In particular, this experiment is planned to confirm the linearity and uniformity of image motion in pixels. Therefore the targets of the experiment are bright objects such as rocket body to ease apparent trajectory detection. The JAXA's three-axes altazimuth telescope in Chofu, Japan is used in the experiment. The camera module in the experiment was composed of focal length 200 mm refracting lens and cooled CCD sensor. While the optical device and the facility location in this experiment is different from assumptions in the simulations, the results of this experiment can be treated as reference in terms of pixel distance characteristics.

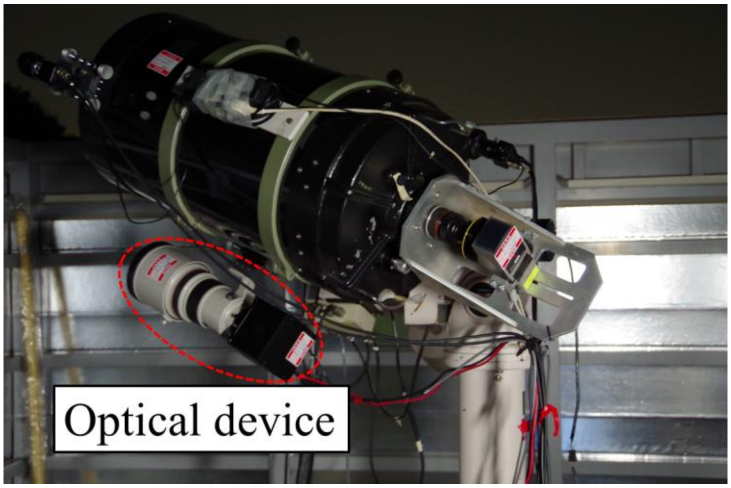

Fig. 5. The optical device used in the tracking observation experiment. The facility is located in Tokyo, Japan.

Table 3. Major specifications of the optical device used in the tracking observation experiment

Focal length	200 mm
F-number	2.0
Field of view	10.3°×6.8°
Pixel number	2004×1336 (2×2 Binned, Nominal: 4008×2672)
Resolution	18.5 arcsec
Exposure time	100 msec
Readout time	Approx. 3.5 sec

The actual configuration of the optical device and its major specifications are presented in Fig. 5 and Table 3. Current configuration cannot change the exposure time during the tracking observation automatically; it is set as a constant value. And the pixels in the CCD sensor are binned to make read-out time quick and resolution close to 22 arcsec. The exposure time used in this experiment, 100 msec, is optimal for an object which have approximately 0.05 deg/sec apparent velocity in pixels.

This experiment aims to evaluate image stacking method applicability from a view period of apparent motion, hence the test object is chosen from the bright object to facilitate detection. The target object in this experiment was a CZ-4 rocket body (20791) and its ephemeris were retrieved from the public database [11]. The forecasted brightness of this rocket body was approximately 7 in magnitude at the experiment.

Table 4. Target's two line elements from object catalogue and error contaminated database for tracking observation experiment

Based on database: TLE (A)	1 20791U 90081D 13219.47152778 .00000129 00000-0 99264-4 0 00003 2 20791 099.1665 273.3479 0052202 308.0068 043.6554 13.92485853165117
Error contaminated: TLE (B)	1 20791U 90081D 13219.47152778 .00000350 00000-0 99267-4 0 00002 2 20791 098.7465 272.9780 0010000 088.0870 263.4254 14.45636520165113

The Two Line Element (TLE) set used in the tracking observation experiment is described in Table 4. The TLE based on the database was propagated at the epoch approximately 10 minutes before the predicted visible pass at the test facility. And the reasonable errors based on the sample orbit estimation results were added to the TLE and this error contaminated TLE was used in the experiment.

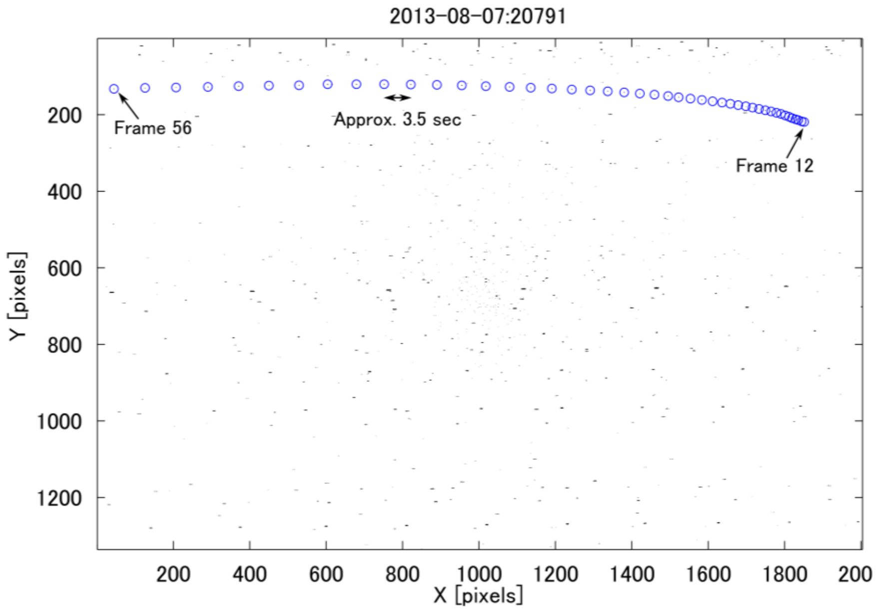

Fig. 6. Lighten composite image of LEO object tracking observation experiment based on the virtual orbit estimation result

Fig. 6 illustrates binarized lighten composite images of the tracking observation experiment. In Fig. 6, apparent trajectory that shows a pattern distinctly different from other light spot i.e., stars. The apparent trajectory framed by blue small circle moves slower than the movement of stars and its flow direction is different from stars. And it is confirmed in our previous study that such characteristics appeared in the ground observation simulation. Therefore it is concluded that the apparent trajectory can be treated as target-derived.

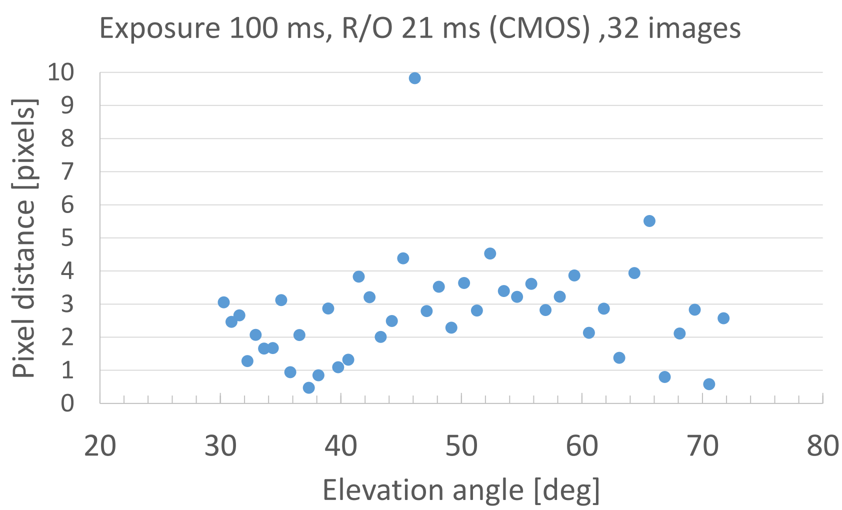

Fig. 7. Differences from linear and uniform apparent motion are plotted as pixel distances. The horizontal axis represents the corresponding elevation angle at each frame. The elevation angles are simulated based on the TLE (A). The pixel distance represents the pixel number between a pixel where the target should be located if the apparent motion is perfectly linear and uniform, and a pixel where the target would be located.

Fig. 7 represents the pixel distance calculated in the same fashion as described in the follow-up observability analysis. In Fig. 7, predicted elevation angles are shown as a line and the maximum elevation angle in this visible pass was estimated at approximately 78 degrees. This observation experiment was conducted with constant exposure time hence adequate time to take 32 images is also constant, approximately 3.8 seconds. While the observation experiment used CCD sensor, the pixel distance calculation is based on sCMOS's read-out time, 21 msec. The results depicted in Fig. 7 show several frames that make pixel distance smaller than 1 pixel at 32 images after. And it also can be concluded that observations in the elevation near the peak have superiority in terms of pixel distance. There are other frames which satisfy pixel distance criteria in low elevation angle. Therefore this experiment confirmed the trend of the pixel distance as shown in Fig. 4. However, it should be noted that this experiment was conducted in constant exposure time setting which was optimized for apparent velocity 0.05 deg/sec, in other words, optimized for observations near the peak elevation. Thus this experiment resulted smaller pixel distances than that of the simulation.

4. CONCLUSION

This paper proposed the collaborative observation method for LEO small debris. This method was composed of the space-based sensor for small object detection and the ground observatories for follow-up observations. The detection capability of the space-based sensors had been confirmed in our previous study hence the sensitivity analysis and the image stacking method applicability were assessed in this paper.

Each ground observatory was assumed to consist with 1 m aperture telescope and a large CMOS sensor. Their sensitivity for LEO objects were summarized as a function of tracking elevation angle and target's moving velocity in pixels. And the result indicated that the observatories had a potential capability to observe objects smaller than 5 cm with SNR 2. This low SNR requirement was based on an assumption that the image stacking method would be applicable for LEO objects.

To confirm reasonability of this assumption, the linearity and the uniformity of the apparent motions were analyzed. The pixel accelerations were calculated to evaluate how the actual pixel was distant from the predicted pixel based on perfect linear and uniform motion assumption. The result indicated that it is possible to superimpose 32 images using apparent motion prediction by the space-based sensor. Especially, it is found that observations around the local peak of tracking elevations had superiority in the pixel distances.

The tracking observation using orbit estimation result based on the space-based observation had taken a simulation experiment in Chofu observatory, Japan. This experiment had been planned to confirm the linearity and the uniformity of the apparent motions in the tracking observations. And it had been confirmed that the image stacking method was potentially applicable for LEO objects even if their orbital elements had had the same level of accuracy with the space-based orbit estimation. However, this experiment used a CCD sensor which has very long readout time in comparison to typical CMOS sensors. Thus we should have additional experiments using CMOS sensors to discuss the applicability more properly.

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