Effective Search Strategy Applicable for Breakup Fragments in the Geostationary Region

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ABSTRACT

This paper proposes to apply the orbital debris modeling techniques to devise an effective search strategy applicable for breakup fragments in the geostationary region. The orbital debris modeling techniques describe debris generation and propagation to effectively conduct predictive analyses of space objects that include characterizing, tracking and predicting the behavior of individual and groups of space objects. Therefore, the techniques enable us to predict population of debris from a specific breakup. The population prediction specifies effectively when, where and how we should conduct optical measurements using ground-based telescopes. The orbital debris modeling techniques also enable us to predict motion of debris in successive images. The motion prediction specifies effectively and precisely how we should process successive images of objects in the geostationary region, taken with ground-based telescopes. This paper also validates the proposed search strategy through actual observations, targeting the US Titan IIIC transtage explosion in the geostationary region.

1. INTRODUCTION

European Space Agency (ESA) has analyzed the current situation in the geostationary region (here defined as orbits with mean motion between 0.9 and 1.1 revolutions per day, eccentricity smaller than 0.2 and inclination below 30 degrees). As in [1], the total number of known objects in the geostationary region is 1274, whereas only 397 are operational to be controlled inside their longitude slot. The basic source is the US Two-Line Elements, whose accuracy at the geostationary altitude is limited to track objects larger than approximately 1 m in size (magnitude of 15). Observations performed by ESA using larger optics indicate that the population in the geostationary region, to a limiting diameter of approximately 10 cm (magnitude of 20), exceeds the catalogued population by a factor of four, as in [2].

Only two breakups in the geostationary region have been confirmed, as in [3]. One is the CIS Ekran 2 breakup on 23rd June 1978. This was the first known fragmentation in the geostationary region. Another is the US Titan IIIC transtage breakup on 21st February 1992. This was the second major fragmentation of a Titan IIIC transtage. These two confirmed breakups are not enough to associate with the large amount of debris detected by ESA, which may have originated from other unconfirmed energetic explosions occurred in the geostationary region. Indeed, ESA has concluded that 10 artificial events should be taken into account to describe the present orbital debris environment in the geostationary region, as in [4,5]. In addition, some scientists have found the evidence for historical satellite fragmentations in the geostationary region (e.g. [6–8]).

This paper proposes to apply the orbital debris (OD) modeling techniques to devise an effective search strategy applicable for breakup fragments in the geostationary region. The OD modeling techniques describe debris generation and propagation to effectively conduct predictive analyses of space objects that include characterizing, tracking and predicting the behavior of individual and groups of space objects. Therefore, the techniques enable us to predict population of debris from a specific breakup. The population prediction specifies effectively when, where and how we should conduct optical measurements using ground-based telescopes. The OD modeling techniques also enable us to predict motion of debris in successive images. This paper demonstrates that the motion prediction clearly distinguish fragments generated by the target breakup event from other detected objects that have originated from other breakups. Therefore, this paper demonstrates that the motion prediction can enhance track-before-detection techniques, which stack successive images shifted according to the assumed motion of the target object.

2. STRATEGY OVERVIEW

Fig. 1 schematically describes the overview of effective search strategy that we propose through this paper. The OD modeling techniques describe debris generation and propagation to effectively conduct predictive analyses of space objects that include characterizing, tracking and predicting the behavior of individual and groups of space objects.

First, we generate fragments from a breakup event in the geostationary region, cited in literatures (e.g. [6–9]), using the NASA standard breakup model 2001 revision (see [10]). Then, we propagate their orbit till planned observation date to predict population of the generated fragments. There is significant uncertainty in debris generation, so that it is unfeasible or impossible to compute an exact result with a deterministic algorithm. Therefore, we apply a Monte Carlo method to aggregate the results of the individual computations into the final result. The mean of 100 computations represents the final result, whereas the standard deviation of 100 computations represents the error of this method.

The resulting population specifies effectively when, where and how we should conduct optical measurements using ground-based telescopes. Secondly, therefore, we conduct "planning and observation" in Fig. 1 based on the resulting population. We select a couple of candidate points in geocentric equatorial inertial coordinates, with consideration that bright stars will not be in the field of view. Then, we keep looking at each point for a relatively long duration. In order to effectively detect debris in the geostationary region, however, images should be taken with non-sidereal mode. Therefore, one set of images will be taken for several minutes with non-sidereal mode, and then the pointing will be changed in order to keep looking at the specified single point in geocentric equatorial inertial coordinates. Actual observations will be conducted at the Japan Aerospace Exploration Agency (JAXA) Nyukasa Observatory in Nagano Prefecture, Japan.

Thirdly, based upon the resulting population, we predict motion of fragments passing through the specified single point in geocentric equatorial inertial cooridinates during the observation. Motion prediction characterizes the behavior of groups of fragments from a single breakup event. Therefore, the motion prediction can clearly distinguish fragments generated by a target breakup event from other detected objects. The motion prediction also specifies effectively and precisely how we should process successive images to detect moving objects. Fourthly, therefore, we apply the motion prediction to a track-before-detection technique, which stacks successive images shifted according to the assumed motion of the target object, in order to detect faint fragments from the target breakup event.

Finally, we assume how the target breakup event has released fragments based on correlated and uncorrelated targets (CTs/UCTs) detected by the image processing, and then properly describe the target breakup event to improve the debris generation. This improvement provides a better definition of the current situation in the geostationary region.

3. POPULATION PREDICTION

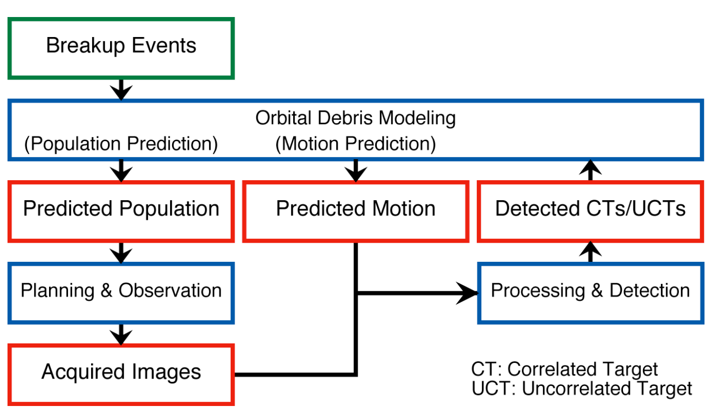

Fig. 1. Approach and Work Flow

For instance, this paper predicts population of fragments from the US Titan IIIC transtage exploded on 21st February 1992. This explosion was the second major fragmentation of a Titan IIIC transtage. This transtage released Environmental Research Satellite (ERS)-28 (also known as Orbiting Vehicle (OV) 5-2) in synchronous orbit, before slightly decelerating and releasing OV2-5 into a slightly lower orbit. This transtage successfully completed its mission and remained on-orbit 281 months before the explosion. A total of 23 objects were observed right after the explosion, but only 8 fragments are being tracked by the Space Surveillance Network to be catalogued.

The NASA standard breakup model predicts 238 fragments down to 10 cm in size, from the US Titan IIIC transtage explosion. Their delta-velocity is predicted to define their initial orbit. Their area-to-mass ratio is also predicted to take into account the solar radiation pressure effects. Their initial orbit was propagated till 4th March 2011 for "planning and observation" in Fig. 1.

This paper compares two different distributions as a function of geocentric right ascension and declination for "planning and observation" in Fig. 1:

1. where most fragments will be, and
2. where most fragments will be detected.

Typically, the propagation error is greatest in the along-track direction because time errors greatly displace the satellite along the orbital path. Therefore, the time-averaged distribution of fragments has been adopted to evaluate the first distribution. The time-averaged distribution of fragments can be used to evaluate the effectiveness of conventional survey observations because the population inside the region where a system will survey provides the number of fragments to be detected by the survey observation. On the other hand, we intend to keep looking at a given geocentric right ascension and declination for a given time interval, so that the latter distribution needs to take into account the duration of the observation. Therefore, the time-integrated distribution of fragments should be adopted to evaluate the effectiveness of the proposed search observation.

Fig. 2 provides the time-averaged distribution of the US Titan IIIC transtage fragments, whereas Fig. 3 provides the time-integrated distribution of the US Titan IIIC transtage fragments. Figs. 2 and 3 look quite similar. Actually, the point where most fragments will be exactly corresponds to the point where most fragments will be detected. However, information that each figure provides is quite different.

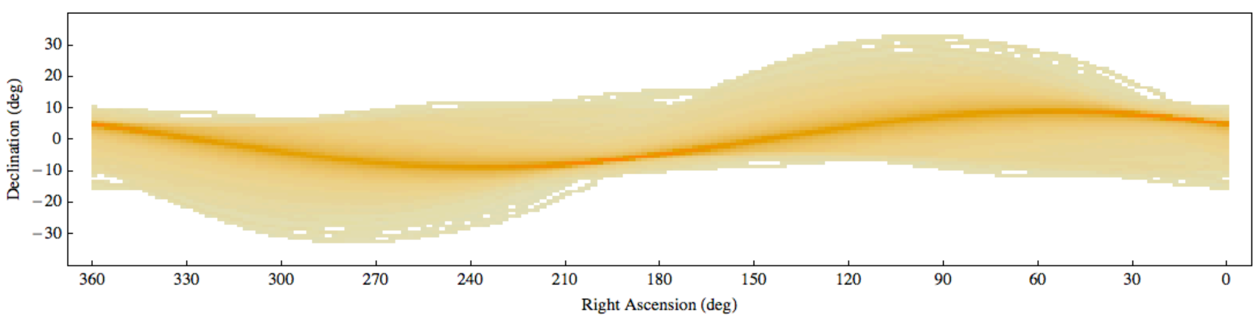

Fig. 2. Time-averaged Distribution of US Titan IIIC Transtage Fragments

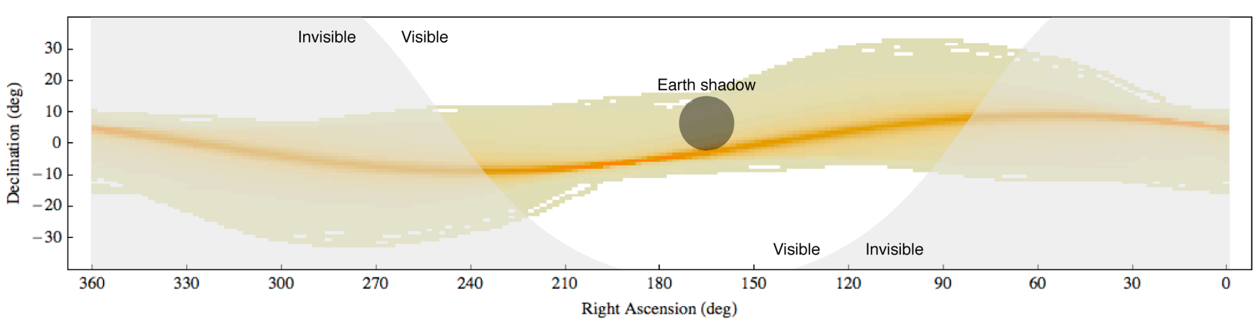

Fig. 3. Time-integrated Distribution of US Titan IIIC Transtaage Fragments

The effectiveness of conventional survey observations can be evaluated by the time-averaged distribution (i.e. Fig. 2). On the assumption that we survey a declination rage between –20 degrees and +20 degrees with a 1-degree field of view telescope, the duration necessary for the survey observation is at least 960 hours to result the detection rate of 0.25 fragments/hour. The time-integrated distribution (i.e. Fig. 3) can evaluate the effectiveness of the search observation proposed herein. If we keep looking at the point where most fragments will be detected with the same field of view telescope for 8 hours, then the detection rate can be up to 8.58 fragments/hour.

4. OBSERVATION PLANNING

JAXA possesses an optical observatory site at Mt. Nyukasa, Nagano Prefecture, for research on orbital debris observation technologies and data analysis processes for the geostationary region. The site is at 138º10′18″ E, 35º54′05″ N, 1870 m altitude. There are a 35-cm telescope and a 2K by 2K charged-coupled device (CCD) camera at the site. The telescope is an ε 350N manufactured by Takahashi Co. Ltd. Its focal length is 1248 mm. It is set on a fork-type equatorial mount 25 EF manufactured by SHOWA. The CCD camera is a FCC-104B, manufactured by Nakanishi Image Laboratory Inc., using a back-illuminated chip, the EEV's 4240. The chip is cooled from room temperature down to –30 degrees Celsius with the Peltier device and circulated water. Readout time of the CCD camera is about 10 seconds. As the pixel size of the chip is 13.5 µm, the total sky coverage of the image area of the system is around 1.27 degrees by 1.27 degrees, and its pixel scale is 2.2 arc seconds. The start and end time of exposure are recorded in the image header with msec accuracy by using global positioning system (GPS) time recorder which senses the shutter motion.

Actual observation was conducted at the JAXA Nyukasa Observatory for this study. Fig. 3 specifies the visible region from the JAXA Nyukasa Observatory and the Earth shadow at the nominal geostationary altitude, both at midnight on 4th March 2011. In the visible region, the point where most fragments will be detected is at 195.5 degrees in geocentric right ascension and –6.5 degrees in geocentric declination. The duration of actual observation was set from 13:00 UT to 20:20 UT (from 22:00 JST to 29:20 JST), so that the JAXA Nyukasa Observatory was able to keep looking at the point during the observation on 4th March 2011. Beside, we confirmed that there was no bright star in the field of view during the observation. Therefore, we decided to keep looking at the point. It should be noted that the detection rate at the point with the 1.27-degree field of view was 7.86 ± 0.19 fragments/hour. Actual observation on 4th March 2011 took 49 sets of 32 successive images to result in the total number of 1568 images.

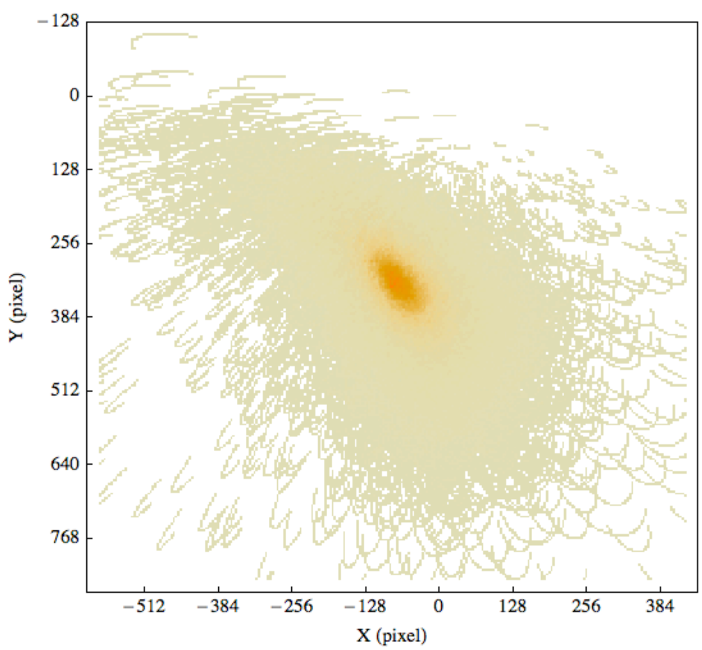

Fig. 4. Distribution of Two-dimensional Shift Values of US Titan IIIC Transtage Fragments in Successive Images

5. MOTION PREDICTION

Motion prediction can characterize the behavior of groups of the US Titan IIIC transtage fragments passing through the single point in geocentric equatorial inertial coordinates, specified by the observation planning. Fig. 4 demonstrates two-dimensional motion of the US Titan IIIC transtage fragments in a series of successive images taken during the observation. As demonstrated in Fig. 4, the US Titan IIIC transrage fragments show a unique and clear trend in the two-dimensional motion. This fact indicates that the motion prediction can distinguish the US Titan IIIC transtage fragments from other objects detected.

Fig. 5 compares predicted motion of the US Titan IIIC transtage fragments and measured motion of correlated and uncorrelated targets detected on the night of 4th March 2011. An ellipse in Fig. 5 represents "most likely" region to include approximately 70 % of the US Titan IIIC transtage fragments. Objects appearing inside the "most likely" region in the two-dimensional shift values are most likely from the US Titan IIIC transtage. Indeed, a correlated target appearing inside the "most likely" region is 1968-081H, a US Titan IIIC transtage fragment. Other correlated targets appearing outside the "most likely" region are not associated with the US Titan IIIC transtage. Those

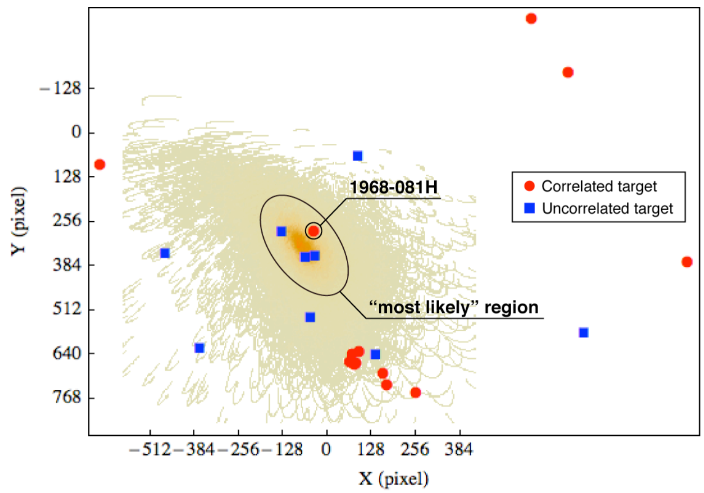

Fig. 5. Comparison between Predictions and Measurements in Two-dimensional Shift Values

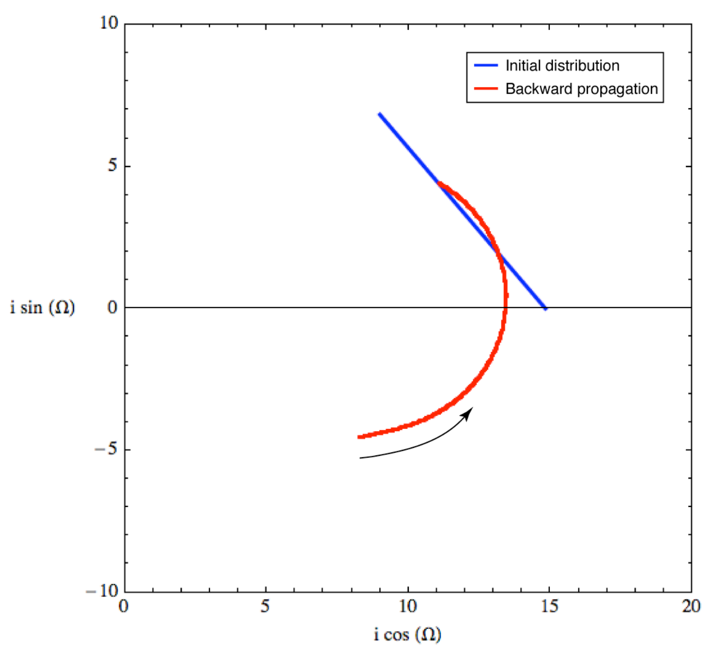

Fig. 6. Backward Propagation of a UCT inside the "most likely" Region

correlated targets include two objects in geostationary transfer orbit, two Russian upper stages, and eight geostationary satellites. It may be noted that the magnitude of correlated and uncorrelated targets plotted in Fig. 5 is relatively bright and over the limiting magnitude of a single CCD image (magnitude of 17).

Fig. 6 demonstrates backward propagation of one of three uncorrelated targets appearing inside the "most likely" region. Red line represents the propagation back to the event date and time, whereas blue line represents the initial distribution of the US Titan IIIC transtage fragments. Therefore, we can conclude that the uncorrelated target is associated with the US Titan IIIC transtage. This "most likely" approach works well to clearly distinguish the US Titan IIIC transtage fragments from other objects. As will be demonstrated later, therefore, we can apply this "most likely" approach to a track-before-detection technique, which stacks successive images shifted according to the assumed motion of the target object, in order to detect faint fragments associated with the US Titan IIIC transtage.

6. IMAGE PROCESSING

Staking method can detect faint objects by stacking successive images that have been shifted according to the assumed motion of the target object. The staking method enables us to detect fainter objects below the limiting magnitude of a single CCD image. JAXA has applied the stacking method to discover minor planets and successfully discovered many minor planets. As illustrated in Fig. 7, sub-images are cropped from many CCD images to fit the movement of a space object. A median image of all the sub-images is then created. In this method, photons from the object are located on the same pixels of sub-images, and field stars are removed by taking the median because they are in different places on the sub-images. Fig. 7 shows an example of an asteroid detected using the method. Fig. 8 (a) shows a part of one CCD image and Fig. 8 (b) the same region of the final image after the process was carried out. Forty images were used for this example. It is impossible to confirm the presence of the asteroid in Fig. 8 (a), whereas the asteroid is bright and no field star can be seen in Fig. 8 (b). Background noise was reduced as

$$\sigma_{median} = \frac{1.2}{\sqrt{N}} \sigma_{individual}$$

where N is the number of sub-images used to make up a median image. This means fainter objects are detectable as

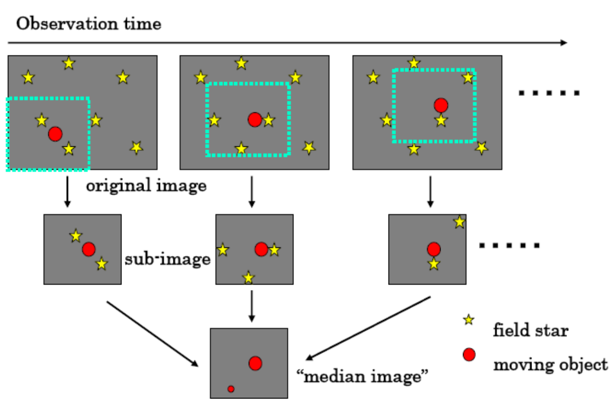

Fig. 7. Concept of the Stacking Method

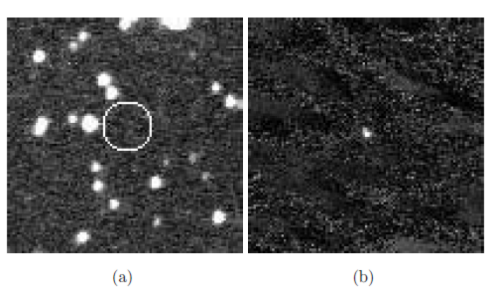

Fig. 8. Example of an Asteroid Detection: (a) One of Successive Images, (b) Final Image Processed

more images are used. The factor 1.2 is calculated from Monte Carlo simulations. If the average is used instead of the median, the factor is 1.0. The average is slightly more powerful than the median in respect of the detection of unresolved moving objects. However, the median has the advantage of eliminating extremely high noises, such as cosmic rays and hot pixels that still remain in an averaged image. The stacking method is not a simple shift-and-co-add method. It is impossible for the simple method to eliminate the effects of field stars, as demonstrated in Fig. 8. Several processes are included in the stacking method to properly eliminate those effects. Details of the stacking method are described in [11]. In order to detect invisible moving object, various shift values of asteroids must be investigated. This is a time-consuming process, so that JAXA is developing a Field Programmable Gate Array (FPGA) system for reducing computation time necessary to process.

This paper applies the stacking method developed at JAXA to detect faint fragments from the US Titan IIIC transtage. Table 1 assumes two different two-dimensional ranges for the stacking method based on the two-dimensional shift values of the US Titan IIIC transtage fragments in successive images, predicted in Fig. 4. As specified in Fig. 9, the former range includes 1968-081H, a US Titan IIIC transtage fragment, and one uncorrelated target, both appearing inside the "most likely" region. On the other hand, the latter range includes two uncorrelated targets appearing inside the "most likely" region. The magnitude of the fragment and three uncorrelated targets is relatively bright and over the limiting magnitude of a single CCD image. Therefore, the stacking method with the assumed motion successfully detects those bright targets.

As demonstrated in Fig. 9, the stacking method also successfully detects one new uncorrelated target at the latter range, not plotted in Fig. 5. This is the first time for the JAXA's stacking method to detect an uncorrelated target below the limiting magnitude of a single CCD image taken at the JAXA Nyukasa Observatory. However, we were not able to determine the orbit of the newly detected uncorrelated target. The stacking method requires a plenty of computation time to process. Computation time necessary for the staking method to process a set of 32 successive

Table 1. Two-dimensional Range Assumed for Stacking Method

	X-direction (pixel)	Y-direction (pixel)
1	–170 ~ –20	200 ~ 300
2	–150 ~ 0	300 ~ 400

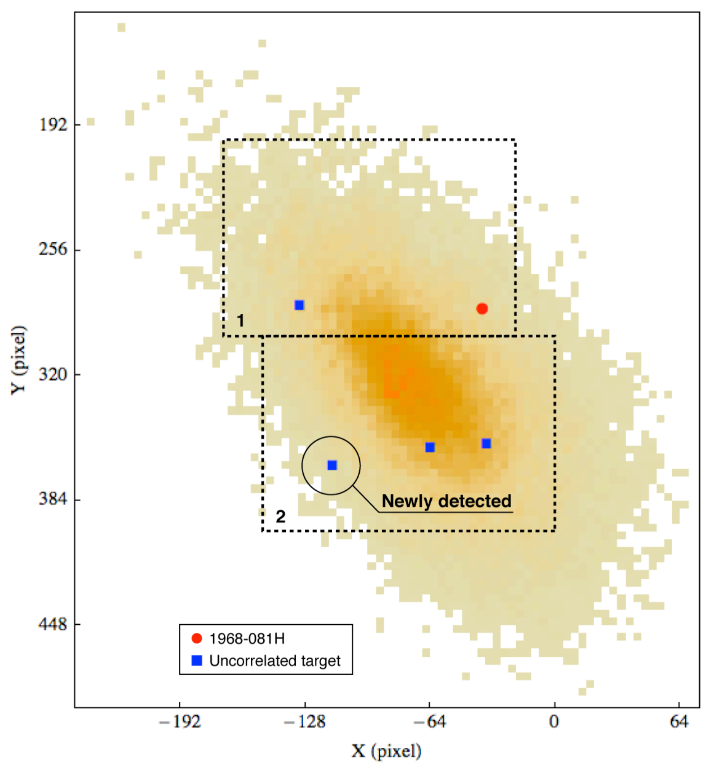

Fig. 9. Comparison between Predictions and Measurements inside the "most likely" Region

images is approximately 4.5 hours. Therefore, it is nearly impossible for the stacking method to complete image processing of 49 sets of 32 successive images before follow-up observation to determine the orbit precisely.

7. CONCLUSIONS

This paper proposes to apply the OD modeling techniques to devise an effective search strategy applicable for breakup fragments in the geostationary region. The OD modeling techniques include debris generation and orbit propagation to define the current situation of the orbital debris environment. First, the OD modeling techniques are applied for observation planning. Fragments from a specific breakup event in the geostationary region are generated using the NASA standard breakup model 2001 revision. Then, their orbit is propagated till a planned observation date to analyze their distribution in geocentric equatorial inertial coordinates. The resulting distribution specifies when, where and how they should be observed using ground-based optical telescopes. Secondly, the OD modeling techniques are applied for image processing. Fragments from a specific breakup event form a unique and clear trend in two-dimensional motion in a series of successive images. The motion prediction clearly distinguishes fragments generated by the target breakup event from other detected objects originated from other events, so that the motion prediction specifies how the successive images should be shifted and stacked to detect faint fragments from the target breakup event. An observation targeting the US Titan IIIC transtage fragments was performed on 4th March 2011 at the JAXA Nyukasa Observatory to demonstrate the search strategy. The stacking method developed at JAXA with the motion prediction successively detected a faint object below the limiting magnitude of a single CCD image.

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