USING SPACE BASED SENSORS TO CATALOG LEO OBJECTS

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ABSTRACT

With the development of their capability and reliability, space-based visible sensors on sun-synchronous orbit have been used to detect and track Deep Space Objects. But until now, they are not used, at least as a primary mission, to detect Low Earth Orbit (LEO) objects with an altitude less than 2000km. This paper intends to present a space-based surveillance draft which can:

- Detect and collect observations of LEO objects to support its catalogue and maintenance
- Using fixed sensors to fulfill the above mission without special pointing operation and mission planning, and
- If possible, be installed on a normal-commercial small satellite with a platform/bus less than 300kg.

The result shows that the equatorial orbit with an inclination of zero degree can be a competent candidate. The given example of a MEO at an altitude of about 9000km can achieve a good enough opportunity for detecting LEO objects with observations that are well-proportioned. When it is equipped with 4 fixed telescopes, each with a FOV of 4.5° ×4.5° , a single satellite can provide sufficient observations to support the catalogue and its maintenance of LEO objects with an inclination greater than 50 degrees. The disadvantages of the draft are the long distance, launch cost, and on-board data processing.

1. BACKGROUND AND PROBLEMS

Since the SBV/MSX satellite was transitioned to SSN as an operational Space Surveillance Sensor in 2000 [1][2], space-based space surveillance has been discussed continuously. With the launch of the SBSS-1 in 2010, it has been forwarded slowly but firmly.

SBV/MSX and SBSS-1 are mainly used to detect/track Deep Space Objects, especially GEO objects [1][3]. Their orbits are sun-synchronous with altitudes less than 1000km and inclinations close to 90 degrees, which means they fly across the equatorial plane nearly in a right-angle. In order to collect observations, the satellite or the space-based sensors are required to be directed and redirected to target according to a mission plan.

The above requirement of orientability makes it difficult both for satellite making and operating. As for SBSS-1, a "highly－agile 2-axis gimbal" was used and "rapid mission planning, prompt upload and execution" are required [3]. As a result, the launch mass of the satellite is more than 1000kg.

And until now, there are still no space-based sensors used, at least as a primary mission, to support a LEO Space Objects (SOs) catalogue. This paper intends to design a space-based surveillance draft which can:

- Detect and collect observations of LEO objects to support its catalog and maintenance.

- Using fixed sensors to fulfill the above mission without special pointing operation (which means without mission planning).
- Be installed on a normal-commercial small satellite with a platform/bus less than 300kg, if possible.

2. REQUIREMENTS AND CONSTRAINS

2.1 Requirements

The meaning of “Detect and collect measurements of LEO objects to support its catalog and maintenance” includes mainly the following 4 parts:
- Detectability: the capability of forming a capture area to ensure the detection and collection of observations of LEO objects during a certain time period
- Determinability: the capability of determining the orbital parameters using the observations collected, especially the initial orbit determination based on the observations within the FOV of a single sensor
- Usability: the capability of using the determined orbital parameters to support the major application of a Space Object Surveillance System, which mainly depends on the precision of orbit prediction
- Repeatability: the capability of revisiting each SO, especially with the longest time interval, which decides the updating frequency of the catalog orbit.

Then, in order to fulfill the mission of “Detect and collect measurements of LEO objects to support its catalog and maintenance”, the satellite should be able to:
- Detect SOs independently (without any guiding data)
- Collect enough observations to create good enough initial orbital elements, which can support a high-efficiency data-target correlation
- Provide plenty of observations, well-proportioned for each SO per day, to support orbit improvement
- Achieve stable revisit rates for each SO to improve the detection timeliness, and support periodically updating the catalog orbit elements
- Satisfy most of the basic usage of Space Object Surveillance System, such as making a mission plan, calculating guiding data for sensors, and finding a satellite maneuver.

2.2 Constrains

Besides the constrains declared before, it should also meet the following items:
- Detect most of the LEO objects greater than a certain size
- Easy to operate and get precise ephemeris
- Easy to manufacture, launch and TT&C
- Fly in a safe space environment.

Here the space environment refers mainly to the Van Allen Radiation Belt [4], which includes:
- The Inner Van Allen Belt: which extends from an altitude of roughly 500km to 5500km, with the highest particle density in the middle, at about 3000km, that are primarily protons
- The Outer Van Allen Belt: which extends from an altitude of roughly 12000km to 22000km, with the highest particle density in the middle, at about 15000km to 20000km, that are primarily electrons.

All satellites should stay out of the Belt mentioned above, especially the equatorial plane, because the particle density is the greatest at the equator, then decreases as the latitude increases. By latitude 50^o or 60^o, north or south, the density in the belt is very low and becomes negligible.

A region between the inner and outer belts, known as the "slot", has a low density of high-energy particles. This region extends from roughly 6000km to 12000km, but can disappear during active solar periods, when the inner and outer belts sometimes overlap.

2.3 LEO Objects Distribution

In this paper, LEO objects are located in Low Earth Orbit between 200km and 2000km altitude. The eccentricity of LEO is less than 0.1, so all LEO objects move in nearly circular orbits. Their distribution in altitude and inclination are the foundation for the design of both the surveillance satellite orbit and the space based visible sensors. The following statistical results are derived from the Satellite Situation Report SSR), which was complied and provided by HQ AFSPC/XOCSUS, U.S.A on March 28, 2011.

Fig. 1 presents the LEO objects distribution according to their altitude of perigee. It shows that:
- The lower margin of LEO objects altitude can be set to 400km, and
- The upper margin of LEO objects altitude can be set to 1500km

Fig. 2 presents the LEO objects distribution according to their orbital inclination. It shows that:
- the lower margin of LEO objects inclination can be set to 60^o (or 74^o), and
- the upper margin of LEO objects 'inclination' (here means the highest latitude of LEO object's ground track) can be set to 83^o for 400km/1500km and 87^o for 700km

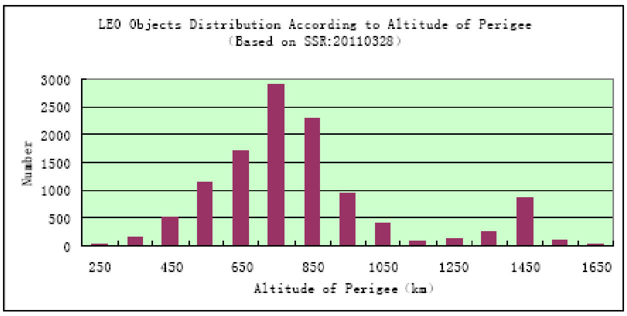


Fig. 1--Histogram of LEO objects according to their altitude of perigee

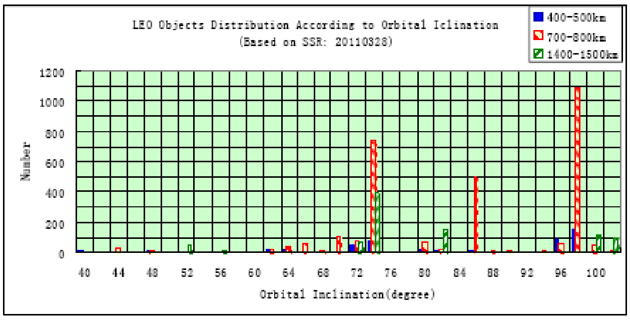


Fig. 2--Histogram of LEO objects according to their orbital inclination

3. OBSERVATIONS ROLE AND ITS OPTIMUM DISTRIBUTION

3.1 Observations Role In Orbit Determination

The observations collected by space-based sensors will be used to determine the space object's orbit. Usually the orbit is determined by the way of Differential Orbit Improvement (DOI). The principle of DOI can be given as:

$$\Delta\vec{r}_i = \frac{\partial\vec{r}_i}{\partial\sigma_i}\frac{\partial\sigma_i}{\partial\sigma_0}\Delta\sigma_0 = A_i\Delta\sigma_0 \tag{1}$$

where:

σ_i, σ_0: Kepler's Orbital Elements set（$a, e, i, \Omega, \omega, M$）at time t_i and epoch t_0

$\vec{r_i}$: Satellite's position vector at time t_i (here $\vec{r_i}$ stands for observations)

The matrix of $C = A^T A$ reflects the role of observations to orbit elements precision. The simplest formulation (two-body, circular orbit) of its diagonal members are:

$$
\begin{aligned}
&C_{11} \approx \sum\left[1+\left(\frac{3}{2}ndt_i\right)^2\right], && C_{22} \approx a^2\sum\left(1+3\sin^2 E_i\right) \\
&C_{33} \approx a^2\sum\sin^2 u_i, && C_{44} \approx a^2\sum\left(1-\sin^2 i\sin^2 u_i\right) \\
&C_{55} \approx a^2\sum i, && C_{66} \approx a^2\sum i
\end{aligned}
\tag{2}
$$

where n is the mean motion and $u = \omega + f$.

The above formulation indicates that:

- Observations with longer dt_i make C_{11} greater. The precision of semi-major axis a will benefit from it.
- Observations at $u_i = \pi/2$, $3\pi/2$ make C_{33} greatest. The precision of orbit inclination i will benefit from it.
- Observations at $u_i = 0, \pi$ make C_{44} greatest. The precision of the right ascension of the ascending node Ω will benefit from it.

And observations at $u_i = 0, \pi/2, \pi, 3\pi/2$ will also reduce the correlation between i and Ω because:

$$
C_{34} \approx -\frac{a^2 \sin i}{2}\sum\sin 2u_i
\tag{4}
$$

3.2 Optimum Observations Distribution

From the view of space, $u_i = 0/\pi$ implies the area at latitude of $\varphi = 0$ (the equatorial plane). And $u_i = \pi/2$, $3\pi/2$ implies that:

- $\varphi = \pm i$ (for $i \le \pi/2$)
- $\varphi = \pm(i - \pi/2)$ (for $i \ge \pi/2$)

So the priority of detection should be given to the areas:

- close to $\varphi = \pm i$, $\varphi = \pm(i - \pi/2)$
- close to equatorial plane

Apparently, the four areas are symmetrically distributed. Maybe for near circular LEO, they are equivalent to any four areas well-proportioned in the orbit.

4. ORBITAL PLANE AND ORBITAL ALTITUDE

4.1 Orbital Plane

Since near circular Low Earth Orbit is symmetrical about the equatorial plane, then a satellite with orbital inclination near zero can detect the above a priori area with fixed sensors at the same time (see Fig.3), so the equatorial plane is selected as the surveillance satellite's orbital plane.

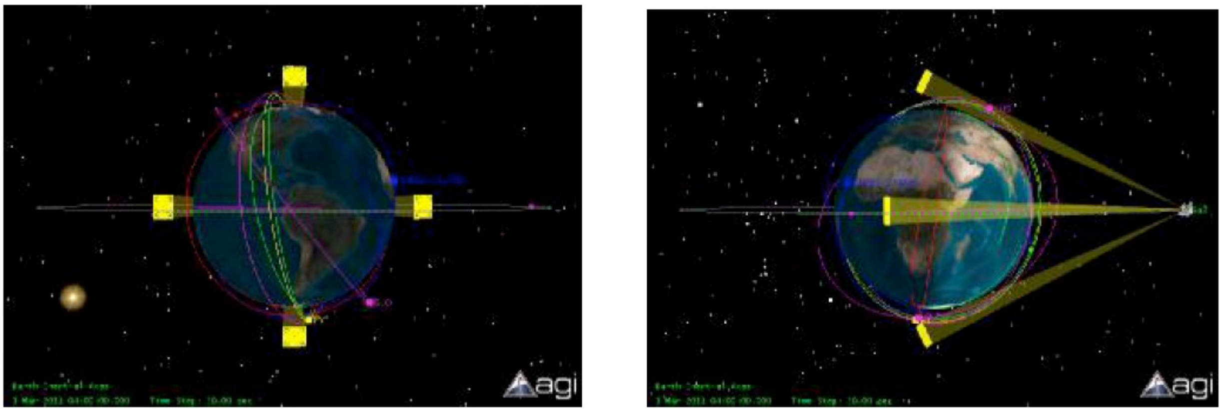


Fig. 3 Equatorial plane and surveying area

4.2 Orbital Eccentricity

Here a near circular orbit with $e \leq 0.01$ is selected as the orbital eccentricity because:
- It can provide a surveying geometry with high regularity
- It is more easy to choose the altitude avoiding the Van Allen Belt of radiation

Although a HEO with apogee located in the line of Sun-Earth may create more time for detection, but it is difficult to

make a balance between:
- Keeping apogee in the line because of the secular changes caused by J2 of Earth Gravity.
- Avoiding passing through the Van Allan Belt of radiation.

4.3 Orbital Altitude

The orbital altitude is determined by the following factors:
- Detect LEO objects with sky as its background
- Lies in the "slot" of Van Allen Radiation Belt

Fig. 4 shows the way for determining the orbital altitude. It uses the minimum altitude and maximum latitude to calculate the angle α, then using the fixed α to calculate the altitude at a different latitude to find if it is greater than zero, which can ensure "detect LEO objects with sky as its background".

Fig .5 is the result for altitude 400km and maximum latitude 83^{o}. It indicates that, when the orbital altitude of the platform is about 8000km, the minimum altitude at any latitude less than 83^{o} is greater than 15km. But in order to avoid the disadvantage of the atmosphere and stay in the middle of the "slot" of Van Allen Radiation Belt, 9000km is chosen to be the orbital altitude.

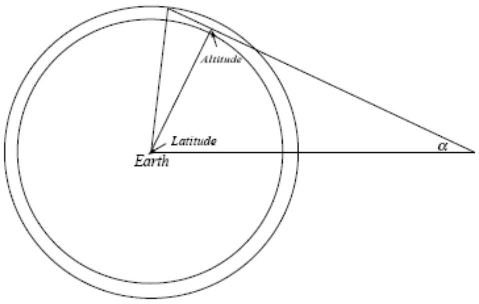


Fig. 4 The way to determine the orbital altitude

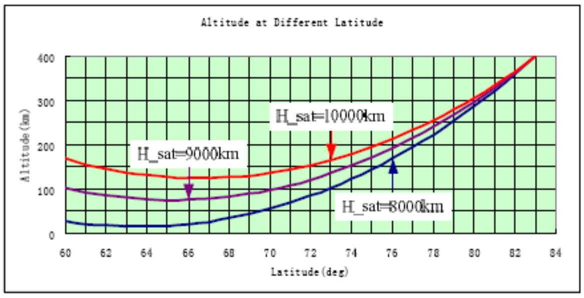


Fig. 5 Altitude at different latitude

4.4 Sensor's Field of View

When the orbital altitude is set to 9000km, then:

- For the lower margin of altitude 400km and latitude 83^o, the value of angle α is 24.812^o, and
- For the upper margin of altitude 1500km and latitude 83^o, the value of angle α is 28.473^o

So the difference between the two α is about 3.661^o. Then considering redundancy, the sensor's Field Of View (FOV) can be set to $4.5^o \times 4.5^o$.

5. SIMULATION AND ITS RESULTS

5.1 Parameters Used in the Simulation

The simulation is aimed to find out the effect of the designed surveillance satellite with 4 visible sensors. It uses STK (Satellite Tool Kit) to calculate the number of accesses and its mean duration for each sensor. Then it makes a statistic to find out their distribution and characteristics. In the simulation, the Kepler's orbital elements of the surveillance satellite are as follows:

$$a = 15378.137\text{km},\ e = 0.0,\ i = 0.0^o,\ \Omega = \omega = M = 0.0^o$$

The satellite will be equipped with 4 visible sensors with FOV of $4.5^o \times 4.5^o$ each. The 4 sensors will point to the North, South, East, West separately (hereafter they will be referred to as Sensor_N, Sensor_S, Sensor_E, Sensor_W). The direction of the center of FOV is 27.05^o, and then the FOV is from 24.8^o to 29.3^o. The four sensors' Euler angles in STK are as follows:

- Sensor_ N: Euler A= 45^o, Euler B=27.05^o, Euler C=0^o
- Sensor _S: Euler A=-135^o, Euler B=27.05^o, Euler C=-180^o
- Sensor_ E: Euler A=135^o, Euler B=27.05^o, Euler C=90^o
- Sensor _W: Euler A=-45^o, Euler B=27.05^o, Euler C=-90^o

Seven LEO objects are selected as samples. Their altitudes range from 500km to 1500km, and inclinations from 52^o to 98^o. The summary information and orbit parameters used are presented in Table 1.

Table 1. Summary information and orbit parameters of the selected LEO objects

CATALOG#	Name	Inclination (°)	Altitude of Perigee (km)	Altitude of Apogee (km)	Two Line Elements
33321	HJ-1B	97.9	613	675	catalog_21_2011_01_10_am.txt
32958	FENGYUN-3A	98.7	826	827	
27550	JB-3 B	97.1	484	494	
35635	COSMOS 2454	83.0	916	946	
26998	TIMED	74.1	615	617	
25693	UOSAT 12	64.6	603	664	
25677	GLOBALSTAR M019	52.0	1522	1525	

The conditions for optical detection are object lighted and the angle of Sun-LEO_satellite-Surveillance _satellite less than 90°. The time span of the simulation is 1 year (from 1 March, 2010 to 1 March, 2011). The valid accesses are those whose duration is longer than 60 seconds.

5.2 Results of Simulation

Fig. 6 and Table 2 present the number of accesses longer than 60 seconds to each LEO object and its mean duration. The results show that:
- The mean accesses per day are more than 6 except for GLOBALSTAR
- The mean duration is about 3 minutes

but:
- The total number of accesses for each object differs greatly
- The total number of accesses for each sensor differs greatly

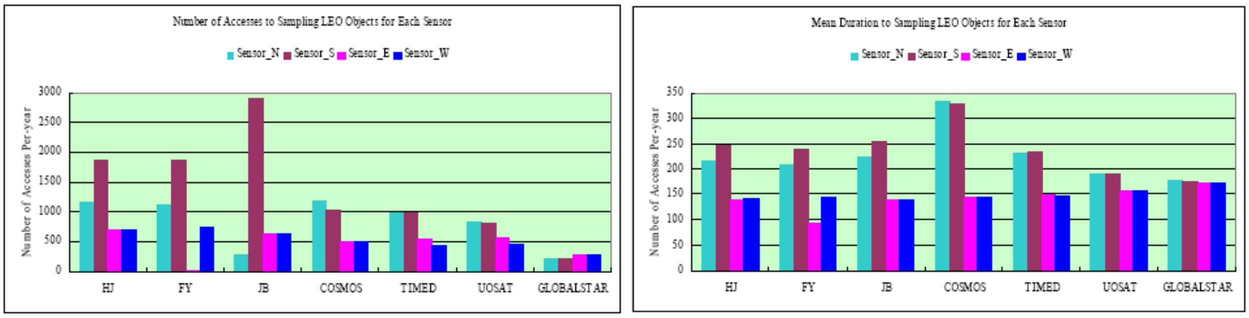


Fig. 6 Number of accesses longer than 60s and its mean duration for each sensor

Table 2. Total Number of accesses for each LEO objects

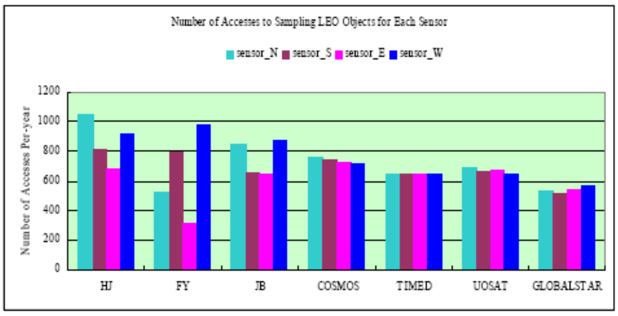
Name	HJ-1B	FENGYUN-3A	JB-3 B	COSMOS 2454	TIMED	UOSAT 12	GLOBALSTAR M019
Total Accesses	4466	3722	4460	3201	2934	2638	962
Mean Accesses/day	12.2	10.2	12.2	8.7	8.0	7.2	2.6
Mean duration(sec)	199	204	201	273	204	177	175

5.3 Improvement Upon the Above Draft

In order to reduce the difference among different sensors/objects, the following simulation will adjust the sensors pointing direction to the middle latitude, pointing to North-East, North-West, South-East and South-West separately (change Euler A =45°/-135°/135°/-45° and keep the others the same). We can imagine that the total accesses will reduce for those objects with high inclination. Fig. 7 and Table 3 present the corresponding results caused by only this change.

The result shows that:
- The mean accesses per day are more than 5 for all sampling objects
- The mean duration is about 2.5 minutes

but:
- The total number of accesses for each object differs gently
- The total number of accesses for each sensor differs gently



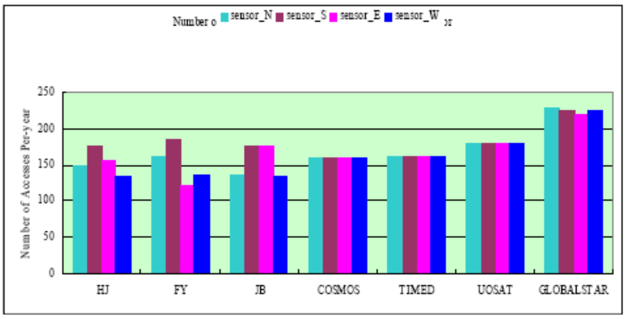


Fig.7 Number of accesses longer than 60s and its mean duration for each sensor

Table 3. Total Number of accesses for each LEO object

Name	HJ-1B	FENGYUN-3A	JB-3 B	COSMOS 2454	TIMED	UOSAT 12	GLOBALSTAR M019
Total Accesses	3447	2607	3017	2931	2576	2655	2135
Mean Accesses/day	9.4	7.1	8.2	8.0	7.0	7.2	5.8
Mean duration(sec)	152	154	152	158	161	178	224

6. CONCLUSIONS AND COMMENTS

From the above analysis, we can see that a satellite:
- Moves in a circular equatorial orbit with altitude of about 9000km
- With 4 fixed visible sensors, each with a FOV of about $4.5^{o} \times 4.5^{o}$.

can achieve a good detectability, determinability, usability, and repeatability in LEO surveillance. It can be competent for supporting LEO objects catalog and maintenance, especially for those with large "size" .

The most serious disadvantage of this draft arises from the long distance between the surveillance satellite and LEO object. It causes the result such as:
- Difficult to detect small debris, and
- Much larger position error at the same angular error.

After all, this is just a concept. Further study on:
- Data-target correlation
- Orbit determination
- Size of SOs
- Diameter of telescope
- CCD specification
- On-board data processing

should be done. And it can only be realized when on-board data processing is possible.

References

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