Large FOV Mobile E-O Telescope for Searching and Tracking Low-orbit Micro-satellites and Space Debris

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Abstract: With the fast increment of space activities, more and more small satellites and debris appeared in low orbits. As such low orbit objects have smaller effective reflective areas and high orbiting speed, it is a big challenge to the existing techniques of ground-based detecting and tracking. This paper analyses the current developing status of detecting and tracking techniques for small objects in low orbit in foreign countries. To meet the detecting requirement in low orbits, an automotive truck-based and large field of view telescope concept designed for micro satellite and small debris searching and detection is proposed. The analysis results demonstrate that the telescope has the capability to search 13.5 magnitude objects (equivalent to 5cm objects in diameter) at 300km altitude orbits, and it can satisfy the practical requirement for searching and tracking micro satellite and small debris in low Earth orbits.

Key words: low-orbit; space debris; small satellite; mobile; searching telescope.

1 Introduction

On April 28, 2008 and September 23, 2009, India launched ten and seven satellites, respectively, using a rocket. In addition to two large satellites with the weight of 690kg and 960kg, the other 15 are all 1~16kg foreign small satellites, and the smallest is only 1kg. On August 30, 2009 and June 11, 2010, South Korea tried to launch a light rocket, its payload is their own small satellites developed by themselves. Prior to that, Iran, North Korea, and other countries have launched rockets, trying to put their own small satellites into Earth orbit. This shows that many countries in the world are actively developing micro-satellites. Some European Universities and research institutes recommend “3*30” micro-satellite technology, that is the micro-satellite with 30cm in size, 30kg in weight, and 30W in power. These micro-satellite are orbiting at a height of 300~700km, with a small object size and high speed. With the increment of these micro-satellites, which are low in cost, simple in function, and launched for emergency, there is a new challenge to the technique on how to efficiently find and recognize these low-orbit micro-satellites, and catalog them[1].

In addition, with the rapid increment of national space launch activities and the occurrence of satellite disaggregation and collision, there are a huge number of small space debris in low Earth orbit (LEO). Debris larger than a centimeter can severely damage a space satellite, especially the manned space experiment station. So, there is an urgent requirement for the detection and tracking of small space debris (1~30cm) in LEO.

At present, the main instruments for ground-based space object detection and tracking are radar and E-O telescopes. As radar is an active detective tool, its detection ability is inversely proportional to the 4th power of the distance, while the detection ability of an E-O system is inversely proportional to the square of the distance. Radar can detect LEO objects with the size of 30cm, while for the object with the size of 1~30cm, a ground-based, large diameter telescope with a wide field of view is a good choice.

The U.S. space surveillance system uses ground-based radar to detect LEO objects with a size larger than 10cm, and uses an E-O system to detect

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middle and high orbital objects. For a LEO object with a size of 1~10cm, the U.S. DOD and NASA have proposed detection and tracking requirements, and they use a ground-based, large diameter, searching telescope with a wide field of view.

Among them, U.S. NASA and AFRL developed a 1.25m MCAT (Meter Class Autonomous Telescope) searching telescope[2], with the purpose of detecting and tracking LEO debris with a size of 1~10cm. DARPA is developing a 3.5m-diameter, 3.5°-FOV, ground-based searching telescope, to detect LEO faint objects, and even use a curved surface CCD[3]. The U.S. Air Force used a 3m rotating mercury, searching telescope to detect LEO objects[4]. In addition, the U.S. astronomical organization is now developing 2m~8m ground-based telescopes[4] to detect small LEO objects, such as the 8.4m-diameter, 3°-FOV LLST telescope, and the four 1.8m-diameter, 3°-FOV PANSTARRS telescope array.

2 Large FOV mobile E-O telescope for searching and tracking low-orbit micro-satellites and space debris

In order to search and detect micro-satellites to meet the needs of manned space early warnings, and the detection of space emergencies such as a LEO object collision, we propose the project of a large FOV mobile E-O telescope for searching and tracking low-orbit micro-satellites and space debris.

2.1 General considerations

A mobile large FOV E-O telescope should increase the FOV while guaranteeing the best image quality, improving the searching capability, and increasing the detection capability. It tries to reduce the weight of the equipment in order to meet the requirement for a motor vehicle. It can automatically identify the object, and have the ability of remote control.

We adopt the form of a main focus optical path, and the effective aperture is 1.2m. The primary mirror uses a dual surface, and the corrective mirror uses an aspherical design, and 80% of the energy concentration in a 2.8° FOV is within 24μm. To meet the requirements of the mobile vehicle carriage, the primary mirror uses lightweight SIC materials, and the 1.2m SIC mirror weighs only 100kg. To reduce the weight of the whole instrument, the system uses a lightweight truss frame altazimuth tracking rack. We use the design ideas of vehicle integration, and the rotating part of the telescope weighs not exceeding 2.5 tons. We use a Houghs transform to improve the system detection capability and the automatic processing of data.

2.2 Optical system

To achieve the large FOV design requirements, and get high quality optical imaging, the optical system uses a main focus form. The primary mirror uses a hyperboloid, with a diameter D1 of 1230mm; the corrective mirror uses four lenses, in which two of them are quadric aspheric surfaces as shown in Figure 1. With the temperature of 20°, the RMS spot diffusion radius at a 2.8° FOV is less than 12μm, the spot diagram is shown in Figure 2. For the system modulation transfer function (MTF), the epaxial value is 0.71(@21lp/mm), while the average MTF at a 2.8° FOV is 0.61(@2l1p/mm)(where the meridian direction is 0.56, and the sagittal direction is 0.68) as shown in Figure 3. The system energy concentration is shown in Figure 4, 80% of the energy is concentrated in a circle of the radius of 10.6μm, and 80% of the energy within a 2.8° FOV is concentrated in a circle of the radius of 12.2μm.

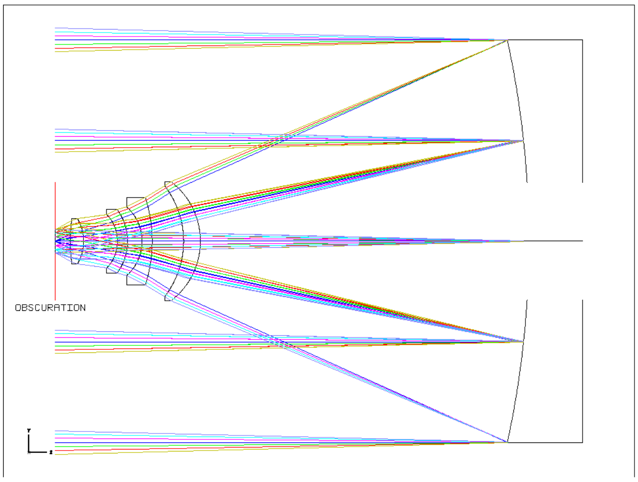

Fig.1 optic system diagram

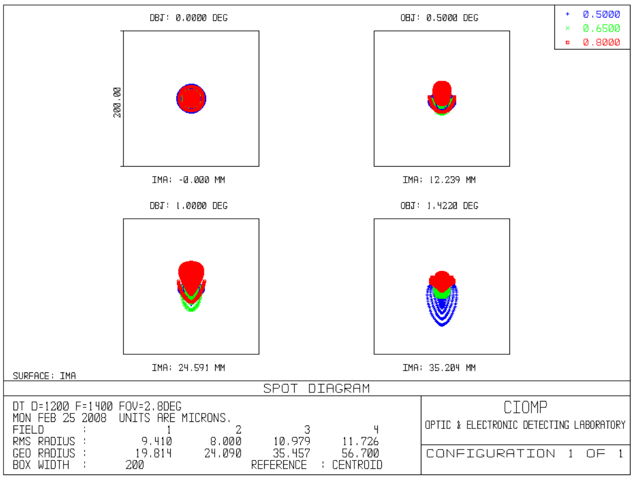

Fig.2 spot diagram

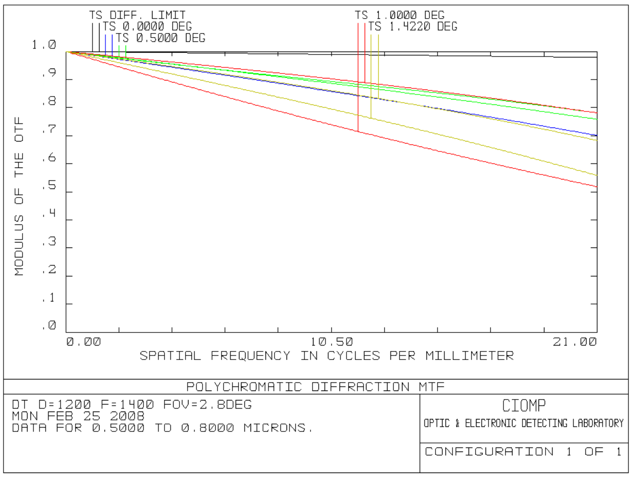

Fig.3 modulation transfer function (MTF)

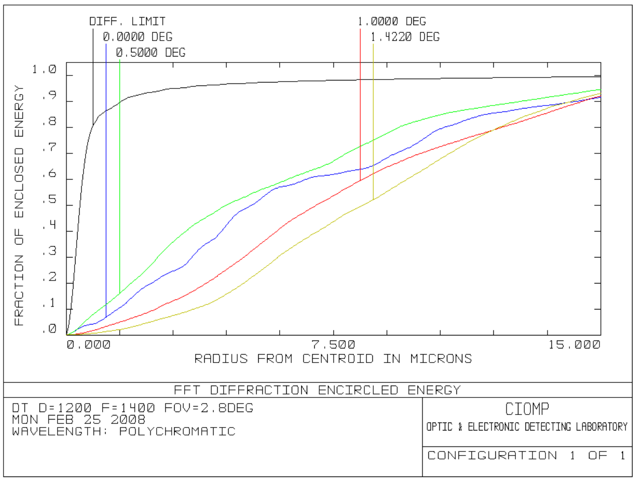

Fig.4 encircled energy

In summary, the optical system design for medium and high orbit space object detection satisfies the predefined requirements, and the design parameters are as follows:

Pupil diameter: 1200 mm
Focal ratio: F = 1.17
Focal length: f = 1400 mm
Detection FOV: FOV = 2.8 ° (diagonal)
Focal Plane Size: 69.54 mm
MTF: 0.62 (@ 21lp/mm)
RMS spot diffusion radius: <12 μm
80% of the energy concentration radius: <12.2 μm
Optical tube length: 1412.68 mm
Back working distance: 43.89 mm

2.3 Optical primary mirror

The materials of the optical primary mirror adopt the lightweight RB-SIC developed by Changchun Institute of Optics, Fine mechanics, and Physics. Compared with other optical materials, the SIC material is more stiff, and the lightweight design with the middle of the sandwich can increase the light weight rate up to 70%. The 1.2m SIC primary mirror is only 100kg, and it greatly reduces the weight of the primary mirror supporting structure, thereby reducing the whole weight of the telescope.

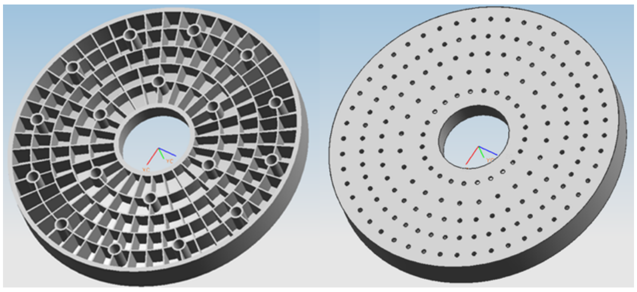

Fig.5 1.2m SiC light weighted primary mirror

2.4 Tracking rack and vehicle

As shown in Figure 6, in order to achieve the telescope's mobile capability, the telescope's tracking rack uses a truss structure. The design of the integrated telescope base and vehicle further reduces the weight, reduces the height of the telescope, and improves the trafficability. The whole instrument, by light weight design, weighs not more than 4 tons.

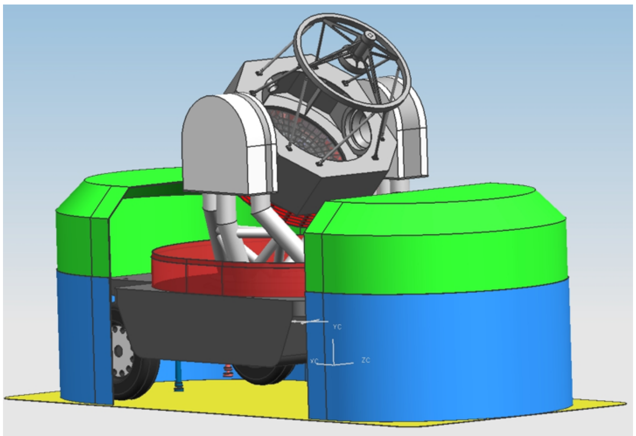

Fig.6 Telescope and vehicle

2.5 Image processing

For low orbit moving object detection, the telescope can be in a quiescent state, waiting for objects across the field of view. As a fast object may appear as a straight line in the field of view, we can use the Hough transform to identify the object. Hough transform is a classical line detection method proposed by Paul Hough, and it achieves the mapping from image space to parameter space. Shown in Figure 7, the Hough transform can quickly identify the object under the condition of 2:1 SNR. The conclusion of reference [6] is that under the condition of 1:1 SNR, the probability of strip satellite image recognition can be up to 50%.

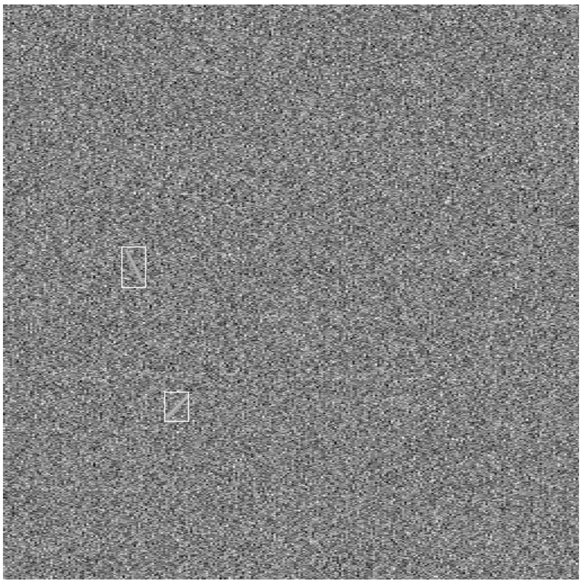

Fig.7 target detection at 2:1 SNR

2.6 Operation mode

The telescope has the operation modes of gaze, tracking, orbit surface interception, and so on. A low-orbit object may use gaze mode. In case of finding the object, it collects data on some points, and guides the acquisition and tracking using a circular orbit forecasting method, and then tracks to obtain the object data on a certain arc. For an inaccurate forecast, adjustment can be performed by the mode of searching along the orbit.

2.7 Detection capability analysis[3]

For a given CCD image of any one pixel, the total detection signal strength is given by the following formula:

$$NetSignal = Sky_S + D_C + S \ , \tag{1}$$

where Sky_S is the photons signal intensity generated by the sky background; D_C is the dark current signal strength; and S is the signal strength of the observing objects. Dark current and sky can produce an unwanted background signal. Combining these factors, the noise can be calculated by the following formula

$$Noise = \sqrt{Rn^2 + Sky_S + D_C + S} \ , \tag{2}$$

where Rn is readout noise. And SNR can be given by the following formula

$$SNR = \frac{S}{\sqrt{Rn^2 + Sky_S + D_C + S}} \ , \tag{3}$$

Finally, by solving the above equation, we can get the relation equation between the object signal strength and the other factors:

$$S = \frac{SNR^2 + SNR\sqrt{SNR^2 + 4(Rn^2 + D_C + Sky_S)}}{2} \ , \tag{4}$$

Then, by associating the relation between the required detection signal intensity under the required SNR and object light characteristics, we can determine the system detection threshold, when the detection integration time is given.

According to the above formula and telescope and detector parameters in Table 1, we calculate the objects detection capability on different low orbits for our 1.2m large FOV telescope.

300km: better than 13.5 magnitude;
500km: better than 14.2 magnitude;
1000km: better than 15.1 magnitude;

Under the condition of 5:1 SNR and 1s integration time, the detection capability is not less than 18 magnitude.

Table 1 Parameters of large FOV mobile optoelectronic telescope for searching and tracking

System parameters	value	System parameters	value
CCD	2Kx2K	System obstruct	10％
Pixel size	24μm	telescope form	main focus
CCD readout noise	$15e^{-1}$	spectral range	400nm~700nm
Dark current	can be ignored	optical coating	standard aluminum
Quantum efficiency	80％	SNR	2：1
CCD quantum efficiency curve	shown in Figure 12	sky brightness	21 mag / arcsec 2
F number	1.2	observations angle	zenith
telescope diameter	1.2m		

3 Conclusion

This paper proposes the use of a large FOV optical design, lightweight primary mirror material, and compact structure design, to meet the requirements of an automotive truck-based large FOV searching telescope. For objects on an orbit of 300km height, the detection capability can reach 13.5 magnitude. This is equivalent to the detection capability of 5cm-diameter object [5], and it can meet the practical requirements for searching and tracking low-orbit micro-satellites and small debris. This mobile large FOV searching telescope can be observed across the whole country for daily observations. When there is an unexpected event, this telescope can be used as emergency equipment to reach the appropriate place in a short time, and perform its task.

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