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Acquisition and analysis of the characteristic of the spectrum from high area-to-mass ratio LEO space debris

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Abstract

An increasing harm to active satellites in orbit and manned space activities has been caused by high area-to-mass ratio space debris. Due to the difficulties in recognition and cataloging of high area-to-mass space debris, it is proposed a method based on spectral observations. This method corrects atmospheric extinction and the impact of telescope optical system on the basis of image preprocessing, extracts space debris reflectance spectroscopy, then compares with the spectral curves of sample materials and recognizes surface materials of high area-to-mass ratio space debris. Results of spectroscopic observations under good conditions demonstrate that it will be fairly accurate if high area-to-mass ratio space debris is composed of a single material, such as aluminum and white paint, the correlation coefficients of aluminum and white paint are approximately 0.9.

INTRODUCTION

The distribution of space debris is quite uneven and mostly concentrated in the area of human space activities. Most of them are in low-Earth orbit (LEO, orbital altitude less than 2000km)[1]. Orbital spacecraft once hit, space debris will damage the parts, or even destroy the spacecraft's structure, make it loss of working ability. Hence, it is a huge challenge for the development of the manned space activities. For the purpose of future space resources sustainable development and the safety of the manned space activities, it is necessary to monitor the orbital space debris, at the meantime establishing a comprehensive database on space debris and collision warning system.

The long-term optical surveys have identified a class of space debris have high area-to-mass ratio (HAMR), which range from 0.1 to 20 m^2/kg and higher[2]. This debris is mostly covered with multi-layer insulation, solar panels, white paint or aluminum, and susceptible to the solar radiation pressure, thermal emission, solar-lunar gravitation and other external factors effect, making HAMR space debris eccentricity, inclination and orbit radius produce strong variations over relatively short periods of time[3]. As HAMR space debris is prone to drifting, it is increasing the collision probability with orbital spacecraft, so the research of these debris is a great significance. Chao and Valk et al. presented some detailed results concerning the short- and long-term evolution of high-to-mass ratios space debris subjected to direct solar radiation pressure. T.Schildknecht mainly focused his attention on the long-term variation of both the eccentricity and the inclination. Moreover, some studies concerning the effects of the Earth's shadowing effects on the motion of such space debris were given in Lemaitre[4]. However, due to HAMR space debris unknown material structure and attitude motivation, it is currently still difficult to catalog and predict. This paper presents a new approach that use low dispersion spectroscopic observations to obtain LEO HAMR space debris continuous spectrum curve, analyze its spectral curve characteristic, and identify HAMR space debris surface material, then by distinguishing the differences of surface materials to identify space debris.

THE PRINCIPLE OF SPECTRAL OBSERVATIONS

In general, almost all the space debris itself does not light and its reflected light mainly comes from the sun. Although different types of space debris, its shape, attitude, surface materials are not the same, the reflected light is composed of coherent scattering component in specular reflection and incoherent scattering or called diffuse component. Paper[5] confirmed, space debris of different types of surface materials have various spectral reflectance. Therefore, by low dispersion spectroscopic observation of space debris, obtain space debris reflectance spectrum, compare with the sample materials, analyze their spectral characteristics, and identify debris surface material composition. Figure 1 shows the geometry of HAMR space debris.

Observations obtained reflectance spectrum of HAMR space debris is a result of the interactions between sunlight and surface materials. Considering the sun-debris-telescope relative motion, the phase angle changes over time, hence there are differences in debris reflectance spectrum of different observed time. The spectral intensity (or spectral radiance), L, of sunlight reflected from debris surface materials has units of W $ster^{-1}\,\mu m^{-1}$. It is a function of both time and wavelength, and can be expressed as follows[6]:

$$L(t,\lambda) = f_{sun}(t,\lambda)\{\textstyle\sum_{j,k} A_{j,k}\langle n_{j,k}\cdot o\rangle\langle n_{j,k}\cdot s\rangle \\ \rho_j(\lambda,n_k,o,s)\varphi_{j,k}(o,s)\} \quad (1)$$

Where $f_{sun}(t, \lambda)$ denotes the illuminating solar irradiance, the k^{th} facet of the j^{th} component is characterized by its surface area $A_{j,k}$, and normal unit vector, $n_{j,k}$, o and s denote satellite-to-observer and satellite-to-Sun unit vectors, and the function $\rho_j(\lambda, n_k, o, s)$ denotes the surface BRDF for satellite component j, which describes the spatial distribution of space debris reflectance spectrum, quantifies the irradiance of reflected sunlight in all directions. Angular brackets denote the non-negative operator, and the non-negative dot products ensure that contributions arise only from facets showing an illuminated side to the observer. $\varphi_{j,k}(o, s)$ denotes the fraction of each facet that is not shadowed nor obscured by other satellite surfaces. For convex bodies $\varphi_{j,k}(o, s) = 1$ for all facets. For non-convex bodies this function generally varies with time.

Based on the above principle, estimate surface material compositions with the measured reflectance spectrum of HAMR space debris by inversion method, requiring the following as input[7]:

1. A set of multi-band measurements of space debris reflectance spectrum, including large amounts of information of surface materials.
2. Geometric model of space debris, including each major exterior sub-component capable of reflecting sunlight.
3. The space debris's attitude, specifying the orientation of all of the body's components at the times of each measurement.
4. Common space material BRDF database.

It is an important part of the judgment to speculate the composition and origin of HAMR space debris by analyzing surface material reflectance spectrum. Figure 2 is the measured spectral curves of common space materials, similar to Chaudhary A's experiment results[8]. In Figure 2, different reflectance spectra curve characteristics (peak, slope, narrow-band characteristics and shape) under different bands can be seen clearly. Therefore, through the spectral characteristics, it can realize the identification of HAMR space debris. The determination of the possible materials is still in a preliminary phase. Future steps plan for a better characterization of HAMR space debris from the observed data, including material composition, structure, orbital parameters, etc.

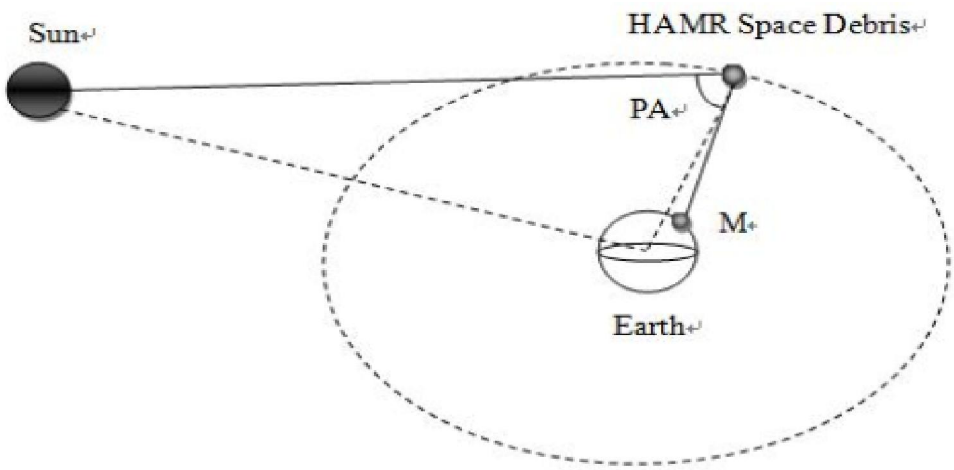

Figure 1 : Geometry of HAMR space debris

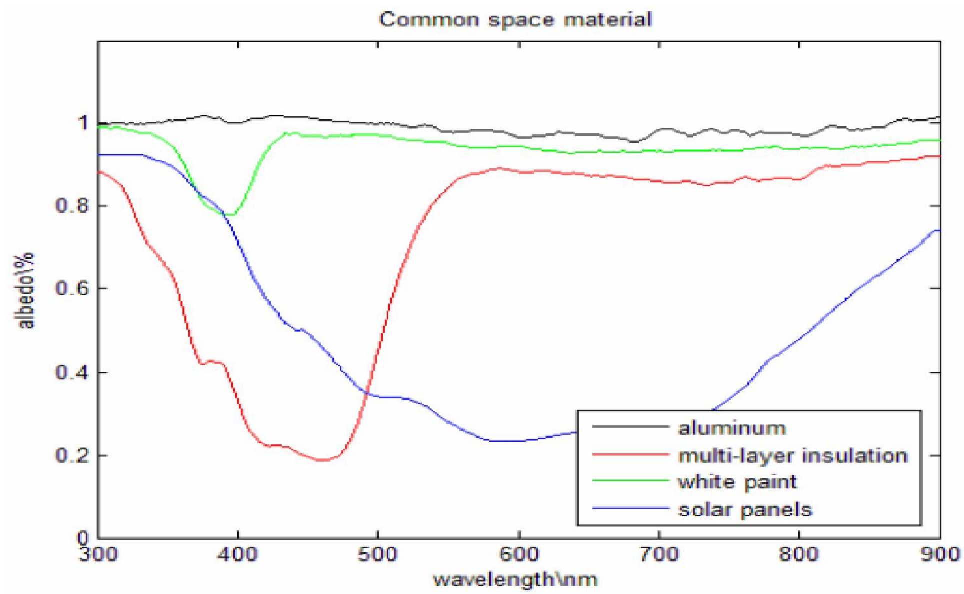

Figure 2 : Common space materials reflectance spectra

SPECTRAL OBSERVATION TECHNOLOGY

In the case of HARM LEO space debris, since the movement is fast, it crosses the field of view in several seconds, at the same time the magnitude of the debris is dark. For this reason, the telescope is operated in satellite tracking mode that the debris is observed by the same position on the image while fixed stars are recorded on the image with streaks of light. It can ensure that photons of the debris fall within a few pixels as far as possible and maximize the observed image signal-to-noise ratio. Meanwhile according to the actual effect of CCD imaging, precisely control the exposure time. Short exposure time may lead to low signal-to-noise ratio, resulting in blurred image, difficult to identify and locate; if exposure time is too long, CCD may receive excessive photons in the unit time, cause the image over-saturation, and also affect the image quality and subsequent calculation[9,10].

Moreover taking into account HAMR space debris reflected light, the ground CCD detector received, under the influence of telescope optical system and atmospheric extinction, spectrum cannot directly reflect the material characteristics. Therefore, the debris image preprocessing is required, including subtracting background, fixing flat-field and dark-field, correcting atmospheric extinction, calibrating wavelength and flux. Eliminate the influence of objective environment on HAMR space debris reflection spectrum and obtain debris real spectral curve.

EXAMPLES OF OBSERVATION

Here select Japanese satellite AJISAI, Chinese Long March series rocket bodies and its debris, three types of HAMR space debris, as research subjects. Figure 3 shows satellite AJISAI (NORAD 16908). AJISAI has the following instrumentation onboard, including 318 mirrors and retroreflector array, and its shape is a sphere. Chinese Long March series rocket bodies shape shown in Figure 4 (Chinese Long March 2-F), and its surface is mainly covered by white paint.

AJISAI (NORAD 16908) satellite reflectance spectrum horizontal axis represents the wavelength, visible wavelength 400-780nm, the vertical axis represents the flux calibration at 550nm after normalized relative flux value. Figure 5 shows two consecutive nights AJISAI spectral curves in the April 20th and 21th, 2013. Spectral curve forms within the visible wavelength are approximate level, while the red and blue bands have obvious falling and rising. The reasons are as follows: 1. since using the ground-based telescope in the observation process, images may be affected by atmospheric turbulence, cloud and other unpredictable factors that

Figure 3 : AJISAI

Figure 4 : The Long March-2F carrier rocket

result in low SNR. 2. The red and blue bands information correction is insufficient in the correction process of the images, reducing the SNR on both ends of the spectrum. Actually AJISAI albedo remains constant over the entire visible band. Because the satellite surface covered a lot of mirrors, its albedo characteristics should be mainly aluminum. Compare the measured spectral curves with the aluminum's in Figure 2, they are rather similar in the 450-730nm (minus ends of the low SNR part, each about 50nm), the correlation coefficients are 0.95 (2013/4/20) and 0.89(2013/4/21). Therefore, it can be speculated that the reflectance spectrum is aluminum.

Figure 6 shows Long March rocket bodies CZ-4 R / B (NORAD 20791) and Figure 7 CZ-4C R / B (NORAD 36835) spectral curve, observation time is April 20th and 21th, 2013. Since rocket body surface material is mainly white paint, the observed reflectance spectrum should be expressed as the characteristic of white paint. In the Figure 6, the albedo of rocket bodies generally remain the same, as shown the spectrum of white paint in Figure 2, the basic spectral characteristic are the same. Just like before, there is a deviation because of the low SNR on both ends. The correlation coefficients of NORAD 20791 between the rocket bodies and white paint (450-730nm) are 0.94(2013/4/20) and 0.88(2013/4/21), The correlation coefficients of NORAD 36417 are 0.94(2013/4/20) and 0.92(2013/4/21). Because the spectra of aluminum and white paint have the similar characteristic, is currently not valid to distinguish the two kinds of materials. The future work will use the wider band to distinguish them, including infrared and ultraviolet. As Figure 2 shown, white paint has an obvious declining characteristic at 300-400nm, if measured, it can accurately differentiate aluminum and white paint.

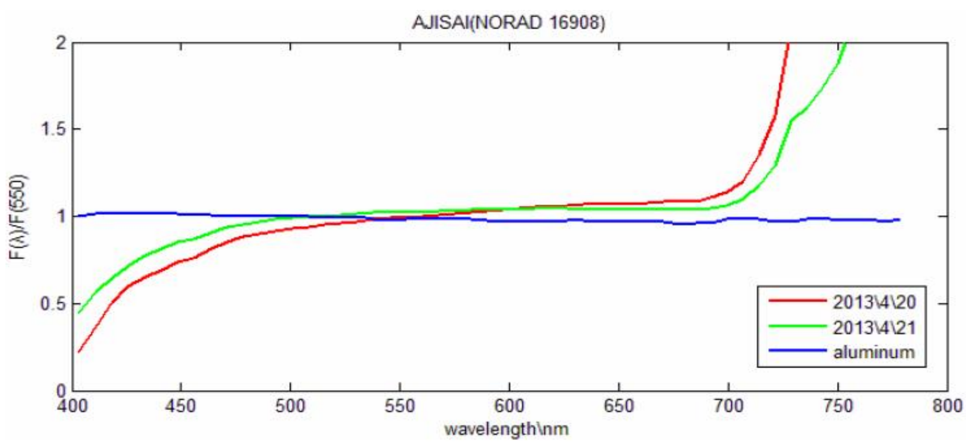

Figure 5 : AJISAI spectra

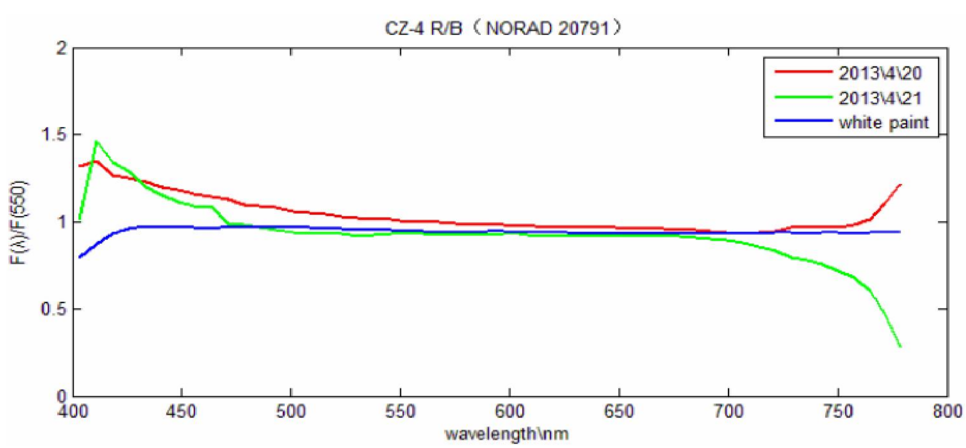

Figure 6 : CZ-4 R/B (NORAD 20791) spectra

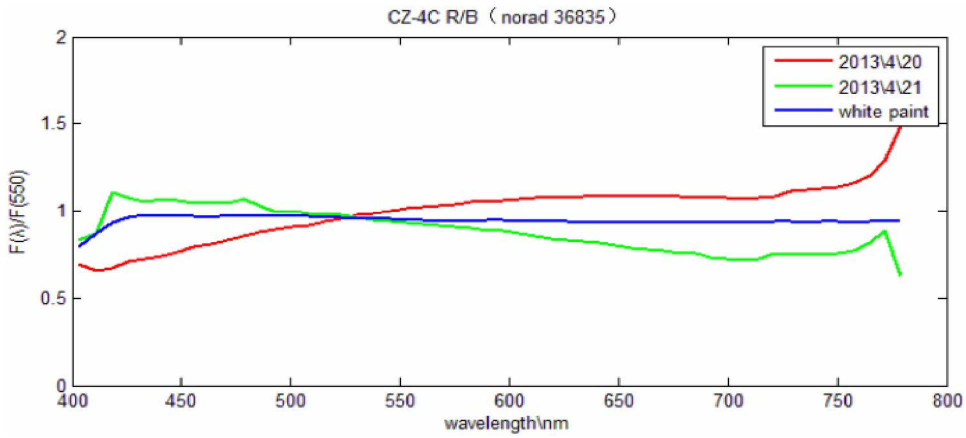

Figure 7 : CZ-4C R/B (NORAD 36835) spectra

Compared to the satellites and rocket bodies, HAMR space debris material composition is relatively complex, moreover, its shape is irregular and attitude is difficult to confirm, therefore, the surface material is more difficult to identify. So for the identification of such debris, often require multiple angle of observation, obtain abundant debris material information, establish database of BRDF and then decide the materials[11]. Figure 8 shows the reflectance spectrum of CZ-4C debris at three nights. Due to debris cross section is varying at different time; there is much diversity in reflectance spectra. 23th spectral curve is horizontal, characterized by white paint or aluminum, can be speculated that the surface material is white paint or aluminum. 20th and 21th spectral curve have multiple forms, maybe the attitude of the debris was changing in the photography process, causing the illumination surface material change. Therefore, accurate analysis requires more priori information, including BRDF data of other common materials and corresponding moment debris attitude, phase angle, etc. Further work need to be done.

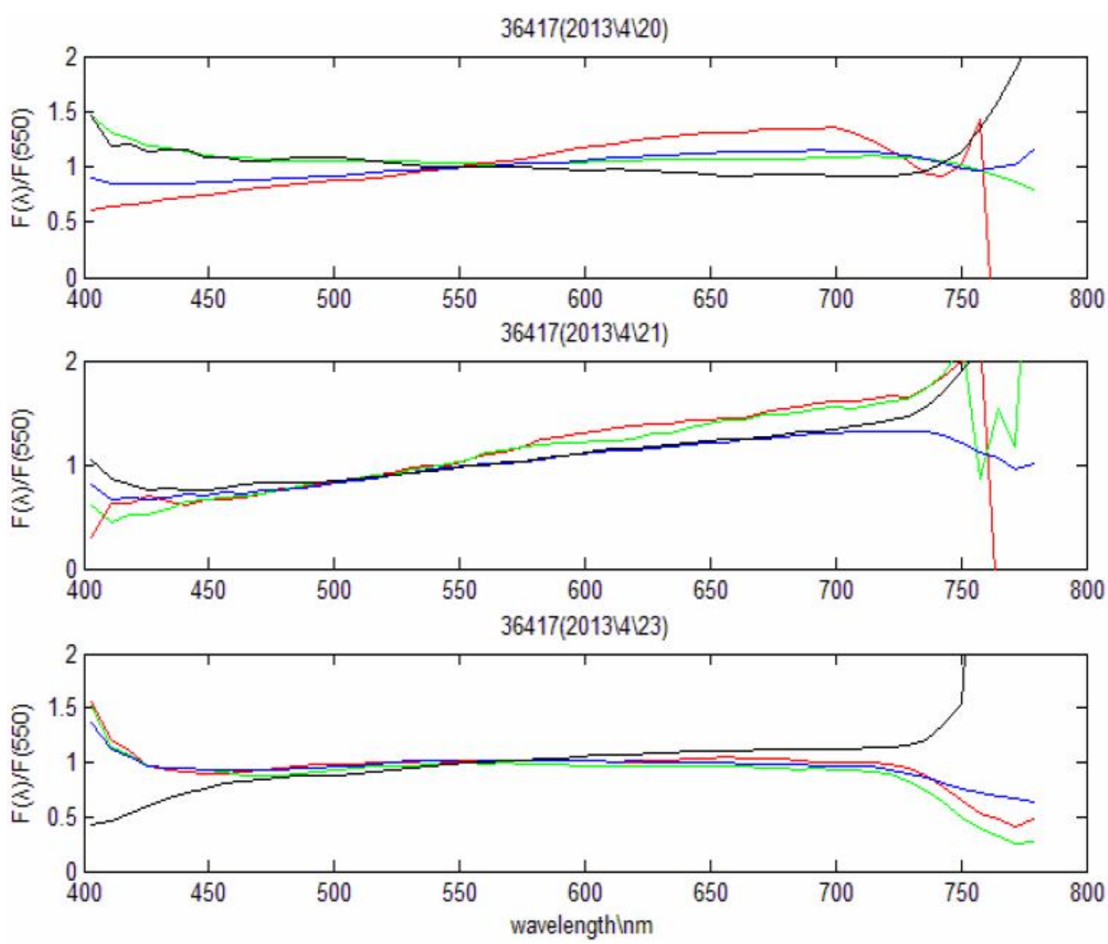

Figure 8 : CZ-4C debris (NORAD 36417) spectra

CONCLUSIONS AND FUTURE WORK

Because of its special physical characteristics, high area-to-mass ratio space debris poses a great threat to orbital satellite and manned space activities. This paper use low dispersion spectral observation technology to analyze three types of HAMR space debris, AJISAI satellite, Chinese Long March series rocket bodies and its debris. Actually measured spectral curve shape and the laboratory measured material samples have good consistency; can achieve identification of HAMR space debris surface material. This method is able to provide a reliable basis on debris cataloging and orbit prediction. At present this method has high identification accuracy on single material HAMR space debris; the correlation coefficient can reach more than 0.9 under good observing conditions. As for multi-materials space debris, analysis requires to combine BRDF model under multiple phase angles. This will be the focus of future work.

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