Design of Light-weight Laser Retro-reflector for Nano-Satellite and Analysis of Laser Ranging

Li Pu[1], Cheng Zhien[1,2], Zhang Haifeng[1], Tang Kai[1], Zhang Zhongping[1], Li Xie[3], Tang Geshi[3]
1.Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai
2.University of Chinese Academy Sciences, Beijing
3.Beijing Aerospace Control Center, Beijing
Email: pulee@shao.ac.cn

Abstract

Nano satellites with the characteristics of light weight, compact, short period of manufacture, low power consumption and the high dense functions have been paid more attentions and have the technical advantages in the field of space scientific experiment platform, satellite communication, optical photogrammetry and atmospheric detection. According to the application requirements of nano-satellites used for atmosphere density detection, the light-weight octahedral laser retro-reflector without any power consumption has been designed with the weight of less than 120g, the effective reflecting area of more than $1cm^2$, the size of Φ96×20mm for performing laser ranging and providing the indispensable supports of high precise orbit measurement for scientific researches and applications. Based on the laser ranging link equation, the technical analysis of nano-satellite laser ranging has also been performed and according with the real measuring results form the ground laser ranging station to serve for orbit determination and atmosphere density detection.

1. Introduction

Nano satellite usually refers to small size, light weight, with the actual use of the function of satellites, which are based on technology of microelectronics, MEMS, micro-optical and other ttechnical development, satellite integrated design and high integration, reflect spacecraft miniaturization trends. With the development of satellite technology and related new technologies, nano-satellite with its light weight, small size, short development cycle, low cost, and function-intensive and so widespread attention at home and abroad, in space science experiment platform, satellite communications, optical photogrammetry, earth observation and measurement, atmospheric exploration, astronomy probe so has technical advantages. Europe and United States and other countries have launched a batch of new technology, nano satellite each year , thus provide opportunities for the timely test of space technology. China's first micro-nano satellites were developed by the National Defense University, "Tiantuo No.1" with the weight of 9.3 kg, was launched on May 10, 2012, whose main task is to carry out spaceborne Automatic Identification System received optical imaging, space environment exploration and other scientific experiments in orbit. Currently Tsinghua University, Zhejiang University, National Defense University, Harbin Institute of Technology, Aerospace Dongfanghong Satellite Company Limited and other units carry out micro-nano satellites, leather satellite development, wireless sensor networks, earth observation, radar and other functional verification and calibration at a relatively low cost of doing research and test new space technologies.

In the atmospheric probe, European Space Agency launched the QB50 Plan and there are 10 Chinese universities participating in the program and the main mission objectives can be described as "demonstration global university team developed 50 cubic satellite network of low-cost launch vehicles, the completion of the atmospheric layer detect fever-class science mission to enhance the ability of low-cost access to space, the atmosphere low thermal layer scientific exploration. China's first nano satellite for atmospheric detection was developed by the Aerospace Ltd. Dongfanghong satellite, with the weighing 15kg, dimensions 392mm × 392mm × 388mm, will be equipped with dual-band multi-mode GNSS receivers, S / X VLBI transmitter, atmospheric density detectors, laser reflectors and other load. The initial orbit height is 530km and working orbit height is 450km and under the effect of atmospheric drag, the height of orbit is gradually degenerated for atmospheric density detection at different heights.

Nano-satellite precision orbit determination is the foundation to achieve its scientific objectives. For LEO satellites, typically using a variety of international satellite GNSS, DORIS, VLBI, SLR and other measuring technology. Because of the size of nano satellite and power constraints, a small chip level GNSS receiver is used as the major way of satellite orbit determination. Taking into account the small GNSS receiver to determine the phase center accuracy is not high, it is difficult to achieve decimeter level orbit determination capability. For this, the satellite is equipped by the non-power laser reflectors for the global precision laser ranging, as an important high-precision orbit determination techniques.

According to the characteristics of nano satellite and the foundation of laser reflector design for low-orbit satellites Shanghai Astronomical Observatory design the compact reflector for a nano satellite to meet the application requirements of light weight and small size and it is applied to the high-precision satellite laser ranging. This article describes the design of the laser reflector, and the performances of SLR for nano satellite are also analyzed.

2. Nano satellite laser reflector design

2.1 Design requirements

With the characteristics of small size, light weight for nano satellites, the requirements of laser reflector structure, weight of cube corner is set forth. The requirements of installation envelope size is (Φ96mm ± 0.2mm) × (20mm ± 0.2mm), the weight requirements of less than 120g. To achieve different height levels of atmospheric density probe, the orbit height is natural decline in the effect of atmospheric drag without the initiative to adjust after the completion of the satellite in orbit testing tasks. It requires the large field of view for laser reflector to maintain good reflection, and compensates for different orbit height of velocity aberration in order to ensure ground stations to receive laser echo.

2.2 Opt-mechanical Design

① Optical Design

a) Single cube corner design

Fused silica glass material is common optical material for current laser reflectors design, which has a good adaptability to the space environment. For nano satellites, consider laser reflector weight and size limits,a single corner reflector with the inscribed circle cutting is used with the aperture of 13.6mm, roof height 10mm.

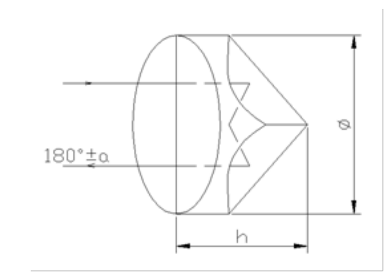

Fig.1 The optical design of single cube corner

b) Corner reflector coating design

From geometrical optics theory, for fused silica corner reflector, with an incidence angle of the light, in the inside corner reflector is reflected in a direction parallel to the incident light emitted from the bottom. For the range of incident angles, consider a corner reflector acceptance angle refers to the angle of light in the non-coated reflector without damage total reflection maximum angle of incidence can be refracted according to the laws of optics and geometric relations:

$$i_c = \sin^{-1}[n\sin(\tan^{-1}(\sqrt{2}) - \sin^{-1}1/n)]$$

Where, n is the refractive index of the optical material cube corner, for fused silica material, refractive index n = 1.455, the acceptance angle is 16.6°. Figure 2 shows the measured cube reflector optical reflectance with the angle of incidence, where the solid line is the incident surface AR-coated, right-angle corner reflector silver film reflector optical reflectance, dashed for the corner reflector incident no AR-coated surface, rectangular optical reflectance when the reflective surface is not coated. It can be seen, for the right angle corner reflector when the reflecting surface is not coated, when the incident angle is greater than 16.6 degree, a sharp decline in their optical reflectivity. For sodium satellite, in its orbit, the laser beam to the incident angle of the corner reflector will appear larger than 16.6 degree. It is indicated that the right angle reflective face of laser reflector should be coated, in order to avoid full reflectance critical angle decline caused problems.

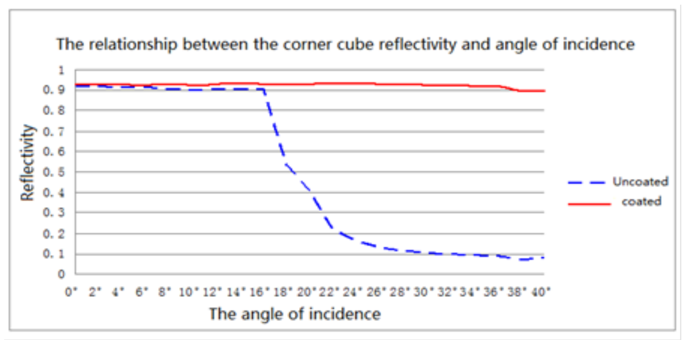

Fig.2 The relation of optical reflectivity to incidence angle for coated and uncoated cube corner

c) Velocity aberration Compensation Design

For nano satellite, the initial orbit height is 530km and working orbit altitude is 450km. Under the effect of atmospheric drag, the final 300km orbit can be reduced and its maximum velocity aberration is about 10.5"-10.8". To ensure the ground station can measure the received echo signal from nano satellite at the different orbital altitude, the rational dihedral offset of cube corner should be designed, so that the far field pattern can meet the demand of velocity aberration compensation. For nano satellite reflector, the offset angle is about 1.5" to change the distribution of far field pattern, shown in Figure 3. As can be seen from the figure, the angular diameter is about 33" with certain intensity and can meet the needs of velocity aberration compensation of nano satellite .

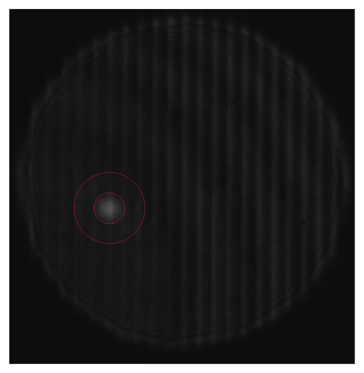

Fig.3 Distribution of Far Field Diffracted Patter for a single cube corner

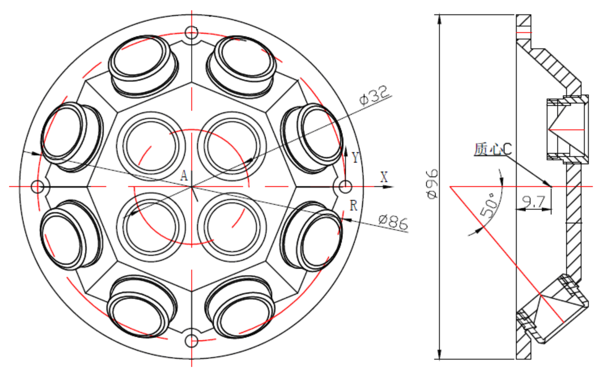

Fig.4 The structure design of laser retro-reflector for nano-satellite

② Mechanical Design

Principle of laser reflector array design is to make the reflector relative to the observed elevation station at 20 degree to 85 degree, it can guarantee effective reflection area. By task analysis for laser reflector and considering the weight, dimensions limits, the number of 12 cube corners with the aperture of 13.6mm is designed consisting of an octagonal table reflector array shown in Figure 4, where 4 corners is installed in the symmetrical octagonal table in the bottom surface, and the remaining eight ones are evenly distributed in eight octagonal table side, whose normal octagonal table with the bottom surface normals angle was 50 degree angle. The diameter of installed base for laser reflector arrays is 96mm, height 20mm, chassis weight about 55g and the array structure centroid distance between the bottom mounting surface distance is 9.7mm.

Single corner reflector mounted in a separate circular aluminum mirror base, with a protective circle around, in order to ensure the stability of the single corner reflectors. In order to adapt the dramatic changes in the ambient temperature of the space, pressure ring gaskets are used between the corner reflector and aluminum to ensure that the reflectors are not changed caused by fragmentation due to temperature. Single corner reflector outer edge caliber 15cm, weight about 5g, the total weight of about 115g.

2.3Simulation of the effective reflection area

① Single corner reflector effective reflection area calculation

For the inscribed circle cut mining individual corner reflectors, clear aperture is D, the reflection area $\pi(D/2)^2$, considering the corner reflector optical reflectance ρ, the effective reflection area becomes $\pi(D/2)^2 \times \rho$, the result is a laser at normal incidence. In the laser incident angle of , the need to consider the relative area of the effective reflection coefficient $\eta(i)$ [7]:

$$\eta(i)=\frac{2}{\pi}\left(\sin^{-1}\mu-\sqrt{2}\,\mu\tan\phi_{ref}\right)\cos i \quad \phi_{ref}=\sin^{-1}(\sin i/n) \quad \mu=\sqrt{1-2(\tan\phi_{ref})^2}$$

Where η is the relative effective reflection area (in the range of 0 ~ 1), is the refractive index of the corner reflector material (fused silica, n = 1.455), then a single corner reflector effective reflection area and the laser incident angle, Aperture the optical reflectivity relation to $\pi(D/2)^2\times\rho\times\eta(i)$.

② Laser reflector array computing the effective reflection area

For laser reflector array effective reflection area, just get a laser beam relative to each corner reflector array of the angle of incidence, using a single corner reflector effective reflection area calculation formula to calculate the respective corner reflector effective reflection area A_j ($j=1,2,\cdots N$), the laser reflector array reflecting the total effective area

$$A=\sum_{j=1}^{N}A_j=\pi(D/2)^2\times\rho\times\sum_{j=1}^{N}\eta_j(i)$$

Shows the proper angle to the incident laser beam is incident to each corner reflector surface normals, the need to establish a coordinate system. Usually in a position on the satellite as a reference point, geocentric direction and operational direction of the two basic axes, the third axis in line with right-hand rule coordinate system. For nano satellite laser reflector, using the coordinate system shown in Figure 5, the coordinate origin is at the center of the bottom laser reflector installation, z axis points geocentric, x axis pointing orbit direction, y-axis in line with right-hand rule, xoy plane for the installation of the bottom surface, xoz plane as the track surface, the figure for the incident beam angle and z-axis angle, this angle of the laser incident angle; after the incident ray xoy plane projected onto the angle between the direction (x-axis).

In the coordinate system, based on satellite laser reflectors satisfied octagonal table arrangement manner, the positional relationship between the respective corner reflector, Table 1 shows the 12 corner reflectors incident surface normals pointing n_j ($j=1\sim12$) and laser beam is directed at the unit vector l XYZ axis component.

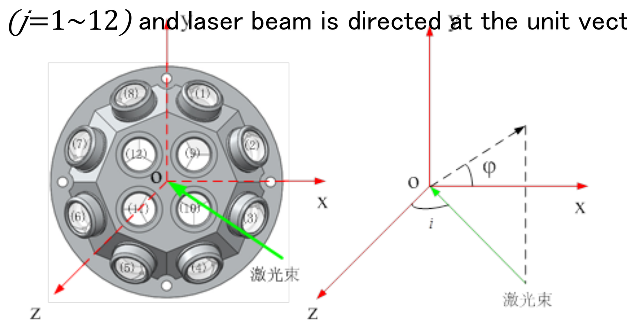

Fig.5 The definition of coordinate for calculating the effective reflecting area

According to the incident laser beam is directed at the unit vector of each corner reflector angle of the incident surface normals pointing unit vector $i_j=\cos^{-1}(n_j\cdot l)$ can be obtained with respect to the laser beam incident angle of each corner reflector i_j ($j=1\sim12$), then by a single corner reflector effective reflection area the formula to obtain the corresponding effective reflection area, 12 corner reflectors and the effective reflection area of, namely laser reflector array effective reflection area. Figure 6 shows a single laser reflector relative reflection area taking the laser reflector array 100 is relatively effective reflection area map, a broken line in FIG concentric series represents the incident angle of the contour line (0 ~ 90 °, the dotted line interval is 20 °), the peripheral spacer 30 degree angle indicates the azimuth φ (0 ~ 360 °), which coincides with the x-axis when φ= 0 °.

Unit vector	X	Y	Z
Corner (1)	0.2932	0.7077	0.6428
Corner (2)	0.7077	0.2932	0.6428
Corner (3)	0.7077	-0.2932	0.6428
Corner (4)	0.2932	-0.7077	0.6428
Corner (5)	-0.2932	-0.7077	0.6428
Corner (6)	-0.7077	-0.2932	0.6428
Corner (7)	-0.7077	0.2932	0.6428
Corner (8)	-0.2932	0.7077	0.6428
Corner (9)	0	0	1
Corner (10)	0	0	1
Corner (11)	0	0	1
Corner (12)	0	0	1
Laser beam	cos(φ)	sin(φ)	cos(i)

Table1. 12 corner reflector laser beam incident face normals point and point to a unit vector

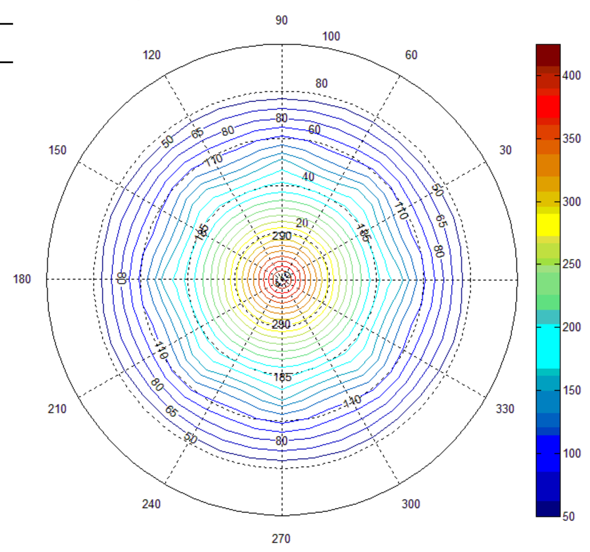

Fig.6 The distribution of the relative effective reflecting area of nano-satellites laser retro-reflector

For the nano satellite laser reflector, the aperture of single corner D = 13.6mm, the incident plane geometry area 1.45cm^2, consider a single corner reflector optical reflectance of 88% @ 532nm, the single angle perpendicular to the incident laser reflectors effective reflection area of 1.45 * 0.88 = 1.27cm^2. According to the calculation results in Figure 5, we can see:

I.When the vertical incident light beam, namely 0 ° Angle of incidence, the effective reflection area is 426.5/100 ×1.27 = 1.27 cm^2

II.When the beam incidence angle θ is 40 °, the effective reflection area of minimum 184.3/100×1.27=2.34cm^2

III.When the beam incidence angle θ is 60 °, the effective reflection area of minimum 105/100×1.27=1.33cm^2

IV.When the beam incidence angle θ is 67 °, the effective reflection area of minimum 83/100×1.27=1.05cm^2

According to the work, the satellite orbit height, the ground observation lowest elevation take 20 degree, corresponding to the laser incident angle about 67 degree.By the simulation calculation shows that within the scope of laser beam incident angle of 0 ~ 67 degree, the laser reflector effective reflection area is not less than 1.05 cm^2.

3. Nano satellite laser ranging analysis

3.1 Nano satellite laser photon echo estimate

According nano satellite laser reflector design results in ground elevation greater than 20 °, the effective reflection area 1.05cm^2 more. In Shanghai Observatory laser ranging system parameters example [8], a laser radar equation is satisfied that the satellite laser photons echo analysis. Laser Ranging radar equation as follows [9], the parameter values are given in Table 2 laser ranging radar equation

$$N_s=\frac{16\cdot E\cdot S\cdot A_s\cdot A_r\cdot K_t\cdot K_r\cdot T^2\cdot\eta\cdot\alpha}{\pi^2\cdot R^4\cdot\theta_t^2\cdot\theta_s^2}$$

Table2 The value of system parameter for calculating laser echoes from nano-satellite

Laser pulse energy (532nm) E:	1mj
The number of photons per joule of energy S:	2.67 ×10^{18} @532nm
Laser reflectors effective reflection area A_S:	1.05cm^2
Ground Station telescope receiving area A_r:	Primary mirror diameter 60cm, Secondary mirror diameter 20cm, then the reception area of 0. 251m^2
Efficiency of the transmission system K_t:	0.6
Receiving efficiency of the optical systemK_r:	0.6
Two-way atmospheric transmittance T^2:	0.2 (elevation 20 degrees)
Photon detector quantum efficiency η:	For SPAD, take 0.2 @532nm
Attenuation factor (atmospheric jitter, turbulence and other effects) α:	0.05
Satellite distance R:	Orbit height 450km, elevation 20 degrees, slant distance of about 1090km
Laser beam divergence θ_t:	8"
Satellite reflector divergence θ_s:	25"

Calculated by the above parameters in the satellite elevation angle 20 degrees, after a single laser pulse emission ground station can receive the laser photon echo number Ns is 2.52 photoelectrons. For the photon detector, photoelectric conversion to produce the number of photoelectrons, Poisson probability was generated by a photoelectron formula $P(1)=1-e^{-N_s}$ obtained in the ground elevation 20 degrees P (1) is 0.918. For laser emission frequency of 1kHz ranging system, the number of photons per second theoretically laser echo to 918.

In the middle of the nano satellite laser ranging, by laser energy fluctuations, the telescope tracking error, the atmosphere of the laser beam is directed disturbances, uncertain influence of background noise photons, etc., the actual number will be less than the above-described laser echo theoretical results. According to the international community has the same orbital altitude satellite (Swarm-A, -B) laser ranging results [10], the ground laser ranging stations can realize nano satellite laser observations, to obtain high-precision laser measurement data.

3.2 Analysis of Nano Satellite Laser Ranging Accuracy

Measurement error of laser ranging data directly affects the satellite precise orbit, orbital test applications such effects. Measurement errors and satellite laser ranging device laser ranging systems, laser atmospheric propagation delay, delay ranging system calibration, laser reflector array structure and so on, can be divided into accidental and systematic errors into two categories. Laser ranging accuracy is defined by the laser ranging measurement equipment, laser reflectors pulse broadening effects caused by two types of random error of the mean square error is within the accuracy of laser ranging data symbol, characterization of laser ranging system measuring device comprehensive measurement performance laser reflector. Transfer formula based on measurement error, laser ranging total measurement error of mean square (RMS) is equal to the square root of the variance of the measurement error of the value of the sum of squares. For Shanghai Astronomical Observatory satellite laser ranging system, the measurement equipment of the mean square error is shown in Table 3.

Table 3 The analysis of measuring error for laser ranging to nano-satellite

measurement equipment error	RMS(ps)	RMS(mm)
1) Laser pulse width (kHz)	~30	~4.5
2) ET(A033)	~8	~1.2
3) start signal detection (PIN+454)	~25	~3.8
4) echo signal detection (C-SPAD)	~30	~4.5
5) Time and frequency reference (HP58503A)	~12	~1.8
Total:	~51	~7.7

For a single corner reflector, the laser beam is incident from the incident surface at different positions, an emitted light beam having the same propagation time, i.e. not generating a laser broadening effects. For laser reflector array composed of a plurality of corner reflectors, the same light beam is incident to a different location within the array of different angles reflector time, resulting in the reflected beam transmission at different times, so that the laser beam in the propagation time spread, causing the so-called laser reflector shape effect measurement errors. For nano satellites, using a miniature octagonal table structure, with certain laser reflector shape effect of measurement error, by probability distribution model, satisfied that the satellite laser reflector shape effect of measurement error (RMS) of about 2-3mm, combine to Table 3 ground the measurement error of the measuring stations, the nano Satellite laser Ranging total measurement error (precision RMS) of about 7.9-8.3mm.

4. Summary

For LEO satellites, the high precision satellite laser ranging has become the important measuring techniques during the process of scientific research and is widely used in the field of laser geodynamics satellites, ocean observation, physiognomy mapping. Nano satellites with the characteristics of light weight, compact, short period of manufacture, low power consumption and the high dense functions have been paid more attentions. For the first nano satellite for atmosphere density detection, the requirement of precise orbit determination should be realized by using the different measuring techniques. Among of them, laser ranging is regarded to be the indispensabe observation.

According to the application requirements of nano-satellites used for atmosphere density detection, the light-weight octahedral laser retro-reflector without any power consumption has been designed with the weight of less than 120g, the effective reflecting area of more than 1cm^2 and the size of Φ96×20mm for performing the laser ranging and providing the indispensable supports of high precise orbit measurement for scientific researches and applications. Based on the laser ranging link equation, the technical analysis of nano-satellite laser ranging has also been performed and according with the real measuring results form the ground laser ranging station to serve for orbit determination and atmosphere density detection.

Reference:

1. Jin Zhonghe,Jin Xiaojun. Development and Applications of pico- and nano satellites, workshop of small satellites, 2011,1-8
2. Zhao Weiyu, Bai Baocun, Jin Zhonghe. Application of pico-and nano-satellites and analysis of characteristics, space international, 2013.8
3. ILRS. International Laser Ranging Service. [2015-09-03]. http://ilrs.gsfc.nasa.gov/ missions /satellites_missions/future_missions/PN-1.html