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A Very Small Astrometry Satellite, Nano-JASMINE: Its Telescope and Mission Goals

By Yoichi HATSUTORI[1)], Masahiro SUGANUMA[2)], Yukiyasu KOBAYASHI[1)], Naoteru GOUDA[1)], Taihei YANO[1)], Yoshiyuki YAMADA[3)] and Masahiro YAMAUCHI[4)]

[1)] *National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo, Japan*
[2)] *Japan Aerospace Exploration Agency (JAXA), 2-1-1, Sengen, Tsukuba-shi, Japan*
[3)] *Kyoto University, Kita-shirakawa-oiwakecho Sakyo-ku, Kyoto, Japan*
[4)] *University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, Japan*

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This paper introduces a small astrometry satellite, Nano-JASMINE. Nano-JASMINE is mounted a 5-cm effective diameter telescope and aims to measure positions of ten or twenty thousands of stars of $z \leq 8$ mag for all-sky with the accuracy of a few milli-arcseconds. The mission goals are clarified and the current status of development of the telescope is reported.

Key Words: Astronomy, Small Satellites, Reflecting Telescope

1. Introduction

Astrometry is a field of observational astrophysics that measures positions and motions of stars on the celestial sphere and determines the distances to them using trigonometric parallaxes due to earth orbit around the sun. Because of the blurring due to the distorting effects of the atmosphere, space telescopes for astrometry have much more advantage than ground-based telescopes. Therefore, HIPPARCOS was launched by ESA in 1989 and observed about a hundred of thousand of stars around the all-sky with one milli-arcsecond angular accuracy[1)]. However, almost 15 years have passed since the end of the HIPPARCOS mission. Then the errors in proper motions have accumulated over the years. Therefore a following mission is beneficial because the individual motions of stars and their uncertainties are large enough to degrade the HIPPARCOS data during these two decades of blank.

We are preparing a nano-size satellite for astrometry named Nano-JASMINE, planning to launch by a piggy-back opportunity in 2010. Fig. 1 shows the overview of Nano-JASMINE. Through Nano-JASMINE mission, some technologies required for our next generation space astrometry mission with micro-arcseconds accuracy, named JASMINE (Japan Astrometry Satellite Mission for INfrared Exploration), will be demonstrated and evaluated. Nano-JASMINE also will demonstrate a first space astrometry in Japan. As a most outstanding feature of the mission, we are challenging to execute measurements comparable to HIPPARCOS by a very small satellite that weighs about 15kg, that is, 100 times lighter than HIPPARCOS[2)]. This paper introduces mission goals of Nano-JASMINE and current status of development of the telescope.

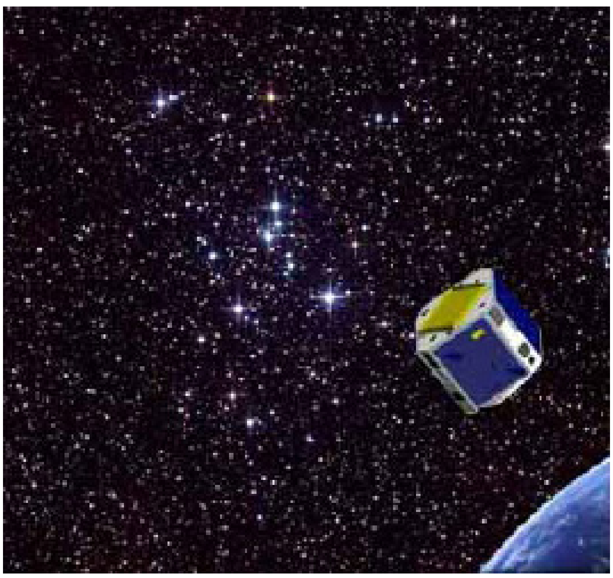


Fig. 1. Overview of Nano-JASMINE

2. Mission target and mission instruments

2.1 Mission target

The objectives of Nano-JASMINE are technical demonstration for JASMINE and scientific astrometry[3),4)]. Through Nano-JASMINE project, we will try the first practical use of the new CCD detector in space, construct an on-orbit system, and experiment first space astrometry in Japan. Table 1 shows the comparison of required accuracy for Nano-JASMINE and JASMINE.

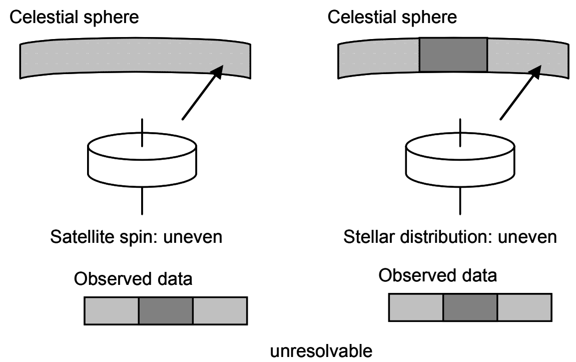
Nano-JASIMINE requires almost all the key technologies that are required for the JASMINE project. For example, telescope, CCD operation, precise attitude control, thermal control, and so on. Telescope observes two different fields of view simultaneously by using beam-combiner. Satellite's spin rate will be synchronized with orbital period. In this paper, satellite's spin rate is assumed at 110 min for one rotation. Moreover optical axes of beam-combiner will be perpendicular to spin axis of satellite. The telescope will then scan the entire sky along a great circle. This measurement is performed in the course of continuous scanning observations of the entire sky. This technique enables us to distinguish between an irregularity in the spin velocity and the distribution of stellar positions. Fig. 2 shows the difference of observed data.

New CCD detector has large quantum efficiency in near infrared range and can be operated in TDI (Time Delay Integration) mode in order to efficiently survey the whole sky. In TDI mode, observed stars move on CCD detector according to satellite's spin motion. These stars pass through the field of view in approximately 8 sec. The rate of charge transfer is synchronized with the scan velocity of the spinning satellite. Then each star is exposed about 8sec. Charges accumulated along the CCD reach the edge, they are digitized by an AD converter and endless stripes of an image is produced. By using TDI mode, CCD can gather the large number of photons. This CCD is a major technical difference between Nano-JASMINE and HIPPARCOS. Therefore Nano-JASMINE will achieve astrometry accuracy comparable to that achieved by HIPPARCOS with such a small satellite. For thermal control and precise attitude control, Sako[2)] described their key technologies in detail. It is instructive for us to test and check these key technologies that are related to the JASMINE project by executing a real satellite mission.

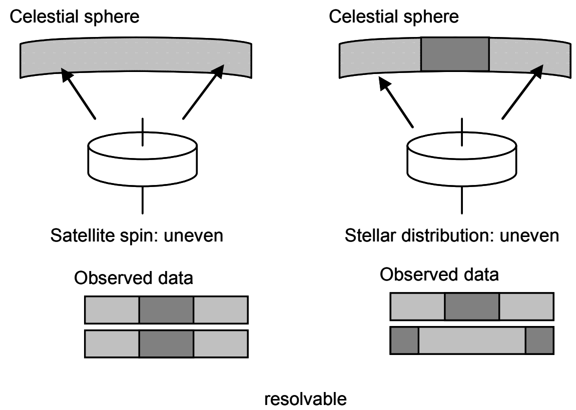
From a scientific viewpoint, the targeted astrometric accuracy of Nano-JASMINE is set to be comparable with that of HIPPARCOS. The HIPPARCOS offered accurate information on the astrometric parameter. However, almost 15 years have passed since the end of the HIPPARCOS mission, and the errors in proper motions have accumulated over the years. Because of the long time span between the epoch of the HIPPARCOS and Nano-JASMINE missions, even if we measure the same stars that were observed by HIPPARCOS with the same accuracy, we can significantly improve the accuracy of proper motion. We can correct the degradation of the HIPPARCOS catalogs. The revised catalog will be the most accurate astrometry catalog.

Table 1 Required accuracy for Nano-JASMINE and JASMINE

	Nano-JASMINE	JASMINE
astrometric accuracy	a few milli-arcsec	10 micro-arcsec
aperture of telescope	5cm	80cm
focal length	1.67m	14.4m
observing magnitude	8mag	11mag
attitude stability	740mas/8.8sec	100mas/2.4sec
thermal stability (telescope)	100mk	20mk
field of view	0.5x0.5 deg	0.98x0.98 deg



(a) one telescope



(b) two telescopes

Fig. 2. Difference of observed data

2.2 Optical system

Nano-JASMINE is a very small and light weight satellite. Therefore optical system is required to make it a small size. Then, effective diameter of primary mirror is decided 5-cm. To obtain diffraction limited performance over wide field of view (0.5x0.5 degree), Ritchey-Chretien type telescope was adopted.

Another important consideration to design optical system is what material should be used for mirrors and structures, and how fabricates and assembles them. Concept design of Nano-JASMINE telescope is simple structured, non-expensive, non-time consuming. Then aluminum alloy is adopted not only to make a telescope structure but also to fabricateing reflecting surface, because aluminum alloy is easy to be shaped by machining process and goes well with single-crystal diamond-cutting tools.

Nano-JASMINE telescope is based on Ritchey-Chretien type telescope. However Nano-JASMINE also has a beam-combiner. A beam-combiner consists of two flat mirrors and can observe two fields of view simultaneously for global field astrometry. Its basic angle is 99.5 degree, so that observed distribution of stars can be resolved into a satellite's motion and actual distribution of stars. Fig. 3 shows an optical layout of Nano-JASMINE telescope, though a beam-combiner that should appear around the secondary is omitted in this figure. Three flat mirrors (M3, M4, M5 in Fig. 3) are adopted to make the optical path after secondary mirror (M2 in Fig. 3) compact volume.

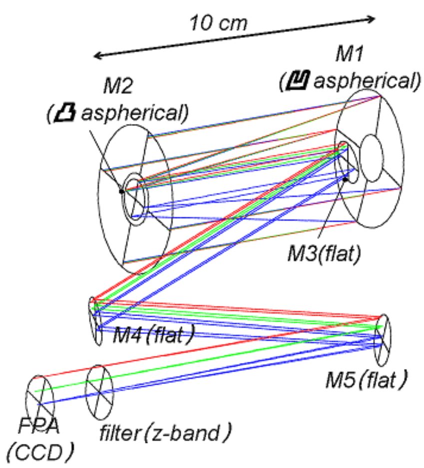


Fig. 3. Optical layout of Nano-JASMINE

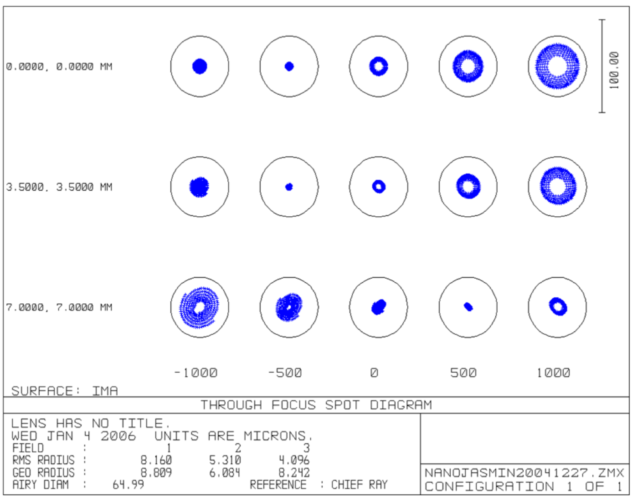


Fig. 4. Spot diagram through focus for Nano-JASMINE telescope

The spot diagram of the telescope at the focal plane array (FPA) is shown in Fig. 4. The circles shown in Fig. 4 indicate an airy diameter that corresponds to about 4 pixels on CCD array. The row and column show off-axis and off-focus respectively.

Fig. 5 shows the field curvature and distortion of Nano-JASMINE telescope. Although distortion is less than 0.02%, it affects position determination accuracy. Therefore distortion will be estimated in analytical algorithm. Table 2 shows the specification of the telescope in detail.

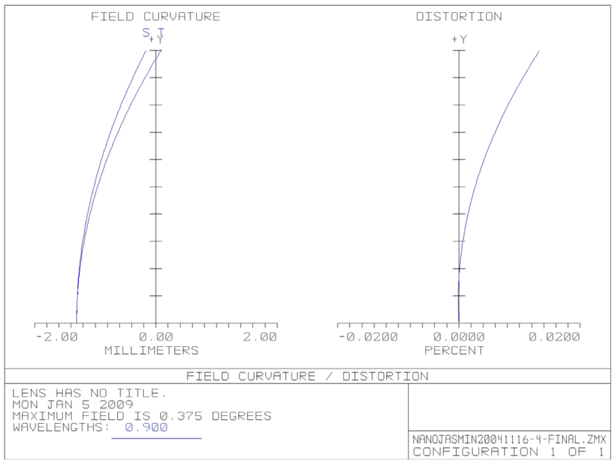


Fig. 5. Field curvature and distortion of Nano-JASMINE telescope

Table 2 Specification of Nano-JASMINE telescope

Aperture (M1)	φ5cm (divided into two by beam-combiner)
Focal length	167cm (F/33)
Optics type	Ritchey-Chretien type, with two aspherical mirros and three folding mirrors
FOV	0.5x0.5 deg
Basic angle	99.5 deg
Wavelength	z-band (λ∼0.9μm)
Detector	Full-depletion CCD(2Kx1K), with Time Delay Integrator (TDI) operation
Pixel scale	15μm (1.76 arcsec/pix)
Operating Temperature	−50℃∼−100℃

3. Thermal analysis

Two telescopes using a beam-combiner make possible to perform global measurement to get parallaxes. However the relative angle of mirror surface of beam-combiner should be kept within 1 milli-arcsecond during a few periods of the satellite spin, because the variation of relative angle affects the position determination accuracy. The major cause of variation of relative angle is thermal variation on orbit. Therefore it is necessary to control the thermal change of beam-combiner within 100mK. Then, thermal analysis is needed to evaluate the feasibility of the optical system. Fig. 6 shows the surrounding structure of the telescope. The telescope is put in radiation shield, insulated from the exterior thermally.

Fig. 7 shows the results of thermal analysis. The telescope is cool downed below 220 Kelvin in Fig. 7-(a).

Moreover, the relative angle of beam-combiner is kept within sub-milli-arcsecond in Fig. 7-(c). Then, it is confirmed that this passive control is feasible. This surrounding structure is in the process of production as structure-thermal model (STM). Thermal tests will be conducted in this summer.

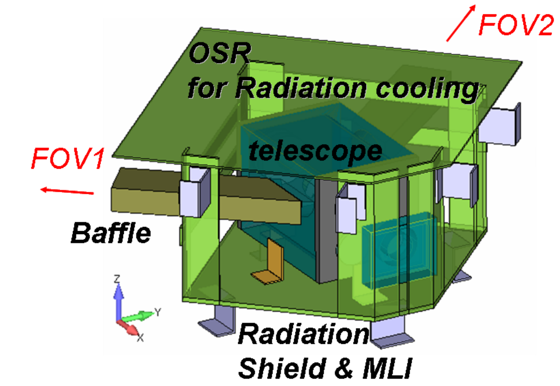
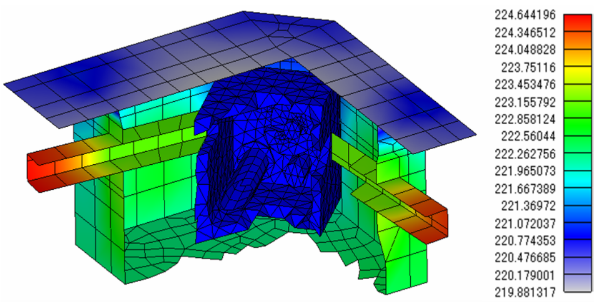
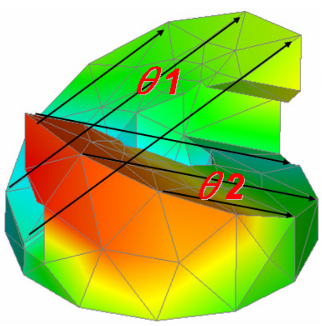


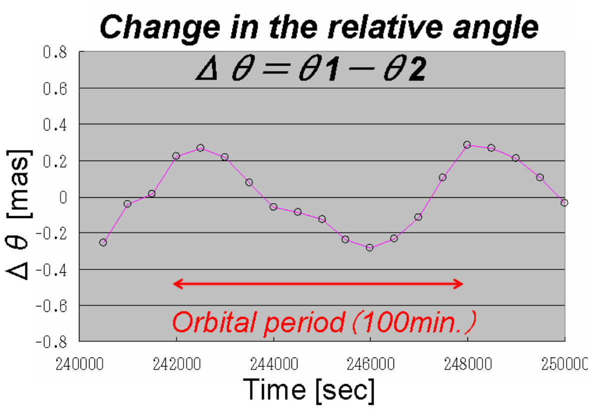
Fig. 6. Overview of telescope and radiation shield



(a) telescope and radiation shield



(b) beam-combiner



(c) the relative angle of beam-combiner

Fig. 7. Results of thermal analysis

4. Performance tests of Nano-JASMINE telescope

All mirrors and their structural supports are shaped out of aluminum alloys by ultra-precise turning machine with a diamond bite which provides us with rapid manufacturing and physical uniformity of the materials. Fig. 8 shows the outlook of assembled telescope. It totally weighs 1.7 kg and occupies a volume of only 17x12x12 cm. Moreover, reflecting surfaces of the mirrors are physically deposited with Cr and Au vapor. Table 3 lists the shape error for each reflecting surface, along with the expected wavefront error on the reflection at it. The values in the bottom line are root-summationed-squares (RSS) for all surfaces. The RSS wavefront error value of $\lambda/14$ indicates that these mirrors have potential to be integrated for a telescope of diffraction-limited performance.

A diffraction-limited performance of the telescope was confirmed by wavefront measurements and imaging observations of real stars. The results of the performance tests are shown in Fig. 9 and Fig. 10.

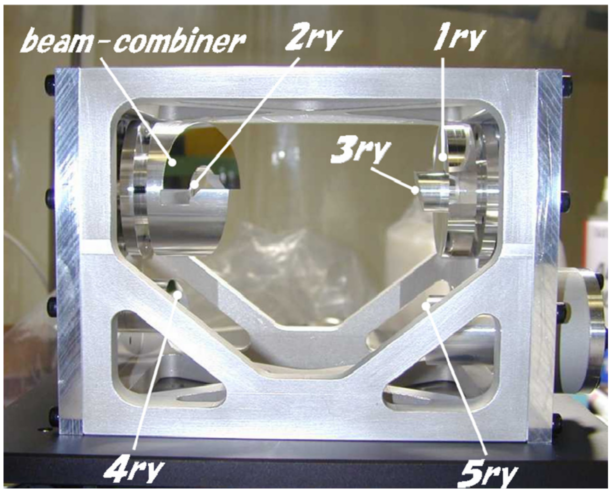


Fig. 8. Outlook of the assembled telescope

Table 3 shape error for each reflecting surface

Surface	Shape RMS (nm)	Wavefront RMS(nm)	Wavefront RMS (λ/σ λ=800nm)
beam-combiner	15	30	λ/27
1ry	15	30	λ/27
2ry	9	18	λ/44
3ry	10	20	λ/40
4ry	11	22	λ/36
5ry	8	16	λ/50
RSS total	29	57	λ/14

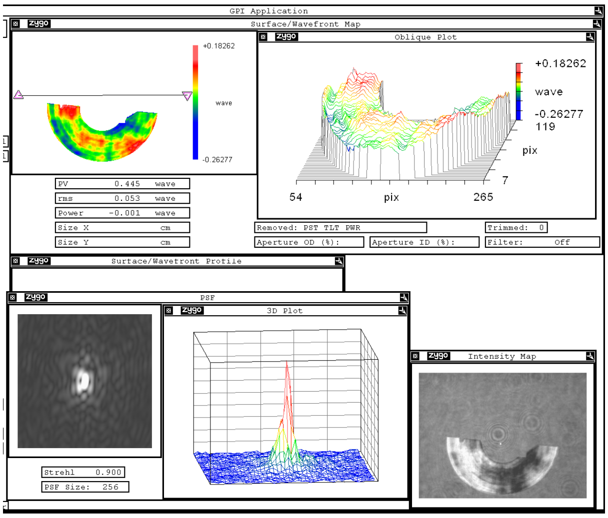


Fig. 9. Observed wavefront errors (Top two windows) and simulated PSF derived from the wavefront (Left and center window in the bottom).

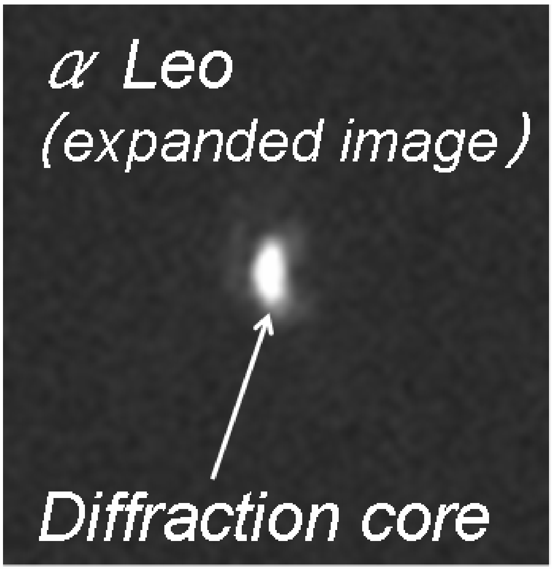


Fig. 10. shot images of the real stars
(α Leo: expanded image)

The total performance of the telescope is measured with interferometer. Fig. 9 shows the optical wavefront error through telescope for one of two apertures of beam-combiner. The measured wavefront error near optical axis for each aperture of beam-combiner is about 35 nm RMS, about $\lambda/20$ at $\lambda = 800$ nm, which means that the telescope achieves near the diffraction limited performance near about optical axis.

Observational test of the real stars was conducted with BITRAN CCD and Nano-JASMINE telescope. Under an ideal seeing condition, the elongated PSF due to the aperture shape of the telescope is observed. Fig. 10 shows a shot image of alpha-Leo. Note that a major axis of elongated PSF is perpendicular to a great circle and only minor axis of elongated PSF is used for spherical reconstruction.

As a result, it is confirmed that the assembled telescope has an enough performance for scientific astrometry.

5. Conclusion

We reported the mission goals of Nano-JASIMINE project and a current status of developing a small, all-aluminum made telescope for Nano-JASMINE. Nano-JASMINE is a nano-size astrometry satellite that will demonstrate some key technologies required for JASMINE in a real space environment and will measure absolute positions of bright stars ($z \leq 8$ mag) with accuracies about a few milli-arcseconds in a few years mission. It has a Ritchey-Chretien type telescope with a 5 cm effective aperture, a 167 cm focal length and a field of view of 0.5x0.5 deg. A series of performance tests and numerical analysis were conducted and its results indicated the telescope has an enough performance for scientific astrometry.

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