STATE RESEARCH CENTER OF THE RUSSIAN FEDERATION
CONCERN **CSRI ELEKTROPRIBOR**, JSC

INTERNATIONAL ASSOCIATION OF GEODESY (IAG)

4th IAG SYMPOSIUM ON
TERRESTRIAL GRAVIMETRY:
STATIC AND MOBILE MEASUREMENTS
(TG-SMM 2016)

12 - 15 APRIL 2016
SAINT PETERSBURG, RUSSIA

PROCEEDINGS

CO-SPONSORED BY:

- *RUSSIAN FOUNDATION FOR BASIC RESEARCH*
- *NATIONAL RESEARCH UNIVERSITY ITMO, RUSSIA*
- *JOURNAL GYROSCOPY AND NAVIGATION, RUSSIA*

2016

The publication represents the Proceedings of the 4th IAG Symposium on Terrestrial Gravimetry: Static and Mobile Measurements (TG-SMM 2016) held on 12-15 April 2016 at the State Research Center of the Russian Federation, Concern CSRI Elektropribor, JSC (St. Petersburg, Russia).

The Proceedings comprise texts of the plenary and poster papers recommended for publication by the session chairmen and reviewers of the International Scientific Committee of the Symposium.

*In the contents poster papers are marked by *.*

Editor-in-Chief
Academician of the Russian Academy of Sciences
Vladimir G. Peshekhonov

ISBN 978-5-91995-033-2

EXPECTED ACCURACY OF A SMALL TELESCOPE LIKE PZT FOR OBSERVATIONS OF VERTICAL GRAVITY GRADIENT AND LUNAR ROTATION

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Abstract

Key words: Photographic Zenith Tube (PZT), Lunar rotation, Vertical gradient of gravity Deflection of the vertical

Development of the PZT type telescope for observations of gravity gradient and lunar rotation was being made, and a Bread Board Model (BBM) for ground experiments was completed. Some developments were made for the BBM such as a new tripod and a stable mercury pool. We performed laboratory experiments and field observations from August to September of 2014, in order to check the total system of the telescope and the software. It is also investigated how the ground vibrations affect the stellar position on CCD.

The results of the preliminary observations showed that the variation of stellar positions was better than 0.1 arc-second in the laboratory and was about 0.4 arc-seconds in the case of field observations. The difference in standard deviation (SD) of the variation is partly due to different signal to noise ratio (SNR) of star images. There was a strong correlation between the SD and SNR. There are, on the other hand, periodic components in the range lower than 6 Hz in a data from continuous record taken by a video camera. The variation became much smaller after removing the periodic components.

Introduction

Photographic Zenith Tube (PZT) is a kind of telescope for positioning astronomy and is known as an instrument which played an important part in observations of the Earth rotation in the International Latitude Service and the International polar motion service (Yokoyama et al., 2000). It has a characteristic of tilt compensation mechanism using a mercury pool put at the middle point of the focal length of an objective, and can measure position of a star with respect to the local plume line (Ross, 1915). Thus, not only the Earth rotation, which affects apparent position of a star, but also the deflection of the vertical (DOV), which is the angle between the plume line (direction normal to the geoid) and the line perpendicular to the surface of the reference ellipsoid, are known from observations by PZT.

Hirt and Bürki (2002) developed a transportable digital zenith camera which is similar to the PZT for the automated determination of DOV by introducing CCD as a detector. The accuracy of the DOV measurements was ranging from 0.1 to 0.15 arc seconds. This accuracy is comparable to that of the Earth rotation in a single observation which was about 0.1 arc seconds (Yokoyama et al., 2000). It was also shown that PZT could be applied to field observations by taking advantage of the tilt compensation mechanism.

On the other hand, observations of lunar rotation using a telescope like PZT set on the Moon were proposed by RISE (Research In SElenodesy) project of National Astronomical Observatory (NAOJ) which is a part of succeeding institute of the International Latitude Observatory (Hanada et al., 2004). It is another kind of observations independent of Lunar Laser Ranging (LLR). Simulations showed that the observation for longer than 1 year with an accuracy of 1 milli-arc-second (mas) can determine the parameters of lunar rotational fluctuations (or the lunar physical librations) better than 1 mas accuracy (Noda et al., 2008). It is necessary to attain this accuracy in order to know if there is partial melting zone or a liquid core inside of the Moon, since libration parameters related to dissipation in the lunar deep interior have an amplitude of at most a few mas (Williams et al., 2001). This observation was named ILOM (In-situ Lunar Orientation Measurement) after International Latitude Observatory of Mizusawa. We have developed a bread board model (BBM) of the telescope for basic experiments of ILOM, and it is also used for preliminary observations on the Earth. Results of ground experiments are examined in this paper.

Development of Technologies

Development of the PZT type telescope was started in the beginning of the 2000s, and a Bread Board Model (BBM) for ground experiments was completed as shown in Fig. 1. It has a tube of 0.1 m diameter with an objective having a focal length of 1m, and a CCD camera composed of an array of 512×512 pixels of 7.4μm×7.4μm (BJ-42L, Bitran Co.) is attached to the side of it (Fig. 2). The resolution of 1 mas corresponds to about 5 nm on the focal plane, which is smaller than 1/1000 of pixel size. During the course of development of the BBM, we concentrated our efforts on the following issues; improvement of determination accuracy of the central stellar positions on CCDs (centroid), reducing the effects of temperature change, adjusting the attitude of the tube vertical automatically and keeping the mercury pool in a good condition for a long time (Hanada et al., 2012).

Some important results were obtained so far. The accuracy of centroid was attained to about 1/300 of pixel size of the CCD of a 512×512 array with 20μm×20μm pixels (BT-213E, Bitran Co.) by laboratory experiments cooperated with JASMINE (Japan Astrometry Satellite Mission for INfrared Exploration) project of NAOJ (Yano et al., 2004).

Kashima (2013) proposed objectives with DOE (diffractive optical element) in order to reduce the effect of temperature change, and showed by ray tracing simulations that the change of about 10 degrees centigrade is allowed for the observation of 1 mas accuracy whereas the temperature change of only 1degree can shift the center position of stellar image by about 3 mas if we use an objective without DOE.

The tripod with a 2-axis driving mechanism composed of two sets of motors and reduction gears can adjust the attitude of the telescope according to the signal from two-component tilt-meters set on the bottom of the tube. It takes about 60 seconds to stand the tube vertical from 2 degree deviation. The consumption power necessary for the motor drive is about 12 W and that for standby is less than 2 W (Funazaki et al., 2008).

The mercury pool set 50cm (a half of the focal length) below the objective is a reflector of a level surface, and distortion and vibration of the surface affects the stability, quality and accuracy of the measurement of stellar position very much. We selected the mercury pool of 0.5mm depth and 84mm diameter as the appropriate one for the telescope considering the sensitivity to tilt, sensitivity to ground vibrations and long-term stability (Tsuruta et al., 2014).

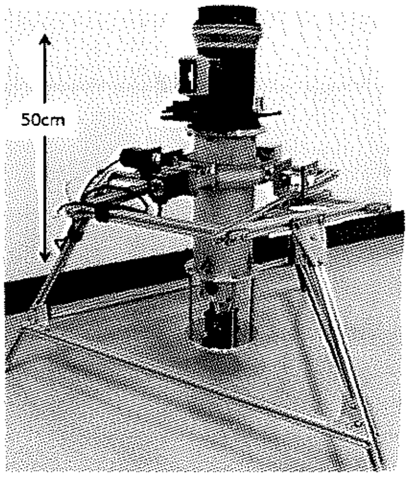

Fig. 1. Bread board model of PZT type telescope forground experiment

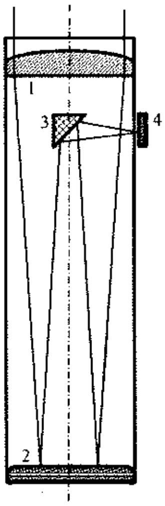

Fig. 2. Optical system of the BBM: *1* – objective, *2* – mercury pool, *3* – prism, 4: CCD

Laboratory Experiments

We performed experiments using the BBM of the telescope at the underground laboratory of Mizusawa VLBI Observatory of NAOJ in August of 2014 in order to evaluate the optical characteristics of the telescope. Receiving starlight is simulated as follows. Artificial light from a tungsten lamp is concentrated at a reticule with 21 pinholes, then the expanded light is collimated through a collimator (CL-1000, Pearl Opt. Ind. Co.) and is introduced to the tube after reflected at a slant mirror set on an aluminum frame (Fig. 3). Star images are recorded either on the CCD camera or on a video camera (MTV63-VTN, Mintron Enterprise Co. Ltd.) which can take pictures of stellar images at the rate of 30 frames/s. The latter was used for comparison with vibration data recorded by 3-component velocity seismometer (MTKV-1C, MTKH-1C, Sato Trading Co.) set on the frame.

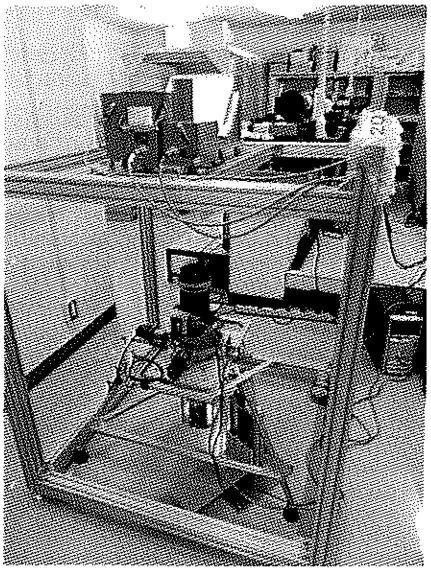

Fig. 3. Experimental equipment for BBM test

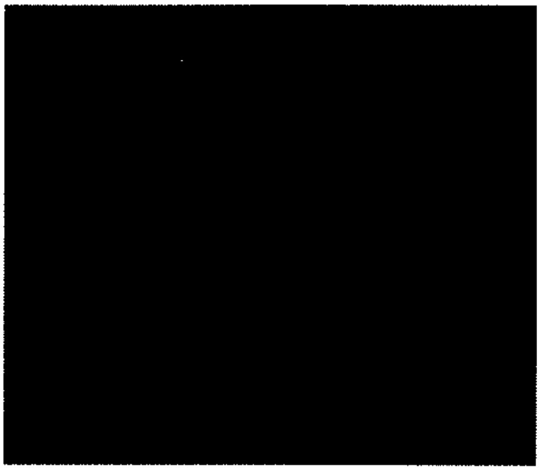

Fig. 4. Artificial star images recorded on the CCD

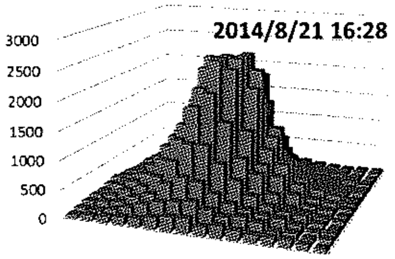

Fig. 5. Example of a stellar image recorded on CCD. Horizontal axes represent the CCD area of 16x16 pixels around the peak of stellar image, and the vertical axis represents intensity of the image, or the value proportional to the number of electrons stored in a pixel

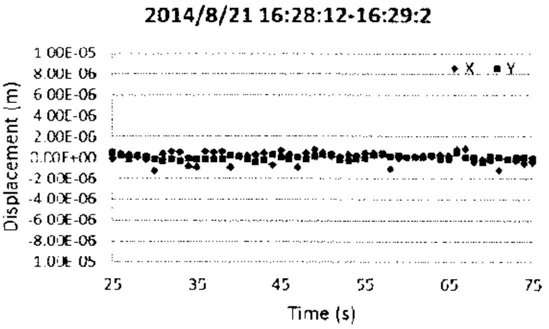

Fig. 6. Variation of measured stellar position recorded on the CCD camera

Fig. 4 shows an example of star images recorded on the CCDs. We determined the center position of a pseudo star by least square fitting to the Gauss distribution as shown in Fig. 5. We made several sets of experiments consisting of 50 second data for several times a day. The position slightly changed due to either fitting error or motion of the images caused by ground vibrations and mercury surface vibrations. We can calculate standard deviation (SD) of the variation of X and Y components of measured position from 50 data. The results are summarized in Table 1 together with corresponding SNR which is defined as the ratio of the peak amplitude of a stellar image to SD of noise outside of the image. The SD of the measured position ranges from about 5×10^{-7} to 5×10^{-5}m (or 0.1 to 10 arc seconds), and there is a tendency of decreasing SD with increasing SNR.

Table 1

Statistics of the variation of the stellar position

	S/N	SD in X (m)	SD in Y (m)
2014/8/19	8.45E+02	3.37E-06	1.63E-06
	9.61E+02	3.53E-06	1.33E-06
	7.25E+02	2.83E-06	1.39E-06
	4.92E+01	2.85E-07	1.23E-06
	3.49E+01		5.09E-05
	4.31E+02	1.17E-05	3.02E-06
2014/8/21	1.66E+03	6.44E-07	2.63E-07
	1.94E+03	5.42E-07	2.65E-07
	1.85E+03	5.82E-07	2.36E-07
	1.70E+03	6.55E-07	2.42E-07
	3.37E+02	1.24E-06	4.71E-07

We also made experiments by using the video camera and took videos for 60 seconds consisting of 1,980 data. The center position of a pseudo star is determined by least square fitting as shown in Fig. 7. The driving mechanism started operation about a few seconds after the beginning, and it became stable about 20 seconds later, therefore the stellar position oscillates during the first 20 seconds. A detailed variation of the stellar position for the last 40 seconds is also shown in the lower part of Fig. 7. There is still remaining periodic components in the time variation data after the motor of the driving mechanism stopped. By applying Fast Fourier Transformation (FFT) to this time series data, we know that there is a strong peak at near 6 Hz in X component. It is not obvious in Y component though.

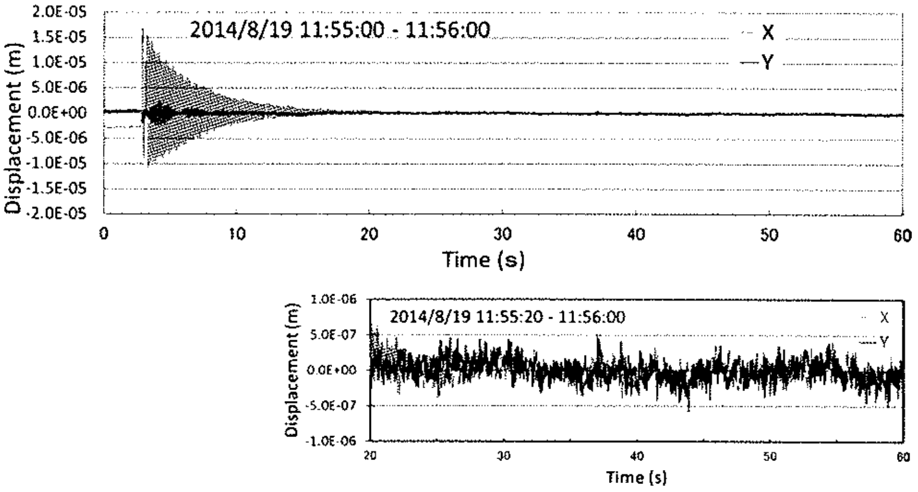

Fig. 7. Variation of measured stellar position recorded on the video camera.
A magnification for the last 40 seconds is also shown below

Ground vibrations, on the other hand, were measured by using the velocity seismometers set on the frame. Spectra of the ground vibrations show different peaks from that of the variation of the stellar position (Fig. 8). The time series data of ground vibrations are apparently very different from those of variation of stellar position (Fig. 9). It partly because that the vibration records do not reflect the vibration of CCD camera nor the mercury pool. Vibrations of the mercury surface have not been directly measured yet.

Nevertheless, the peaks in the spectra do not seem to be from fitting error but rather from vibrations occurred in some part in the optical system. The fitting error is likely not to be periodic but random. Then we can much reduce the variation of measured position by eliminating the periodic components included in the variation of stellar position. It is expected to be less than 2×10^{-7}m (or 0.04 mas) judging from the amplitude of the spectrum in the range of higher than 6Hz.

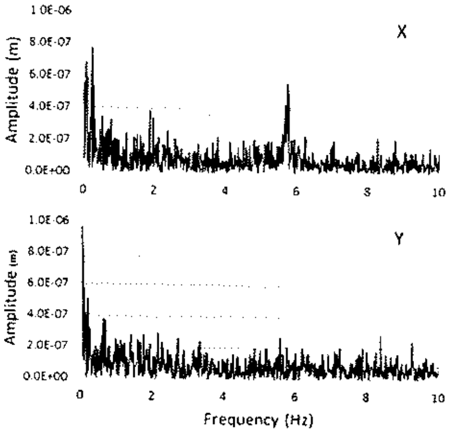

Fig. 8. Spectra of variation of the stellar position

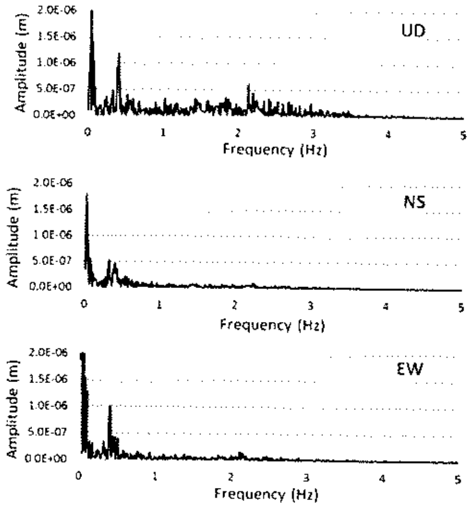

Fig. 9. Spectra of ground vibrations

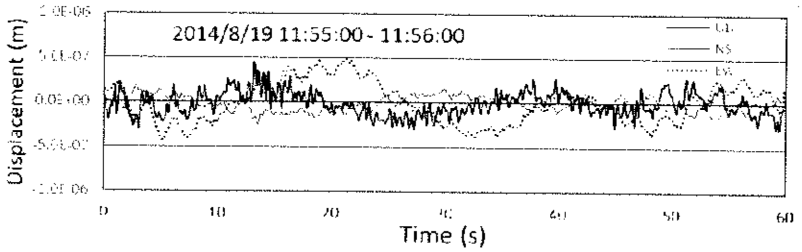

Fig. 10. Three components of ground vibrations for the same period as Fig. 7

Field Experiments

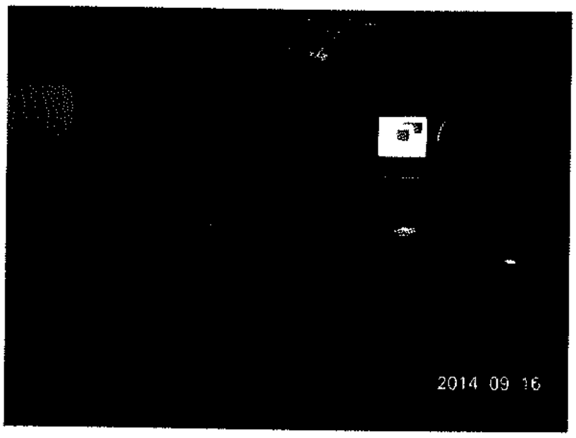

Fig. 11. Field observations in the campus of Mizusawa VLBI Observatory of NAOJ

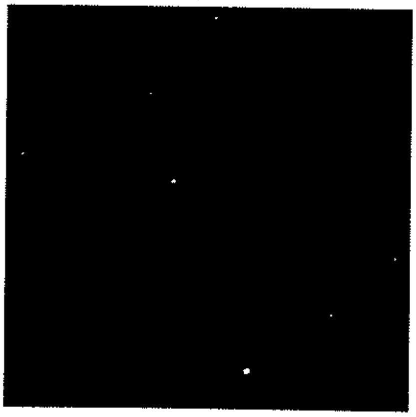

Fig. 12. Star images recorded on the CCD in the field observations

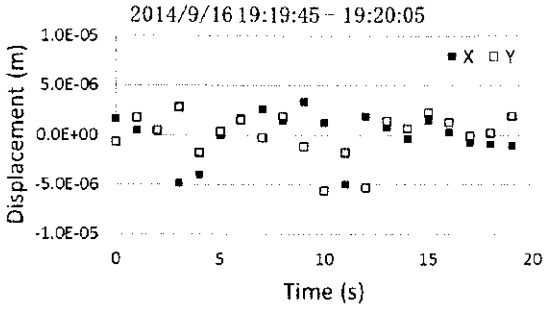

Fig. 13. Variation of center position of a stellar image

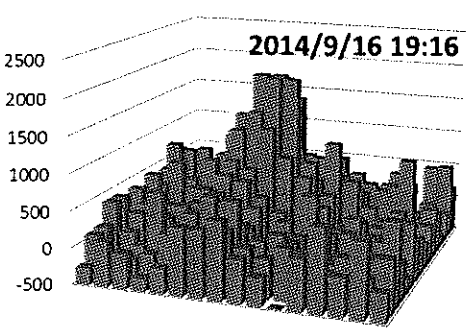

Fig. 14. Example of a stellar image recorded on CCD

We performed field observations in the campus of Mizusawa VLBI Observatory of NAOJ in September of 2014, in order to check the total system of the telescope and the software for the real stars (Fig. 11). It is also important to evaluate the effect of the ground vibrations and temperature change upon the stellar position on CCD. PZT has achieved the accuracy of 0.1 arc second in observations of DOV as mentioned above. Therefore, target accuracy of the field observations was set to be 0.1 arc second.

Several stars of magnitude from 7 to 8 were observed with 1 second exposure time as shown in Fig. 12. We carried out two sets of observations on Sep. 16 and took 20 pictures at intervals of 1 second with the CCD camera in each set. We determined the center position of stars in the field of view by the same way as that for the laboratory experiments.

An example of variation of the center position of a star after fitting to the Gaussian distribution is shown in Fig. 13. The variation of the center position looks larger than that for the laboratory experiments. It seems partly due to smaller SNR of a star image than the laboratory experiments as shown in Fig. 14. Relation between the SNR and the SD for each star in each experiment is summarized in Table 2. The SD ranges from about 1.5×10^{-6} to 5×10^{-6}m (or 0.3 to 1 arc seconds), which is a little larger than that for the laboratory experiments on average, and there is also correlation between the SNR and the SD although it is not very strong.

Table 2

Statistics of variation of stellar position (field observations)

	S/N	SD in X (m)	SD in Y (m)
2014/9/16a	2.18E+02	4.18E-06	5.00E-06
	1.36E+02	3.09E-06	3.17E-06
	1.19E+02	3.62E-06	2.42E-06
2014/9/16b	2.72E+02	2.30E-06	2.26E-06
	3.14E+02	1.91E-06	2.85E-06
	1.93E+02	1.52E-06	1.98E-06
	2.93E+02	1.62E-06	2.66E-06
	1.99E+02	1.77E-06	2.65E-06

Evaluation of the Results

The SD of variation of the center position of stellar image is a little larger in the field observations than in the laboratory experiments, and that there is a correlation between the SNR of the stellar image and the SD of the variation as mentioned above. In order to make it clear, we summarized the relation between the SNR and the SN in Fig. 15. The correlation between the SNR and the SD still holds also for the data sets including both the laboratory and field experiments. In other word, the SD is in inverse proportion to the SNR.

We carried out a simulation in order to investigate the relation between the SNR and the SD. Correlation between these parameters have been confirmed as shown in Fig. 16. Coefficient of inverse proportionality, however, is different between for these experiment and for the simulation. We need to change the scale of the vertical axis of Fig. 16 from the unit of the size of a pixel to the unit of meter in order to compare these coefficient. Considering that the size of a pixel in the CCD used for the experiments is 7.4μm×7.4μm, the SD should be about 1×10^{-5}m for the experiments and be 7.4×10^{-8}m for the simulation if SNR=100. This difference is too large even if we consider the effect of vibrations as mentioned in the section of laboratory experiments. Another possible cause for the difference is deviation of stellar image from the Gauss distribution as can be imagined from Fig. 14. Time variation of stellar image is also possible.

There is also a difference in the dispersion of the stellar position between these experiments and the centroid experiments made by Yano et al. (2004) which showed the dispersion of about 1/300 pixel. If we apply the relation of Fig. 15 to the result of the centroid experiment, the SNR should be about 10,000, which is not plausible. Further investigation will be necessary in order to clarify the cause for these differences.

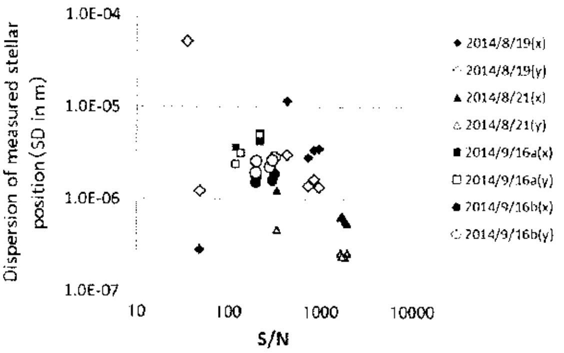

Fig. 15. Relation between the SNR of stellar image and the SD of variation of the stellar position

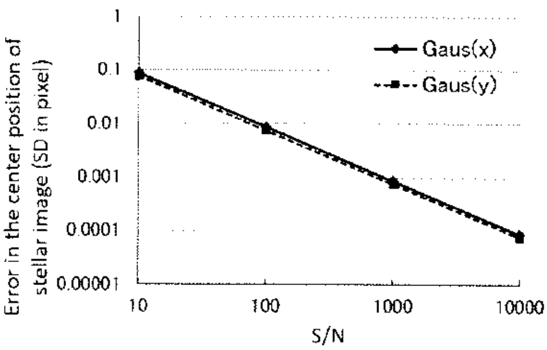

Fig. 16. Relation between error in the center position of stellar image and SNR (simulation results)

Concluding Remarks

We performed the Laboratory and the field experiments by using BBM of the telescope. The dispersion of the stellar position is a little bit larger for the field experiments than the laboratory ones. This difference can be explained by the difference in SNR of stellar images. Anyway the accuracy of better than 0.1 arc-second has been attained in these experiments. This research was supported by JSPS in Japan–Russia Bilateral Joint Research Program (140377l1-000086) for 2014-2015.

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