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# Investigation on a Magnetic Theodolite with the Functions of Both DI and FT Theodolites Combined

by

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## 1. Introduction

The angle measuring instrument at the Kakioka Magnetic Observatory, DI-72 magnetic theodolite, was fabricated and installed during the period from 1970 to 1972. Because almost 30 years have passed since it was installed, various problems associated with its aging and deterioration occur, such as noises generated from the rotary mechanism of a search coil, slip at the micrometer knob, a malfunction of the oscilloscope that displays signal waveforms, etc. It is becoming increasingly hard to collect reliable data by making an absolute observation every week. In this situation, it was thought that a new theodolite should be installed to replace the existing DI-72 magnetic theodolite. At the Kakioka Magnetic Observatory, the "Committee for the Update of Geomagnetic Absolute Observation Instrument" was established with the director of the Observatory as chairman to examine the problems of the existing DI-72 magnetic theodolite and to determine what type of magnetic theodolite is to be introduced. In the course of discussing this matter at the Committee, a magnetic theodolite with the functions of both DI and FT theodolites combined (hereinafter called the DI-FT combined magnetic theodolite) was highlighted as one candidate. (In this paper, the DI magnetic theodolite denotes a theodolite that is capable of measuring the D and I components of the geomagnetic field simultaneously, such as DI-72 and a GSI-type theodolite. The FT magnetic theodolite is a DI flux theodolite, in other words, it has a single core fluxgate magnetometer on a non-magnetic theodolite.) The investigation was conducted using the DI-FT combined magnetic theodolite to collect the necessary data for decision making by the Committee.

The DI-FT combined magnetic theodolite has a dual-axis Fluxgate Magnetometer (FM) sensor mounted on a non-magnetic theodolite and the capability of measuring the declination D and inclination I simultaneously. Although similar investigations were conducted using a ring-core FM sensor by Muromatsu (1987) and Shimizu *et al*. (1996), they encountered interference between sensors and theodolites, as well as difficulty in mounting the sensors properly. As a result, trial observations could not be made. This report describes the results of the trial observations that we conducted using the DI-FT combined magnetic theodolite and the problems encountered during the trial observations.

## 2. Prototyping the DI-FT Combined Magnetic Theodolite

In this investigation, the MO-II magnetic theodolite (hereinafter called MO-II) was used as a theodolite, and the MB-163 made by Shimadzu Corporation was used as an FM sensor. The MO-II is a Wild-Edelmann's magnetic theodolite (made in Germany). It was modified by Sokkisha Corporation and used for absolute measurements at the Memanbetsu Magnetic Observatory during the period from 1960 to 1975. Its scale unit is 0.05' with a vernier in a horizontal direction, and is 0.1' in proportional divisions in a vertical direction. The MB-163 FM sensor was used as a magnetic field direction detector. It has a small sensor block (a Bakelite cube with sides 50 mm in length) containing a solenoid-type dual core for sensing each component. One drawback to this

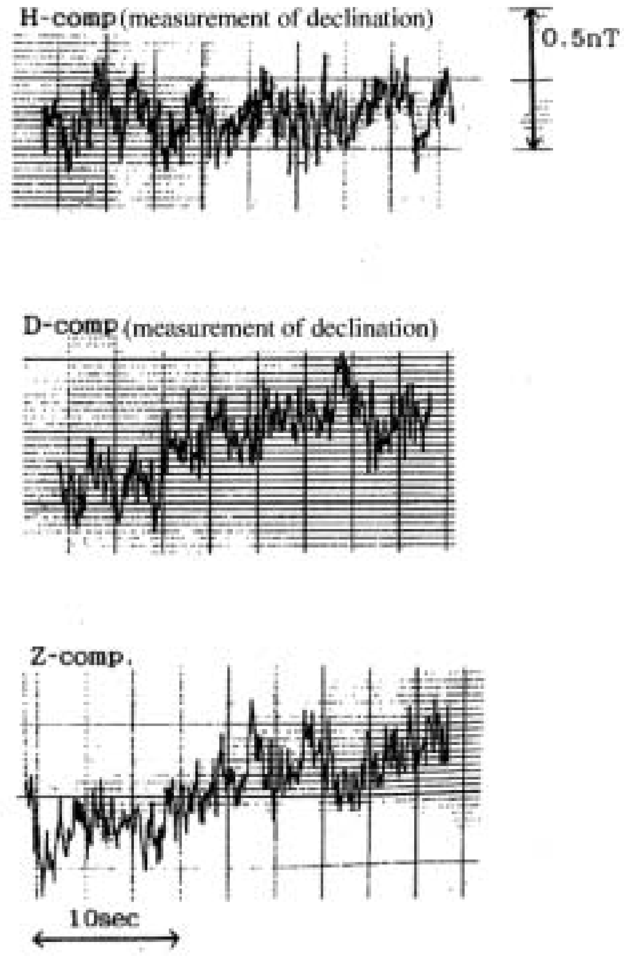



Fig. 1 Noise amplitude of MB-163

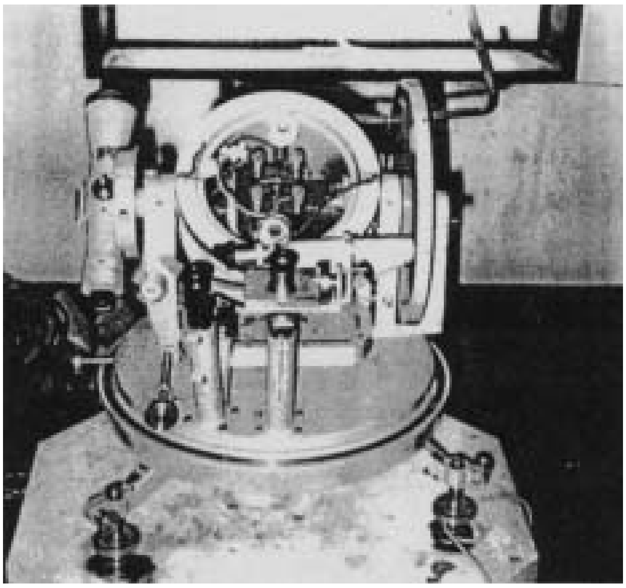


Fig. 2 Prototyped magnetic theodolite

sensor is that the level of noise is rather high, due to the short sensor core. Figure 1 shows the analog output with a filter operated at frequencies from DC to 1 Hz in the 500 nT range. The peak to peak amplitude of noise is about 0.2 nT for each of all three components.

The magnetic theodolite was modified in the steps shown below:

(1) The search coil and the handle were dismounted from the MO-II.
(2) The MB-163 FM sensor was disassembled.
(3) Wires of the FM sensor were connected to the MO-II.
(4) The FM sensor block was mounted on the MO-II.

Necessary parts were cut or carved out of acrylic plates and Bakelite rods with consideration given to the ease of axis adjustment. Using these parts, the FM sensor block was mounted in the middle of the Helmholtz coil frame, as shown in Figure 2.

## 3. Axis Adjustments

For the prototyped magnetic theodolite to function properly, the FM sensor block must be mounted perpendicular or parallel to the portion between the axis of horizontal rotation and the axis of vertical rotation of the theodolite. Mounting the FM sensor block this way is analogous to adjusting DI-72 or a GSI-type magnetic theodolite to obtain uniform measurements with the search coil in all four sensor orientations, that is, the so-called "Up," "Down," "East" and "West" directions. The FM sensors were mounted on the theodolite and adjusted so that the D-axis of the FM sensor is used to measure the declination, and the H-axis was used to measure the inclination, as the FM sensor functions as a search coil. Even if it was carefully adjusted, however, there were inevitably slight angular misalignments in the rotation axes of the theodolite and imperfect perpendicularity in the axes of the FM sensor. Therefore, it should be noted that it cannot be expected to obtain perfectly uniform measurements using the prototyped magnetic theodolite.

Because the D-axis and H-axis of the FM sensor were fixed to each other in the block, the two axes could not be adjusted individually. Therefore, only the D-axis for declination measurement was adjusted. Specifically, the D-axis was adjusted such that it was at right angles to the optical axis of a telescope and in parallel with the horizontal plane of the theodolite. It was adjusted in much the same way as the FT magnetic theodolite mounting of a single-axis FM sensor made by Shimadzu Corporation is adjusted (Kakioka Magnetic Observatory, 1994). The adjustment procedure is shown below:

(1) The theodolite is leveled.
(2) The FM sensor block is turned to the direction "Up," where a "＋" is shown as the Z output. The theodolite is adjusted until the D output becomes 0. The horizontal angle reading is then noted.
(3) The theodolite is turned 180 degrees horizontally so that the D output becomes 0. The horizontal angle reading is then noted.
(4) The horizontal angle of the theodolite is adjusted to the average of the horizontal angle readings noted in (2) and (3) above. The FM sensor block is then adjusted until the D output becomes 0 and the D-axis becomes parallel to the horizontal plane of the theodolite.
(5) The FM sensor block is turned to the direction "Up," where a "＋" is shown as the Z output. The theodolite is adjusted until the D output becomes 0. The horizontal angle reading is then noted.
(6) The FM sensor block is turned to the direction "Down," where a "－" is shown as the Z output. The theodolite is adjusted until the D output becomes 0. The horizontal angle reading is then noted.
(7) The horizontal angle of the theodolite is adjusted to the average of the horizontal angle readings noted in (5) and (6). The FM sensor block is then adjusted until the D output becomes 0 and the D-axis becomes perpendicular to the axis of a telescope of the theodolite.
(8) Adjustments are made by performing steps (2) through (7) repeatedly until the same horizontal angle is obtained in all four sensor orientations, i.e., "Up," "Down," "East" and "West," when the D output is adjusted to 0.

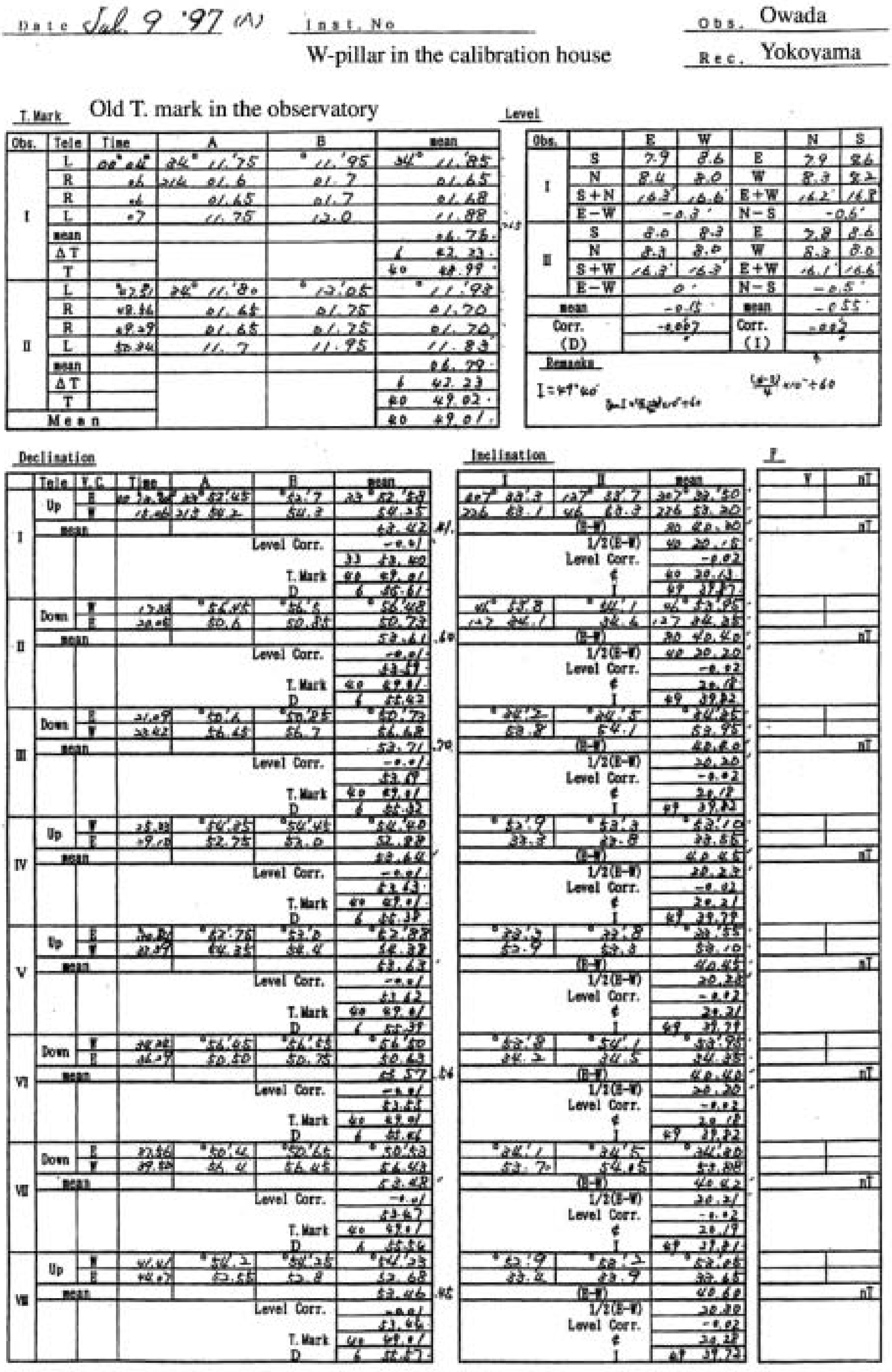
Having a slight misalignment of the axes in the theodolite as described previously and difficulty of fine adjustments with the handmade parts for the FM sensor axes (the block was actually adjusted, not the axes), perfect adjustments could not be made. To compensate for this imperfect axis adjustment, the sensor block was set in 4 different orientations, and the average of measurements made in each of these orientations was adopted.

## 4. Trial Observations and Results

Trial observations with the prototyped magnetic theodolite were made on the west pillar in the calibration house during the period from July 3 through August 13, 1997. The results of the trial observations were processed into the D and I baseline values for geomagnetic field variations measured by the high-sensitivity FM (90FM) and were compared with those obtained by using DI-72. The trial observations were made on the same days when the absolute observations were made by DI-72, as much as possible. The scale unit of DI-72 is 1" in both the horizontal and vertical directions.

The trial observations were made based on the field observation sheet shown in Figure 3, and the same number of measurements as that of DI-72 was obtained. In the case of DI-72, errors caused by the right and left rotation of the search coil must be removed. In the case of the FM sensor, however, those errors do not need to be considered, and therefore, the magnetic theodolite was operated 16 times, which is half the number of times that DI-72 was operated, to take eight measurements. Figure 4 shows the time required for each observer to obtain one round of measurements. That the time bars become shorter from top to bottom shows that each observer became more skillful in operating the magnetic theodolite. Each observer completed measurement in about 50 minutes, which means that the time required for measurement is the same as that made by DI-72. Blank columns titled as "F" in the field observation sheet means that a total magnetic force could not be measured, due to the unavailability of a 6-digit multimeter, although an attempt to do so was made by using the Z-axis.

In calculating the baseline values for 90FM and their standard deviations from the trial observations, instantaneous values of 90FM



Date Jul. 9 '97 (A) Inst. No
W-pillar in the calibration house
Obs. Owada
Rec. Yokoyama

T. Mark Old T. mark in the observatory

| Obs. | Tele | Time | A | B | mean |
|---|---|---|---|---|---|
| I | L | 08h 44m | 34° 11'.75 | ° 11'.95 | 34° 11'.85 |
| | R | 46 | 214 01.6 | 01.7 | 01.65 |
| | R | 46 | 01.65 | 01.7 | 01.68 |
| | L | 47 | 11.75 | 12.0 | 11.88 |
| | mean | | | | 06.76 |
| | ΔT | | | | 6 42.23 |
| | T | | | | 40 48.99 |
| II | L | 47.81 | 34° 11'.80 | ° 12'.05 | ° 11'.93 |
| | R | 48.46 | 01.65 | 01.75 | 01.70 |
| | R | 49.29 | 01.65 | 01.75 | 01.70 |
| | L | 50.04 | 11.7 | 11.95 | 11.83 |
| | mean | | | | 06.79 |
| | ΔT | | | | 6 42.23 |
| | T | | | | 40 49.02 |
| Mean | | | | | 40 49.01 |

Level

| Obs. | | E | W | | N | S |
|---|---|---|---|---|---|---|
| I | S | 7.9 | 8.6 | E | 7.9 | 8.6 |
| | N | 8.4 | 8.0 | W | 8.3 | 8.2 |
| | S+N | 16.3 | 16.6 | E+W | 16.2 | 16.8 |
| | E−W | −0.3 | | N−S | −0.6 | |
| II | S | 8.0 | 8.3 | E | 7.8 | 8.6 |
| | N | 8.3 | 8.0 | W | 8.3 | 8.0 |
| | S+W | 16.3 | 16.3 | E+W | 16.1 | 16.6 |
| | E−W | 0 | | N−S | −0.5 | |
| mean | | −0.15 | | mean | −0.55 | |
| Corr. (D) | | −0.007 | | Corr. (I) | −0.02 | |

Remarks

Fig. 3 Sample of the field observation sheet

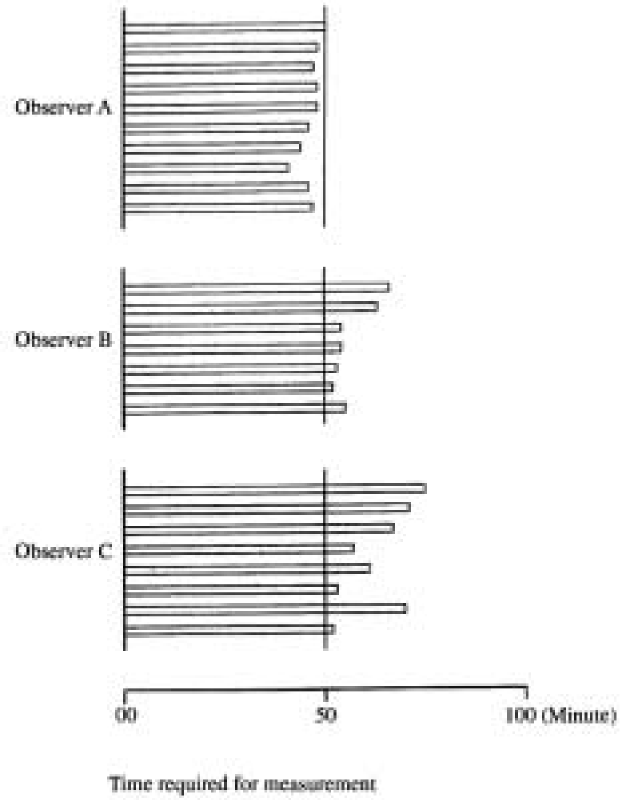



Fig. 4 Time required for measurement by observers

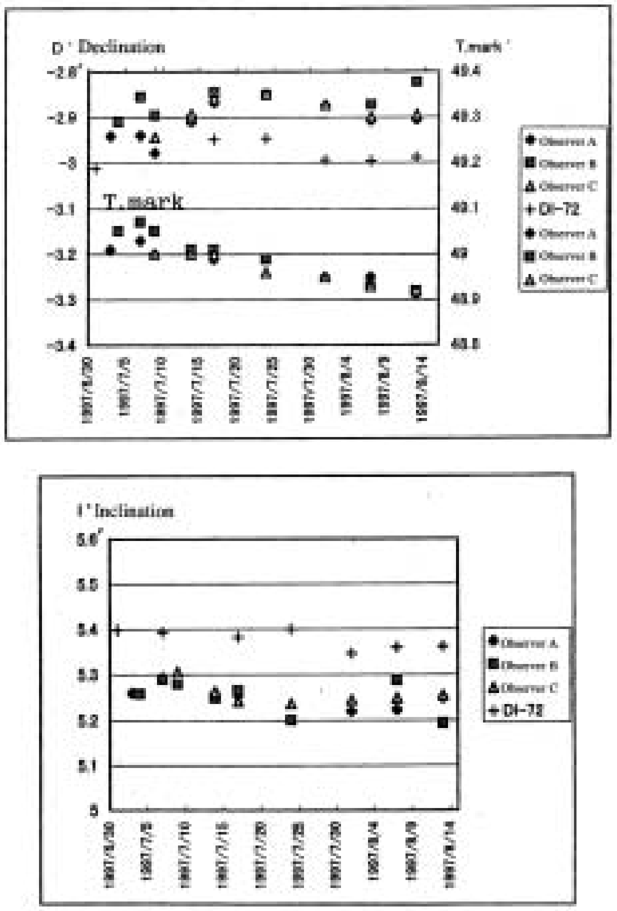



Fig. 5 Comparison between baseline values for 90FM given by DI-72 and those given by the prototyped magnetic theodolite

measured in each trial observation time were extracted and were subtracted from values of the trial observations measured by the DI-FT theodolite, and the average of the differences measured in four different orientations of the theodolite (Up-East, Up-West, Down-West and Down-East) was calculated and adopted as one measurement. (During the period from July 3 through July 14, instantaneous values were estimated by simple interpolation on the one-minute mean values, and the I component of 90FM was calculated based on the H component of 90FM and the F component of the Overhauser magnetometer). Ultimately, the average of four average values and their standard deviations were compared with those measured by DI-72. In Figure 5, the measured baselines of D are shown at the top, and those of I are shown at the bottom. The values of the measured baselines are shown in Table 1. Standard deviations given by DI-72 are larger than those given by the prototyped magnetic theodolite. This is because one round of observation made by DI-72 is divided into first-half and second-half observations, and two persons took measurements, one for the first half and the other for the second half, to minimize errors associated with the skill of observers. Therefore, standard deviations given by DI-72 contain the errors associated with the skill of observers.

After July 17, declination measurements are in good agreement with those given by DI-72. Before July 14, considerable variations are noted. This is thought to be attributed to the fact that observers had not yet gotten fully used to operating the prototyped magnetic theodolite (skills for measurements of a reference azimuth mark, reading values on the scale plate, detecting a zero magnetic field, etc.), and also to the fact that data on the measurements given by 90FM, which was used to calculate baseline values, was processed in different ways. Drift was noted with measurements of a reference azimuth mark (T. mark measurements), but the cause of the drift was unknown.

I measurements taken by the prototyped

magnetic theodolite did not agree well with those taken by DI-72, whereas there is a high degree of agreement between the D measurements taken by them. Table 1 shows that standard deviations of the I component are smaller than those of the D component, although the scale readings of the D component are in units of 0.1'. Because measurements of the D component were taken in the direction at right angles with a horizontal vector, a difference of about 0.7" occurred at Kakioka if there was a remainder of 0.1 nT of the FM output. In the case of the I component, however, the difference is about 0.4" at Kakioka, because measurements of the I component were taken in the direction at right angles to a geomagnetic field vector. Additionally, measurements of the I component did not contain errors by T. mark measurements. This means that measurements of the I component are superior to those of the D component in accuracy. Nevertheless, actual measurements of the I component are somewhat different from those given by DI-72. The cause of this will be explained later in this paper.

## 5. Checking How Measurements Stabilize in a Short Period of Time

To check on how measurements taken by the prototyped magnetic theodolite stabilize in a short period of time, measurements were taken 6 times in total, twice per person on July 14. Figure 6 shows the observed baseline values for 90FM in time sequence. A vertical line crossing through the center of a filled circle (●) shows a standard deviation. A variation of about 0.05' in both D and I components is noted. A review of standard deviations shows that it is unreasonable to interpret this variation as an observation error. We suspected that a difference between geomagnetic field variations at one observation point and another is a factor responsible for this variation. Figure 6 also shows the geomagnetic field variations measured by 90FM when trial observations were made. Figure 7 shows the relationship between the observed baseline values and the geomagnetic field variations. Thick and thin lines show the fitting lines of the baseline values for 90FM and for the Overhauser magnetometer (OHM), respectively, to the geomagnetic field variations measured by 90FM. The coherence between the baseline value and geomagnetic field variation of 90FM is higher than that between the baseline values for OHM and the geomagnetic field variation of 90FM in both the D and I components. The slopes of the fitting lines shows the same tendency. This means that there is a

Table 1 Baseline values and standard deviations for 90FM observed with DI-72 and the prototyped magnetic theodolite

| | DI-72 | | | | Prototyped magnetic theodolite Observer A | | | | Prototyped magnetic theodolite Observer B | | | | Prototyped magnetic theodolite Observer C | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | D | | I | | D | | I | | D | | I | | D | | I | |
| 1997 | obs. BL | S.D. | obs. BL | S.D. | obs. BL | S.D. | obs. BL | S.D. | obs. BL | S.D. | obs. BL | S.D. | obs. BL | S.D. | obs. BL | S.D. |
| JUL. 1 | −1.562 | 0.018 | −0.298 | 0.027 | | | | | | | | | | | | |
| JUL. 3 | | | | | −2.941 | 0.022 | 5.260 | 0.018 | | | | | | | | |
| JUL. 4 | | | | | | | | | −2.910 | 0.014 | 5.258 | 0.009 | | | | |
| JUL. 7 | −1.492 | 0.019 | −0.293 | 0.022 | −2.939 | 0.023 | 5.284 | 0.006 | −2.855 | 0.014 | 5.290 | 0.021 | | | | |
| JUL. 9 | | | | | −2.980 | 0.014 | 5.293 | 0.018 | −2.886 | 0.013 | 5.279 | 0.005 | −2.944 | 0.018 | 5.306 | 0.015 |
| ~ | | | | | −2.968 | 0.017 | 5.265 | 0.011 | | | | | | | | |
| JUL. 14 | | | | | −2.875 | 0.015 | 5.281 | 0.003 | −2.920 | 0.006 | 5.240 | 0.012 | −2.896 | 0.034 | 5.255 | 0.024 |
| ~ | | | | | −2.945 | 0.019 | 5.224 | 0.009 | −2.893 | 0.019 | 5.258 | 0.006 | −2.890 | 0.023 | 5.270 | 0.009 |
| JUL. 17 | −1.499 | 0.007 | −0.283 | 0.023 | −2.868 | 0.010 | 5.254 | 0.005 | −2.846 | 0.019 | 5.265 | 0.004 | −2.859 | 0.018 | 5.241 | 0.015 |
| JUL. 24 | −1.497 | 0.024 | −0.299 | 0.031 | | | | | −2.851 | 0.009 | 5.200 | 0.014 | −2.849 | 0.017 | 5.236 | 0.019 |
| AUG. 1 | −1.544 | 0.021 | −0.247 | 0.031 | −2.874 | 0.011 | 5.219 | 0.012 | | | | | −2.873 | 0.015 | 5.244 | 0.017 |
| AUG. 7 | −1.546 | 0.030 | −0.260 | 0.044 | −2.908 | 0.021 | 5.223 | 0.006 | −2.873 | 0.024 | 5.288 | 0.010 | −2.900 | 0.023 | 5.248 | 0.016 |
| AUG. 13 | −1.540 | 0.017 | −0.262 | 0.029 | −2.906 | 0.010 | 5.249 | 0.006 | −2.824 | 0.009 | 5.193 | 0.005 | −2.895 | 0.021 | 5.254 | 0.034 |
| | mean | 0.019 | | 0.030 | | 0.016 | | 0.010 | | 0.014 | | 0.010 | | 0.021 | | 0.019 |

* In the case of DI-72, measurements were taken by dividing one round of observation (8 measurements) into a first-half part and a second-half part, and one person took 4 measurements in the first-half part, and the other person took 4 measurements in the second-half part. S.D. is simply calculated from 8 measurements. Because measurements taken by DI-72 contain individual differences and other errors, the measured values are larger than those taken by the prototyped magnetic theodolite.

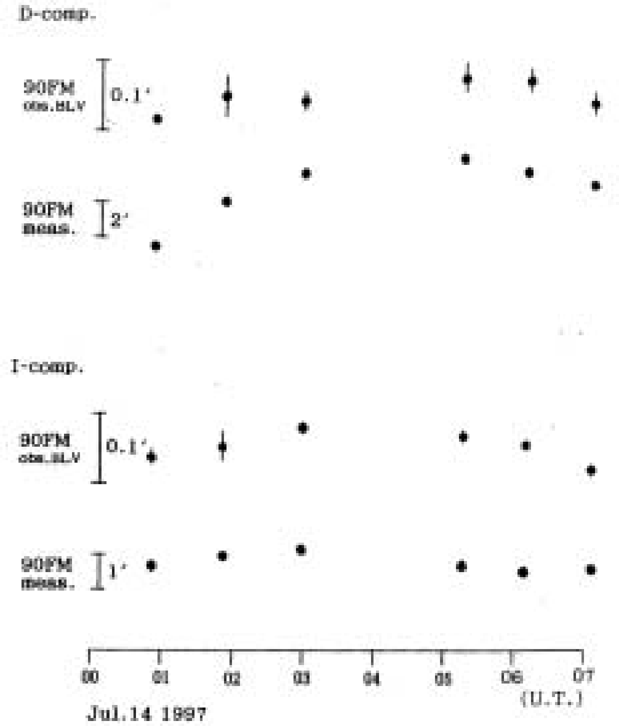



Fig. 6 Observation baseline values for 90FM given by the prototyped magnetic theodolite

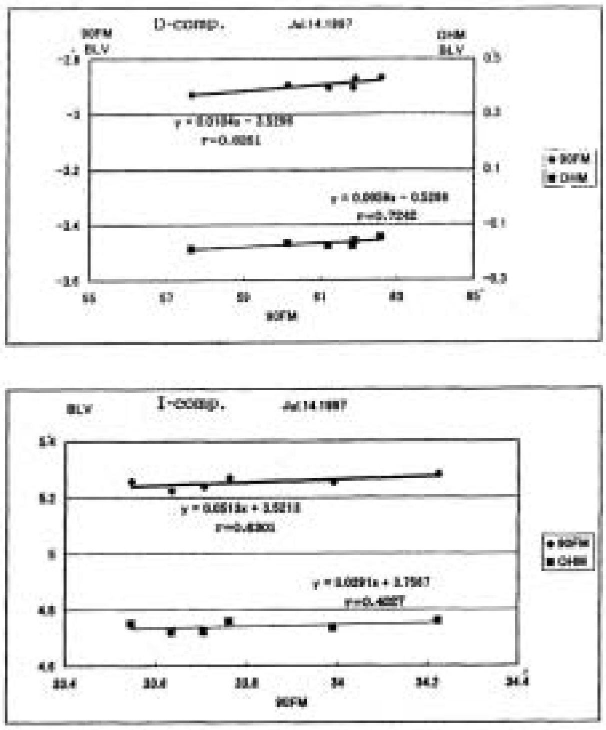



Fig. 7 Relationship between the geomagnetic filed variation measured by 90FM and the observed baseline values

difference between the geomagnetic field variation at the point where 90FM is installed and that at the calibration house where trial observations were made. The slopes of the fitting lines for OHM, which is located closer to the calibration house, are about half of those for 90FM. Additionally, the slopes of the fitting lines in the I component are about five times larger than those in the D component. This indicates that the difference between the geomagnetic field variation at one observation point and that at another affects the results of measurements taken on one day. Considering the short distance of 250 m between the two observation points, however, the difference of 5% in the I component would be too large. Additional observation is necessary to specify whether the cause of this is the measurement location or the structure of the observation house, etc., by conducting a continuous observation using fluxgate or proton precession magnetometers in the calibration house.

## 6. Verifying the Factors Responsible for Observation Errors

This chapter describes the observation errors of the prototyped geomagnetic theodolite.

### 6.1 Errors caused because the H-axis of the FM sensor is not at a right angle to the D-axis during observation of I component

The errors caused because the H-axis of a fluxgate magnetometer (FM) is not at a right angle with the D-axis during inclination measurement are identical to the errors caused by a displacement of the FM sensor axis from a magnetic meridian plane during I measurement using a conventional FT-type magnetic theodolite. Therefore, the error can be expressed by the following equation:

$$\tan(I) = \cos(\alpha) \times \tan(Ie)$$

where I is a true inclination, α is an angle of displacement of the FM sensor axis from a magnetic meridian plane, and Ie is an inclination containing errors. Assuming an allowable error is 0.004' (0.24"), considering that the I component is presented in units of 0.01', α is 7' 28".

Because the angle of displacement ∠HD between the H-axis and D-axis of the FM sensor is about 33', the observation error is 4.7". However, this error is canceled out by changing the orientation of the FM sensor during measurement.

### 6.2 Errors caused because the FM output is not 0nT during the detection of magnetic field direction

If the FM output is not 0nT during D and I observation (assuming that there is no offset), the errors can be expressed as follows:

Declination: Error" $= \sin^{-1}$ (d/H)

Inclination: Error" $= \sin^{-1}$ (d/F)

where d is a value output by FM, H is a horizontal component, and F is a total magnetic force.

Assuming that the FM output is 0.1nT, an error of 0.7" for D and an error of 0.4" for I would be observed. Because the FM used in the trial observations had a short sensor core, the level of noise was high. The peak to peak amplitude of FM noise generated through the analog output was about 0.2nT (i.e., ± 0.1nT), which causes errors of ± 0.7" and ± 0.4" to the D and I measurements, respectively. Actual measurements show that the level of noise is ± 0.2nT. Therefore, it is appropriate to estimate the errors at ± 1.4" for D and ± 0.8" for I.

## 7. Summary

New findings obtained from the results of the trial observations by the prototyped magnetic theodolite are as follows:

(1) It is possible to take measurements of both the D and I components simultaneously.

(2) Measurements of the D component are in good agreement with those taken by DI-72. Although the measurements of the I component are somewhat different from those taken by DI-72 due to a difference in the geomagnetic field variation between the observation points, the overall measurement results were satisfactory.

(3) More individual differences among observers are noted in the D measurements than in the I measurements.

(4) The standard deviation of the measurements taken in one round of observation is similar to that of the measurements taken by DI-72.

(5) It takes about 50 minutes to complete one round of observation. This time length is about the same as the time required to complete one round of observation with DI-72.

(6) One-handed operation makes observation easier.

(7) There is no sign of interference with the magnetic theodolite that was observed in the case of the ring-core sensor. (An engineer of a manufacturer says that the cause of interference may be a high excitation frequency in the case of the ring-core sensor.)

The problems noted during the trial observations are as follows:

(1) A high level of noise did not make measurement easy:
Hand detailing was not easy around 0 due to a high level of noise.

(2) The long interval with which FM produces digital output (display) did not make measurement easy:
Because FM produces a digital output (display) around once every second, the operator must wait for update of the display, so that hand detailing is not easy around 0. Hand detailing will be made much easier if the output interval is changed from once to twice every second.

(3) The small diameter of the fine-adjustment knob did not make the I component measurement easy:
Because measurements of the I component were made in the direction perpendicular to a geomagnetic field vector and those of the D component were made in the direction perpendicular to a horizontal vector, the sensitivity with which the I component was measured was about 1.8 times higher than that with which the D component was measured. With this prototyped magnetic theodolite, the fine vertical adjustment knob was smaller than the fine horizontal adjustment knob, and this did not help fine adjustments very much. An acrylic cap was attached to increase the diameter of the fine vertical adjustment knob. As a result, a considerable improvement was made.

It is judged from the above summary that the DI-FT combined magnetic theodolite can be put to practical use. If a magnetic theodolite can be developed by combining the theodolite equivalent to DI-72 and the FM sensor with a low level of noise, we will be able to increase the level of observation accuracy to that of DI-72 or to achieve an even higher accuracy level.

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