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Evaluation of KVH C100 compasses for use in CAL MODS

What follows are the results of several weeks of experiments run to test the KVH C100 flux-gate compass. We attempted to confirm that the compasses measured up to manufacturer's specifications and Dumand expectations in regards to calibration, angle reproducibility, relative angle change, and agreement between compasses. We found the compasses to be, on the whole, extremely accurate and useful once one understands the conditions needed for maximum accuracy. The compass is surprisingly sensitive to distortions in the earth's magnetic field induced by the presence of any ferromagnetic material and also to tilt. However, once moved at least 2 meters away from all metal shelves, floor and ceiling beams, wrenches, etc., the C100 performed admirably as long as it wasn't tilted between readings. In fact, the compasses performed well enough to allow us to measure, with statistical significance, a diurnal change in the external component of the earth's magnetic field -- an effect that spans only .3 degrees.

Motivation

The primary justification for installing compasses in the CAL MODs is that the vertical riser cables shadow a region of the ocean, and strings in this shadowed region will receive only indirect illumination from scattered light. The compass mounted in a CAL MOD determines the angular orientation or heading of the module so that the shadow regions can be determined. The accuracy required from the direction measurement is that the direction uncertainty be small compared to the angular width of the shadow. The riser cables are about two feet apart so each is a foot from the scintillator ball. The size of the riser cables varies from about two inches in diameter near the SCC to very small at the top and bottom of the array. We take 1.5 inches as a typical size. The illuminated spot size and uncertainty in aiming the laser is approximately an inch. Thus the maximum extent of the suspected shadow region is (2.5/12) radians or about 12 degrees, and a compass heading accuracy of about a degree is adequate to locate the shadow region. We will also be interested in measuring the rotation and twist rates of the strings. These rates are likely to be extremely slow, so the capability of measuring small rotation angles will permit measurement of rotation rates in shorter times.

Previous Results

Jeff George, a physics graduate student with Dumand at the University of Washington, tested the KVH and other compasses. He found an accuracy of .2 degrees or better and repeatability within .2 degrees. He also found that the compass is affected by vibration. "Only on the longest damping, 24sec, did I get the .5 deg rated accuracy while tapping the head." In addition, he found that tilt does indeed affect the compass reading. Using the model with the gimbal in it (which is supposed to be OK for tilts up to 45 degrees) he found that the gimbal itself has 2 to 2.5 degrees of play in it and also that (with the gimbal fixed) a 5 degree tilt changed the read-out by .3-.4 degrees. Finally, he tried to test the effect of currents near the compass, but eventually concluded that the change he saw was due to the presence of alligator clips near the compass and not to the current in the wire near the compass. (He found that the calibration routine is excellent for constant magnetic environments, but its of no use for any changes in that environment -- for instance the change caused by bringing alligator clips within a few centimeters of the compass.)

The results quoted above are from tests that "were sort of rough." The compass was turned on a piece of paper and lines were drawn along the edge of the board. Relative angles were then calculated from the slopes of these lines. One of the final suggestions of that report was to come up with some way to measure angles precisely and then repeat the tests.

Experimental Set-Up

We mounted three compasses on a platform which was bolted to a (plywood) table in such a way that the platform could rotate to any angle and the table could be tilted at angles up to 10 degrees. The platform was attached to a meter-long "pointer" which allowed us to determine the angle through which the platform had been rotated to within .1 degrees. The table was originally located about .8 meter off the floor near the side of our lab, but we found that using compass readings to measure relative angles did not agree with the angles computed through trigonometry. A digital hand-held compass (Autohelm Personal Compass) confirmed our suspicion that a set of metal shelves was the culprit. The reading on the hand-held compass changed by as much as 30 degrees when moved (without rotation) to within 20cm of the shelves! Eventually, we relocated our table to the middle of the room, pushed all shelves and tables toward the walls, raised the platform 1.2 meters above the floor, and repeated our experiments. They turned out much better and the rest of the results quoted in this paper are all from the latter set-up.

The Autohelm compass proved very useful in finding a location for our set-up which was unaffected by local distortions in the earth's magnetic field. We slid the compass along the edges of the table and looked to see if its reading changed. When it did, we knew we needed to move the table to a different location in the laboratory because something was distorting our measurements.

All of our compass readings were taken using a VAX 3600 which could take readings from three compasses within milliseconds of each other. Data was taken using the RS232 compatible port configured to 300 Baud. The compass readout in this mode is an ASCII formatted reading to one tenth of one degree. (Where measurements are quoted to hundredths of degrees it is because that reading was found by averaging 60 measurements taken at one second intervals -- we did find occasional erratic readings and therefore we highly recommend some sort of averaging technique using multiple compasses or multiple readings so these fluctuations can be eliminated.) Six different compass were used in the tests described and were found to be indistinguishable. Brief experiments also convinced us that the compasses do not interfere with each other when mounted near each other and operated simultaneously (we had them 12cm apart). The power wires and computer leads do not seem to affect the compasses either.

Calibration

The KVH C100 compass microprocessor is designed with an eight-point calibration routine programmed into it. The routine is designed to familiarize the compass with its magnetic environment and to compensate for local distortions in the earth's magnetic field. The C100 does a good job of compensating for ferromagnetic materials that rotate along with it, as would be the case on a ship, but it is important to keep in mind that the calibration algorithm compensates only for this class of distortions.

We set the compass to a known angle and then brought two wrenches within 30cm of the compass. The presence of the iron in the wrenches caused a distortion in the earth's magnetic field which changed the reading of the compass by about 5 degrees. We then left the wrenches in place and recalibrated the compass. When the iron was taped to the rotating platform, the compass was able to compensate for it and after recalibration it gave the same results that it had given before the wrenches had been taped to the platform.

However, when the wrenches were taped to the table (and thus did not rotate when the compass was rotated for calibration), the compass was unable to compensate and correct itself even after it was recalibrated -- deviating from prior measurements by as much as 100 degrees!

Angle Reproducibility

The manufacturer states that the C100 should be accurate within .5 degrees and that angles should be reproducible to within .2 degrees. We had no means of testing the absolute accuracy of the compass to within better than a degree or two. (It agreed with our hand-held compass to within the latter's accuracy.) However, we did spent significant time testing the C100's ability to reproduce angles and also to measure relative changes in angle.

We found that the C100 does a near-perfect job of giving the same value for the same angle when moved away from a point and then back again. [See Table 1] Using the same compass and without recalibrating, we were able to reproduce angles to within .1 degrees or better. Using different compasses gave us differences of as much as .2 degrees. It is interesting to note that the difference between compasses does not seem to be in the compasses themselves, but rather in the calibration routine. Calibrating the same compass in the same environment leads to errors of .2 degrees. That is, recalibrating the same compass introduces the same amount of error as using a different compass.

Measurement of Relative Angle Change

Before building our table and platform we derived a trigonometric equation that would allow us to independently measure the angle a compass is rotated through and compare this to the difference in compass readings. Basic trigonometry yields:

theta = Arccos[1-(c^2/(2 L^2))]

where L is the length of the pointer, theta is the angle the compass is rotated through and c is the (straight line) distance the end of the pointer moves. Simple error analysis shows that this method is excellent at small angles -- an error of 1mm in c translates into only a few hundredths of a degree of error in theta. At 45 degrees that 1mm error becomes a .1 degree error in theta while at large angles (approaching 180 degrees) the error increases dramatically. (This problem can be avoiding by measuring large angles as the sum of small angles.) Our pointer was 93.25cm long and we used angles that covered a total of almost 180 degrees.

Several compass were rotated to several different points. When the differences in compass readings were compared to the trigonometric values for angles, they were found to agree to within 1/4 degree. [See Table 2] The worst agreement found for any pair of points was .3 degrees. Typical disagreements were on the order of 0.3%. In addition, our metersticks were probably introducing at least as much error as the compasses.

We conclude that the KVH C100 flux-gate compasses provided a very accurate measure of rotation. They can be trusted to correctly measure a change in orientation within at least .3 degrees.

Sensitivity to Tilt

When nothing else is varied, the effect of a change in tilt of as little as a few degrees can be seen. We tilted our table by as much as 7.5 degrees and observed that the compass reading changed by as much as one degree. [See Figure 2 -- note that "0" was only defined by convention and was not perfectly level] For more reasonable tilts of 5 degrees or less, the read-out changes by .4-.5 degrees. We turned the compass platform so that the table was tilted parallel and perpendicular to the compasses and saw the same effect at each orientation. This means that the compass will still do a good job of measuring relative changes in angle when tilted, however, comparing tilted to untilted readings will introduce a sizable error.

In order to take full advantage of the precision offered by the KVH

C100 compass, it is necessary to consider and correct for the angle at which the compass is tilted. Dumand may not need to worry about this effect because it is drowned out by other errors unless the compass is tilted by more than 2-3 degrees. However, it should be kept in mind. It is not known how the manufacturer concluded that the compass only varied by .3 degrees when tilted by 15 degrees.

Damping

We were able to find no significant difference in the performance of the compass when set to different damping modes. Predictably, the compass took longer to "settle down" to an answer when in 24-second mode than when in 3 second mode. In addition, it seemed to fluctuate less in the longer modes. However, we were able to detect no positive or negative change in accuracy or performance when damping was varied as long as measurements were made after a suitable wait. Since we expect very slow rotations in the ocean, we see no reason to recommend one damping setting over another.

Susceptibility to Temperature and Voltage Changes

The C100 stands up well under significant changes in temperature and voltage. [See Tables 3&4] We heated one compass by 20 degrees Celsius and were unable to see any systematic change in its readings or performance as it was heated, when it was heated, as it cooled, or after it cooled. In addition, we were unable to detect any change in performance as input voltage was varied from 8V to 16V.

Diurnal Changes in the Earth's Magnetic Field

We left the compasses running for days at a time and plotted hourly averages of the compass readings. These graphs showed a reproducible 24-hour cycle that bottomed out around 8am and peaked in mid-afternoon. [See Figure 1] The compass reading changed by as much as .3 degrees even though the compass was never moved. The pattern was seen in different compasses set at different angles on the same and different days.

Our first hypothesis was that the compasses were temperature dependent and were just telling us that air conditioning gets shut off over night. However, as described above, we were unable to see any systematic change in their readings when temperature was changed by as much as 20 Celsius degrees. Our second hypothesis was that the power must fluctuate overnight, but the compasses were also shown to be insensitive to changes in power supply voltage.

Finally, we found that we had rediscovered an effect first seen 270 years ago when a compass needle was put under a microscope. (See Merrill and McElhinny's The Earth's Magnetic Field or Parkinson's Introduction to Geomagnetism for in depth discussions of everything). Since then many tests at many sites have shown that the components of the earth's magnetic field vary slightly in intensity and direction over the course of the day. The variation is not the same every day, but is usually at least similar. The main cause of this diurnal variation is attributed to the sun heating the upper atmosphere. This temperature change causes the current in the upper atmosphere to flow differently and those changes in current flow change the externally produced contribution to the earth's magnetic field. (The earth's magnetic field is due mostly to the earth's mantle and core, but there is a significant contribution from currents in the upper atmosphere. This latter contribution is the part that shows a diurnal variation which we feel confident we have seen.)

Most books measure the change in intensity of the horizontal and vertical components of the earth's field rather than its direction. However, since the C100 compass derives its direction reading from the intensities of these components, it is effectively measuring changes in intensity and reporting them as changes in direction. Calculations convinced us that the .3 degree variation we saw corresponds to the 50-100 nanotesla variation in the north and east components of the earth's magnetic field that has been measured near Nashville's latitude.

While this observation may not be directly relevant to Dumand, it does provide an excellent demonstration of the compasses' accuracy and sensitivity. In addition, it shows that we would have to include time dependent corrections to magnetic north in order to utilize the full accuracy available with the KVH compass.

Conclusions

Our most important conclusion is that the C100 compass is easily thrown off by any metal within 2,3, or maybe even 5 meters (that does not rotate with the compass). In order to obtain precision results, every effort must be made to place the compass in a "clean" magnetic environment. If the compass is to be used in a laboratory it should be mounted halfway between the floor and ceiling and away from all metal. This means it should be on an all-wood platform away from all walls, shelves, metal benches, chairs, tools, and even power supplies. In addition, every effort should be made to mount the compass on a level platform and if the compass is going to tilt during operation (and accuracy to within 1/2 degree or better is desired), that tilt should be corrected for. If these precautions are taken, the KVH C100 flux-gate compass has proven to give all-purpose readings that are accurate within at least .3 degrees.

Acknowledgements

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Table 1 - Angle Reproducibility

We picked five random points and tested different compasses under the same and different calibrations to see if they all gave the same readings. "R" means the compass was recalibrated. These results were all taken at approximately the same time of day, so they are not much affected by the diurnal change in the earth's magnetic field described near the end of this report. Each reading represents the average of a number of readings taken at 1-3 second intervals.

Point	C-1	C-1	C-1 R	C-1 R	C-1 R	C-2	C-2	C-2 R
1	243.94	243.94	243.90	243.80	243.80	243.82	243.83	243.80
2	256.10	256.13	256.10	256.00	256.13	256.10	256.10	255.95
3	303.14	303.20	303.40	303.20	303.40	303.15		303.00
4	335.00	303.07	335.28	335.07	335.30	334.90	334.88	334.64
5	189.04	189.05	188.93	188.92	188.91	188.70		188.70

Table 2 - Relative Angle Change

We used trigonometry and a ruler to calculate the angle through which a compass was rotated and compared that to the difference in the compass' readings. The results are presented below.

Change according to trig.	Change according to Compass 1	Compass 2	Compass 3
12.25	12.20	12.30	12.23
32.06	32.14	31.86	31.75
47.10	47.20	47.15	47.15
59.50	59.30	59.50	59.40
79.20	78.90	79.01	78.78

Table 3 - Temperature Dependence

We heated the compass by 20 degrees Celsius and took angle readings as it cooled. No trend appeared. The temperature readings are approximations made by placing a thermometer under the compass.

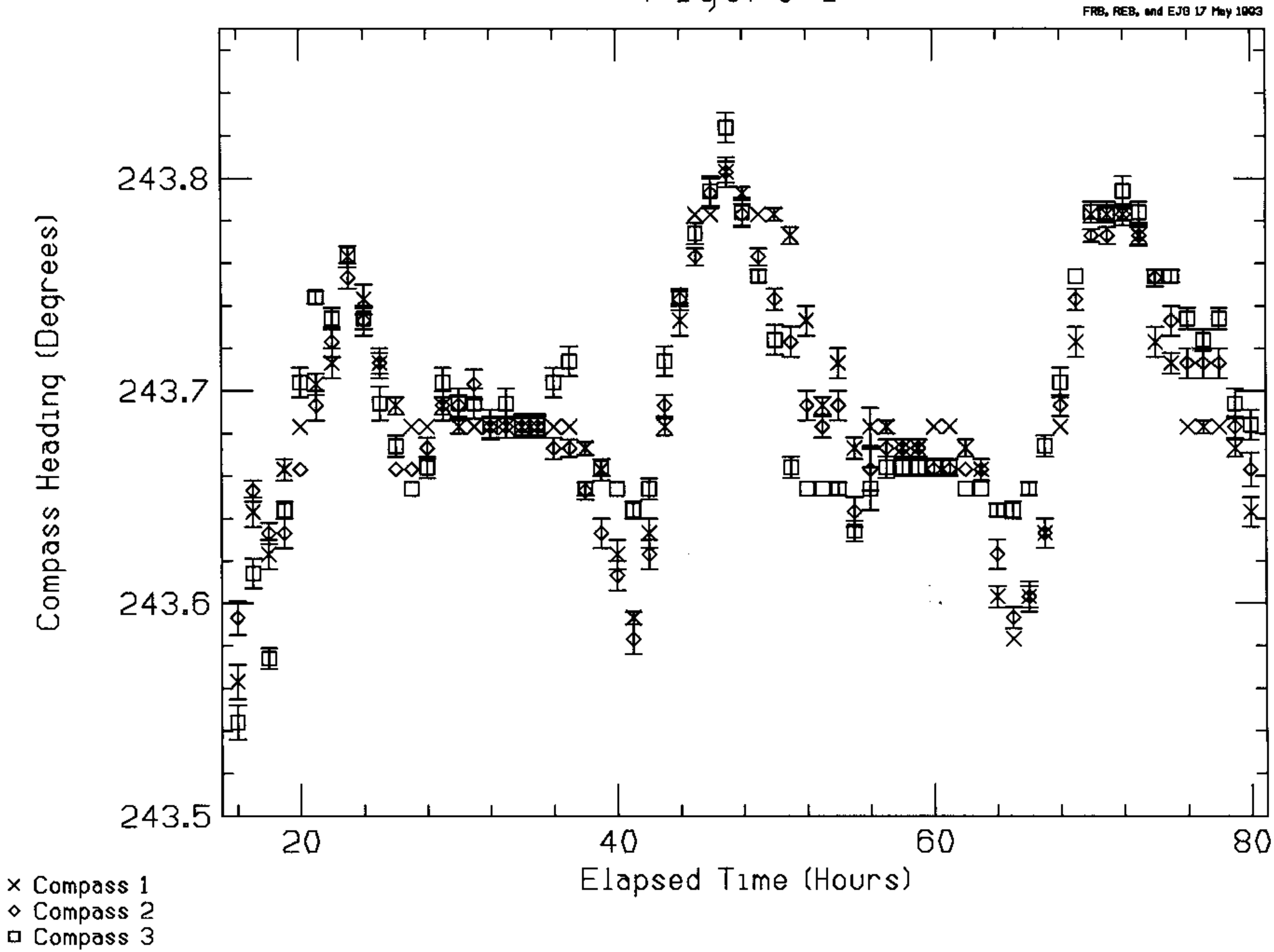
Temperature	Reading
23.7	243.8
44.1	243.9
42.0	243.9
40.1	243.9
38.5	243.9
37.0	243.9
35.5	243.9
35.2	243.8
34.4	243.8
33.8	243.9
33.3	243.8
32.7	243.8
32.4	243.8
32.0	243.9
31.7	243.8
31.4	243.8
30.9	243.8
30.3	243.8
30.2	243.8
29.6	243.8

Table 4 - Voltage Dependence

We hooked up three compasses simultaneously and pointed them in the same direction. We then varied input voltage and observed the compass readouts. The slight disagreement between compasses is believed to be due to small differences in their magnetic environments.

Voltage	Compass 1	Compass 2	Compass 3
8.7	243.77	243.31	243.42
10	243.77	243.31	243.50
12	243.70	243.30	243.50
14	243.70	243.30	243.50

Figure 1



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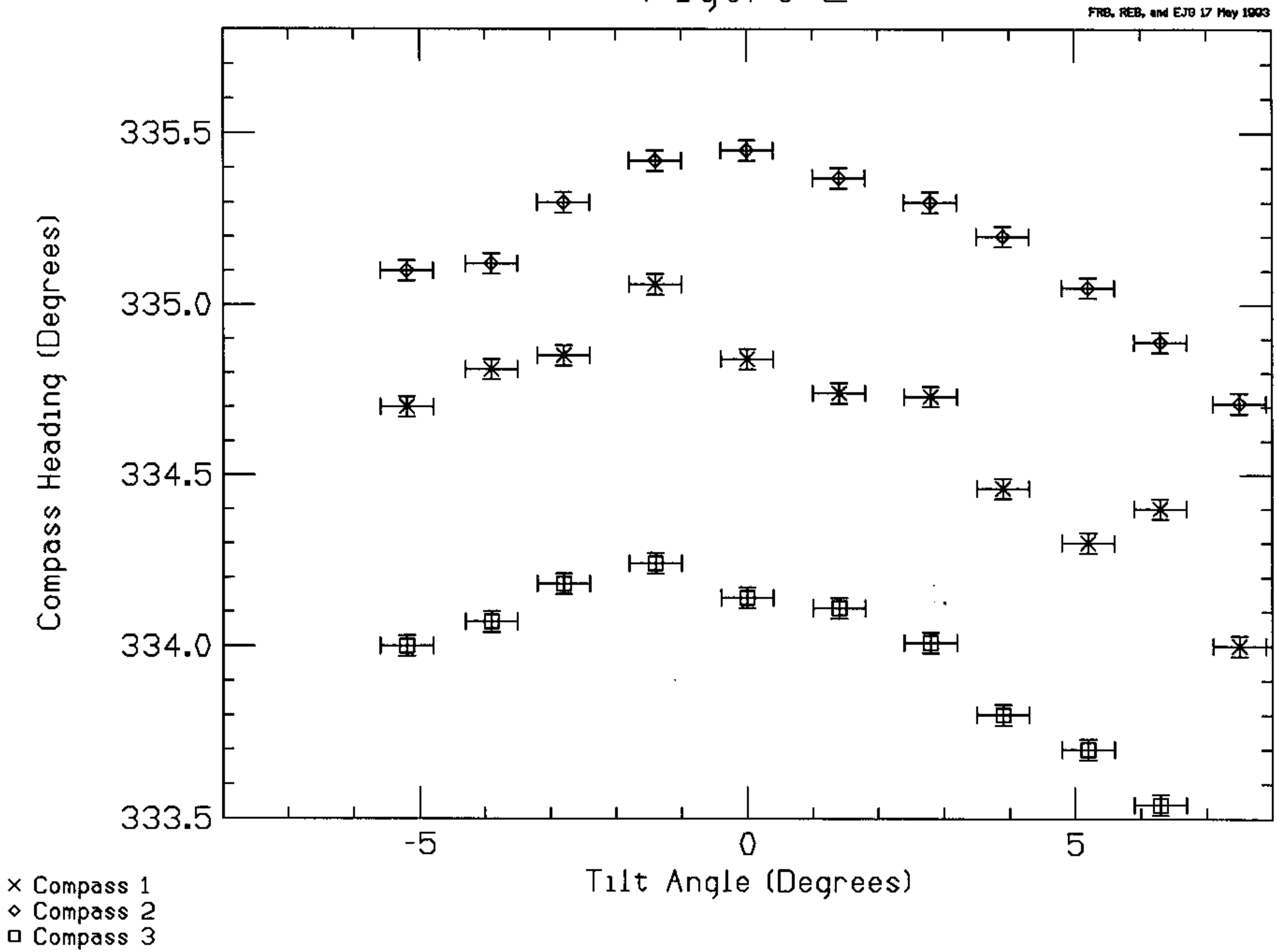
243.8
243.7
243.6
243.5
20
40
60
80
Compass Heading (Degrees)
Elapsed Time (Hours)
× Compass 1
◇ Compass 2
□ Compass 3

Figure 2



FRB, REB, and EJG 17 May 1993
335.5
335.0
334.5
334.0
333.5
Compass Heading (Degrees)
-5
0
5
Tilt Angle (Degrees)
× Compass 1
◇ Compass 2
□ Compass 3