Real Sky Performance of the Prototype Ørsted Advanced Stellar Compass

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Abstract— The Danish microsatellite, Ørsted, is quipped with an autonomous, advanced stellar compass (ASC). The ASC consists of two separate units, a Charge Coupled Device (CCD) camera head (based on a commercial Sony interline CCD detector) and a data processing unit with a powerful microcomputer (Intel 80486 type processor). The microcomputer memory contains a star catalogue which enables the microcomputer to recognize the constellations of stars in the field of view and thus derive the attitude of the ASC camera head.

operational

The mission, and the design, operation, and performance of the ASC are described. Results of ASC prototype tests at the JPL Table Mountain Observatory (TMO) facility are given.

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1. INTRODUCTION: THE ØRSTED PROJECT

The purpose of the Danish Ørsted micro-satellite project is to perform an accurate mapping of the Earth's magnetic field. The scientific objective of the Ørsted project is to improve our understanding of the origins of this field, and its interaction with the solar wind [1].

It has been more than a decade since the last precision mapping mission, NASA's Magsat, ended. Ørsted may be regarded as a follow-on to it, The Ørsted mission has international support. The U.S. effort is coordinated by NASA and includes GSFC and JPL, science data analysis and interpretation, Air Force or NASA satellite launch in March of 1997, a JPL supplied global position ~~receiver~~ (GPS) receiver, and JPL test and evaluation of the ASC.

The Ørsted microsatellite has been enabled by two major technical developments. The first one is the availability of high reliability, low cost, low power consumption electronics. The second one is the availability of low cost launch opportunities as secondary (piggyback) payloads on launch vehicles such as the French Ariane and the U.S. Delta rockets.

The Ørsted payload includes a vector fluxgate magnetometer, an Overhauser scalar magnetometer, an ASC [2], six charged particle detectors, and a Turbo Rogue Global Position (GPS) receiver. Mission requirements are to determine the magnetic vector accuracy to at least 3 nT and 20 arcseconds.

The physical characteristics and orbit of the Ørsted microsatellite are given in Table 1. An 8 meter long deployable boom carries the two magnetic-field measuring instruments and the ASC as shown in Figure 1 and the block diagram in Figure 2. The boom isolates the instruments from the perturbing magnetic field generated by the satellite main body. Satellite attitude control is by gravity gradient stabilization, supplemented by active magnetic-torquer coils. The Position is determined by the GPS receivers.

The primary purpose of the ASC is to provide a reference coordinate system to the vector magnetometer. The secondary purpose is to

Table 1. Microsatellite physical properties

Parameter	Value
Mass:	61.4 kg
Width:	45.0 cm
Depth:	34.0 cm
Height:	68.0 cm
Boom:	8.0 m
Power:	Solar panel/batteries, avg. 54/22 W
Stabilization:	Gravitational/magnetic-torquers
Orbit:	Polar, 450 x 850 km

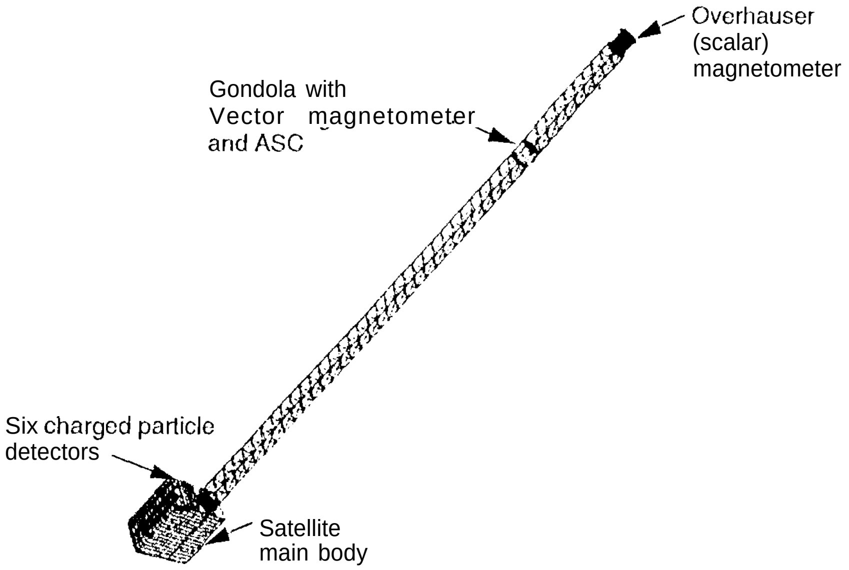

Figure 1. Drawing, of the Ørsted microsatellite with boom deployed

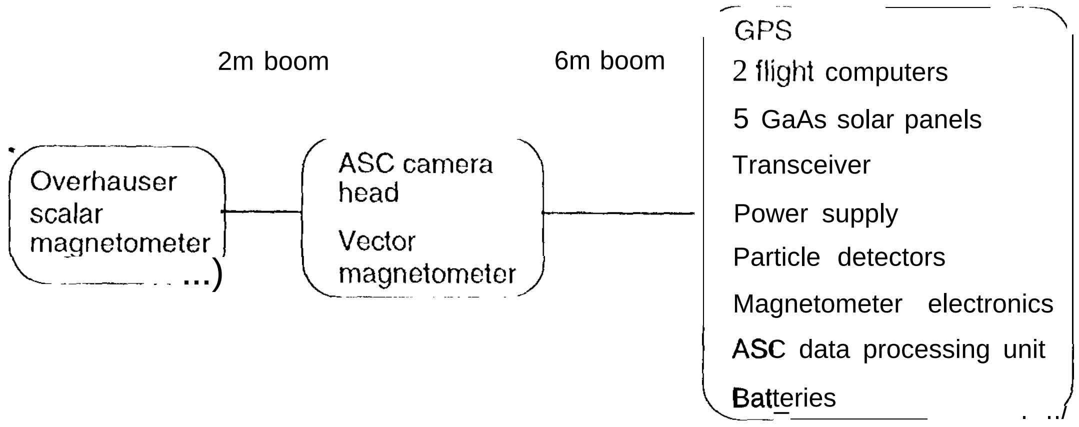

Figure 2. Ørsted block diagram

provide data for attitude control use. The ASC camera head and vector magnetometer are integrated into a common Si-SiC optical bench.

2. THE ADVANCED STELLAR COMPASS

Only one attitude reference frame exists that fulfills the need for the high accuracy required to support the vector magnetometer- the celestial coordinates of the stars on the firmament. This reference frame has an intrinsic, average accuracy of better than 0.3 arc-second per star. The ASC operates in the stellar reference frame and outputs an attitude quaternion [3] based on the highly accurate celectrial coordinate system,

In order to provide the computing power necessary to fulfill the task, utilization of a powerful microcomputer is unavoidable. Such computers consume a substantial amount of power and the electric noise from such devices contain frequencies from 0 to 50+ MHz and have magnetic and highly conductive. materials (e. g., the aluminum housing). Since the camera head must operate in close proximity to the vector magnetometer, and the computer does not have to, the computer is separated and moved to the satellite main body. This, then> is a straightforward approach to minimizing magnetometer interference from the ASC. The resulting two ASC components are shown in sounding rocket (Thunderstorm 111) configuration in Figure 3 [4]. Thunderstorm III was launched in September of 1995 and was the first space flight operation of the ASC.

The camera head is based on a commercial interline micro-lens CCD; the SONY CD X039 AL and its companion CMOS decoder and driver chips. The CCD has a resolution of 752 by 582 active. pixels, each with a dimension of 8.6 µm by 8.3 µm. The mass of the camera head is 170 g and it consumes 0.5 watts. It is depicted in Figure 4.

A customized, flat-field, 7-element lens was chosen as the image-forming objective. The 16 mm focal length, f/0.65 lens is wide field and extremely fast. It is optimized to yield a point spread function diameter of 50 µm over the entire field of view,

The optical system has a spectral bandpass of 400 to 800"11111 and a Field of View (FOV) of 28°. The lens is equipped with a baffle to extinguish stray light and minimize the effect of bright objects outside the. FOV. The bright Object exclusion cone is 84° vertically, and 106° horizontally.

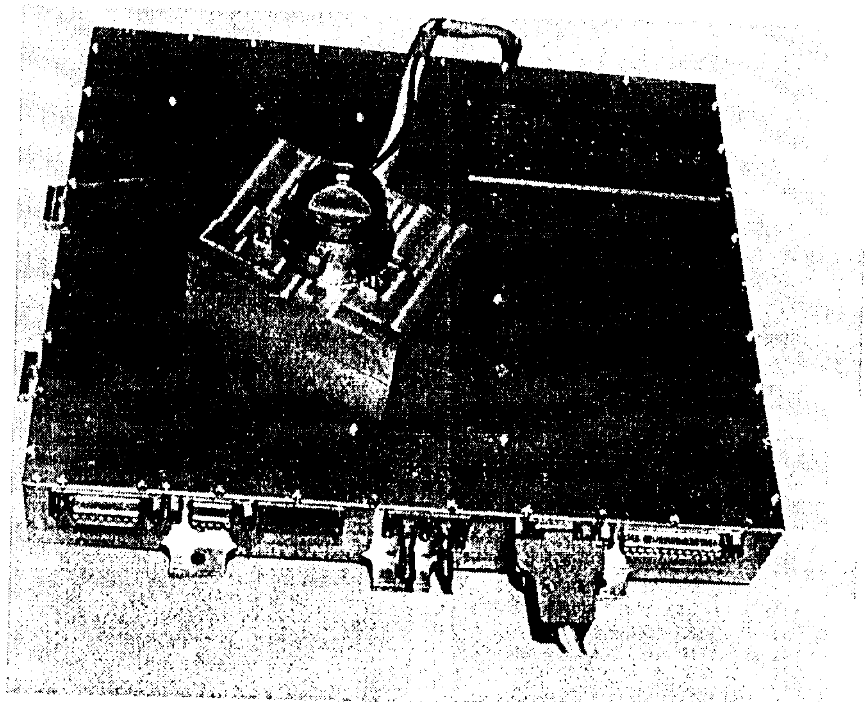

Figure 3. The ASC, shown in Thunderstorm III sounding rocket configuration.

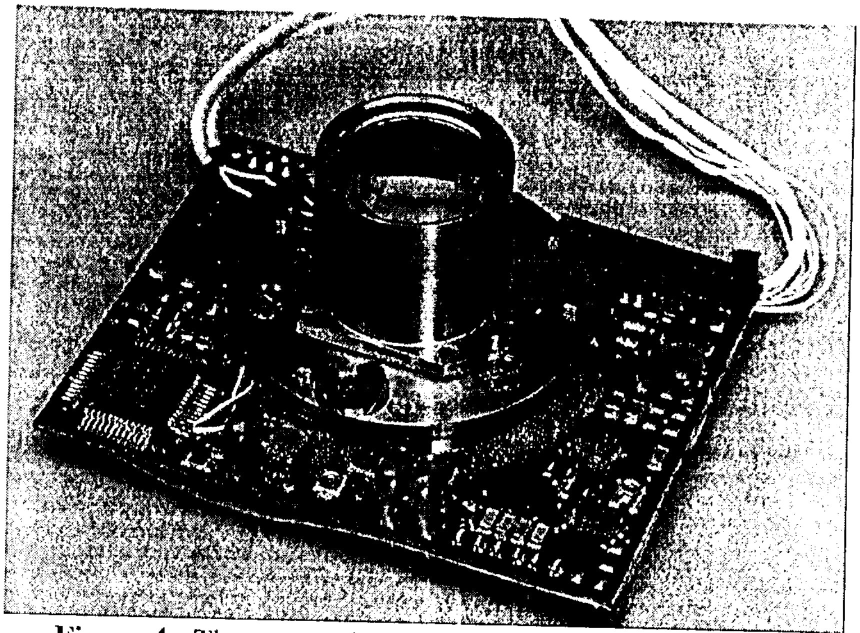

Figure 4. The camera head in Ørsted flight configuration

The CCD image integration time is 1 second with a noise-level equivalent to 10 electrons. The 1 V p-p analog output of the camera is connected via the 6-m boom cables to the data processing unit.

The ASC consists of the logical blocks shown in Figure 5 [5]. The image is digitized and stored by the frame-grabber and can be read either by the central processing unit (CPU) (in normal mode) or directly by an

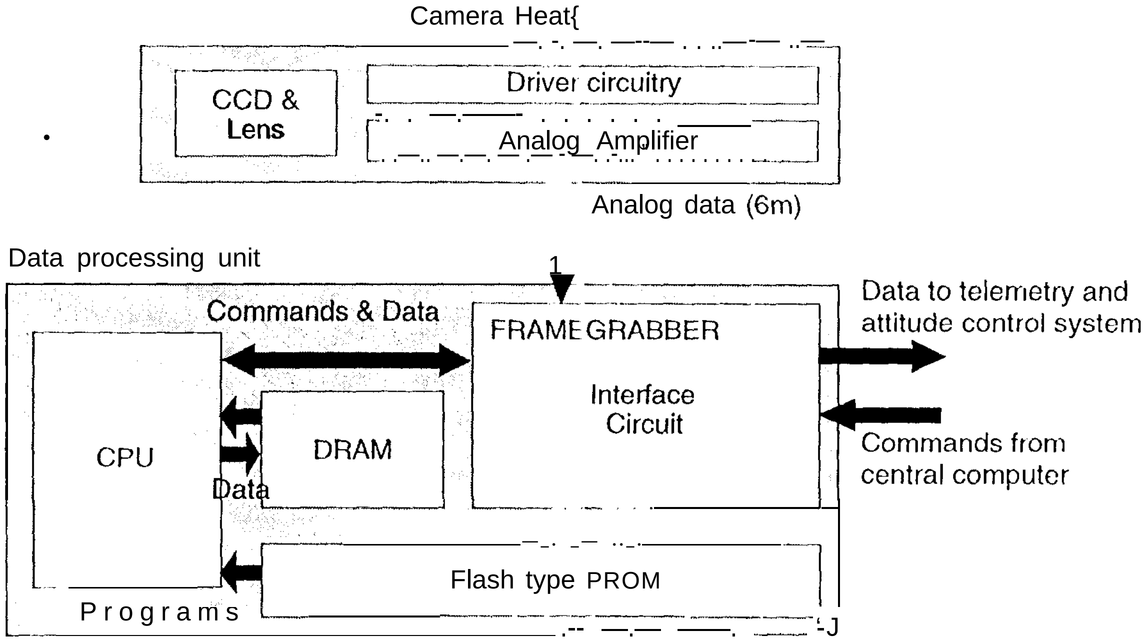

Figure 5. Block diagram of the ASC

external device (in bypass mode). The CPU derives the attitude based on the image and the star catalogue stored in the Hamming code protected memory. All communication is routed via the telemetry interface.

The ASC contains a catalog of 10,000 stars which are at least as bright as an instrument magnitude of 6.5. From this catalog, up to 2(KI stars, and typically 65, are tracked per frame. The residual error in an individual frame is reduced by the square root of the number of stars which are being tracked. Thus, high accuracy is obtained with a wide FOV due to the large number of stars being tracked. Since small star trackers, with such a low mass potential (790 grams, including the CPU proposed for ASTRID 2), have failed to achieve high accuracy before this, the ASC represents a breakthrough, or paradigm shift in star tracker implementation.

In normal mode the data processing unit does all necessary data reduction, calculates the attitude, compresses images, services the telemetry IF, and updates the internal orbit model. For redundancy purposes, the instrument includes a bypass mode. In this mode, the communication interface (IF), frame grabber, and camera head are operated separately. In the bypass mode the necessary data reduction is done by the flight computer.

The processor is a 50 MHz INTEL 80486, with an OPTI 495slc/206 support chipset. All of the active components were tested and selected for radiation resistance. The compressed program and star data base are down loaded from a Hamming code protected (2 bits detection, 1 bit correction) flash-ram to the 4Mb DRAM. All major chips are protected against latch-up via current measuring shunts in the power circuits. Excessive current causes the power supplies to turn off, momentarily, thus resetting the latched component.

The protection mechanisms inherent in the 486 architecture are fully utilized to catch and correct single event upsets (SEU) and bit-flips (e.g., the processor runs in "protected mode"). At regular intervals the CPU performs bitwash on the flash-ram to avoid double faults. All programs, data, and system settings (exe.cpt for a core loader) can be changed, verified, or uploaded during flight. The mass of the data processing unit is 1.6 kg and it consumes 4.0 watts of regulated, secondary power. Note that over 1.0 kg of mass of the the data processing unit is represented by its solid aluminum chassis, and will be greatly reduced in future, proposed models.

Operational Principles

In normal operation on a 3-axis stabilized satellite, the angular difference between two consecutive images is so small that the following procedure is adequate. The image is sifted for stars. All star centroids are derived and then corrected for lens distortion. Based on the previous attitude and the star catalogue, the corresponding catalogue star locations are calculated. The star centroid frame and the star catalogue frame are then oriented, relative to each other in order to minimize the spatial differences between them. This is done by a least squares fit and results in the relativistic attitude (not corrected for light time aberration) of the camera head, for that frame. This attitude is then corrected for astronomical (light time) aberration and the quaternion is output to the telemetry queue.

In a number of situations, such as, following power cycling, SEU, or invalid images (bright objects in the field of view etc.), the previous attitude is invalid or missing. In these cases an additional image processing step, initial attitude acquisition, is then applied.

In initial attitude acquisition, the star centroids are analyzed for triplets of nearest and second-nearest neighbors. The resulting set of triplets is then matched to a preflight compiled version of' the star catalog, c- the star database. The entries in this star database include all of the possible star triplets. Based on this match, an attitude is obtained which is used in the consecutive processing instead of the previous invalid attitude [6].

In order to transform the relativistic attitude, including light time aberration, to the absolute attitude, the velocity vector of the spacecraft relative to the heliocentric system is required. This vector is derived from an orbit model that needs to be updated at regular intervals. On the Ørsted microsatellite, these updates are based on GPS data. The operational flow diagram of the ASC is shown in Figure 6.

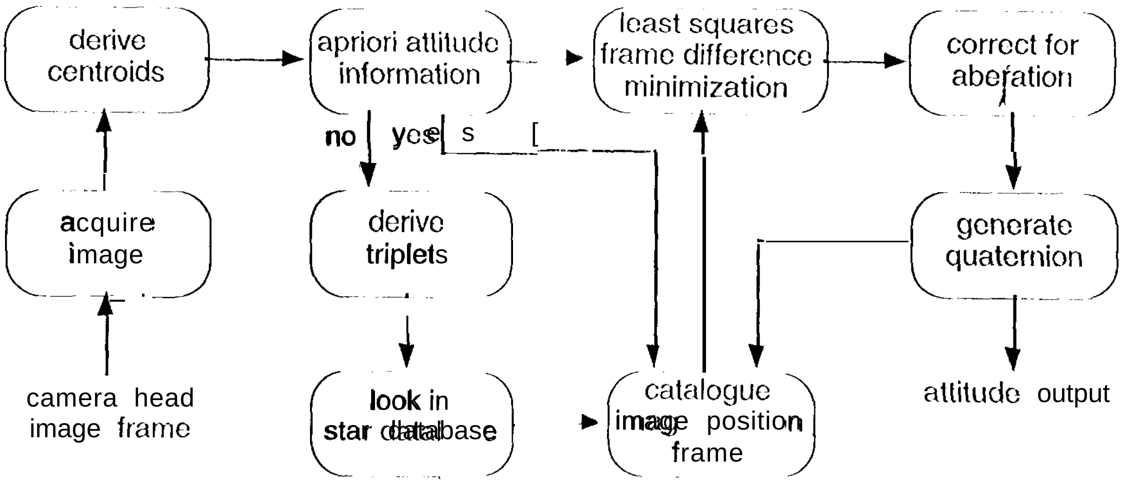

Figure 6. ASC Operational Flow Diagram

3. REAL SKY TEST

In order to determine the performance of the ASC, it has been evaluated with real sky images* at JPL's Table Mountain Observatory (TMO) facility [7].

The ASC was mounted on the front of a 24-inch telescope as in Figure 7. It should be noted that even with the long interconnection, only a small degradation in performance, due to noise pickup, was observed.

Figure 7. The JPL TMO 24-inch telescope in star tracker test configuration

Several parameters of the ASC were, evaluated—primarily to determine the noise equivalent angle (NEA) of the system. However, other essential parameters of the stellar compass can also be evaluated during a test like this (e.g., lens correction function, star color class response, acceptable image motion smear, relative accuracy etc.).

A total of 728 exposures were taken with the telescope tracking or stationary (exposures subjected to no motion smear or just the effect of the sidereal rate, respectively).

The NEA (including star field variation) of the ASC was determined by pointing it toward zenith and acquiring continuous attitudes. The (inclination of the boresight remains essentially constant and the right ascension changes with the sidereal rate. The NEA is then determined statistically from a series of attitude measurements.

The attitude measurement series was acquired over a period of one hour. This implies that the star field in the last image is completely different from the star field in the first. Hence, this test includes seeing (the atmospheric distortion), NEA, variation in the star field, etc. The attitude measurements are shown in Figures 8 through 10.

Figure 8 shows the declination measured by the ASC versus the image number (i.e., the time). The reason for the slight slope of the declination is the epoch of star catalogue (J2000). The pole position is some 250 arcseconds from the pole position at the date of image acquisition (Sept. 1995). Because of this, a diurnal sinusoidal variation in the declination will arise. The amplitude of this variation is currently 250 arcseconds. The 3σ accuracy of this measurement is shown to be 5.7 arcseconds.

The right ascension is depicted in Figure 9. The accuracy in this axis is harder to estimate, as this axis changes with the sidereal rate. If the sidereal rate were subtracted, the accurate timing of the single images would have to be used. This was not available. However, in spite of this, the measurements with the

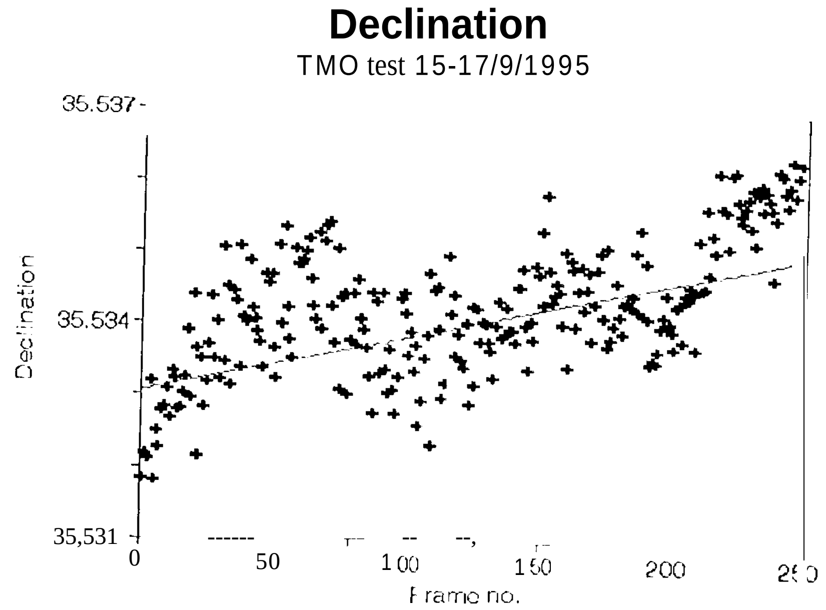

Figure 8. Declination for TMO zenith measurements (star catalogue epoch J2000, no precession nor nutation correction), 2 arcseconds seeing).

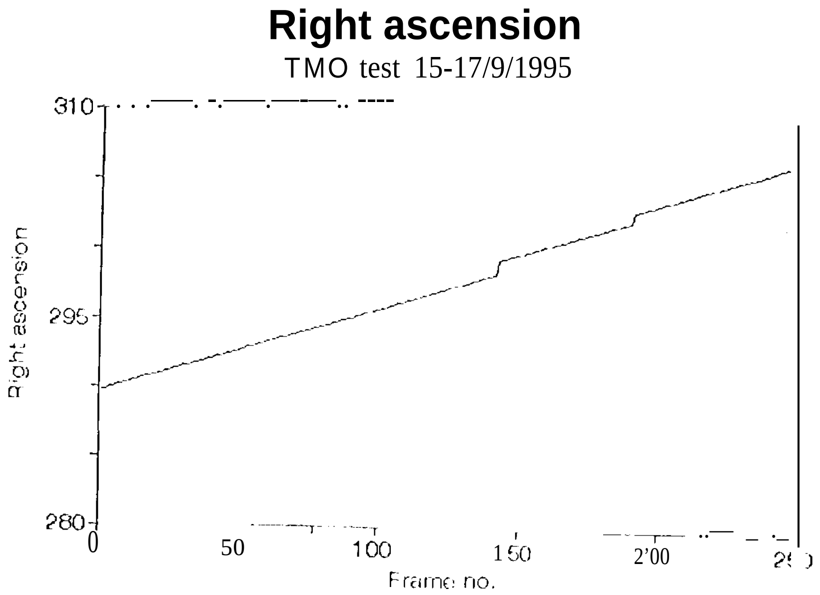

Figure 9. Right ascension for TMO zenith measurements (star catalogue epoch J2000, no precession nor nutation correction, 2 arcsecond seeing). Note that individual star positions are not resolved due to the. scale of the figure.

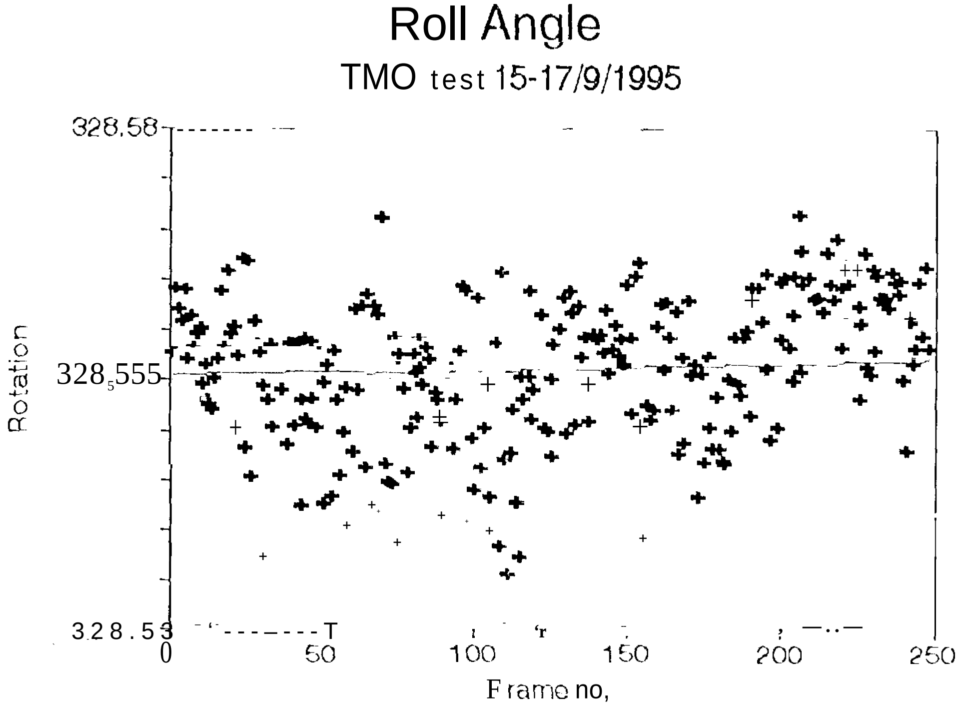

Figure 10. Roll angle for TMO zenith measurements (star catalogue epoch J2000, “ no precession nor nutation correction, 2 arcsecond seeing).

telescope tracking show that the declination and right ascension are equally accurate, as expected. The two “jumps” in right ascension were due to operator intervention.
Figure 10 shows the measured rotation (or roll angle) around the boresight. Again, this parameter is affected by the J2000 coordinates. The accuracy is 42 arcseconds, 3σ.

It should be noted that the test results obtained with this prototype camera head are not as good as those that are expected from the flight ASC. The lens distortion correction was not optimized, causing, an uncorrected systematic error, nor was the 800 nm cutoff optical coating incorporated, resulting in greater chromatic aberration. Also, the flight kinematic mount of the camera head was not used. Tests of a full, flight version of the. camera head and data processing unit are planned at TMO in December of 1995.

The tests in Figures 8, 9, and 10 include stat field variation, NEA, and seeing. However, in order to exclude the star field variation, the same test was performed With the telescope tracking (the exact same image in the field of view). The variations in attitude information will thus only include NEA and seeing. The result of this test is shown in Figure 11. This shows that the 3σ NEA is 4.25 arcseconds.

4. CONCLUSION

The design, operation and performance of the prototype version of the Advanced Stellar Compass (ASC) for the Danish Ørsted microsatellite have been described. The ASC represents a paradigm shift in star trackers because it combines the benefits of low mass, low power consumption, fully autonomous operation, quaternion output and high accuracy with a low cost implementation. The measured relative accuracy was 5.7 arcseconds (3σ) for each Of two axes, 42 arcseconds 3σ for roll angle about the boresight and an NEA of 4.25 arcseconds (3σ) for each of the two axes. Flight versions of

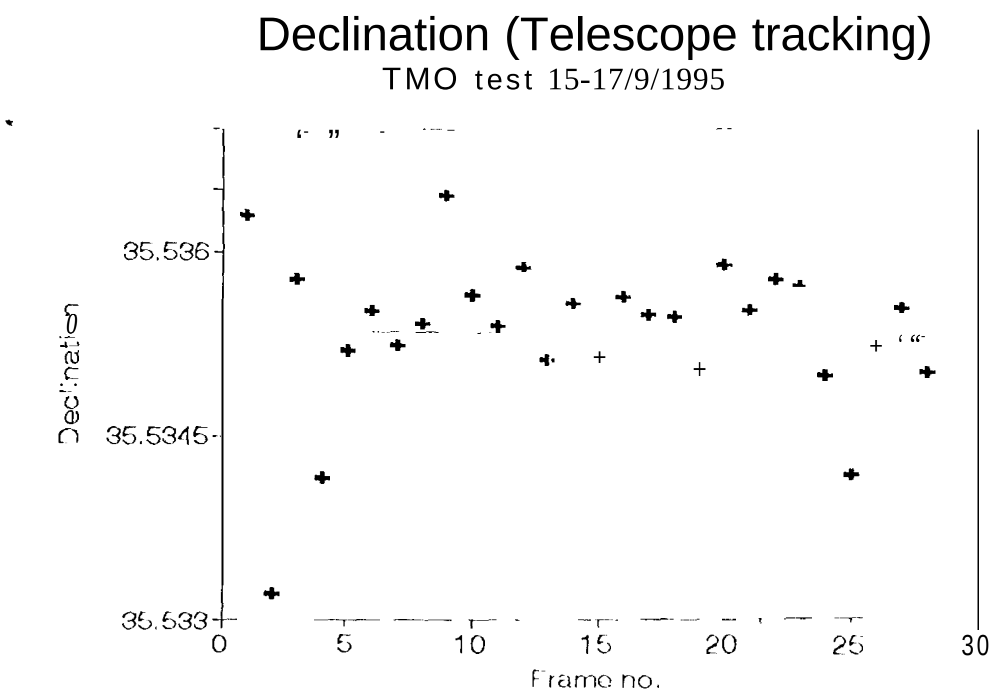

Figure 11. Declination for TMO zenith measurements (star catalogue epoch J2000, no precession nor nutation correction, 2 arcseconds seeing).

the ASC are expected to exhibit better accuracy. This performance is obtained by typically tracking 65 stars per frame vs. less than 10 stars per frame for conventional star trackers. The low power, mass and cost were realized by using reliable, commercial components which have been selected for a high level of radiation resistance.

5. ACKNOWLEDGMENTS

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6. REFERENCES

[1] "The Ørsted Satellite, Mission Summary," Computer Resources International A/S, Copenhagen, Denmark.

[2] "Star Trackers for Attitude Determination," C. C. Liebe, IEEE Aerospace and electronics magazine, p. 1016, June 1995.

[3] "Spacecraft Attitude Determination and Control," J. R. Weitz, Boston, MA: D. Reidel, 1985.

[4] "The AEF/DTU Star Imager Instrument, Department of Electrophysics," J. L. Jørgensen, Technical University of Denmark, 1994.

[5] "Development of the Ørsted Precision Attitude Instrument the Star Imager," J. L. Jørgensen, The Chapman Conference on Measurement Techniques for Space Plasmas, Santa Fe, New Mexico, April 3-7, 1995.

[6] "Pattern Recognition of Star Constellations for Spacecraft Application," C. C. Liebe, IEEE AES magazine, p. 34-41. June 1992.

[7] "Preliminary Report on the Star Imager Measurements on the "Table. Mountain Observatory," J. L. Jørgensen, C. C. Liebe, Department of Electrophysics, Technical University of Denmark, Denmark, November 1995.

7. BIOGRAPHIES

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