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SCIENCE DIRECT
PII: S0273-1177(02)00619-1

THE NANOSATELLITE *MUNIN*, A SIMPLE TOOL FOR AURORAL RESEARCH

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ABSTRACT

The scientific objective of the nanosatellite *Munin* is to collect data of the auroral activity over both the northern and southern poles. The satellite has been developed by Swedish Institute of Space Physics under international cooperation. The purpose of the *Munin* project is both to achieve the scientific objectives and to show that it is possible to achieve such objectives by a very small satellite. A passive magnetic attitude control system is used to stabilize *Munin* along the direction of an intensity vector of the local geomagnetic field. The paper presents the development of the attitude control system and gives a brief discription of the tools and algorithms used for the attitude determination.

INTRODUCTION

The Swedish Institute of Space Physics (IRF) in Kiruna has develop and build the *Munin* nanosatellite as demonstration of the capabilities of nanosatellite to solve the real scientific tasks. The satellite has total weight of only 6 kg and carries combined electron and ion spectrometer *MEDUSA*, a solid-state detector *DINA*, and miniature CCD-camera. *Munin* is supposed to gather data of auroral effects in the upper atmosphere and ionosphere of the Earth's northern and southern poles.

The data concerning the instantaneous conditions of the magnetosphere will be made accessible in real-time through the Internet. The miniature CDD-camera will provide pictures of the polar lights. The camera has 32° wide field of view, 340 × 240 pixels (0.2 × 0.2°) resolution, 64 shades of gray, 1/1000 s shortest exposure time, and $0.5 \div 1$ s working exposure time in $450 \div 800$ nm band. Additionally, two single-axis magnetometers are included in the payload and there is a capability to measure the output separately from each of the six solar panels. The satellite is a cube of 21-cm edge. Silicon solar arrays cover six sides of the cube and provides 4 W average power with a voltage of $15 \div 20$ and together with Li-Ion buffer battery can provide a peak power of 11.6 W required during data transmition. UHF-band is used for the up- and downlink to the ground station located in Kiruna. A digital signal processor provides instrument control, data compression, and telemetry formatting as well as a software modem servicing. The mass and power budgets can be found at the *Munin* Satellite Homepage (http://munin.irf.se/). The satellite has been completely integrated, tested, and is scheduled for a piggy-back launch by Delta 7320-10 rocket in 2000 – 2001 as in an orbit of 98° inclination, and 707 and 1965 km perigee and apogee respectively[1].

MISSION OBJECTIVES

The primary mission objective is to explore and forecast the auroral activity around both the northern and southern poles of the Earth. Another objective is to train students in satellite engineering through their participation in the processing and interpretation of the data.

The northern and southern auroral ovals are always present, day and night (Brekke and Egeland, 1994). From the Earth they can be seen by the naked eye at latitudes between 60 and 80 degrees north and south.

[1]The satellite *Munin* was launched in orbit on 21st of November, 2000 and succesfully stabilized

Adv. Space Res. Vol. 31, No. 2, pp. 313–318, 2003

Printed in Great Britain
0273-1177/03 $22.00 + 0.00

The northern and southern auroral ovals are always present, day and night (Brekke and Egeland, 1994). From the Earth they can be seen by the naked eye at latitudes between 60 and 80 degrees north and south. The aurora is the visible manifestation of the particles precipitation along the Earth's magnetic field lines at high latitudes. Since the aurora can be viewed only during cloud-free nights, the use of satellites in polar orbit provides a capability for a more regular monitoring of this phenomenon.

With Munin it is proposed to use a new paradigm for the dissemination of the data. Until now the data from research satellites were published in scientific papers and became accessible for the public only after preprocessing and analysis. We are going to make the data from the satellite instruments available through the Internet in real time to everyone interested. It will include the information about electrons and ions distribution above the auroral ovals and fluxes of energetic particles (ions and neutral particles), as well as images of the aurora taken by the CCD-camera. This way of presenting the results should increase the public interest in science, technology, and space exploration.

The complexity of modern space projects and the long duration of their development make it difficult to provide opportunities for students to participate in such projects. Even if they have a chance to take part, they usually are responsible for only a narrow segment of the satellite. In the *Munin* project students from universities of Sweden, USA, and Russia have instruments, developed measurement processing algorithms, and will assist provide the ground control.

Since the Munin satellite is designed to study the physical phenomena in the geomagnetic field, it is preferable to orient the satellite along the local field vector **H**. This assures a proper orientation of the instruments and of the CCD-camera with respect to the objects to be studied. The satellite does not require a high orientation accuracy or a fast-response, nor is there a need for re-orientations during the flight. The deviation from **H** should not exceed $10 \div 15°$ degrees. The duration of the initial transient motion should not exceed 2 - 3 weeks. The limited budget of the satellite dictates minimal usage of moving parts, consumption of power and information resources for attitude control. The goal has been to develop a system with adequate characteristics as cheaply as possible. Based on this criterion, the choice of attitude control system (ACS) was uniquely solved with the selection of a passive magnetic system.

MAGNETIC ATTITUDE CONTROL SYSTEM

It is necessary to solve two basic problems regarding the development of restoring and damping torques for the design of a passive magnetic attitude control system. The problem of maintaining a restoring torque is easily solved by mounting a permanent magnet along the selected axis. To solve the second problem, a damping device for the dissipation of the energy of disturbed attitude motion is required. Two different types of damper could be considered. The first uses interaction between two bodies connected by hinge with friction and tension, the other uses magnetic hysteresis effects. In the coupled two-body system one body is the satellite's structure, but the other body must be installed additionally. To achieve the best time response of this type of damper, the magnitudes of the moments of inertia of the two linked bodies have to be similar; alternatively, to avoid the similarity of these moments of inertia one can rely on spin stabilization of the satellite. However, neither to spin the satellite nor to attach an auxiliary body with a mass similar to the spacecraft is acceptable in the case of Munin.

Another minor aspect of the damper used an internal friction as a source of energy dissipation is rotation of satellite with damper together as a rigid body without decreasing of .

In conclusion, despite the limited disturbing effects of a magnetic hysteresis damper on the magnetometer measurements it is the best technique for energy dissipation. The time-response of this damper can be increased as much as required. Only the requirement for steady-state motion precision limits this time-response. Finally, from among the available damping devices, hysteresis rods manufactured from soft magnetic material, were chosen to solve the problem of energy dissipation. The rods are re-magnetized in the geomagnetic field under the influence of the satellite rotation relative to the direction of the field. Let us consider the problems arising from the use of a permanent magnet and hysteresis rods for ACS development.

It is not possible to provide a *precise* orientation of the satellite's pointing axis along the field vector **H** because of the non-uniform rotation of the vector **H** along the orbital path of the satellite. Mathematically this fact appeares due to a nonuniformity of the equations describing the rotation of the satellite relative to the vector **H**. It is only possible to reduce the amplitude of the forced librations. The forced librations

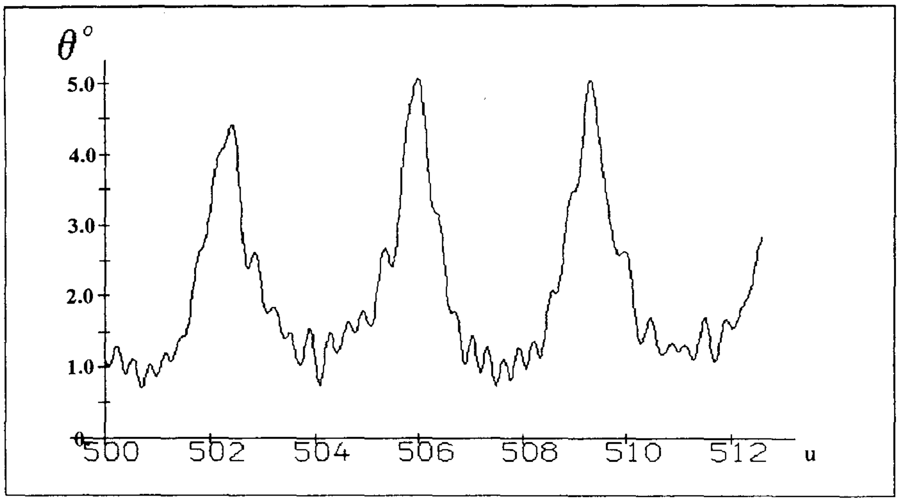

Fig. 1. The angle Θ for two orbits

may result in the appearence of resonance effects due to interactions between the natural frequency of the satellite and the periodicities of the external torques, that is, due to commensurability of natural and forcing frequencies.

Hysteresis rods are able to damp arbitrary angular motions of the satellite but require accurate mathematical simulations of satellite dynamics to determine the optimal parameters. Additionally, they imply rather hard constraints positioning of the in the satellite's body. The complex motion of the satellite around the vector **H** may result from the remagnetization of rods with particular hysteresis loops. They can results in a prolongtion of the duration of the transient motions. Whether this situation actually occurs will depend on the initial conditions of angular motion of the satellite after release from the launcher and also on the ratio between satellite moments of inertia around the principal axes. The result of an analysis of the transient and steady-state motion of the Munin satellite has been published (Ovchinnikov, Penkov, Norberg, and Barabash, 2000).

Based on this analysis, a permanent magnet with a dipole moment $m_s = 0.3\,\mathrm{A} \cdot \mathrm{m}^2$ was chosen to provide the restoring torque. To dissipate energy, six molybdenum permalloy 79 NM hysteresis rods, each of 15.5 cm length, are used. The results of a steady-state motion simulation are presented in Fig.1, where the dependence of angle Θ of the pointing axis deviation from the vector bf H as a function of time is shown for two orbits. In this figure the transient process is already close to completion. Gauss's model of the geomagnetic potential with factor extrapolation for December, 1999 has been used. Two distinctive time intervals can be noted here. The first is close to half of the orbital period, the second close to the period of satellite natural oscillations. There is one more time interval close to half a day, which is excited by the diurnal motion of the geomagnetic dipole relative to the orbital plane of the satellite. It is difficult to see this third interval in Fig.1.

DETERMINATION OF ATTITUDE MOTION OF SATELLITE

It is necessary to determine the angular position of the satellite reference system relative to a basic reference system, for instance, the inertial one, in order to process the payload readings properly. For the *Munin* project there are no special sensors available to determine the orientation of the satellite with the required accuracy. Nevertheless, there are several satellite instruments, whose readings can be interpreted as attitude sensors readings. They are:

— two single-axis magnetometers, whose sensitive axes are nominally directed perpendicular to the magnetic axis of the ACS permanent magnet;

— six solar arrays with separately measured outputs;

— a CCD-camera with a wide field of view (FOV).

Let us consider why the above devices are not attitude sensors in the general sense. The two magnetometers can only measure a projection of the external magnetic field on a plane where the axes of these magnetometers are situated. Also, the permanent magnets and the hysteresis rods influence non-symmetrically on the measurements of the external field direction. The reliability of the readings of the solar arrays, when considered as a sun sensor is limited by the calibration accuracy and the effect of the Earth's albedo. Difficulties may appear at small Sun elevation angles since the solar panels measures both direct radiation from the Sun, and radiation reflected from the Earth. The use of the CCD-camera as a star sensor is complicated by the wide FOV and the irregular sampling of the sky. Nevertheless, using all these data and their pre-computed values it is possible to determine the attitude motion of the satellite. We shall consider both local and statistical techniques for the processing of these measurements.

APPLICATION OF LOCAL METHODS

Two single-axis magnetometers are situated in the satellite. They can measure two projections of the local magnetic field inside the satellite body. Let us define a reference system $O_b x_{b1} x_{b2} x_{b3}$ connected with the three planes of the satellite geometrical symmetry. The axes are parallel with the three orthogonal edges of the body. The origin coincides with the satellite's center of mass. We will assume that the dipole moment $\mathbf{m}_s$ of the ACS permanent magnet is oriented parallel with axis $O_b x_{b1}$. We will then take the two axes of the magnetometers to be parallel with the two other axes of the above reference system. We designate the measured projection of the external field vector $\mathbf{H}$ by h_2 and h_3, and the unit vectors of the reference system axes by e_{b2} and e_{b3} accordingly. The cosines of the angles θ_2, θ_3, which the vector $\mathbf{H}$ forms with these axes are given by the expression $\cos\theta_j = h_j/|\mathbf{H}|$, $(j = 2, 3)$. Then, we obtain an expression for the angle θ_1,

$$\cos\theta_1 = \pm\sqrt{1 - \cos^2\theta_2 - \cos^2\theta_3} = \pm\sqrt{H^2 - h_2^2 - h_3^2}/H, \tag{1}$$

of the deviation of the orientation axis from the vector $\mathbf{H}$.

Using the simple expression (Eq.1), the following problems appear:

— it is not possible to determine the current magnitude of vector $\mathbf{H}$ contained in (Eq.1) due to absence of the third component of vector $\mathbf{H}$ measurement;

— a determination of the sign associated to the radical in (Eq.1) is also not possible; the orientation of the satellite axes with respect to $\mathbf{H}$ depends on this sign; its determination by the local method is impossible if measurements of only two magnetometers are available.

Another possibility for the attitude determination assumes the presence of a pair known noncollinear vectors measured in the satellite reference system and pre-computed in inertial system. Let such pair of vectors be the vector $\mathbf{H}$ of the geomagnetic field intensity and the vector of a direction to the Sun. We will call the second one the Sun-vector, $\mathbf{S}$. The onboard sensors are able to measure the two components of the vector of magnetic field intensity $\mathbf{h} = (h_1, h_2, h_3)$ and unit vector $\mathrm{s} = (s_1, s_2, s_3)$ directed to the Sun assigned by the projections onto axes of the satellite reference system. We can also compute the components of vectors the $\mathbf{H}$ and $\mathbf{S}$ in the inertial reference system as follows $\mathbf{H} = (H_1, H_2, H_3)$, $\mathbf{S} = (S_1, S_2, S_3)$.

Let the matrix $\mathbf{D}$ with elements d_{ij}, $(i, j = 1, 2, 3)$ describes the transformation from the inertial to the satellite reference system. Then, it is possible to write four matrix relationship

$$\mathbf{S} = \mathbf{D}\mathrm{s}, \quad \mathbf{H} = \mathbf{D}\mathbf{h}, \quad [\mathbf{S} \times \mathbf{H}] = \mathbf{D}[\mathrm{s} \times \mathbf{h}], \quad \mathbf{S} \times [\mathbf{S} \times \mathbf{H}] = \mathbf{D}\mathrm{s} \times [\mathrm{s} \times \mathbf{h}]. \tag{2}$$

We form a matrix using three mutually orthogonal unit vectors and write the relation between the measured and the computed vectors by this matrix

$$\left(\mathbf{S}, \frac{\mathbf{S} \times \mathbf{H}}{|\mathbf{S} \times \mathbf{H}|}, \frac{\mathbf{S} \times [\mathbf{S} \times \mathbf{H}]}{|\mathbf{S} \times \mathbf{H}|}\right) = \mathbf{D}\left(\mathrm{s}, \frac{\mathrm{s} \times \mathbf{h}}{|\mathrm{s} \times \mathbf{h}|}, \frac{\mathrm{s} \times [\mathrm{s} \times \mathbf{h}]}{|\mathrm{s} \times \mathbf{h}|}\right). \tag{3}$$

It is easy to obtain an expression for matrix $\mathbf{D}$ from (Eq.3). Perhaps, this is the most simple local method of the satellite attitude determination. However, the problems of the accuracy of the attitude determination and uncertainly of the third component of the vector $\mathbf{H}$ measuring still remains.

The third method relies on the use of the star images made by the CCD-camera. Firstly, the stars detected in the picture have to be identified. For this purpose a set of stellar-parts is selected from a star catalog according to the angular distances between them. The chosen distances being equal within the given accuracy to the angular distances measured between objects found in the star image. A test of the

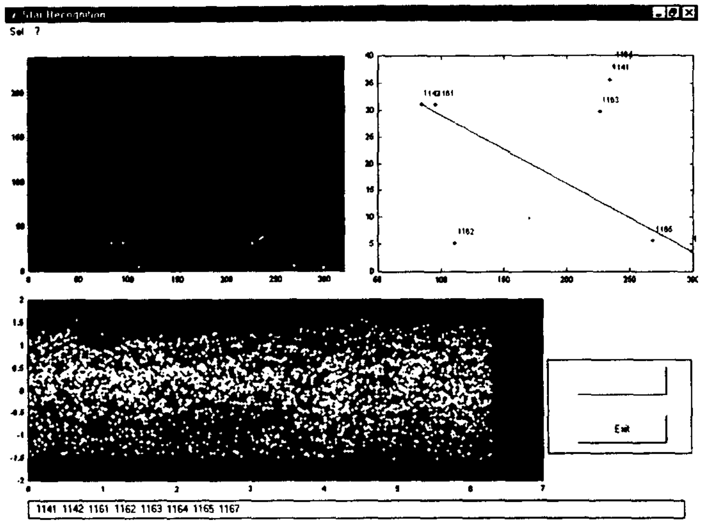

Fig. 2. Test of star identification algorithm

star identification algorithm is shown in Fig.2. Here we use a section of the sky with angular dimensions corresponding to the FOV of the camera. The corresponding star catalog with 3125 stars is shown below the screen. At the left side one can find the selected segment of the sidereal sky with several stars which are supposed to be unknown. On the right side above the resulting identification the catalogue numbers of stars and line connecting a pair of widely separated stars are shown. The same numbers are shown at the bottom of the screen.

Among the identified objects in the picture, we select the two most widely separated stars. This is done for reduction of the error in calculating the transformation matrix. The local method described above allows to determine the attitude of the satellite in a given point of the orbit using a pair of two vectors obtained by measuring the stars in the satellite reference system and computing in the inertial system. For the two stars selected as described above the unit vectors directed to these stars are determined. These unit vectors $\mathbf{e}_1 = (e_{11}, e_{12}, e_{13})$ and $\mathbf{e}_2 = (e_{21}, e_{22}, e_{23})$ given by their projections onto the axes of satellite system. The components of these vectors $\mathbf{E}_1 = (E_{11}, E_{12}, E_{13})$ and $\mathbf{E}_2 = (E_{21}, E_{22}, E_{23})$ in the inertial system are obtained from the star catalog. Then, the matrix D is fully determined.

APPLICATION OF STATISTICAL METHOD

The local methods of attitude determination described above allow by itself to determine the attitude of the satellite only in some specific points along the orbit. To use the local method one needs to use the pictures of the sidereal sky or obtain the rough representation of the attitude under the ambiguous and rather approximate readings from the magnetometers and output of the solar panels. To increase the accuracy of the attitude determination necessitates the use of statistical methods. Let us utilize the readings of the magnetic and solar sensors and also the matrix computed on the basis of the identified stars and a limb, that is, a border line between the Earth and the sky. The sun-sensor here is understood as the set of six solar panels. A statistical algorithm is used for the determination of the angular motion of the satellite using the data from the onboard measurements of magnetic field and Sun-vector. But it works properly since there are always measurements of either the geomagnetic field or the Sun-vector. The current angular motion of the satellite is determined by a minimization of the misalignment between the measured and the computed projections of the magnetic field intensity vector, Sun-vector, matrices and the angles formed by the limb with the sides of the picture. The functional is minimized in the beginning with respect to the state variables of satellite as initial orientation and angular velocity. At the second stage we also include in the processing the inertial and magnetic parameters of the satellite.

A general view of the functional is as follows

$$\Phi = \Phi_S + \Phi_H + \Phi_{st} + \Phi_l,$$

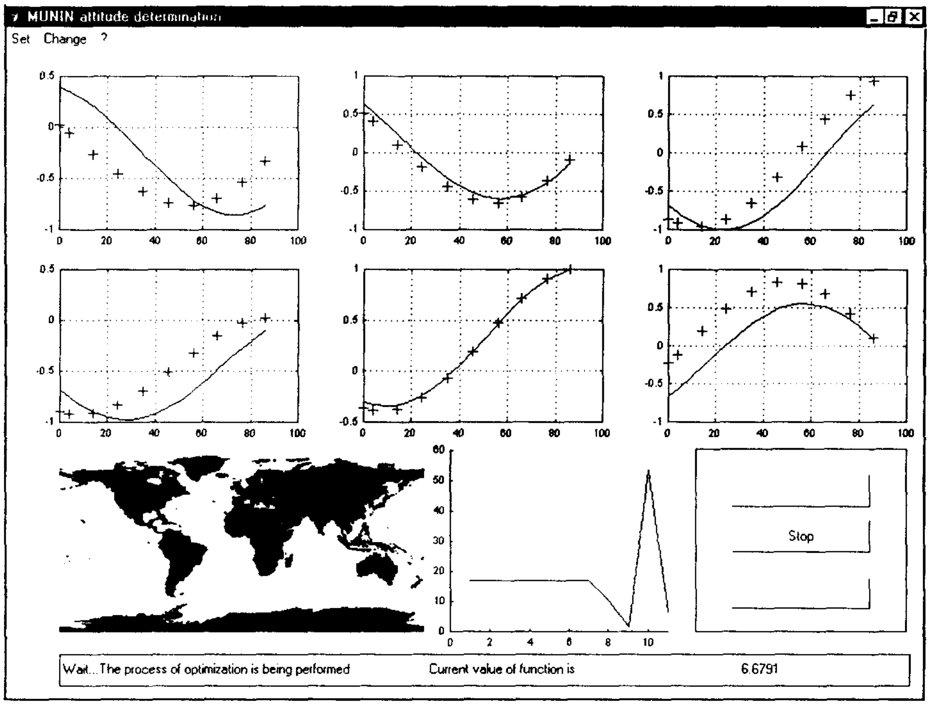

Fig. 3. Sample of screen during measurement processing

where

$$\Phi_S = \sum_{n=1}^{M}\sum_{i=1}^{3}\left(s_i^{(n)} - \sum_{k=1}^{3} S_k^{(n)} a_{ki}(t_n)\right)^2, \quad \Phi_H = \frac{1}{H_0}\sum_{n=1}^{N}\sum_{i=1}^{3}\left(h_i^{(n)} - \sum_{k=1}^{3} H_k^{(n)} a_{ki}(t_n)\right)^2,$$

$$\Phi_{st} = \sum_{n=1}^{K}\sum_{i=1}^{2}\sum_{j=1}^{3}\left(d_{ij}^{(n)} - a_{ij}^{(n)}(t_n)\right)^2, \quad \Phi_l = \sum_{n=1}^{K}\sum_{i=1}^{3}\left(\tilde{\delta}_i^{(n)} - \delta_i^{(n)}(t_n)\right)^2,$$

M is a number of Sun-vector readings, K is a number of pictured used for construction of matrixes $||d_{ij}^{(n)}||$, function $a_{ij}(t_n)$ and $\delta_i^{(n)}(t_n)$ are elements of matrix and angles of the limb computed along the solution $z(t)$ of the equations of the satellite attitude motion. They specify the orientation of the satellite system relative to the inertial system and the corresponding position of the limb in the picture.

In the screen at the measurement processing (Fig.3) the asterisks designate values of the six elements of matrix **D** obtained by star recognition. The continuous curves are obtained by integration of the motion equations. As a result of this process we get the initial conditions of motion, and the satellite inertial and magnetic characteristics.

Algorithms described above have been tested and prepared for attitude determination after the launch of the satellite.

ACKNOWLEDGEMENTS

The work was performed and presented under financial support of RFBR (grant # 00-01-00174), FP "Integration" (project # A0110), Swedish Institute of Space Physics, and COSPAR (grant # 69.20). Authors are pleased to acknowledge Dr. Niel Lund for useful assitence in preparation of this paper .

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