GEOMAGNETIC FIELD INVESTIGATION ON THE POLAR MICROSATELLITE SACI-I

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ABSTRACT

The first Brazilian Scientific Microsatellite, SACI-1, is scheduled to be launched in July 1999 in a near circular polar orbit at an inclination of 98.5° and an altitude of 750 km. It will carry a three-component fluxgate magnetometer constructed by IGPP/UCLA for measuring three components of the Earth's Magnetic Field in space at a rate of 10 samples per second. The scientific objective is to study field-aligned currents in the auroral oval and the electrojet of the equatorial ionosphere. Together with the geomagnetic data from other polar orbiting spacecraft e.g. POLAR, FAST, OERSTED, it will be possible to obtain a truly global picture of a field-aligned current system. The experimental details and the plans of this project are presented here.

INTRODUCTION

Carrying four experiments SACI-1 (Satélite de Aplicações Cientificas) is the first Brazilian Microsatellite to study near Earth plasma. SACI-1 is planned to be a polar orbit satellite in a near circular orbit at an inclination of 98.5° and an altitude of 750 km. It is scheduled to be launched as a piggyback ride along with a large satellite CBERS (China Brazil Earth Resources Satellite) in July 1999 from China by a Chinese launch vehicle. The four experiments are ORCAS - Solar and Anomalous Cosmic Rays Observation in the Magnetosphere, PLASMEX - Study of Plasma Bubbles in the Ionosphere, FOTSAT - Airglow Photometer, MAGNEX - Geomagnetic Experiment conducting geomagnetic field measurements aboard SACI-1.

The geomagnetic field controls the motion of charged particles in the Earth's environmental space and protects the Earth from direct incidence of the solar wind. It also couples the upper atmosphere with the magnetosphere and solar wind via field-aligned currents. Simultaneous geomagnetic field measurements on the surface of the Earth and in the near Earth plasma environment allow the monitoring of this coupling.

Over the last 30 years field-aligned currents in the auroral region have been extensively studied by operating magnetometers aboard satellites. Recently Fukunishi *et al.* (1990) have given a detailed and extensive review of the geomagnetic experiments conducted on satellites in the last couple of decades and also an excellent account on the magnetic field observations on the Akebono (EXOS-D) satellite launched in 1989. Significant space plasma research has been done by several low-altitude polar satellites carrying three component fluxgate magnetometers viz. TRIAD, MAGSAT, DMSP/F7, AKEBONO and VIKING, to name just a few.

The proposed effort is to realize the geomagnetic field measurements on the Brazilian satellite SACI-1. The magnetic field investigation is a "joint" U.S.-Brazilian effort in which the magnetometer electronics and sensors were constructed at UCLA and the digital processing unit was built at the National Institute for Space Research-INPE in São José dos Campos, Brazil. The idea is to analyse SACI-1 geomagnetic data together with simultaneous geomagnetic data from US missions like FAST, POLAR and DMSP. This investigation will probe the field-aligned currents of the auroral oval and the electrojet of the equatorial ionosphere. In collaboration with other polar orbiting spacecraft, it will determine both local time and altitude variations in these current systems. The SACI-1 mission is planned for a 750 km altitude orbit at an inclination of 98.5º. Once a verified data set exists, we will combine these data with those obtained by FAST and POLAR, with the imagery available from POLAR and other field-aligned current-measuring missions such as DMSP and Oersted to provide a truly global picture of the field-aligned current system.

SCIENCE OBJECTIVES

The science return from the magnetic field investigation on the SACI-1 mission will lie principally in the measurement of field-aligned currents simultaneous with the measurements of the solar wind and the magnetosphere by the spacecraft of the ISTP program and contemporaneous measurements by other low-altitude spacecraft such as FAST, DMSP and Oersted (successfully launched in February, 1999).

Field-aligned currents play an integral role in transporting stress from one part of the magnetosphere to another. The stresses that are applied to the magnetosphere by reconnection with the interplanetary magnetic field cause the plasma in the outer magnetosphere to flow perpendicular to the magnetic field. The high electrical conductivity of the magnetospheric plasma causes the entire flux tube of plasma to flow along the region to which the force is applied except at the foot of the flux tube where the ion-neutral collision frequency is high and the atmosphere drags on the tube. To overcome this drag, field lines bend or, equivalently, field-aligned currents flow. The currents close through the low-altitude ionospheric plasma exerting a JXB force, which acts to oppose the drag force, thus transmitting the original magnetospheric stress to the ionosphere.

Field-aligned currents are thought to play a similar role in magnetospheric substorms. For example the neutral point model of substorms postulates that a sudden increase in the reconnection rate between the oppositely directed magnetic flux in the tail lobes leads to an inrush of plasma in the night magnetosphere. The motion of the feet of these field lines is similarly opposed by the drag of the ionospheric plasma. Thus field lines in the nighttime magnetosphere also bend and field-aligned currents flow that close in the ionosphere. These currents transmit the magnetospherically induced stresses to the ionosphere.

Because of their importance field-aligned currents have received much attention in recent years. The two principal currents are called the region 1 and region 2 currents. The region 1 system flows poleward of region 2, downward on the dawnside and upward on the evening side of the auroral oval. Region 2 currents flow equatorward of region 1 currents, downward on the evening side and upward on the morning side. Closure of the currents in the ionosphere is through the auroral oval and across the polar cap. The sense of the currents is to oppose the drag of the ionosphere on the two-cell convection pattern.

Field-aligned or Birkeland currents have been observed in the Earth's magnetosphere at both high and low altitudes. Studies at high altitudes have also found Birkeland currents, at both the inner and outer edges of the plasma sheet [Aubry *et al.*, 1972; Fairfield, 1973; Sugiura, 1975; Frank *et al.*, 1981; Kelly *et al.*, 1984]. These studies reported on the observations and dynamics of Birkeland currents principally in the nightside magnetosphere.

The statistical properties of Birkeland currents have been determined principally from studies of low-altitude magnetic field data [Iijima and Potemra, 1976; 1978]. These studies showed two persistent, large-scale current systems, the region 1 and 2 currents systems. These currents were shown to exist throughout all local times. The properties of Birkeland currents have been reviewed by Potemra [1979] and Stern [1983].

Suzuki and Fukushima (1984) and Suzuki *et al.* (1985) analyzed geomagnetic data obtained from the MAGSAT satellite applying Ampére´s theorem to the integration of Bt (component of observed magnetic field tangential to the satellite orbit) along a complete satellite orbit and were able to demonstrate the existence of net anti-sunward currents under the MAGSAT orbit. Also using MAGSAT data Olsen (1997) was able to study a mid-latitude field-aligned current system proposed by van Sabben (1966). One can repeat this work using SACI-1 data.

On the one hand, we know much about field-aligned currents from these earlier missions but in fact much of our understanding comes from statistical summaries of the data and we do not have a good picture of the instantaneous behavior of the current systems. As experience with the magnetosphere has shown, the average behavior of a process and its behavior at a particular time or place might be very different than the statistical picture. The importance of the SACI-1 measurements, thus, are not just that they add further to our statistical database but rather that they add significantly to the constellation of spacecraft that can monitor the "instantaneous" response of the field-aligned current to magnetospheric dynamics. Much like the flotilla of spacecraft at synchronous orbit have been used to monitor particle injections at substorm onsets, we will be able to use SACI-1, FAST, DMSP and Oersted to determine the evolution of the current systems with time and space after an onset. We do not know this at present because field-aligned currents are difficult to determine from ground-based data. Multiple spacecraft provide our only way to determine how the field-aligned currents respond to dynamic events. Only a small investment is needed to ensure that the SACI-1 measurements are similar in quality to those from the other missions and to ensure that the data are analyzed in consort with the other measurements from these other missions.

A major hole in our understanding of the behavior of the magnetosphere is that we lack a global model (not even a statistical one!) for the field-aligned potential drop in the magnetosphere. Perhaps it is confined to field-aligned current regions. Perhaps it is associated with auroral processes. While we can image the auroral zone continuously for long periods of time with POLAR, we cannot relate these images to the processes at low altitude without ground truth in the images. SACI-1 will provide some of that ground truth by which we will be able to develop global field-aligned current and field-aligned potential drop models.

A secondary objective is the equatorial electrojet. The equatorial electrojet flows at about 104 km altitude and its return current extends to about 12° with a peak intensity at 4° (Onwumechili and Ezema, 1992). The current appears to be narrowest when it is most intense both on a day-to-day basis and on a diurnal basis (Onwumechili *et al.*, 1989). On occasion the effects of the electrojet can be observed up to 25° (Rastogi, 1991). While these measurements are much more difficult because the effect of the equatorial electrojet is much weaker at the altitude of SACI-1 than that of the field-aligned currents; if we do our data validation accurately, we should be able to detect it with the SACI-1 instrument.

The electric fields responsible for the equatorial electrojet are several: lunar and solar gravitational tides, the solar thermal tide, gravity waves from disturbances in the lower atmosphere and magnetospheric sources (Stening, 1985, 1995; Raghavarao and Anandarao, 1987; Somayajulu *et al.*, 1985; Zi *et al.*, 1989; Shen and Zi, 1991, Rastogi *et al.*, 1995). Thus it is not surprising that there are still controversies over the relative importance of these effects. One of these effects is the counter electrojet in which the electrojet changes direction. Rastogi and Patil (1989) attribute this direction change to a strong semidiurnal tidal force maximizing at 0900 LT and minimizing at 1500 LT. However, both dawn and dusk counter electrojets are seen. The electrojets also have some interesting effects on pulsations. Pulsations of periods greater than 20 seconds have their amplitudes enhanced, whereas at periods less than 20 seconds they are attenuated (Sarma and Sastry, 1995). By measuring the magnetic field above the electrojet with SACI-1 and below it with ground arrays, we would hope to determine how these currents close and separate magnetospheric from atmospheric/ionospheric influences.

A most intriguing observation was recently made by Yumoto *et al.* [1994] who have discovered current vortices at L-values from 1.03 to 2.13. These current vortices are clockwise, at least in the southern hemisphere, and move about 7 km/sec at about 40º latitude. Accompanying the observation of these vortices whose amplitudes can reach 50 nT is a moderately strong ring current, with a Dst index of less than-130 nT, and subvisual aurora. We would expect the occurrence of such phenomena to increase as solar maximum is approached. The importance of this discovery of Yumoto *et al.* [1994] is that it underscores how little we understand the energetics of this inaccessible part of the magnetosphere. SACI-1 will be able to determine the cause of such disturbances by flying through the ionospheric source of these vortices. Again, as we stress below, achieving a level of accuracy sufficient to make these low-latitude measurements will be difficult; hence, the proposed effort is quite important to its success.

APPROACH

These objectives will be achieved through the construction of an accurate magnetometer, and a robust spacecraft, and through the successful test and integration program, and finally launch and operations. Since the two elements of the program with which we will interact in the proposed effort are the spacecraft and the magnetometer we describe them here.

The Spacecraft

The SACI-1 spacecraft is a scientific satellite in a Low-Earth Orbit. The satellite will fly in a circular orbit inclined 98.5° with respect to the Earth's equatorial plane, at an altitude near 750 km, in a 10 A.M. - 10 P.M. sun synchronous orbit. During the passes visible either from the tracking stations or a user's ground-data collecting station, scientific data will be transmitted to the ground. When not in view of a tracking station, data are stored in the onboard computer (OBC).
The main characteristics of the satellite are the following.

- The total mass is 60 kg;
- The payload mass is 20 kg;
- The dimensions are 570 X 440 x 440 mm;
- The conception is modular, with simple technical solutions;
- The thermal control is passive;
- The total cost, including bus and scientific payloads, is U.S. $ 4.6 million;
- The satellite expected lifetime is 18 months;
- The payload power requirement is 30 W;
- The satellite is spin-stabilized, 6 RPM;

The shape of the spacecraft mechanical structure is a rectangular box of 440 x 440 x 570 mm with the greater dimension parallel to the launcher axis.

The main structural elements are stacked standard aluminum modules. Figure 1 shows the exploded view of the satellite. In SACI-1 there will be four deployable solar panels. Three of the solar panels will support ionospheric sensors and the fourth panel will support a magnetometer head. In each deployable panel will be mounted two panel hinges that will be connected to the main body satellite structure. The solar panels will be looking continuously at the Sun with a pointing accuracy of 1 degree.

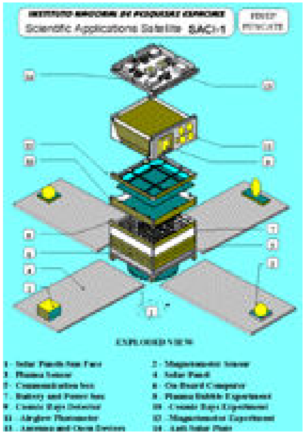

Fig. 1. Exploded view of SACI-1 microsatellite

The Communication System subsystem is responsible for sending the housekeeping telemetry to the ground, for receiving the telecommand, and sending data to the ground. Dual redundant transmitters provide a standard S-band (2255.2MHz) telecommunication signal to the ground with BPSK modulation and a 128, 256 or 512 Kbits/second selected data transmission rate. The modulation bandwidth of the order of 200 MHz, allows the transmitted date rates to achieve 128 Kbps, and a 2 watts RF output power of each transmitter is divided over two antennas with gains that assure the reception of these data by a 3.4 m diameter ground antenna located at Natal (5.8° S, 35.2° W).

The dual redundant receivers perform ground to satellite S-band (2018.8 MHz) telecommunication at 19200 Kbits/second data transmission. The redundant receivers are both connected to the two reception antennas through a hybrid device. Once the spacecraft command reaches the two redundant receivers, the output of these two units, in principle identical, is processed by the onboard computer, and the final commands are either transferred to command lines or stored for later implementation. The OBC is able to handle up to 64 telecommands. The spacecraft has 25M bytes of internal storage.

The Magnetometer

The magnetometer is a three-axis fluxgate magnetometer in which the second harmonic signals from the orthogonal fluxgate sensors are detected and the sensors are kept in a null field by appropriate feedback derived from the outputs of the sensor coils.

The ring core sensor assembly of the proposed magnetometer is mounted at the tip of one of the four solar panel arms. Hence the ring core sensor assembly will be 50 cm away from the main body of the satellite. The sensor assembly is covered with a thermal blanket in order to protect the sensors from large temperature variations. The magnetometer is capable of measuring geomagnetic field intensity in the range of +65536 nT to -65536 nT with a resolution of ± 1nt.

The ring core sensors are made of high permeability magnetic material, 6-81 molybdenum permalloy, similar to the fluxgate sensors developed for the MAGSAT magnetometer. The toroidal sensor core is wrapped by drive, and combined sense/feedback coils. The material for accommodating the ring cores has been carefully selected.

The electronics unit on the main body of the spacecraft drives the sensors with signals at 9 kHz. The amount of second harmonic signal in quadrature with the drive frequency is detected from the sense winding. A feedback circuit nulls the second harmonic signal applying enough current to keep the core in zero field. The current applied is a measure of the strength of the external field. The electronics unit contains drive, sense and feedback circuitry for all three sensors, clocks, multiplexer and A/D convertors. The magnetometer data will be sampled at 100 Hz and then averaged to 10 samples per second and stored for later transmission. The noise level of this system is about 2x10^{-5} nT^2/Hz at 1 Hz.

C. T. Russell's group at UCLA provided the analog part of the fluxgate magnetometer. The completed flight board is shown in Figure 2. INPE is responsible for providing a clock signal from a crystal oscillator and a power supply of ±12 volts at 110 ma and +5 Volts at 50 ma. INPE is providing the circuit board for analog to digital conversion at a precision of 16 bits.

Fig. 2. Photograph of the fluxgate magnetometer flight board and the sensor.

ACHIEVING THE DESIRED ACCURACY

The nominal pointing accuracy of the SACI-1 spacecraft is 1°. At 750 km above the auroral zone, this angular error would result in a 600 nT error in the components perpendicular to the main field such as the direction of the pertubation due to field-aligned currents. There are two ways to obtain the correct field-aligned current in the presence of this angular error. The first approach has been used on many historical missions, just adapt the base line established prior to and after the auroral passage and assume that these are pertubations of the field only over the auroral zone. The second way is to use the field variations well away from the auroral zone to determine the attitude of the spacecraft very accurately and then interpolate that attitude through the auroral zone. Although the former approach is usually successful, there are occasions when there are significant pertubations of the field all the way across the polar cap. This technique does not allow one to identify such distortions. Thus, we prefer to use that data over the equatorial position of the orbit to determine the attitude and extrapolate into the polar region. Our (UCLA) experience on the POLAR spacecraft has helped us to assess and gain confidence in existing models and to determine their accuracy under varying magnetospheric conditions. We will use these models and the measured magnetic field to solve for the attitude of the spacecraft during each orbit for which we have data and then model the variation of the attitude between determinations. In this way we expect to determine the attitude to better than 0.1°. How much better we can achieve remains to be determined and depends in part on the success of the magnetic cleanliness plan we will implement as the spacecraft is assembled.

Measuring the equatorial electrojet current from space requires greater accuracy than we expect to achieve if we attempt to determine the vector field. However, if we restrict our attention to the total field strength as we cross above the electrojet, we will be able to make an accurate measurement. To check this estimate, we compare with ground-station estimates during overflights of the ground station. Once we have validated our measurements, then we should be able to use them at any longitude, independent of the presence or absence of a ground station.

In short then the high intrinsic accuracy of the SACI-1 magnetometer attitude allows us to 'bootstrap' an accurate attitude measurement from the existing field models and to extrapolate that through the auroral zone. A good magnetics plan, a well-calibrated magnetometer and accurate field models allow us to calculate much more precise orientations than those provided by the spacecraft systems. Thus we can achieve good accuracy on this small spacecraft.

Once we have verified the pointing and calibration of the instrument through comparisons with models, we will begin to assemble a database of field-aligned currents. A low-altitude spacecraft crosses the auroral oval on average every 25 minutes. If Oersted, FAST, SACI-1 and two DMSP satellites are simultaneously providing data, then we will have on average a field-aligned current measurement somewhere every five minutes. Even without correlative ground-based data, this data set can be readily used to develop and test global models of the response of field-aligned currents to magnetospheric dynamics. If, as we expect, imaging is still available from POLAR, we will be able to relate globally the relationship of the changing current system to the dynamics of the auroral activity. Moreover ground-based magnetic records and ionospheric convection measurements with the SuperDARN radars can be combined or assimilated mathematically with the in-space data to provide a robust estimate of the minute-to-minute variations of the current system. While such an assimilation is not presently performed (or necessary since most analysis is retrospective), we would work toward that goal in this project.

SCHEDULE

Launch is scheduled for July 1999. The payload is well tested and calibrated. The experiment has successfully undergone a shake test and environmental test in LIT/INPE. Presently integration of the satellite is being done at LIT/INPE and soon the crucial job of certifying magnetic cleanliness and finding the magnetic moment of the satellite will be done. Simultaneously we are finalizing the software for data reduction of a spinning satellite in a polar orbit. We will check our software carefully to ensure its compatibility for future joint analysis with the UCLA satellites FAST and POLAR. We are looking forward to a very comprehensive study of the coupling of the magnetosphere to the ionosphere through these field-aligned current systems.

PARTICIPANTS

The scientific participants in this effort are Drs. Nalin Babulal Trivedi (INPE), Christopher T. Russell (UCLA), Naoshi Fukushima (Tokyo), Fritz Primdahl (Denmark), Jose Marques de Costa (INPE), Severino L. G. Dutra (INPE), Daniel J. R., Nordemann (INPE) and Rajaram P. Kane (INPE). These individuals are assisted by engineers Robert C. Snare (UCLA), Joseph D. Means (UCLA), William Greer (UCLA), Silvana Rabay (INPE) and Maria Jose Faria Barbosa (INPE).

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