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STATE OF THE ART SCIENTIFIC INSTRUMENTATION DEVELOPED FOR A MICROSATELLITE ON A SCIENTIFIC MISSION TO STUDY PLANET EARTH*

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Abstract—An outline design for a relatively inexpensive 50 kg microsatellite (EISAT-1), to be launched into a near-polar Sun-synchronous 550 km orbit, is presented. A strawman payload for the spacecraft, based on an existing heritage of successfully flown space instruments with the capability to make important measurements of the Earth's energetic particle environment; studies of the cold terrestrial ionospheric plasma and remote sensing of terrestrial features sensitive to global change is described. These devices represent part of a mature genre of lightweight space instruments which can contribute significantly to the implementation of first class scientific programs on micro- or small satellites so as to both complement and fill thematic gaps in the science programs of the major agencies. Partners are sought to provide financial backing for individual instruments of the payload in return for mission/data participation. An alternative method of participation could be the provision of another instrument, or instruments, with the capability to carry out a significant scientific research program aboard EISAT-1, which is expected to be launched in 1997.

1. INTRODUCTION

Among the many benefits attending the emergence on the market of highly sophisticated microsatellites (10–100 kg) and minisatellites (100–500 kg), is the opportunity they provide to enable first class science to be carried out in space at a moderate cost. To take advantage of the window of opportunity thus offered, lightweight fault-tolerant instrumentation suitable for flying on board such spacecraft are required with the capability to provide measurements that will both complement and fill thematic gaps in the science programs of the major agencies.

Plans are presently in train to bring together (a) the capability to build highly sophisticated lightweight scientific instruments (in the approximate range 1–5 kg) developed, within the last decade, at Space Technology Ireland Ltd (STIL) and (b) the capability to build modular microsatellite platforms and Remote Sensing cameras developed in parallel at Surrey Satellite Technology Ltd (SSTL), to mount a mission, EISAT-1, to study various aspects of the Earth's environment.

The present paper describes this spacecraft, its scientific objectives and its strawman payload and suggests ways in which international participation in the EISAT-1 Mission to Planet Earth can be realized.

2. THE SPACECRAFT

Figure 1 presents a view of the proposed spacecraft. A key aspect of the design is the use of a modular system. The spacecraft bus is a derivative of the highly successful UoSAT range of microsatellites developed at SSTL [1]. For EISAT-1, the system has been somewhat modified to support an Earth Observation mission. The technical specification of the spacecraft is shown in Table 1.

Data transmission to ground is realized using packet transmission formats and the store and forward communications transponder. Provision is provided to protect the data files against Single Event Upsets, while the integrity of the data transmitted to the ground station is ensured by the use of packet communications protocols which ensure error free transfer [2, 3].

3. SCIENTIFIC RATIONALE FOR PARTICLE RADIATION MONITORING

Computer models of the Earth's radiation environment such as AP-8 and AE-8 developed by NASA from data taken in the 1960s and early 1970s have been widely used for the definition of missions and spacecraft. Recent investigations by Lemaire [4] and Daly [5] have, however, identified significant disparities and functional weaknesses in these models. Apart from separate versions for solar maximum and solar minimum, the radiation models currently

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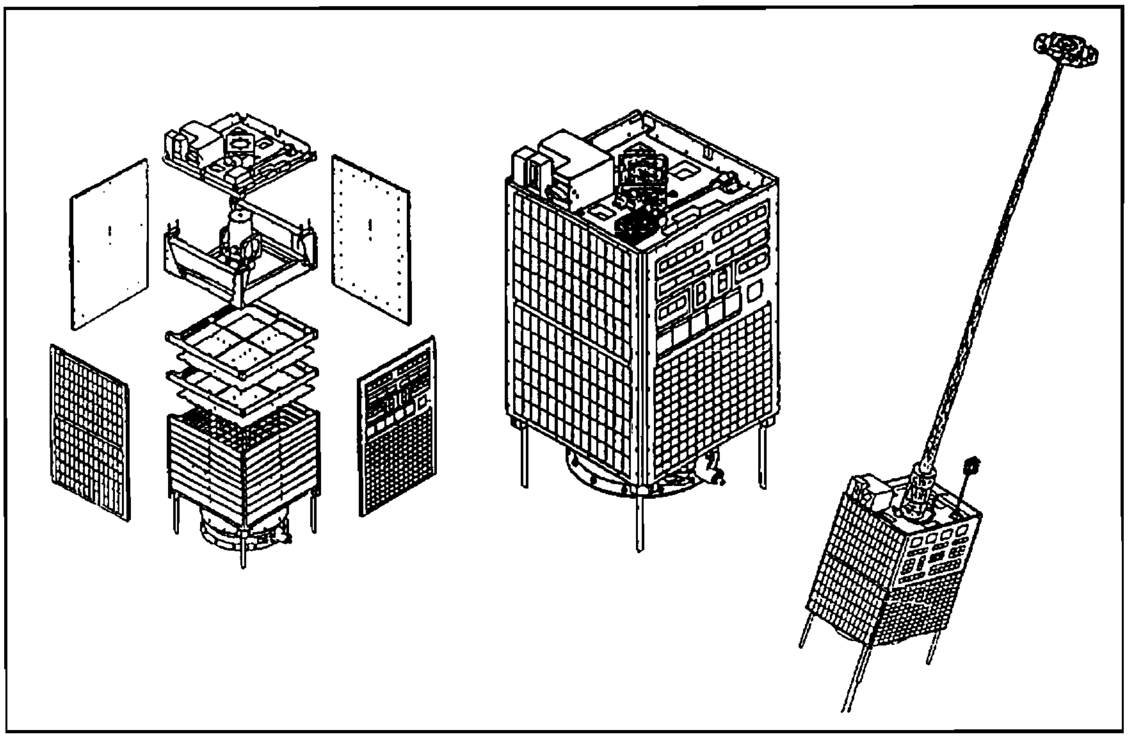

Fig. 1. EISAT-1 modular microsatellite platform.

available contain no information on temporal behaviour or frequency statistics for different flux levels. Also, variations in the Earth's magnetic field with time, which are important at low altitudes, and the anisotropy of the low altitude environment are not modelled. With these problems in mind, Lemaire *et al.* [4] recommended to the world community that all possible flight opportunities be exploited to collect particle radiation measurements so as to provide ongoing monitoring for an urgently required new generation of particle radiation models.

It is noted that such data are not only of key scientific importance in their own right, but an accurate knowledge of the Earth's radiation environment is also imperative due to present requirements to utilize in space advanced semiconductor detectors and other devices which are more sensitive to radiation than those of 20 years ago. Over optimistic models would be a disaster for mission operations whereas too pessimistic models would lead to unnecessarily heavy shielding of the spacecraft or to the choice of costly alternative orbits. Also, there are implications for astronaut exposure, under certain circumstances, in the International Space Station. To benefit space scientists, engineers and spacecraft users then, there is clearly a need for particle radiation data to be taken synoptically at many locations in space, simultaneously, and over long periods of time.

Three devices which could be used on a microsatellite in Low Earth Orbit to provide continuous monitoring of various aspects of particle radiation "weather" over a substantial portion of the sunspot cycle are described below. In respect of spacecraft lifetime it is noted that the SSTL microsatellite UoSAT-1 launched in 1981 was still operational at

Table 1. Technical specification of the EISAT-1 microsatellite

Mass	50 kg
Dimensions	350 × 350 × 678 mm
Solar arrays	672 GaAs solar cells mounted on body
Power	49 W raw peak power 20 W processed average over one orbit
RF systems	Triple redundant VHF uplink (9.6 kbits/s) Dual redundant UHF downlink (38.4 kbits/s) and 9.6 kbits/s
Attitude control	Computer-driven magnets, complementing a 6 m gravity gradient stabilizing boom
Sensors	2 magnetometers; Sun sensors and Earth sensors
Telemetry	128 analogue channels 144 digital status indicators
Telecommand	4 redundant microcontrollers 120 latched command signals
Computers	Primary computer: 8 MHz, 80C186 primary on-board computer 16 Mbytes RAM, 72 bits parallel I/O 4 Channels multiprotocol I/O Quadron Operating System Secondary computer: 25 MHz, 80386EX secondary on-board computer 16 MBytes RAM, 48 bits parallel I/O Redundant interface to Local Area Network High performance serial communications controller Imaging computer: 20 MHz T800 Transputer parallel processor 2.5 MBytes RAM (16 k SOS)

Table 2. Summary of the specifications of the energetic proton detector

Property	Value
Total mass (per unit)	2.5 kg
Dimensions	170 × 150 × 100 mm
Power consumption	1.5 W
Detection range	30–500 MeV for protons < 100 MeV for alphas and heavy ions
Energy resolution	Software configurable, 1024 channels
Time resolution	Software configurable from 50 ms upwards
Bit rate	Programmable
Spacecraft interface	Intelligent (microprocessor controlled)
Processor design	Cold redundant 80C85RH

re-entry in 1989 [1]. UoSAT-2, which was launched in 1984, is still operational. The radiation monitors described all arise from a heritage of space proven devices and represent state of the art technology.

3.1. Energetic proton detector

Table 2 summarizes key characteristics of a uniquely reliable Energetic Proton Detector developed by STIL to operate in the range 30–500 MeV. The instrument mass is 2.5 kg, its power consumption is 1.5 W and its dimensions are 170 × 150 × 100 mm. The energy resolution is software configurable and can provide a channel resolution of 1024 (maximum measurement resolution 0.5 MeV at the bottom of the range). The integration time is configurable from 50 ms upwards (deadtime 5 μs per event).

The detector system consists of three ion implanted silicon detector layers, stacked as shown in Fig. 2a. The upper (very thin) silicon layer is used to distinguish between protons and electrons. The second layer is used for energy loss analysis. The entire surface of the detector stack is covered by a dome-shaped tantalum shield (1.5 mm thickness), see also the energy loss diagram (Fig. 2b). Two orthogonally arranged telescopes with a conical viewing angle of 45° can provide limited directional information. Two such units viewing in opposite directions are foreseen for EISAT-1.

It is intended to use a HARRIS 80C85RH radiation hardened 8 bit CPU, along with HARRIS rad-hard memories. Although these devices are not entirely latchup free, they are rather tolerant to transient upsets (10^8 rad/s) and also remain operational above 10^5 rad total dose. In addition to this, special HW latch-up protection is built into this system which prevents overcurrent through the silicon substrates. However, the main attraction of this device, which is cold redundant, lies in the following features (a) it remains operational with full continuity in case of a total CPU failure (switching over to the redundant CPU will not result in re-start and data loss since the CPU will continue working from when the failure occurred; (b) it is able to provide continuous Single Event Upset (SEU) data correction in both its program and data memories, thereby greatly increasing its own fault tolerance against the very effect (SEU) that threatens the functionality of any microprocessor system flying in a high radiation environment; (c) a key element in the design is the operating software that ensures continuous operation. This is a real time multi-tasking system which, as a system service, stores information about its own status in a protected memory area.

3.2. Energetic electron detector

A very lightweight (700 g), low volume (dimensions 100 × 110 × 120 mm) and low power (1 W) electron telescope, with energy range 1–5 MeV, featuring 1 MeV energy resolution and a time resolution configurable from 50 ms upwards, is under development at STIL, see Table 3. This device is based on 2 mm thick ion-implanted detectors and is designed

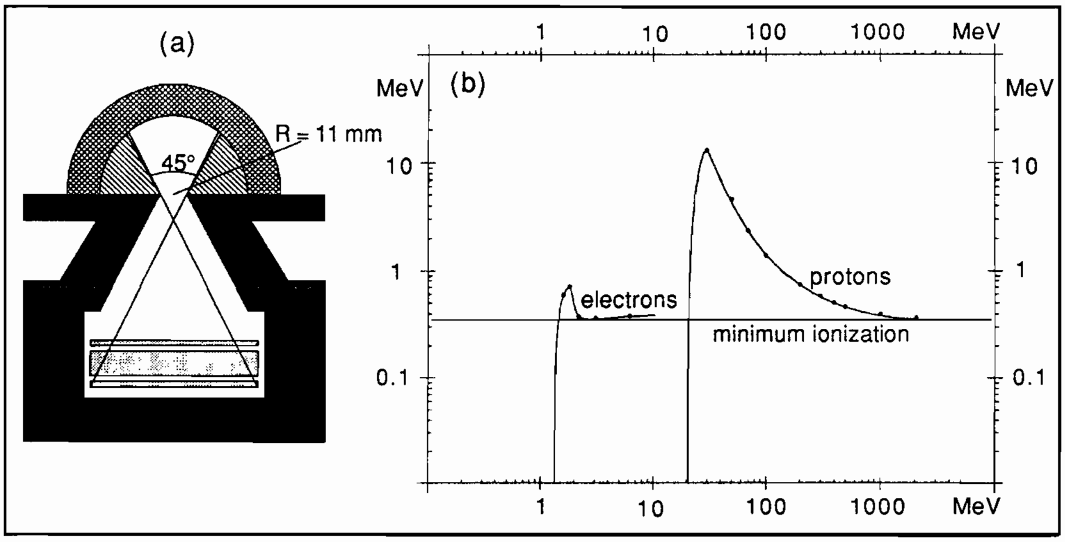

Fig. 2. (a) Conical proton telescope with tantalum shield. (b) Energy loss curves for protons and electrons in 1000 μm silicon detector behind 1.5 mm tantalum shield.

Table 3. Summary of instrument technical specifications

Detector energy range	1–5 MeV electrons
Detector type	Ion implanted
Energy resolution	1 MeV with 4 channels
Time resolution	HW configurable from 50 ms upwards
Bit rate	HW configurable from 100 bits/s upwards
Spacecraft interface	HW configurable
Total mass	Approx. 700 g
Dimensions	100 × 110 × 120 mm

to operate in high-flux environments (up to 1 million events/s). This unit has the capability to reject protons and alpha particles from the measurements and is designed to monitor a little known part of the near Earth electron spectrum. Its very small physical dimensions and mass and power consumption make it particularly useful for microsatellite applications.

3.3. Space dosimetry

The purpose of the Charge/Energy Deposition Experiment (CEDEX), developed by SSTL, is to characterize the space radiation environment as it effects spacecraft electronics. This device occupies one half of a standard UoSAT payload module (which is 330 mm square and 26 mm deep), has a mass of 1.1 kg and a power consumption of 2.0 W.

Data from the experiment are sent to the primary on-board computer, which handles time-stamping and data storage in the spacecraft's solid-state data recorder. Files stored in the data recorder are protected against Single Event Upsets (SEUs) by software coding/wash routines, and the downlink is error-controlled by the AX 25 packet communications protocols, ensuring error-free data at the ground station.

The CEDEX instrument complements the EISAT-1 particle detectors by monitoring the internal radiation environment of the spacecraft. It achieves this through providing pulse-height analysis of the charge (or equivalently the energy) deposition spectra in a single, fully-depleted, 300 μm thick, 30 mm × 30 mm PIN diode. A second, identical, PIN diode is used to form a "telescope" arrangement so that the direction and linear energy transfer (LET) of the particles can be more accurately determined.

The sensor diode is connected to a charge amplifier and a "CR-RC" (constant peaking-time), pulse-shaping circuit which, in turn, is connected to an event-driven, hardware-logic controlled multichannel analyser. The overall experiment is controlled by an 83C200 CAN-controller with its own data-storage memory and built-in data compression and communications software. The instrument can cope with both low and high flux conditions and has a "dead time" (from detection to baseline restoration) of less than 5 μs.

The multi-channel analyser has 512 channels, each of equal width, equivalent to an 0.05 pC charge deposited in the detector. The total useful range of the instrument is approximately 0.2–26 pC charge deposited, equivalent to a normal incidence LET range of 64–8360 MeV cm^2 g^{-1}. The instrument has its own built-in calibration pulse, with a fixed charge injection, for in-flight performance verification.

In operation, the particle-induced charge-pulses from the PIN diode sensor are amplified and shaped, and the pulse-height is recorded by a fast semi-flash 10-bit analogue-to-digital converter. The output of this converter is used to address self-incrementing memory locations which can hold a count of up to 16,777,215 (i.e. 2^{24}). These counts are summed over a fixed period of 150 s and data from four such periods are stored internally and processed using a loss-free data compression coding scheme, before transmission to the on-board computer via the spacecraft's CAN-bus data network.

For simplicity of design, the three bytes of count-data for each channel are stored in four bytes of data memory. The fourth (remaining) byte is used to store a fixed bit pattern which is examined for SEUs.

The sensor elements are shielded at the sides by 10 mm thick aluminium walls, preventing most primary electrons and all low-energy ions from contributing to the spectrum (for example, protons require more than 45 MeV energy to penetrate the walls). The faces of the detector are shielded by the rest of the spacecraft structure, which, in this regard, provides approximately 10 mm of aluminium above, and between 20 and 40 mm of aluminium below, the device.

4. SCIENTIFIC RATIONALE FOR IONOSPHERIC MONITORING

Despite the fact that the Earth's ionosphere has been studied for several decades, many questions concerning the global distribution of its key parameters; their evolution in relation to the solar cycle and the short- and long-term reactions these parameters display in response to solar related geomagnetic disturbances are still unanswered, particularly at high and low latitudes. Further the International Reference Ionosphere (IRI), which is currently widely used for many scientific and practical applications, is seriously incomplete.

A unique instrument Terriprobe, originally developed at the Space Research Institute in Moscow to provide the first global measurements of the near Martian cold plasma during the Mars-94 mission (official manufacturer STIL), has now been adapted to study the cold terrestrial ionospheric plasma and flown on the ACTIVNY and APEX satellites. Figure 3 shows data obtained by Terriprobe aboard ACTIVNY during 13 polar orbits (apogee 3500 km; perigee 450 km; inclination 84 degrees).

4.1. Cold plasma monitoring using Terriprobe

Terriprobe consists of three components (a) a Cold Plasma Meter (CPM); (b) a Spherical Ion Probe (SIP) and an electronic block. The CPM, which has a

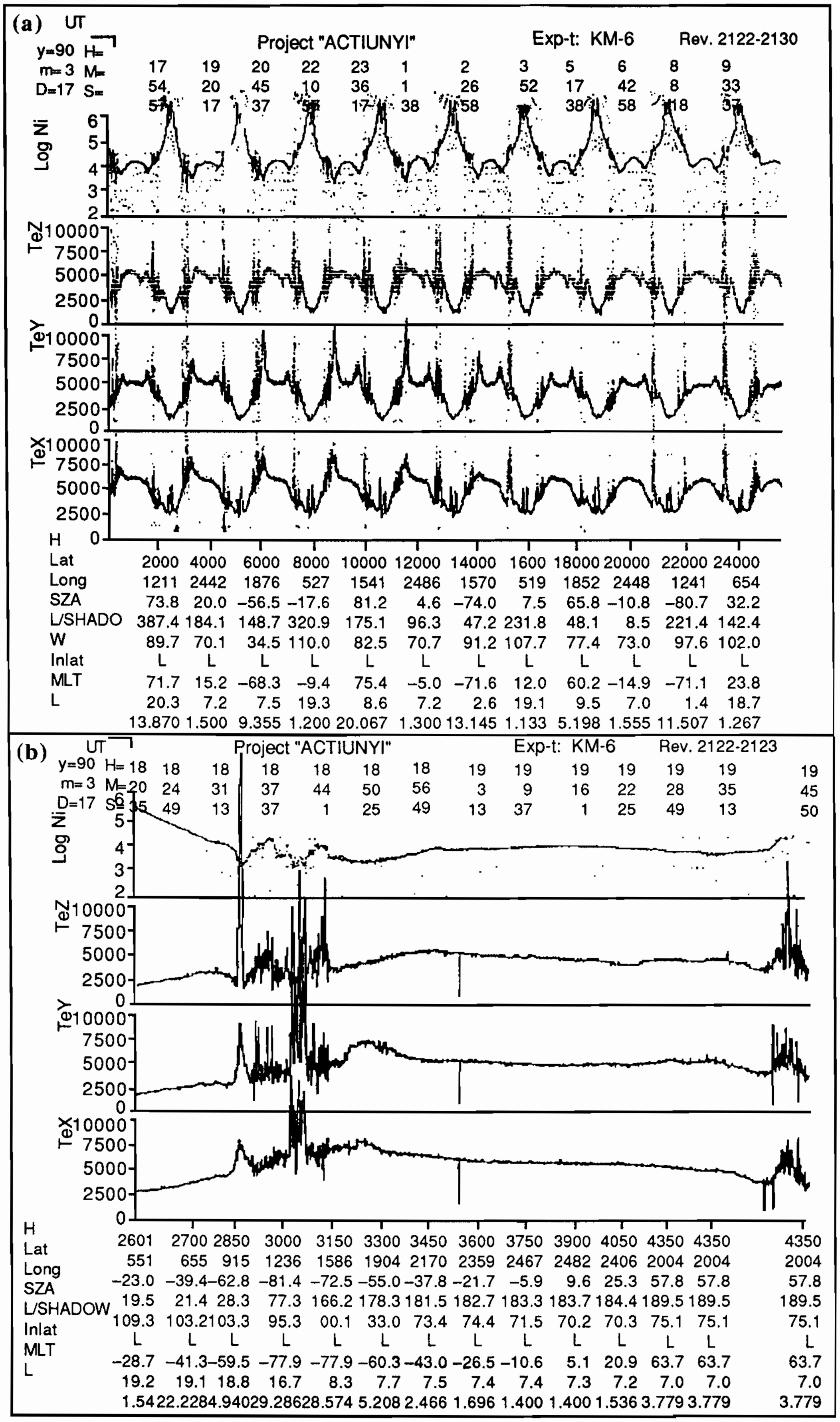

Fig. 3. Terriprobe data.

volume of 150 × 150 × 100 mm comprises a complex of sensors. Namely

(1) A Retarding Potential Analyser (RPA) to measure ion density, Ni; ion temperature Ti and masses of the major ionospheric ions, Mi.

(2) A Driftmeter (DM) to measure two components of ionospheric plasma drift—thereby providing monitoring of electric fields in the polar ionosphere.

(3) An Electron Temperature Probe (ETP-x) to measure Te in the x-direction.

(4) ETP-y and ETP-z to measure electron temperature anisotropy in mutually perpendicular directions.

(5) RPA-z to measure ion flux coming from the plasmasphere (including suprathermal).

(6) RPA-Mz to measure the suprathermal ion flux accelerated upwards from the ionosphere.

In full configuration, Terriprobe will weigh about 3.5 kg and consume about 3 W of power. The following parameters will be measured: ion density; ion temperature; mass composition (2–3 major masses); electron temperature Te; anisotropy of Te; Ion drift (velocity, angle); ion flux variation frequency spectra ($f < 2000$ Hz); upward ion flux; downward ion flux and spacecraft potential.

The Spherical Ion Probe (SIP) will measure ion density with very high temporal/spatial resolution (not less than 1000 times per second or faster—depending on the ionospheric density).

CPM should be oriented in the direction of the spacecraft velocity so as to always record incoming flux. It may be mounted on a 50–100 cm boom. SIP may be mounted on a similar boom with the requirement that it should not be in the shadow of the spacecraft.

This configuration of sensors allows simultaneous monitoring of practically all of the major ionospheric parameters and will: (i) allow us to study ionospheric inhomogeneities arising from numerous wave–particle interaction processes and plasma instabilities that influence radio wave propagation; (ii) enable us to carry out long-term ionospheric global monitoring, thereby gathering high quality data suitable for improving existing models of the ionosphere (in particular the IRI); (iii) permit investigations to be carried out of numerous aspects of ionospheric behaviour which are not presently understood, including the ionosphere–plasmasphere interaction; the ionospheric thermal balance and various aspects of the Earth–Sun interaction. An intriguing possibility is to seek for signatures of antroprogenic effects in the ionosphere. Also, to look for earthquake-related ionospheric signatures.

To achieve these measurements, a strong requirement is imposed on spacecraft attitude control. In cases where the spacecraft orientation is not precisely predictable, it is necessary that the rate of spacecraft rotation and rolling should not be so large as to change the attitude of the spacecraft relative to incoming flux during the cycle of measurement (this in turn depends on the ambient ionospheric parameters). Exact knowledge of the spacecraft attitude is obligatory.

For spacecraft where the attitude control cannot be guaranteed, a version of Terriprobe can be used which measures a fewer number of parameters. This package consists of an electronic block and two sets of sensors (SIP and the Spherical Electron Temperature Probe). Each pair of sensors should be mounted on booms viewing in opposite directions. This configuration will guarantee that measurements of total ion density (Ni) and electron temperature (Te) can be achieved independently of spacecraft orientation, and with time resolution not less than 10 s^{-1} for Te and up to 1000 s^{-1} for Ni. Also, measurements of ion flux inhomogeneities up to frequencies of about 1000 Hz will be possible.

Figure 3a presents (Top) data obtained during 9 revolutions of the Earth (2122–2130; top right corner) using Terriprobe. Upper curve: Log Ni provides ion density per cubic cm (log scale). The next three curves display electron temperature in 3 mutually perpendicular directions in Kelvin degrees. Information under the plots: First line, no label (TM frame number); H (Height in km); LAT, LONG (Geographic Latitude and Longitude); SZA (Solar Zenith Angle); L/SHAD (Indicates if the spacecraft was in the Light (L) or in the Shadow of the Earth); INLAT (Invariant Latitude); MLT (Magnetic Local Time); L (Macillwain's magnetic shell parameter); Upper left corner (day month and year followed by Universal Time). The plot commences on March 17, 1990, UT at about 17 h and continues into the next day for about 10 h (a total of 17 h of flight data are shown). The two arrows indicate a part shown expanded in Fig. 3b.

Figure 3b (Bottom) shows the same data for March 17, 1990 for the interval 18.20–19.45 UT. The spacecraft passed from left to right from −23° in the southern hemisphere at 650 km height via the south polar region at 900–1500 km (note the intensive variations in all three Te and in Ni), to the apogee at about 2500 km over the equator to the north polar region at about 1500 km. Fine details of the behaviour of Ni and of Te can be studied on this record.

5. SCIENTIFIC RATIONALE FOR EARTH OBSERVATIONS

At the present time, the urgent need to advance our understanding of the causes and effects of global change provides a major motivation to conduct long-term, synoptic, measurements from space of diverse aspects of the Earth's environment. Such data, combined with Earth-based calibration and validation programs, can provide those inputs required to develop numerical models that can provide significant advances in our understanding of the state of the Earth, its changes, feedbacks, interactions and global trends over extended time scales.

Of particular interest are the studies that can be made of vegetation cover and its variability at the semi-arid to arid zones boundary, a region which displays particular sensitivity to even small changes in climate parameters.

5.1. A lightweight CCD camera

The teaming of two-dimensional semiconductor charge-coupled devices (CCDs) with computationally powerful microprocessors (Transputers) featuring low power consumption, now enables Earth imaging systems to be conveniently carried aboard microsatellites. A wide angle camera (2 km/pixel: 1500 × 1050 km), and a narrow angle camera (200 m/pixel: 150 × 150 km), presently available from SSTL can provide up to 200 m ground resolution and good separation of arid/vegetation and land/sea boundaries. The performance achieved is comparable with that attained by NOAA and METEOSAT but at a very modest cost.

6. INVITED PARTICIPATION

Partners are sought to provide financial inputs in respect of the construction, integration, testing and operation of individual instruments of the EISAT-1 payload in return for participation (a) in the Mission and (b) in the analysis/publication of the scientific data gathered by the instrument supported. An alternative method of participation would be to provide another instrument, or instruments, for the payload, with the capability to perform first class science, together with sufficient financial backing for necessary associated integration, testing and operational activities.

7. CONCLUSION

A 50 kg microsatellite (EISAT-1) to be launched into a near polar Sun synchronous 550 km orbit has been described together with a strawman payload based on a mature genre of lightweight instruments which can make important scientific measurements of different aspects of the Earth's environment. Mechanisms for international scientific participation in this mission, which is expected to be launched in 1997, are outlined.

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