AUSTRALIAN SPACE RESARCH: THE FEDSAT MICROSATELLITE

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ABSTRACT

Australia will launch its first satellite in thirty years late in 2001 or early 2002. Named FedSat as a celebration of Austalia's Centenary of Federation, it is a research microsatellite with a complement four scientific and engineering payloads onboard. It will be placed in a near-circular sun synchronous 10:30 LT polar orbit at an inclination of 98.7° and altitude 800 km. The primary scientific experiment is a fluxgate magnetometer which will observe field aligned current structures above the auroral zones and other current systems and ultra-low frequency (ULF) plasma waves in the upper ionosphere. The spatial and temporal relationships between ground and FedSat magnetic signatures will be studied. Also important will be the continuous monitoring of the main geomagnetic field for reference field modelling in the Australian region and disturbances associated with space weather events. An on-board GPS receiver will monitor the vertical and oblique total electron content (TEC) up to the GPS satellites at an altitude of 20,000 km. The communications experiment will test systems in the UHF and Ka bands for use in future LEO constellations and satellite-ground communications. Research in satellite navigation will concentrate on the use of GPS for small satellite real time tracking and precise orbit determination, while a high performance computer will test the operation of reprogrammable hardware. This paper briefly describes FedSat and its payloads and concentrates on the research to be undertaken using the fluxgate magnetometer.

1. INTRODUCTION

In 1997 the establishment of the Cooperative Research Centre for Satellite Systems (CRCSS) under the Australian Government's CRC Program saw Austalia return to active participation in space research. The specific mission of the CRCSS is to deliver a new sustainable advantage for Australian industries and government agencies, including universities, involved in services based on the applications of future generations of small satellites.

The first and primary project of the CRCSS is to launch a low Earth orbiting microsatellite, FedSat into an 800 km circular polar orbit with an inclination of 98.7°. The launch will take place sometime between September 2001 and April 2002, and FedSat will become operational late in the celebrations of Australia's Centenary of Federation. FedSat will be launched as a secondary payload to the Japanese ADEOS-2 spacecraft on an H-IIA launch vehicle. It will have a mass of 58 kg with the approximate dimensions of a 50 cm cube and the addition of a 2.55 m deployable boom. The satellite platform is under construction at Space Innovations Limited (SIL), a UK company, and is based on their MicroSIL™ bus. The attitude control employs a 3 axis stabilisation system and is nadir pointing. Figure 1 illustrates the satellite in orbit.

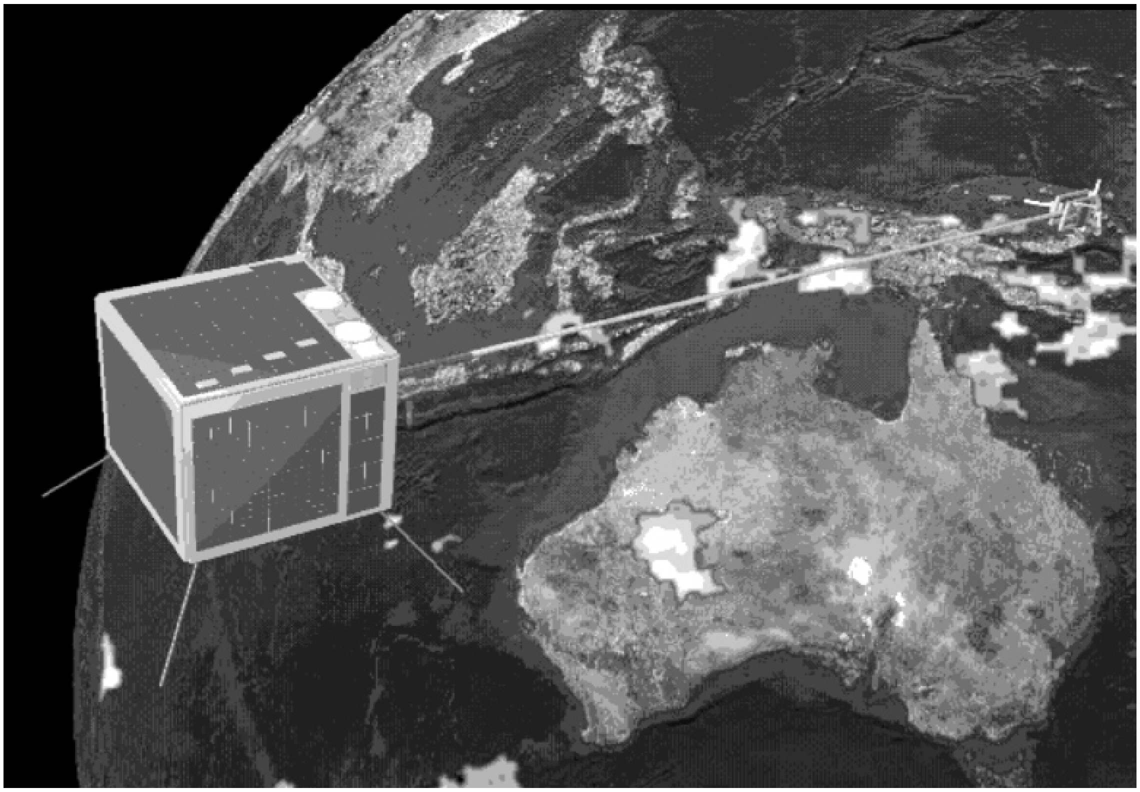

Fig. 1. The proposed FedSat microsatellite in orbit.

FedSat is not a mission dedicated to a single scientific or engineering goal. Instead, it will carry a range of experimental research payloads which are based on the engineering and scientific research activities of the participants in the CRCSS, in order to gain experience. Payloads include a fluxgate magnetometer; a UHF data transfer system; a Ka-band communications system; precise orbit determination and TEC measurements using GPS; and a high performance computer experiment. These CRCSS activities are focussed under four programs, the Space Science Program (University of Newcastle; La Trobe University), the Communications Program (University of South Australia and University of Technology, Sydney) and the Satellite Systems Program including navigation and high performance computing (Queensland University of Technology).

Although this paper is primarily concerned with the space science program and in particular the magnetometer experiment, brief details of the other experiments are included in the following two sections. Further details on the FedSat platform are given in Graham (2000).

2. SATELLITE COMMUNICATIONS

The aim of this, the largest research program on FedSat, at the University of South Australia, is to develop new communications techniques for use in future LEO satellite communications and Earth observation constellations. This will include the development of innovative solutions to communications network management and to satellite tracking and control. It is proposed to test applications in new services such as two-way paging, mobile computing and Internet access for uses in remote areas. New antennae and components for communications at Ka-band frequencies (above 20 GHz) are also being developed using FedSat. Further details of the communications experiments are given in Graham (2000).

3. SATELLITE SYSTEMS

Future generations of small satellites for communications and remote sensing will involve constellations of up to hundreds of satellites in non-geostationary orbits. Research interests at the Qeensland University of Technology are concentrating on the use of GPS for real-time tracking of small satellites and precise orbit determinations using data from a Spectrum-Astro GPS receiver on FedSat provided by NASA. Also under this research program is the design and operation in space of a high performance computing system (HPCE) for small satellites. The emphasis is on the development, in collaboraton with the Johns Hopkin's Applied Physics Laboratory, of architecture for on-board computing including reconfigurable logic and reliable software design.

4. THE SPACE SCIENCE PROGRAM

The NewMag experiment on FedSat will monitor the geomagnetic field and its perturbations and the GPS receiver will measure the ionospheric total electron content (TEC), in order to:

(i) Conduct basic research on the structure and dynamics of the ionosphere, exosphere and magnetosphere, using magnetic field observations and propagation delays of Global Positioning System (GPS) signals.
(ii) Apply the results of this research to space weather and communications prediction models.
(iii) Study the dynamics of field aligned currents in the auroral zones and the equatorial current system.
(iv) Study oscillating wave fields and their variability in the ionosphere and exosphere, including ELF ion cyclotron waves and ULF hydromagnetic waves, in conjunction with ground station observations.
(v) Provide vector measurements for mapping the geomagnetic field over Australia, and contribute to secular variation and solid Earth studies.
(vi) Provide improved accuracy for GPS applications that deliver benefits to the navigation and position-service industries, including geomagnetic mapping.

4.1 The Near-Earth Plasma Environment

The ionosphere and exosphere represents a transition between the highly ionized plasma dominated magnetosphere and the lower altitude neutral atmosphere. The topside ionosphere is an important boundary region that exerts an important influence on the evolution of the planetary atmosphere. In the regions above the auroral zones in the northern and southern hemispheres the topside ionosphere is continuously being replenished with plasma at the rate of several kg s^{-1} (Chappell *et al.*, 1987). This plasma outflow is due to heating and energization processes associated with downward electron acceleration and upward and transverse acceleration of ions. Although FedSat will orbit at 800 km, below the 1000-10,000 km altitude of the acceleration region, it will pass through the region connecting currents and propagating wave energy to the ionosphere.

The behaviour of a magnetised plasma can be described in terms of the configuration of the magnetic field or the currents that are flowing. In examining the coupling of the ionosphere to the magnetosphere it is traditional to describe these in terms of field-aligned current systems. The region 1 and region 2 current systems (Iijima and Potemra, 1976) couple the stresses applied to the magnetospheric plasma by the solar wind and internal convection of the plasma.

4.2 Field-Aligned Currents

Figure 2 shows the magnetic fields measured by the FAST magnetometer with the Earth's field removed, on a pass through the dayside auroral oval and across the polar cap. The antisunward twists in the field at about 65° latitude are the characteristic signatures of field-aligned currents. The currents flowing near midnight around the onset of substorms, the so-called substorm current wedge (McPherron *et al.*, 1979), are believed to arise from the rapid reconfiguration of the tail when magnetic reconnection in the tail begins. There is not consensus on the mechanisms by which these stresses arise and this particular problem will be addressed through the FedSat fluxgate magnetometer measurements. Additional studies to be undertaken include identifying polar cusp magnetic signatures, and relating low altitude observations with higher altitude spacecraft including IMAGE and CLUSTER using field line tracing and simulations. Also important will be correlation with ground observations made at the Australian Antarctic stations of Davis, Casey and Mawson, and the USA Automatic Geophysical Observatories located on the southern polar cap.

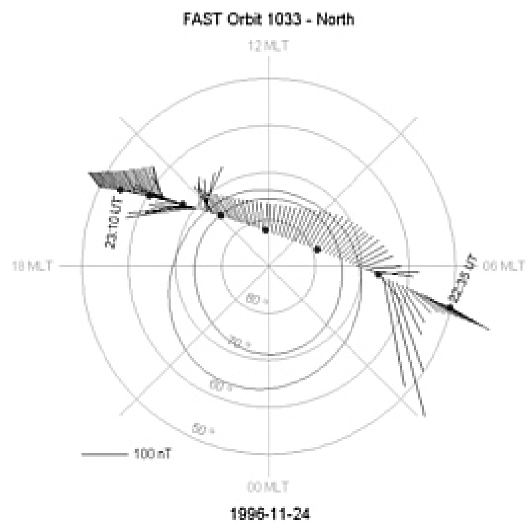

Fig. 2. Residual magnetic fields with the model IGRF removed on a FAST pass over the northern polar cap. The antisunward residuals near 65° are the signatures of region 1 and region 2 currents.

4.3 ULF Waves

Ultra-low frequency (ULF) waves, naturally occurring plasma waves in the 1 mHz - 5 Hz band, are seen in all regions of the magnetosphere from high to equatorial latitudes (Anderson *et al*. 1990; 1992). Many types of ULF waves are also transmitted from the magnetosphere through the ionosphere to the ground. Since the ionosphere acts as a "short circuit" or sink for many magnetospheric phenomena, ground-based and ionospheric signatures play an important role in understanding the interactions with solar energy sources. Interactions that will be observed by the FedSat magnetometer and Antarctic and other ground stations include flux transfer events (FTEs) which are signatures of transient dayside reconnection (Russell and Elphic, 1979) and solar wind pressure and other variations. These signatures can also be seen at middle and low latitudes.

The more regular Pc3-5 ULF waves in the 1-100 mHz band are generally observed signatures of resonances in the magnetosphere, while the higher frequency Pc1-2 (0.1 - 5 Hz) waves result from wave-particle interactions in the magnetosphere, or low altitude resonances. At Pc5 frequencies using VIKING data Potemra *et al.* (1988) have observed resonant geomagnetic field line oscillations on the same field lines that guide region 2 currents in the morning sector. We will be looking for lower altitude signatures using FedSat. With these longer period waves it is important to separate the spatial properties associated with spacecraft motion from the temporal properties. These FedSat studies will be complemented by ground-satellite correlations using data from Australian Antarctic and middle/low latitude stations.

In the higher frequency Pc1-2 ULF band wave-particle interaction in the equatorial region of the middle and outer magnetosphere generates electromagnetic ion cyclotron (EMIC) wave packets which propagate down field lines to the ionosphere (Fraser *et. al.*, 1996). Impulsive magnetic signatures associated with these have been observed on the MAGSAT satellite at an altitude of 400 km by Iyemori *et al*. (1989) and associated with ground observations. An example, shown in Figure 3 indicates wave amplitudes in the range 2-15 nT. These will also be seen by FedSat in its polar orbit. When the EMIC wave packets propagating down the field line reach the ionosphere some of their energy is reflected and some is mode-converted from the left-hand polarised ion cyclotron wave into the right-hand polarised isotropic fast mode wave. It is well known that two distinct waveguides exist in the ionosphere. One is centred on the F2 region electron density peak with a width ~300 km and supports the horizontal propagation of wave energy at f~1-5 Hz over many thousands of kilometers, especially at night when attenuation is low (Fraser, 1975). A second and much wider resonance region exhibiting harmonics in the 0.3-10 Hz band, the so called sub-protonospheric cavity (Trakhtengertz and Feldstein, 1987), has upper and lower boundaries at the Alfven velocity gradient at ~3000 km and the E region, respectively. It is expected that waves in both waveguides would be observed by FedSat as it traverses the middle and high latitudes. Because of their small-scale structure these propagating waves may be used as tracers in diagnostics to improve our knowledge of the ionosphere and exosphere/inner plasmasphere.

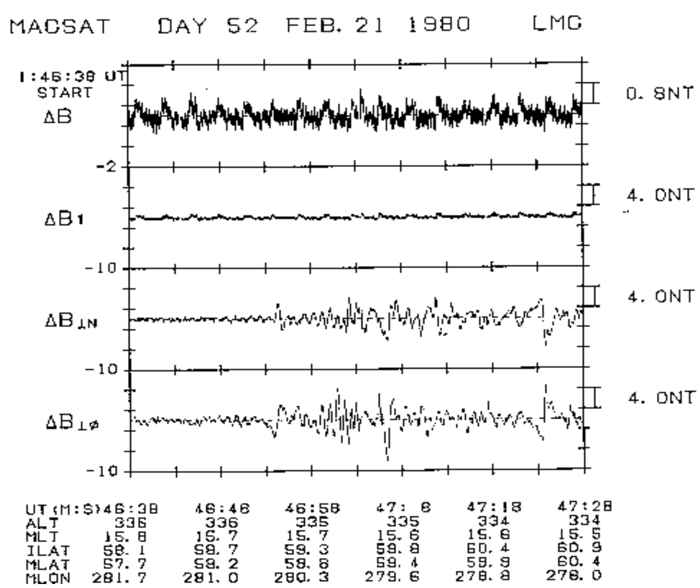

Fig. 3. An example of a Pc1 ion cyclotron wave signature seen by MAGSAT. The impulsive wave frequency matches that of a sustained Pc1 event seen on the ground (Iyemori and Hayashi 1989).

4.4 Lower-band ELF Waves

In the high latitude auroral and cusp regions there are many propagating wave modes which are generated in boundary or acceleration regions. The properties of these waves are generally controlled by the plasma characteristic frequencies, primarily the H^+ cyclotron frequency and the corresponding O^+ and He^+ heavy ion frequencies. At high latitudes and lower exosphere altitudes the H^+ cyclotron frequency is typically ~700Hz, the He^+ cyclotron frequency ~200Hz, and the O^+ cyclotron frequency ~40Hz. With an upper limit on the FedSat fluxgate magnetometer bandwidth of 50Hz it will only be possible to observe electromagnetic waves near and below the O^+ cyclotron frequency. Plasma turbulence provides a significant contribution to the electromagnetic spectrum at these frequencies. There is a rich spectrum of waves below the H^+ cyclotron frequency and examples of these have been given by Erlandson (1989).

In addition to the waves described above there is also a tropospheric contribution to the ELF wave flux in the ionosphere. A lightning strike in the atmosphere generates a broad band electro-magnetic pulse that is absorbed at the local proton cyclotron frequency as it propagates upwards. The usually right-hand polarized wave is converted to a left-hand wave at the H^+ crossover frequency in the multicomponent ionospheric plasma. These are ion cyclotron whistlers (Gurnett *et al.* 1965). Similar resonances with He^+ and O^+ ions have also been observed, with the latter occurring in the FedSat magnetometer bandwidth.

The recent discovery of lightning discharges between the tops of clouds and the lower ionosphere, commonly referred to as red sprites and blue jets (Sentman *et al*. 1995) has caused a rethinking of our understanding of atmospheric electricity. The red sprites also radiate at VLF frequencies. It is not known whether a further type of optical emission seen in the lower ionosphere referred to as ELVES (Fukunishi *et al.* 1996), has an ELF electromagnetic signature. It is important to look for coupling processes at all frequencies which may transfer energy from the troposphere to the ionosphere. FedSat will pass over the South-East Asian thunderstorm region present above Australia between November and March.

4.5 Signatures of the Equatorial Electrojet

Currents in the ionosphere above the equatorial region have not been studied to any great extent. Although this low altitude current system is more difficult to measure by satellite than the auroral system it is equally dynamic with upflowing plasma playing an important role. This region is of great importance in modern day communications. FedSat magnetic field data will be analysed for possible equatorial electrojet signatures.

4.6 Space Weather Forecasting

It is now known that solar induced variability in the near-Earth space environment can affect the performance of technological systems. High energy magnetic cloud events outbursting from the Sun can impinge on the Earth and destroy satellites, disrupt power grid systems, HF radio communications and GPS navigation systems. These disruptions will maximise at the peak of the sunspot cycle at the time when FedSat is expected to be launched. Continuous multipoint spacecraft measurements of the global magnetic field and plasma environment are required for the early warning of impending events and inclusion in space weather prediction models currently being developed. FedSat will make an important contribution here. The NEWMAG experiment will provide near real-time data to the Space Environment Centre of NOAA in Boulder Colorado and the World Data Centre for Solar Terrestrial Science (Ionospheric Prediction and Space Services) in Sydney.

4.7 The Geomagnetic Field in the Australian Region

The Australian Geological Survey Organisation (AGSO) provides reference magnetic field data to the geophysical exploration and mining communities for mineral exploration. Since the geomagnetic field is continuously changing, this information must be updated every few years and is usually undertaken through expensive ground magnetometer surveys. Spacecraft observations of sufficient accuracy have not been available for a number of years since MAGSAT in 1979-1980. This has recently been improved by the launch of the Oersted and SunSat, microsatellites which use star imagers to precisely determine magnetometer sensor head attitude. A star imager will be flown on the FedSat platform, thereby providing a greatly improved knowledge of attitude down to about a tenth of a degree. It is hoped that data from the highly stable and accurately calibrated FedSat fluxgate magnetometer will be used in conjunction with data from dedicated magnetic field satellites, including Oersted and SunSat, and CHAMP, and SAC-C in the future, to help upgrade magnetic field measurements over Australia and other regions.

4.8 GPS Monitoring of the Ionosphere and Plasmasphere

The aim of this program is to use GPS data and advanced processing to further our understanding of the ionosphere and plasmasphere and improve current ionospheric models. The GPS network of stations on the ground and in orbit provides a unique opportunity to make these measurement. Total electron content (TEC) measurements will be undertaken between GPS satellites at apogee (20,000 km) and the Spectrum-Astro GPS receiver onboard FedSat at 800 km altitude, thereby providing information on the exosphere inner plasmasphere. TEC occultation observations made with a number of GPS satellites will provide slant measurement which may be converted into a vertical profile. The data will also be used to provide electron density distributions over the southern oceans and Antarctica. Further details of the FedSat TEC measurements and their applications are given in Essex *et al*. (1999) and in these proceedings (Essex, 2000).

5. THE FEDSAT PLATFORM

The multiple payloads described in the sections above will be accommodated in a platform based on the Space Innovations Limited MicroSIL™ satellite bus. The subsystems are based on SILs suite of standard on-board equipment with minor modifications. A view of the FedSat internal structure is shown in Figure 4. The bus is a two tiered shelf structure with the payload on the top shelf and the subsystems on the bottom shelf. The subsystems are load-bearing, thereby providing considerable mass and volume savings. The payload shelf consists of two panels, one interfacing the subsystems and the second for payload use.

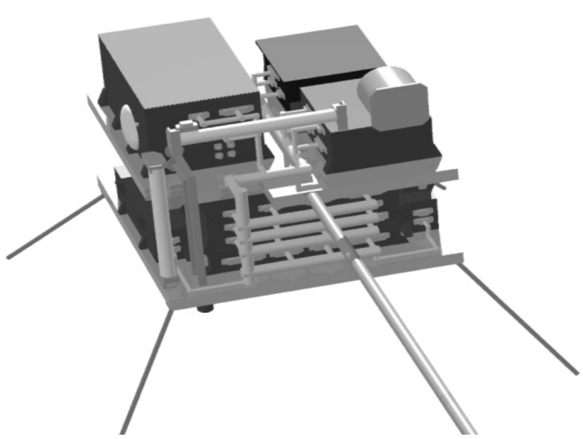

Fig. 4. A view of the basic MicroSIL platform structure with the payloads on the top shelf.

The payloads within the spacecraft are accommodated in three separate enclosures as shown in Figure 4. One contains the GPS receiver, the second the communications experiment and the third, the magnetometer analogue and digital electronics, and the HPCE. The magnetometer experiment requires the spacecraft design to incorporate a magnetic cleanliness program to minimise both steady state and time varying magnetic fields, and the fluxgate heads will be mounted on a 2.55 m boom. This boom has been built by Stellenbosch University and is same as that used on the recently launched South African micro-satellite SUNSAT. It consists of six segments with flexible interconnections and the fluxgate heads are mounted at the end. It is seen in its extended position in Figures 1. The attitude control system employs three rod magnetotorquers, a three axis fluxgate magnetometer, three reaction wheels and three two axis digital sun sensors. This system will provide a pointing knowledge currently quoted as better than 2° to maintain the satellite pointing within 4° of the target direction. More details on the FedSat platform and in particular the NewMag magnetometer subsystem are included in an accompanying paper by Bish *et al*. (2000).

7. DATA ANALYSIS AND ARCHIVING

The magnetometer data will be transmitted to a ground station at the University of South Australia in Adelaide. In the first year of operation UCLA and the University of Newcastle will be responsible for developing and implementing algorithms to decode the level zero data. The routine calculation will then be taken over by the University of Newcastle. All data will be validated by comparison with models such as the well-established International Geomagnetic Reference Field (IGRF) over regions of low perturbation by external current systems (e.g. at low latitudes) where the Earth's field is well-defined. The absence of a spacecraft spin component in the magnetic data enables the coordinate transformation to be accomplished much more accurately and quickly than with a spinning spacecraft. Pure state and other multi-channel signal analysis techniques (Samson, 1983) will be used to detect the coherent signals and minimise noise. All raw and level one data will be archived at UCLA and the University of Newcastle. It will also be freely available to the international scientific community on a NEWMAG website and through the National Scientific Satellite Data Centre (NSSDC) in Washington DC. In addition to the international availability of FedSat magnetic field data Australian research collaborations are being established. Satellite-ground studies of auroral processes and waves above the Australian Antarctic stations at Casey, Davis, Mawson, and Macquarie Island will be undertaken with the Australian Antarctic Division. Near real time data will be made available directly to the World Data Centre for Solar Terrestrial Science and IPS in Sydney. The WDC.STS-IPS is a member of a group of world-wide ionospheric and space weather warning and forecasting centres. We also anticipate that main geomagnetic field measurements will contribute to the research of the Australian Geological Survey Organisation (AGSO) through the mapping of the geomagnetic field above the Australian region. Ideally these studies would be more reliable and useful if FedSat was at a lower altitude. However, the inclusion of a star camera for precise attitude determination down to 0.1^{o} will enhance this capability. Accurate calibrations will be carried out on NewMag prior to launch. This may be undertaken at magnetic test facilities at AGSO in Canberra or at NASDA (Tsukuba) in Japan.

8. CONCLUSION

A brief description of FedSat, an Australian research microsatellite, to be launched late in 2001-2 has been presented with emphasis on the magnetometer space science experiment. Rather than being a satellite mission dedicated to a specific research task it is a satellite which takes advantage of current Australian space science, communications and satellite systems research and integrates it with space engineering expertise. It will lead Australia back into space after thirty years absence while making a significant contribution to space science and engineering.

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