ASTRID
AN ATTEMPT TO MAKE THE MICROSATELLITE A USEFUL TOOL FOR SPACE SCIENCE

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ABSTRACT

The ASTRID microsatellite (27 kg) was built and launched to demonstrate that "good science" can be done with a microsatellite. It has deployable solar panels to provide plenty of power, a high downlink data rate and a flexible structure design to provide a good field-of-view for the scientific sensors. The satellite was developed and launched in 15 months at a total cost of $1.4 million and has provided pioneering imagery of energetic neutral particles in the earth's magnetisphere.

1 A new role for microsatellites?

Very small satellites with a total mass below 50 kg, i.e. microsatellites, have been used for technology tests and amateur radio for almost two decades. Because of their minute size they have not generally been viewed as useful for cutting-edge space science research.

The low power level available to the payload has been one reason behind the lukewarm interest. Lack of DC power also limits transmitter ouput and downlink data rate. Microsatellites are often "a box of electronics" with solar panels covering the outside of the box which makes it difficult to locate scientific sensors for the best field-of-view.

At the Swedish Space Corporation (SSC), we think that microsatellites will be common in future space science primarily because the lack of funds will lead to long intervals between larger projects. Microsatellites can fill the gaps between these "major" flight opportunities. Microminiaturization will help make such small satellites more and more capable. SSC and the Swedish Institute of Space Physics carried out the ***ASTRID*** project to address the perceived shortcomings of the microsatellite and demonstrate that "good science" can be achieved with such a small space vehicle.

The ASTRID microsatellite was built quickly and at low cost at the Swedish Space Corporation with the "small team approach" first used in the FREJA project (Grahn[2]). ASTRID was launched into orbit from the Plesetsk cosmodrome in Russia on 24 January 1995. ASTRID was as a piggyback passenger on a Kosmos-3M rocket from the Polyot Design Bureau in Omsk. The satellite is in a circular orbit at about 1000 km altitude and 83° inclination. ASTRID carries an neutral particle imager, an electron spectrometer and two UV imaging photometers. The neutral particle data set gathered during the mission is a first in space science (Norberg et. al[1])

2 The development of ASTRID

2.1 The scientific instruments

The ***Neutral particle imager***, PIPPI (Prelude in Planetary Particle Imaging), is ASTRID's main instrument. The operation of PIPPI in orbit was the first time that a dedicated instrument measured the neutral particle flux from the ring current. The instrument consists of two cameras. The SSD camera use solid state detectors which resolve the energy of detected particles. The MCP camera uses a technique whereby incoming neutrals cause charged secondary particles to be emitted from a graphite target. The secondaries are then detected by a microchannel plate (MCP). Both cameras have deflection systems which can reject charged particles up to an energy of 140 keV. The instrument aperture plane is perpendicular to the spin plane, all directions are thus covered in half a spin period or approximately 1.5s. PIPPI also serves as the data processing unit for EMIL and MIO (see below).

PIPPI Features	SSD Camera	MCP Camera
Energy range [keV]	13-140	0.1-70
Energy resolution	8 levels	-
Sampling time [ms]	31.25	31.25
Number of apertures	14	31
Angular resolution [degrees]	23x5	11x9
Geometric factor [cm^2 ster]	0.035	0.08
Bit rate [kbps]	60.5	16
Mass	3.1 kg	
Power	4.0 W	

The ***Electron Spectrometer***, EMIL (Electron Measurements - In-situ and Lightweight) consists of a swept-energy toroidal electrostatic analyzer and a microchannel plate (MCP) detector. The instrument measures the electron distribution at 62.5 ms or 125 ms resolution.

No. of angular channels	6 sectors in spin plane.
Energy range	50 eV - 40 keV, resolution ($\Delta E/E$)=0.10
Energy steps	32 or 64
Sampling time per step	2 ms
Geometric factor/ sector	4×10^{-4} cm^2 ster keV/keV
Bit rate	24 kbps
Mass	0.9 kg
Power	0.9 W

The ***UV imaging photometers***, MIO (Miniature Imaging Optics), are mounted in the satellite spin plane. One observes Lyman alpha-emission from the Earth's geocorona, the other observes auroral emissions. Each photometer consists of optics mounted in a stainless steel tube with a ceramic channel electron multiplier in the opposite end.

MIO-1 passband	(Lyman-α) 121 nm (MgF_2 + Oxygen gas filter + KBr)
MIO-2 passband	(Oxygen)125-160 nm (CaF_2+KBr)
Focal width	255 mm
Field-of-view	1 degree

Sampling time	2 ms
Geometric factor	2×10^{-4} cm^2 ster
Bit rate	8 kbps
Mass	0.3 kg
Power	0.16 W

2.2 Designing for "good science"

Detailed technical specifications for ASTRID are listed on page 9 , the main features of the satellite are shown in Figure 1 and the dimensions of ASTRID are found in Figure 2. However, the requirements of the science instruments satellite's determines the design of ASTRID in terms of its *shape, structure, attitude and power generation.*

The size and shape of the satellite

ASTRID weighs 27 kg. In the launch configuration the dimensions of the satellite are approx. 0.45 × 0.45 × 0.29 m. We picked this size and mass because it is roughly half of the maximum permitted size and mass of a microsatellite that the Ariane rocket accommodates on its platform for small auxiliary payloads, ASAP. The Swedish Institute of Space Physics specified that the scientific sensors needed to scan the sky, so it was natural for us to decide that the satellite should spin.

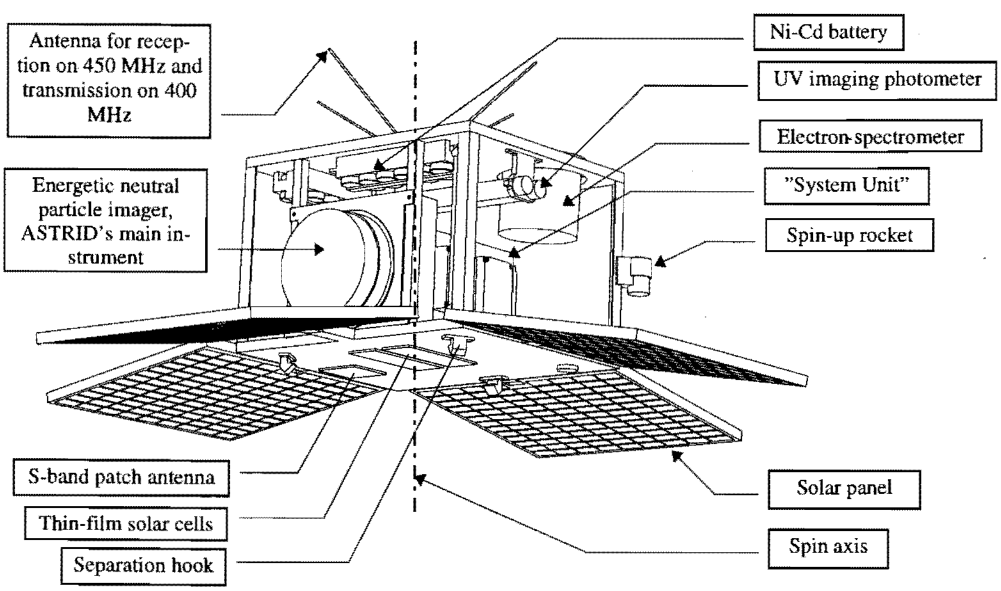

Figure 1 Main features of the ASTRID microsatellite

To achieve a stable spin the moment-of-inertia ratio (axial/transverse) needed to be larger than 1.0. An oblate shape makes it easier to achieve this ratio. This was the main factor in the choice of the dimensions of the satellite - especially the height. We kept the transverse dimensions compatible with the Ariane ASAP. The small size and mass of ASTRID also helped to keep launch costs low - it is always easier to find room for a small piggyback payload than a large.

Electrical power for the experiments and the data link

The easiest way to obtain a high output from the solar arrays is to keep them perpendicular to the direction of the Sun. Four solar panels deploy from the base of the satellite to a position roughly perpendicular to the spin axis. Commands from the ground keep the spin axis pointing towards the Sun. This arrangement provides plenty of power from the solar arrays (≤45 W) to supply the experiments and the radio transmitters - the largest consumers of power. The experiments and their memory unit consume up to 9.3 W and the S-band transmitter consumes 16 W.

The energy balance is also a problem for a micro-satellite. To save electrical energy we do not run the command receiver continuously. The receiver is a spare part from the FREJA project and its substantial current drain of 106 mA is reduced by letting the on-board computer switch it "on" for one minute and "off" for four minutes. In case the computer "crashes" the default state of the switch is to turn the receiver "on". If a command is received the receiver stays "on" for five minutes.

How to provide a good view for the scientific sensors

The scientific sensors that we mounted on ASTRID were developed for other projects, so it was impossible to redesign them during the ASTRID project, which lasted only seventeen months from first idea to launch. It was easier to design the satellite to fit the sensors. A conventional design of the structure with honeycomb equipment platforms and longerons to connect the platforms is very flexible and allowed us to fit the instruments and still provide the required fields-of-view. Other satellite units were relatively easy to "move around" on these platforms to accommodate the sensors. Of course some units could not be placed anywhere. The batteries, for example, have to be located on the shadowed platform in order to keep them cool.

It was necessary to make the top and bottom platforms 0.42 × 0.35 m , i.e. not perfectly square, to accommodate the main instrument, the energetic neutral particle imager, on one side face of the satellite. In this way it could have a 360° field-of-view in a plane parallel to the spin axis.

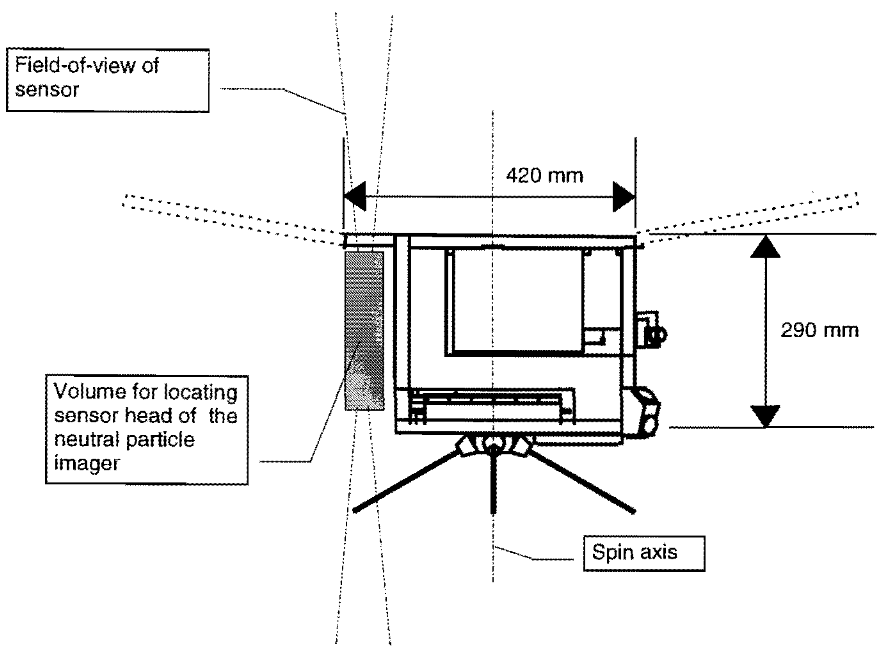

Figure 2 The location of ASTRID's main instrument.

The conventional platform - and longeron structure made this arrangement (see Figure 4) ràther easy to implement.

2.3 ASTRID's Subsystems

ASTRID's subsystems are similar to those of our previous satellite, FREJA, described by Grahn[2], but ASTRID is a ***single-string system*** ,while FREJA was fully redundant. Some units, such as the transmitter and the command receiver are FREJA flight spares. The main electronics box, the ASTRID System Unit (see below) is an improved version of the FREJA System Unit and we used some parts "left over" from FREJA, mostly quality level B-2 microcircuits and JANTXV semiconductors. Among the FREJA surplus parts we also found ASTRID's main spacecraft microprocessor, the 80C31 from Matra-Harris.

The basic ***satellite structure*** consists of two platforms (15 mm Al-honeycomb panels with 0.3 mm face-sheets and aluminum edge-beams) connected with four L-beams (20 x 20 x 2 mm). ASTRID was connected to the launch vehicle with three small hooks on the satellite's bottom platform, equally spaced on a 170 mm radius. The hooks on the satellite are held to a triangular support plate (4 mm Al) on the launch vehicle side by grappling hooks. The grappling hooks are held in locked position by one single tensioned steel cable (Ø1.5 mm) which forms a triangle between the three hook positions. At separation, the cable is cut by a pyro cable-cutter (guillotine) freeing the grappling hooks. Three separation springs accelerate the satellite to 1 m/s. SSC made the whole ***separation system*** (Figure 3) including the support plate on the launch vehicle side. The plate is fixed to the launcher by eight bolts. The electrical interface to the launcher is a 4-pin connector for the cable-cutter.

Four solar panels (designed by SSC) provide ***electrical power***. There are four strings with 78 solar cells (Si, 20 x 40 mm) each. There are two additional strings with 82 cells in series to charge the battery. These can also be used to power the main bus when the battery is fully charged. Each of the four solar panels holds one 78-cell string and half an 82-cell string. Most cells are covered with Pilkington 0.15 mm CMX Cerium-doped cover glass, but we also tried a simpler type of glass on one panel.

The four solar panels deploy in orbit. The hinge design is based on the universal hinge system designed by the Max-Planck Institute for Extraterrestrial Physics in Garching, and uses a Teflon-sintered bronze bearing as the key element. Steel wires hold the solar panels in the stowed position during the launch phase. Pyrotechnic guillotines cut these wires on a command from the ground.

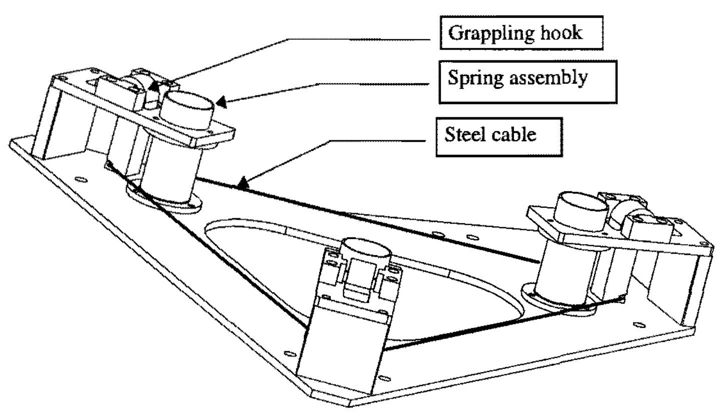

Figure 3 ASTRID's separation system

Each solar array string is connected to the main bus via a series regulator. Thus, in sunlight the bus voltage is determined by the solar array. The voltage of the solar array regulators is slightly higher than that of the voltage regulators connecting the battery to the main bus via diodes. Therefore, in sunlight the battery is disconnected from the bus.

The battery consists of twenty-two standard Ni-Cd cells (36 mm high, 32 mm in diameter) from Gates each with a 2.3 Ah capacity. The cells are mounted in milled aluminum blocks to provide a uniform cell temperature. Matching cells were found by extensive computerized testing.

We ***control the temperature*** of the satellite by covering the top and bottom platforms with 15-layer multi-layer insulation (MLI) and by covering the side faces of the satellite with black single-sheet foil. Heaters controlled by the spacecraft computer keep the temperature of the battery within limits that can be set by ground command.Without heaters, the battery temperature drops to below 0 °C. During the flight of ASTRID we have kept the battery at temperatures above 8 °C.

ASTRID uses magnetic ***attitude control.*** Magnetic torquers - air-core coils - make the spin axis track the sun. These electromagnets interact with the Earth's magnetic field. Current in the "precession coil" is switched on and off in certain parts of the orbit where the interaction with the Earth's magnetic field makes the spin axis move in the desired direction. The "spin coil" acts a the rotor in a DC electric motor where the Earth's magnetic field acts as the stator. The magnetic field sensor (magnetometer) acts as the commutator and changes the direction of the current through the spin coil as the satellite rotates. The spin coil is used to change the rotation speed of the satellite.

The precession coil is placed around the "bottom" platform (where the solar array hinges are placed). The spin control coil is placed on one of the side faces of the satellite. The coils are made of thin copper wire wound on an aluminum frame.

The Nutation Damper consists of a closed aluminum tube filled with a viscous fluid. When the satellite separates from the launch vehicle it is tumbling slowly and to spin it up we used a small solid propellant rocket motor mounted on a corner beam. This motor provides 10-20 Ns of impulse to "freeze" the spin axis in the desired direction. Its ignition is controlled by the System Unit and occurs when a sensor showed that the angle to the sun is less than 70°. The rocket motor contains a few tens of grammes (5.7g $\rightarrow$10 Ns) of HTPB propellant. The motor is designed and manufactured by the Swedish Defense Research Establishment and the igniter is produced by the Bofors company.

ASTRID uses two sensors to ***determine its attitude***. A flux-gate magnetometers (made by SSC) is used as one attitude sensor. The other is a solar aspect angle sensor, made by ACR (Sweden). This sensor has 4π steradians field of view when the satellite spins. Attitude sensor data can be collected at a predetermined point along the orbit, stored on-board and then transmitted to the ground station for calculation of the attitude. In this way the best attitude sensor observation geometry can be obtained. The magnetic field component perpendicular to the spin axis is used by the System Unit (see below) to determine when to change the polarity of the current in the spin rate control magnetic torquer.

"Platform functions" are normally provided by several units connected by the harness. ASTRID uses a scheme from the original FREJA design, the AMPTE/IRM spacecraft (Häusler et al.[3]) and other satellites, i.e. to have a common unit that performs most "platform functions". Outside this unit are only batteries, solar panels, radios, attitude sensors, attitude actuators and propulsion units.

Functions performed by the ASTRID System Unit

- Encodes telemetry
- Signal conditioning for "housekeeping" channels
- Decodes commands
- Stores attitude and other commands
- Regulates the power bus voltage
- Distributes power
- Controls battery charging
- Fires pyro devices
- Drives the magnetic torquers

It is called the ASTRID ***System Unit*** (ASU). It is a box that weighs 5 kg and contains 8 printed circuit boards (212 × 130 mm). It performs the functions listed above.

The ASU uses Matra-Harris' 80C31 microprocessor to control these tasks. This processor has performed very well during the flight of

ASTRID's "big sister" FREJA, which has now lasted more than 1000 days. The processor can tolerate a total radiation dose of at least 18 kRad and simply does not suffer upsets or latch-up. The System Unit communicates with experiments through a two-way serial link. All telemetry data going to the ground is also available to all experiments and commands are sent to the experiments only as part of this serial bit-stream.

The ASU also contains an 8 MB ***memory*** for collecting science data around the orbit. This memory is developed by Saab Ericsson Space and it is controlled by their new ***Thor*** microprocessor developed especially for use in space. The memory chips are MT4C4001J883CN-12, 1M x 4 bit 120 ns DRAMs from Micron Semiconductor Inc. The contents of the memory can be dumped to ground simultaneously with real-time telemetry. In addition to the memory the ASU also houses a data compression unit, RONJA, developed by the Finish Meteorological Institute.

No ranging is used for ASTRID, so a transponder is not needed and the ***radio system*** consists of separate transmitters and receivers. Such units cost very much less than a full transponder. An S-band transmitter (Aydin Vector Inc) sends 131 kilobits/second phase-modulated data at 2 W output power. The 400 MHz transmitter has the same power but uses frequency modulation and transmits low-speed data at 8192 bits per second.

The Command receiver is manufactured by Aydin Vector and operates at 450 MHz. It receives the frequency-modulated uplink signal. The link coding is bi-phase-L and the asynchronous byte-oriented protocol on the uplink is transmitted at 4800 bits per second.

The two S-band transmit ***antennas*** are so-called patch antennas (made by FFV Aerotech, Sweden), i.e. planar conducting sheets of copper on a dielectric substrate. These patches are mounted flush with the upper and lower platform surfaces.

Subsystem	**Unit**	Mass (kg)	Power (W)	Average power in orbit (W)
Structure	Structure, incl. solar panels	5.60	-	-
	Balance masses	1.36	-	-
Data handling	ASTRID System Unit (ASU)	6.50	5.00	5.00
	Pyro unit	0.48	-	-
Radio	S-band and UHF Transmitters	0.90	16.00	2.60[1]
	Command receiver	0.27	3.00	0.60[2]
	Antennas + diplexer + RF cables	1.58	-	-
Attitude Control	Magnetic torque coils	1.00	9.60	1.40
	Sunsensors	0.30	0.27	0.27
	Magnetometers	0.10	0.5	0.00
	Nutation damper	0.30	-	-
	Spin-up rocket	0.15	-	-
Power	Cable harness	1.30	-	-
	Ni-Cd battery	2.50	-	-
Thermal Control	Thermal blankets	0.30	-	-
Payload	Energetic Neutral Particle imager (PIPPI)	3.14		
	Electron Spectrometer (EMIL)	0.74	4.08	4.08
	Miniature Imaging Optics (MIO)	0.33		
	Data compression unit (mass incl. in ASU)	-	1.30	1.30
	Memory Unit (mass incl. in ASU)	-	4.00	4.00
	Payload DC/DC conv. (mass incl. in ASU)	-	2.50	2.50
	Payload cable harness	0.15	-	-
Total satellite		**27.00**	-	**21.75**
Platform		22.64	-	9.87
Payload		4.36	-	11.88

[1] The average transmitter power assumes that the transmitter is "ON" 16% of the time
[2] The command receiver is "ON" for one minute and "OFF" for four minutes to save energy.

Table 1 Mass and Power budget for ASTRID

The 400 MHz low-speed telemetry link and the 450 MHz command link both use the same canted turnstile antenna mounted on the side of the satellite opposite the separation mechanism. The turnstile has quarter-wave elements (cut for 400 MHz) and produces a circularly polarized wave. A diplexer and phasing network (developed by Letron KB, Sweden) connects the 400 MHz transmitter and the 450 MHz receiver to the antenna.

2.4 The Test Philosophy

For newly designed electronic equipment we built an engineering models and a protoflight model. The satellite as a system was first tested in the so-called bench-test model. This model consists of all satellite equipment spread out on a table and connected with a realistic cable harness. We use engineering models or flight models of equipment in this type of test. Otherwise, we used the protoflight model philosophy on the system level, which means that one satellite was built, qualified and flown. There were two vibration tests, one qualification test of the structure equipped with mass dummies and one acceptance test with the entire satellite. An extra solar panel was made and we vibrated it mounted on the satellite structure during the qualification vibration test of the structure. The solar panels were also calibrated with an artificial sun. The battery packs went through extensive thermal cycling in vacuum. A solar simulation test in vacuum was performed at the Swedish Institute of Space Physics. We also made spin balance tests, antenna range tests and a magnetic survey to calibrate the magnetometers.

2.5 ASTRID's Mass & Power budgets

The power budget is shown in Table 1. The orbit-average power available at the maximum eclipse duration is 26.2 W - if the satellite points straight at the Sun. The output power of the solar panels decreases as the cosine of the solar aspect angle. In that case it will be possible to run the satellite continuously with all experiments "on" for all solar aspect angles up to $\arccos(21.75/26.2) \approx 34^{\circ}$.

3 The Project Schedule

SSC proposed the project as an idea in August 1993 and development started in October 1993. SSC started the project on our own risk and in the beginning of 1994 the Swedish National Space Board decided to fund SSC's procurement of equipment of services from outside suppliers while SSC contributed all the labor costs out of our own funds. We had the first contact with the Polyot design bureau in early March 1994 and signed the launch contract with them on 30 April 1994.

The qualification test of the structure took place in June 1994. The acceptance vibration test, spin balancing, thermal vacuum test and the magnetic survey occurred during the period October-November 1994. During December 1994 we ran functional system tests, including flight simulations and conducted the Flight Readiness review.

We shipped the satellite to Russia on 9 January 1995 and our Russian colleagues mounted ASTRID on the Kosmos-3M launch vehicle on 20 January. Erection of the rocket on the launch pad took place on 23 January - the day before launch.

4 The Design of the Ground Station

The control center at ESRANGE for the FREJA satellite also controls ASTRID. The software that we use for ASTRID is almost identical to that used for FREJA. ESRANGE uses their big 9 m S-band dishes for telemetry reception. However, we also designed a small "secondary" ground station operating on 400/450 MHz with a yagi antenna array pointed at the satellite with amateur satellite antenna rotors. This station is capable of automatic unattended reception and storage of telemetry as well as unattended transmission of previously prepared commands. These commands can be created with an editor tool and templates of command sequences. The station sends a report to the operator after each pass of the satellite via a radio pager or via Internet. In this way the person responsible for the station can keep on an eye on the station and the satellite while doing other work.

A low-cost satellite project cannot be burdened with high operational costs, so automation is necessary. The experience from the operation of the secondary station for ASTRID has convinced us that our next microsatellite can be operated by one part-time operator using a ground station that is programmed to run autonomously for a week or more.

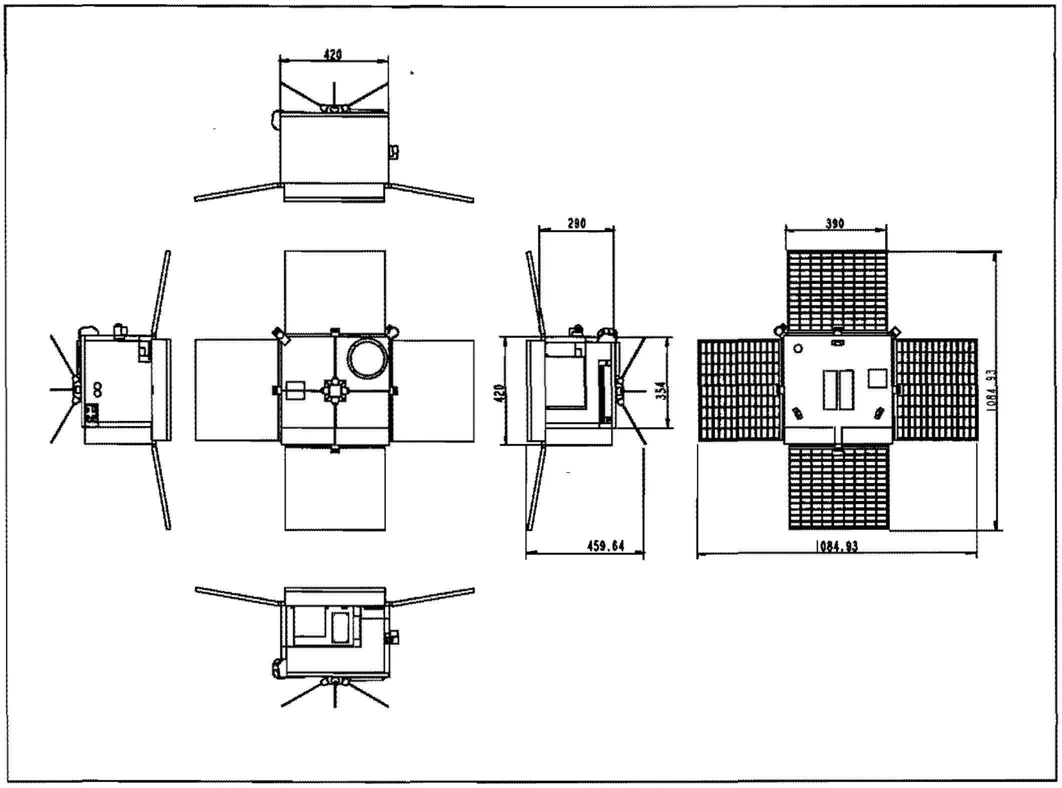

Figure 4 Dimensions of the ASTRID microsatellite

5 The Launch and Flight of ASTRID

ASTRID was launched together with the Russian navigation satellite Tsikada from Launch Complex 132 of the Plesetsk Cosmodrome at 0354:22 UT on Jan 24, 1995 on a Kosmos-3M rocket. The Russian satellite was equipped with a special adapter for accommodating two microsatellites. In addition to ASTRID the US FAISAT was carried on this adapter. Total mass of the three satellites and adapter was 942.5 kg, including 114.5 kg of FAISAT and 27 kg of ASTRID. The Tsikada main satellite separated from the second stage at 0457:25 UT while passing over the Antarctic. ASTRID separated from the adapter on Tsikada 23 seconds later. FAISAT was separated more than four hours later.

The first contact with Swedish Space Corporation's ground station in northern Sweden (ESRANGE, 68 N 21E) took place at 0532-0545 UT, i.e. less than 35 minutes after separation from the launch vehicle. Telemetry indicated all was normal. The second pass over Europe took place at 0719-0735 UT and solid S-band telemetry was again received indicating normal temperatures, 18 rpm spin rate (16 rpm was the intended rate) and a solar aspect angle (angle between spin axis and the sun line) of 41 degrees. This showed that the on-board computer had correctly triggered the spin-up rocket when the sun-presence detector saw the sun.

ASTRID key facts	
Launch site	Plesetsk
Launch date	24 Jan 1995, 0354:22 UT
Launch vehicle	Kosmos-3M
International number	1995-02B
Catalog number	23464
Mass	27 kg
Size (excl. solar panels)	0.42 × 0.42 × 0.29 m
Transmitter frequency 1	2208.1629 MHz
Transmitter frequency 2	400.55 MHz
Command frequency	449.95 MHz
Apogee[1]	1026.9 km
Perigee[1]	966.3 km
Inclination	82.9295 deg
Nodal period	105.074 min

[1] height above a spherical Earth with a radius of 6378.135 km

ASTRID Specifications

ON-BOARD COMPUTER

Processor	Matra Harris MHS, 80C31 12 MHz
Memory	4 kB PROM (Boot, TC decoding..) 32 kB RAM (Cmd queue, variables) 28 kB EEPROM (Applications software)
Parallel I/F	Telemetry 96 bits command register
Serial I/F	Telecommand input from TC bitsynchro-nizer. Output to 8192 bps Bi-phase modem feeding UHF FM transmitter
Software	Sequential Multitasking Orbital Operations Software in 'PL/M'

TELECOMMAND/TELEMETRY FUNCTIONS

Command outputs	32 latched commands 24 bit command interface/user (4 users) 7 pyro commands
Main telemetry	Random access addressed TM channels
Analog TM	48 × ± 5 V subcommutated 10 × ± 5 V supercommutated
Digital TM Status	16 × 0/5V CMOS
OBDH	Star network transmits TM and TC to/from 15 users at up to 1 Mbits/sec.
Analog/Digital	12 bits conversion
TM Serial Output	PCM bi-phase synchrounous data stream at 128 kbps rate.
Data Memory	8 MB Sequential DRAM data storage; logs parts of the telemetry format.

POWER DISTRIBUTION

Main Bus Voltage	26-29 Volts (design for: 24-32 V)
Main Bus Regulation	Solar array series regulator in sunlight, one per solar array string. Battery series regulators in eclipse
Power Switching	8 over-current/under-voltage resettable fused switches
Current monitoring	10 monitors for critical equipment

MAIN BUS SOLAR ARRAYS

Numbers of strings/cells	4 strings, 78 cells in series in each
Cells	20 x 40 mm 14% (Si)
Output	42 Watts at 29.8 Volts, BOL

BATTERY

Capacity	2.3 Ah
Cells	22×Gates, 32 mm diam., 36 mm height

BATTERY CHARGING SOLAR ARRAY

Number of strings/cells	2 strings, 82 cells in series in each
Cells	20 x 40 mm 14% (Si)
Output voltage/current	34 Volts/280 m A per string.

RF TRANSMITTERS

High speed	Frequency: 2208.1629 MHz RF output power: 2 Watts Phase modulation
Low speed	Frequency: 400.55 MHz RF output power: 2 Watts Frequency modulation

COMMAND RECEIVER

Frequency	449.95 MHz
IF bandwidth	180 kHz
Modulation	FM

ANTENNAS

S-band Transmit	Two patch antennas, G>-3 dBi within ±90° of spin axis. axis. Right hand circular polarization.
UHF Tx & Rx	Turnstile with quarter-wave elements. G>-10 dBi over hemisphere, typically +0dBi within ±60° of spin axis.

STRUCTURE

Platforms & Walls	Perforated, corrosion-resistant Al/Al honeycomb core, 0.3 mm Al face-sheets glued to the core. Aircraft grade.
Structural inserts	Potted inserts with Stycast 1090 with minimum void (»1%)

ATTITUDE DETERMINATION AND CONTROL

Analog Sun Sensor	Coarse range: 10°-180° from spin axis, ± 2° resolution.Fine range:0°-20°, ± 1° resolution
Magnetometers	Two 2-axis flux-gate magnetometers Dynamic range ± 60 mT (0-5V, 12 bits)
Magnetorquers	Precession: 12 Am^2, air core Spin: 7 Am^2, air core
Nutation damping	Fluid damper.

PROPULSION

Spin up/down rocket motors.	Solid propellant, HTPB, (10-20 Ns)

ENVIRONMENTAL

All equipment qualified to meet Kosmos-3M requirements for vibration and will be subjected to thermal vacuum cycling tests. The electronics Unit has been tested over a temperature range of 0°C to +40 °C.

Table 2 ASTRID Technical Specifications

We deployed the solar panels by a ground command on the following orbit shortly after 0900 UT. The spin rate dropped to 13 rpm, as expected. Later, we commanded the satellite to increase the spin rate to 15 rpm.

Testing of the instruments started immediately and after the satellite had entered eclipse on 6 February (at launch the orbit was in constant sunlight) the scientific instruments were fully operational. A data-set was acquired during more than a month that proves that magnetospheric imaging is indeed a very useful concept. All three instruments contributed to this data set which included about ten data collection periods in eclipse, when the neutral particle imager was undisturbed by sunlight and the Earth's' albedo. In total the scientists have some 150 orbits, or 20-30 hours of data to digest.

Figure 5 is a sample of this data set, an image of the Energetic Neutral Atoms (ENA) acquired by ASTRID's main instrument (PIPPI) at the geomagnetic pole. As explained by Norberg et al[1]. the image is a fisheye view covering half the unit sphere, roughly centered in the anti-sunward direction and with the Earth's limb indicated by the curved solid line. Dawn is to the left and dusk to the right. Only one energy level (26-37 keV) is used. The counts registered above the limb are ENA from the ring current.

The common DC/DC-converter for all the three instruments could not be switched on after orbit 494 (1 March 1995). Analysis of telemetry and laboratory tests with the DC/DC-converter suggests that the converter is somehow overloaded, perhaps through a "short" in one of the instruments.

We have continued to operate the satellite to gather experince for follow-on satellites. In April 1995 we used the satellite's TM/TC links on 400 and 450 MHz in a communications test. Short text messages were relayed via ASTRID in a bent-pipe mode and in a store-and-forward mode. One station was located at SSC's headquarters in Solna and the other station was mobile and changed its location between three consecutive passes of the satellite.

The testing of the Thor microprocessor has also continued as well as the evaluation of the performance of a vacuum-deposited thin-film silicon solar cell test coupon.

During the summer of 1995 we uploaded new flight software for autonomous attitude control. We hope to demonstrate automatic sun-pointing of ASTRID so that we can use this concept for follow-on microsatellites.

6 Technical Lessons Learned

The ASTRID project has taught SSC some technical lessons concerning the differences between a microsatellite and a satellite, say, ten times heavier.

The first such lesson is that the ***magnetic dipole moment*** of a satellite is not reduced at the same rate as the moment-of-inertia when the satellite mass is reduced. The satellite's magnetism comes from parts that are needed on a satellite regardless of the size, such as relays for example. Therefore, the attitude disturbance torques created by the satellite's intrinsic magnetic dipole moment are quite noticeable in the drift of ASTRID's spin vector. So, magnetic cleanliness is important also for a very small satellite.

Another effect of the small size is that the ***thermal mass*** of the satellite is smaller and the temperature variations around the orbit are quite large, so heaters are necessary to keep the Ni-Cd battery warm enough. Heater power needs to be kept at a minimum, so the thermal design of a microsatellite is not trivial.

The satellite's small size also makes it difficult to design VHF/UHF ***antennas*** with good ***patterns*** because the size of the satellite is of the same order of magnitude as the wavelength. Therefore, on our next microsatellite we plan to use S-band frequencies for both up- and downlink. In this frequency band the antennas are small and the satellite dimensions are larger than the wavelength.

We also found that accommodating equipment on a small satellite is complicated if the satellite spins. Not only must you find a place for all equipment, but you must also try to locate equipment so that the satellite is balanced. Otherwise you need a lot of ***balance masses***. Making all units as small as possibe helps in choosing their right location for balancing. Therefore we have decided that the System Unit of our next microsatellite must be reduced to half the volume.

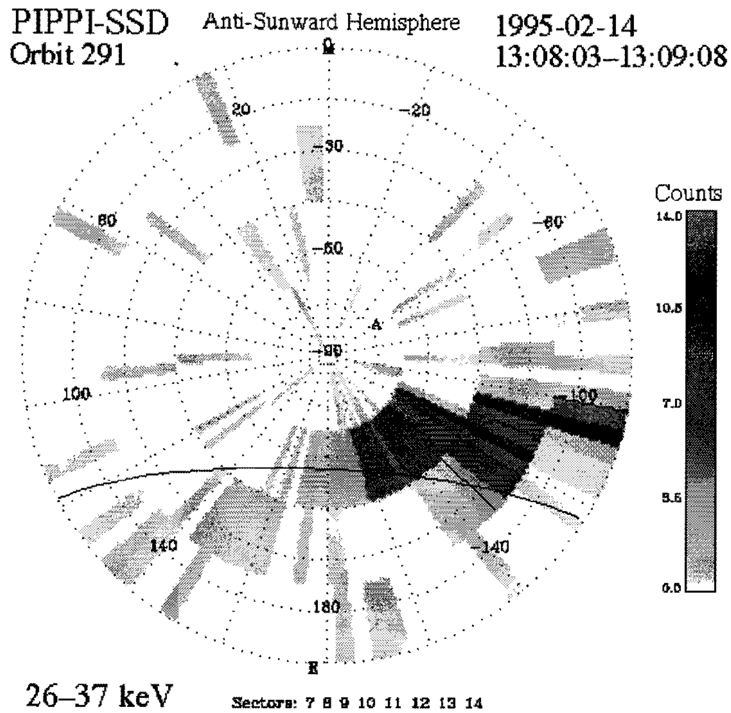

Figure 5 ENA image, PIPPI SSD camera, 14 Feb. 1995 (Courtesy the Swedish Institute of Space Physics).

7 Conclusions

The ASTRID project was intended a precursor to more sophisticated microsatellites for space science and as a test flight of a basic microsatellite design. The project has showed us that a microsatellite with a serious space science mission can be built in about a year and at a total cost, including launch, of $1.4 million. As a result of this success the Swedish Space Corporation is now under contract with the Swedish National Space Board to develop a second microsatellite, ASTRID 2, scheduled for launch in 1997.

8 References

[1] Norberg O. et al, "The Microsatellite Astrid", Proceedings of the 12 th ESA Symp. on European Rocket and Balloon Programmes and Related Research", Lillehammer, Norway, 29 May-1 June, 1995.

[2] Grahn S., "The FREJA Magnetospheric Research satellite, Design and Flight Operations", Proceedings of the 7th Annual AIAA/USU Conf. on Small Satellites, Logan, Utah, September 13-16, 1993.

[3] Häusler et al, "The AMPTE/IRM Spacecraft", IEEE Transactions on Geoscience and Remote Sensing, VOL. GE-23, No 3, May 1985.

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