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Joint Australian Engineering (Micro) Satellite (JAESat) - A GNSS Technology Demonstration Mission

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Abstract. JAESat is a joint micro-satellite project between Queensland University of Technology (QUT), Australian Space Research Institute (ASRI) and other national and international partners, i.e. Australian Cooperative Research Centre for Satellite Systems (CRCSS), Kayser-Threde GmbH, Aerospace Concepts and Auspace which contribute to this project. The JAESat project is conducted under the leadership of the Queensland University of Technology. The main objectives of the JAESat mission are the design and development of a micro satellite in order to educate and train students and also to generate a platform in space for technology demonstration and conduction of research on a low cost basis. The main research objectives of JAESat are the in-orbit test and validation of the SPARx receiver and its performance, the performance of the on-board Orbit Determination (OD) concept, the test of an integrated GPS-Star Sensor system concept for a 3-axis Attitude Determination (AD) and its related algorithms and also various aspects of Relative Navigation. The aspects of atmospheric research will not be addressed within this article. This article will describe the overall JAESat concept and concentrate on the QUT space applications receiver SPARx and related GPS software concepts for OD and AD. The test environment for the development of GNSS space applications will be outlined and finally simulations and respective results including GPS hardware in the loop will be presented and discussed.

Key words: Spacecraft navigation, attitude determination, orbit determination, GPS space receiver, GNSS space applications, micro satellites

1 Introduction

The JAESat mission outlined in Enderle (2002, 2004) will ultimately consist of two micro-satellites (see Figure 1) which will fly in a formation. The JAESat micro-satellite itself will have two components, a master satellite and a so-called slave satellite. The components of JAESat will be attached to each other during the launch phase and will be separated in space, after the release of JAESat from the launcher. The JAESat mission is designed to conduct a variety of experiments based on the mode of interoperation between the payloads on-board the two satellites. A communication link between the two satellites will be established in the form of a RF Inter-Satellite Link (ISL). It is anticipated that JAESat will be launched in 2006. Negotiations with a launch provider for a piggy back launch are ongoing. For this reason the final orbit is not definite yet. However, it is intended to have a circular, nearly polar orbit with an orbit altitude of about 800 km. The operational life time of JAESat is expected to be round 12 months. After the separation of the slave from the master satellite the two satellites will drift away from each other with a low drift rate. JAESat is designed to have a high degree of on-board autonomy. The operations will be conducted via a ground station located at the Queensland University of Technology in Brisbane, Australia.

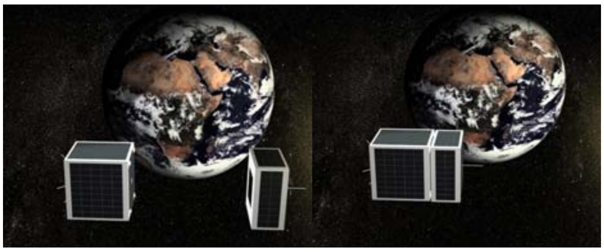

Fig 1 JAESat master and slave satellite concept before and after separation in space

2 JAESat Mission Concept

The JAESat micro-satellite project is an educational and GNSS technology demonstration mission, which will also generate data for scientific use. JAESat's high level mission objectives are:

- Design, develop, manufacture, test, launch and operate the educational/research micro-satellite JAESat
- Develop payloads with a technological and scientific relevance
- Use JAESat as a sensor in space and GNSS technology demonstrator mission

As can be seen in the high level mission objectives, the education and training aspects play an important role in the JAESat mission. The GNSS mission objectives are driven by the SPARx (SPace Applications GPS Receiver), a development by the Cooperative Research Centre for Satellite Systems/Queensland University of Technology. Functions and performance of SPARx will be tested and validated in space within the JAESat mission. A key element of the GNSS activities will be the testing of a new sensor concept for attitude determination, based on Star Sensor and GPS attitude information.

As already noted, JAESat will consist of two micro-satellites (master and slave) flying in a formation. JAESat master and slave satellites will fly in the same orbital plane. After the split between master and slave, the two micro satellites will then slowly drift away from each other. The master satellite will be a cube with a side length of 390mm. The slave satellite will have the following dimensions 390mm x 390mm x 195mm, which is half the height of the master satellite. The JAESat master satellite will be 3-axis stabilized, whereas the JAESat slave satellite will be gravity gradient stabilized. The mass of the slave satellite will be around 10kg, and the mass of the master will be around 30 kg, so that the total mass of JAESat will be around 40 kg. The orbit of JAESat will be a Low Earth Orbit (LEO) with an expected altitude of 800 km and an orbit inclination of around 90 deg. The ground track of JAESat is outlined in Figure 2.

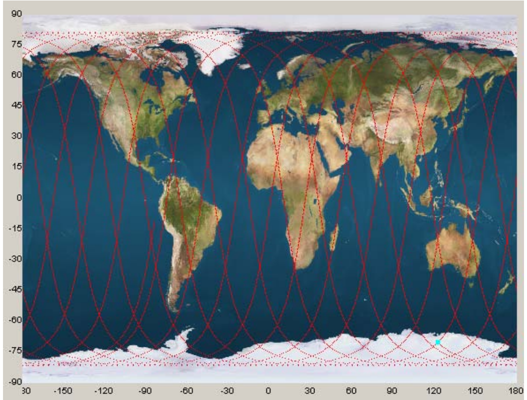

Fig 2 JAESat ground track

3 JAESat Satellite System

3.1 Structure

The JAESat structure concept is based on a tray approach. JAESat will have a total of eight trays. Figure 3 provide an overview of the JAESat structure concept.

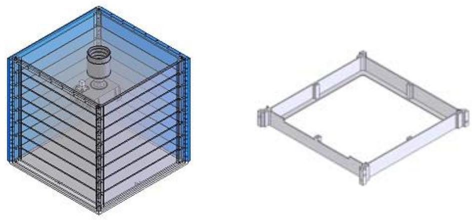

Fig 3 JAESat structure – tray concept

3.2 Power

The JAESat power system will consist of batteries and solar cells. The available power at the master satellite will be around 22 Watts (min) orbit average, based on the current JAESat design and the chosen solar cells.

3.3 Flight Computer

The JAESat on-board flight computer will be an Intrinsyc CerfBoard. The operating system is based on LINUX. The processor is an Intel XScale PXA255 microprocessor @ 400 MHz. The size of the board is:57.2mm x 69.9mm x 25.4mm. Power: 5V DCregulated, 400mA with no

CompactFlash device; peak of 1.1A with CompactFlash. The board has also a Battery Backed Real-Time Clock

3.4 Communication

The overall communication concept is outlined in Figure 4. The receiver is capable of 9600 baud and has low power and space requirements.

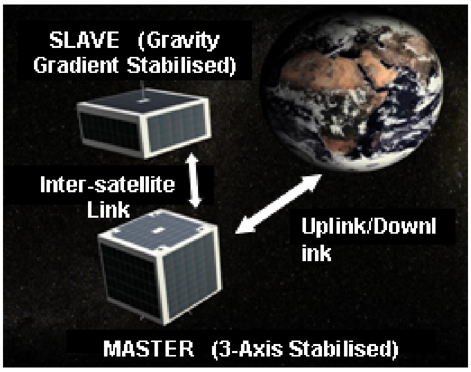

Fig 4 JAESat Communication Concept

3.5 Attitude Control System (ACS)

The master satellite will be 3-axis stabilized by using magnet torquers (air coils). The slave satellite will be gravity gradient stabilized without using a boom. Instead the moments of inertia will be designed so that a gravity gradient stabilization will be the result. After separation from the launcher, the JAESat master and slave will still be attached to each other. JAESat master ACS will than reduce the rotation rates around each axis and finally orient the satellite in such an orientation that the slave will be in its gravity gradient orientation and than JAESat will split into two satellites. After splitting into two satellites, JAESat will drift away from each other. The ACS of the master will be used for controlling the orientation and changing of rotation rates, necessary for testing of the new integrated Star Sensor GPS attitude sensor concept. Only one requirement for the attitude accuracy of the master has been derived, resulting from the need to have an Inter Satellite Link established. The master attitude accuracy requirement is 5 deg. The overall ACS concept is described in Figure 5.

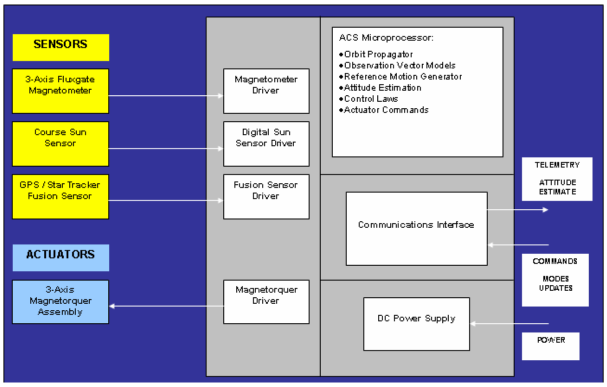

Fig 5 JAESat ACS Concept

4 JAESat Payloads

The JAESat payloads concept is driven by simplicity. The payload itself will be distributed between the JAESat master and slave satellite. One of the positive aspects of this distributed concept is that in the event of problems on one of the two satellites, or in the worst case scenario, the loss of the slave satellite, significant research can still be conducted.

The JAESat master satellite will have the following payloads on board: 1. The SPARx – GPS receiver for positioning (absolute and relative), on-board orbit determination and 3-axis attitude determination. 2. The Star Sensor- KM 1301 for 3-axis attitude determination. 3. Specific antennas for conduction of atmospheric research.

The JAESat slave satellite will have the following payloads on board: 1. SPARx - GPS receiver for positioning (absolute and relative). 2. A mini Video Camera (Web camera type). 3. Specific antennas for conduction of atmospheric research.

4.1. GPS Receiver – SPARx

The CRCSS/QUT GPS SPARx (see Figure 6) development is based on the MITEL GP2021, GP2015 and GP2010 Chip set and is a modification of the MITEL Orion GPS receiver demonstrator. The base for the development of the source code is the MITEL GPS Architect development kit. The source code modifications are specifically targeted towards robust and accurate operation on-board a satellite (see Enderle and Roberts 2003). Key elements of functionality are positioning and timing for satellite applications. Ongoing R&D activities are the development of a GPS receiver for on-board orbit determination (SPARx-OD) and also GPS receiver for satellite attitude determination (SPARx-AD). On-board the JAESat master satellite, either one SPARx-AD or three SPARx will fly with the capability of performing 3-

axis attitude determination. The on-board orbit- and attitude determination will be performed within the Flight Computer. The main characteristics of a GPS SPARx are given in Table 1.

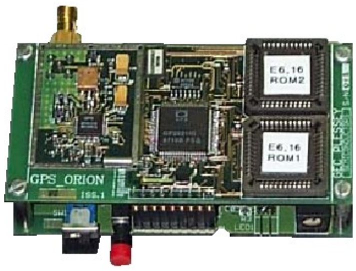

Fig 6 Orion GPS demonstration board

Tab. 1 SPARx – physical characteristics of GPS receiver and interface board

Physical Characteristic – SPARx GPS Receiver Board	
Power (Vdd into receiver board)	+5 volts DC, +/- 10%
ACTIVE-ANTENNA POWER	+5 volts DC available
POWER CONSUMPTION (Vdd)	GPS Receiver Board only: 370mA 1.85W With Antenna: 395mA 1.98W
SIZE: (GPS Receiver Board only)	95mm x 50mm x 20mm
SIZE: (GPS Receiver Board plus Interface Board)	95mm x 50mm x 30mm
CONNECTORS	RF: SMA socket I/O: 9-pin(1x9), 0.1” pitch plug
Physical Characteristic - SPARx Interface Board	
INPUT POWER SUPPLY	+8 volts to +30volts DC
MEMORY / RTC BACKUP BATTERY	+3.6 v NiCad, 110mAhrs
BATTERY CHARGE RATE TOTAL RECHARGE TIME	7.5mA typical 18 hours approx
BATTERY BACKUP LIFE (when supplying Vdr pin on Orion receiver board)	8 weeks approx
DATA I/O LEVELS	RS232 levels (±10v)

A conceptual diagram for the JAESat attitude determination based on GPS is outlined in Figure 7. In addition to orbit and attitude determination, it is also intended to perform relative navigation between the JAESat master and slave satellite. Finally, SPARx will be used for collecting data from specific GPS antennae attached to the sides (looking to the horizon) of JAESat in order to perform atmospheric research.

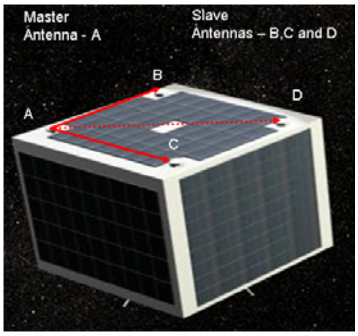

Fig 7 SPARx antenna array for JAESat 3-axis attitude determination. antenna D will be optional

4.2 Star Sensor – KM 1301

The Star Sensor KM-1303 is a contribution of the German Aerospace Company Kayser-Threde GmbH towards the JAESat project. . The Star Sensor KM 1301 is a low-cost single-package design for star recognition, relative and inertial attitude determination. This Star Sensor will be used in the testing of a new integrated attitude determination sensor concept. Star Sensors are the most accurate sensor types for satellite attitude determination. However, these types of sensors have some limitations/restrictions related to their range of operations. One limiting factor is the sensitivity of such a sensor systems with respect to rotation. If the satellite rotation rates are too high (the actual rates depending on the individual model, for the KM-1301 the angular rates are around 5 deg/sec), the Star Sensor will have difficulties with the identification of the stars and therefore an attitude determination can not be performed. However, this problem can be solved by using additional, external information from the GPS attitude sensor. The probability of achieving a star identification and an attitude solution, resulting from an attitude determination process will for this reason increase substantially.

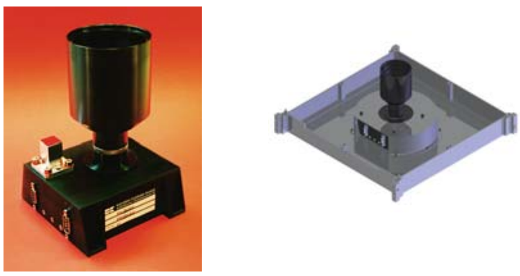

Fig 8 Star Sensor KM 1301 and its integration into the tray structure

5 JAESat Experiments, Testing and Simulations Environment

5.1 Experiments

The JAESat main experiments can be summarized in the following way; First, testing and evaluation of CRCSS/QUT GPS SPARx, including Attitude capability. Second, testing of a new integrated Star Sensor/GPS navigation sensor concept for 3-axis attitude determination. Third, Relative Navigation between JAESat Master and Slave satellite. Fourth, testing and evaluation of different Orbit Determination concepts, On-Ground - Precise orbit determination based on GPS Code and Carrier phase measurements and On-board orbit determination based on GPS receiver position solutions. Fifth, establishment of stable RF inter satellite links and seventh, atmospheric research.

5.2 Testing and Simulations Environment

The testing and simulations environment (shown in Figure 9) at QUT involves several aspects. The core of the testing environment is the Welnavigat GPS signal simulator. The signal simulator is capable of simulating the entire GPS satellite constellation and transmitting RF signals on six channels. Various simulations are possible including a satellite orbit scenario. An important feature in this context is the option to import scenario files, generated by the user.

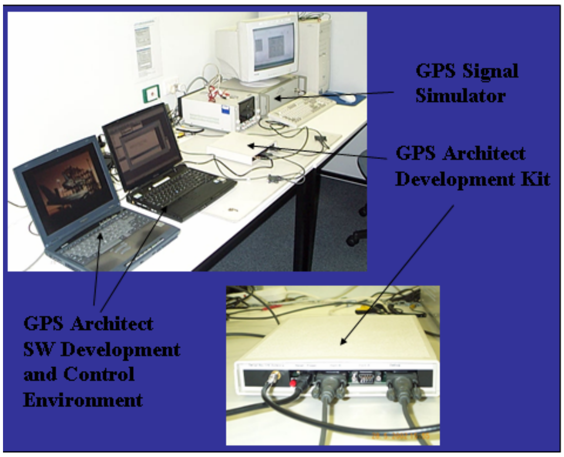

Fig 9 GPS testing and simulation environment

6 JAESat Operations

JAESat is designed for a high degree of on-board autonomy. However, the operations of JAESat will be conducted via a ground station located at the QUT in Brisbane, Australia. The number of ground station over flights is in the order of 4 – 6 per day. JAESat will be visible by the ground station for a period of 8 – 12 min per overflight. In Figure 10, the ground antenna, ground equipment and visibility plots are shown.

Fig 10 JAESat ground station at the Queensland University of Technology in Brisbane, Australia

7. JAESat – Testing, Simulations and Results

Testing and simulations are ongoing activities in order to demonstrate the feasibility of the proposed GNSS experiments and also obtain information about functionality and performance. The results shown here are related to the expected performance of the SPARx in space, the position, velocity and time solution, the capability of Orbit Determination (OD) and also the performance related to the Attitude Determination (AD) based on GPS measurements. Test and simulations have been conducted with and without Hard Ware in the loop.

7.1 Results from GPS Signal Simulator and SPARx

The main objective of these tests was to identify the GPS signal acquisition and tracking performance of SPARx based on different code versions. Results of tests conducted for JAESat including the GPS signal simulator and SPARx are given in Figure 11 and Figure 12. As it can be seen, the acquisition, reacquisition and the tracking behaviour of SPARx is good. SPARx generates a 3D position solution for more than 80% of the time per orbit within this HW in the loop simulation. In this context it is also important to understand that the GPS signal simulator only provides a total of six simulated channels. This means that these tests can be seen as a kind of worst case scenarios. One of the test objectives was also the testing of the time synchronisation performance and the generation of a Hard Ware Pulse Per Second (PPS) output based on code modifications (Bruggemann and Enderle 2004). Currently SPARx generates an HW PPS with an accuracy of better than 50nsec (1 Sigma) steered towards UTC. SPARx performance for a 3D absolute position solution in space is better than 25 m (1 Sigma).

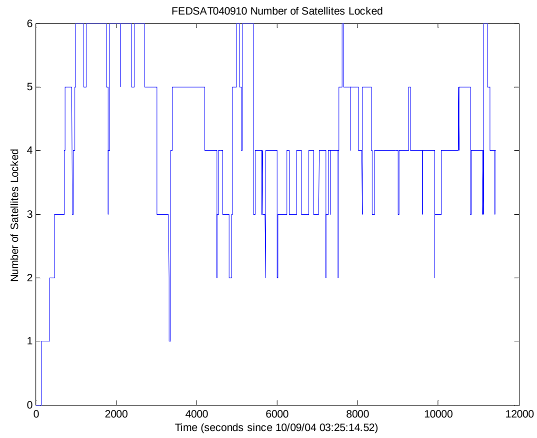

Fig 11 SPARx tracked GPS signals for a typical orbit scenario

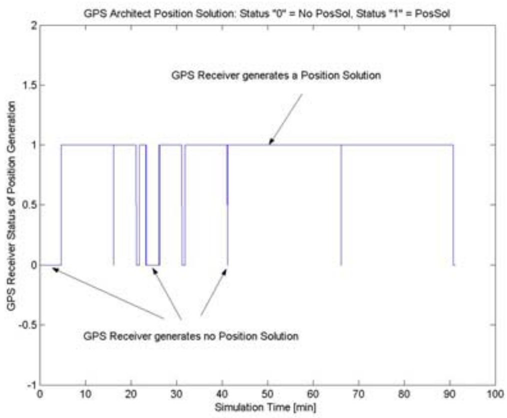

Fig 12 SPARx acquisition and tracking performance

7.2 Simulations for Orbit and Attitude Determination based on GPS

Simulations for the Orbit and Attitude Determination have been conducted. The results are presented in Table 2 (see also Figure 13). For the attitude simulations, the orientation of the antenna array was anti nadir. The baseline length was 36 cm for baseline AB, AC and 51 cm for baseline AD. The multipath error was assumed to be 3mm on the carrier Single Difference (SD). The Orbit Determination concept is based on GPS position solutions Enderle, Feng and Zhou. (2003), a total data arc of 6 hours was used with a position solution every 10 sec.

For the generation of a reference orbit, an Earth gravity field with order and degree of 20 was used and numerically integrated. No other forces have been taken into account.

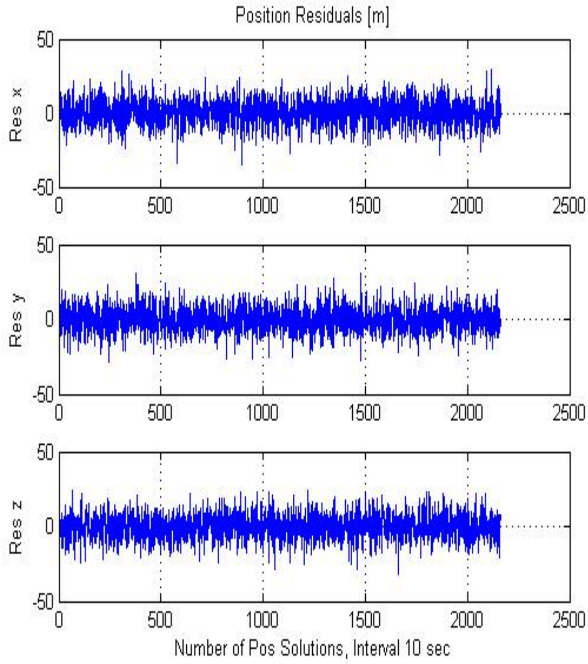

Fig 13 Position residuals for a simulated 6 hour orbit scenario

Tab. 2 Orbit Determination (OD) based on GPS position solutions. The results are obtained from a simulation. The position solution error was simulated with a 1 Sigma value of 25 m.

	Estimated State Vector	**Error wrt Reference State Vector**
Position x [m]	-3283178.224	-17.819
Position x [m]	-3652268.345	3.330
Position x [m]	5251321.252	-4.850
Velocity x [m/s]	2323.540285	0.002362
Velocity y [m/s]	5037.512456	-0.000726
Velocity z [m/s]	-4954.785328	0.000864

The results in Table 2 show that a satellite 3D position accuracy of around 18m can be achieved. The implementation of the code onto the on-board flight computer is one of the next steps. The implementation of the OD code will than be evaluated and optimised for robustness and performance.

The results for the JAESat Attitude Determination (AD) based on GPS, presented in Figure 16 are highlighting that GPS based AD would already by sufficient to comply with the JAESat attitude accuracy requirements. In Figure 14, it can also be clearly seen that the number of visible GPS satellites for JAESat lies between 4 SV and 12 SV with an average of about 8 SV. This means a substantial higher number of visible GPS satellites for the JAESat as have been used within the simulations using the GPS signal simulator (only 6 physical channels can be simulated).

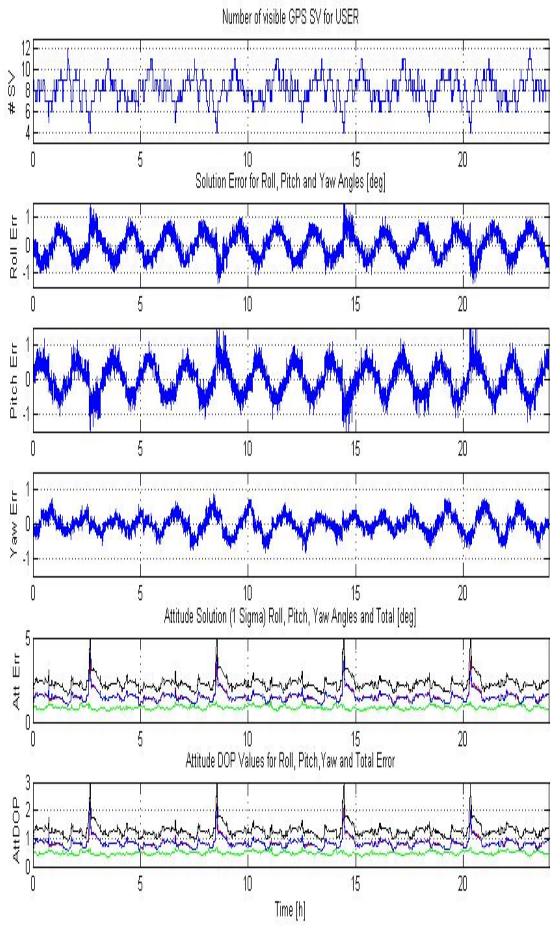

Fig 14 Attitude determination results for a simulated JAESat scenario

8. Conclusions

The tests and simulations have clearly demonstrated the feasibility of the JAESat GNSS experiments in terms of absolute positioning, timing, on board orbit and attitude determination. Further development and testing will be undertaken in order to cover the relative navigation aspects. Special emphasis will be given in the near future for the testing of the integrated attitude sensor based on Star Sensor and GPS attitude information. Between 2003 and 2004 a total of 24 students have worked on the JAESat project in various areas. This means that one of the high level mission objectives has already been achieved – the use of JAESat as an education and research platform.

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