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Advanced Attitude Control on Swedish Small Satellite Odin

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ABSTRACT

The Swedish small satellite Odin combines the two scientific disciplines of astronomy and atmospheric research, using the same main experiment, a radiometer. To make this possible, the attitude control system features 3-axis stabilisation with high accuracy, both during inertial pointing towards celestial targets (15 arcseconds absolute pointing) and during scanning of the earth's atmosphere.
Star trackers and gyros are used as primary sensors. Actuators are reaction wheels and magnetic coils. Sensors and actuators are connected to a specially developed interface processor in the data handling system that takes care of the communication with a dedicated attitude control computer. The attitude control is organised into modes based upon satellite activity and sensor/actuator selection.
A high fidelity simulator has been developed to test the attitude control software. The tests will follow a rigorous plan dictated by the modes of the control system.
In summary, the Odin attitude control is advanced, with high performance – especially for a small satellite project. It has been developed by the Swedish Space Corporation (SSC), as prime contractor for Odin, but involved equipment and services supplied also by other companies and organisations in Sweden, France, and Canada. The design is a strong contender for future SSC scientific and applications missions being studied.

ODIN INTRODUCTION AND MISSION OVERVIEW

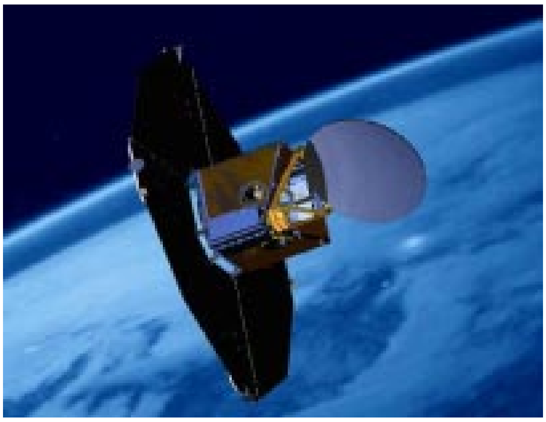

Figure 1 : conception of Odin in orbit

The Swedish satellite Odin has a dual-purpose mission that presents unique attitude control challenges. This mission is comprised of an astronomy segment to study star formation and early solar systems and an aeronomy segment to study ozone layer depletion mechanisms and depletion extent. Since both of these missions are studying the same molecules and, in many cases, the same radiative transitions, only one main instrument, a 1.1 metre radio telescope is required. This telescope has four receivers in the 500 GHz range and one receiver for 119 GHz signals. It is affixed to the spacecraft body, which is then pointed either at the earth's limb or at the sky depending upon the observational requirements. Thus a 3-axis stabilised platform with reference to inertial space is required. Odin also carries an optical slit spectrograph developed in Canada and called OSIRIS (Optical Spectrograph and InfraRed Imaging System). This instrument complements aeronomy observations by detecting aerosol layers and abundancies of some other molecules. The scientific goals were developed by the Odin Science Team consisting of scientists from Sweden, Canada, Finland, and France. These goals established the performance of Odin's Attitude Control System (ACS). The pointing accuracy in staring mode is 15 arcseconds (1 σ) half cone pitch and yaw. The telescope has an accuracy of 7 arcseconds, thus requiring 8 arcsecond accuracy of the

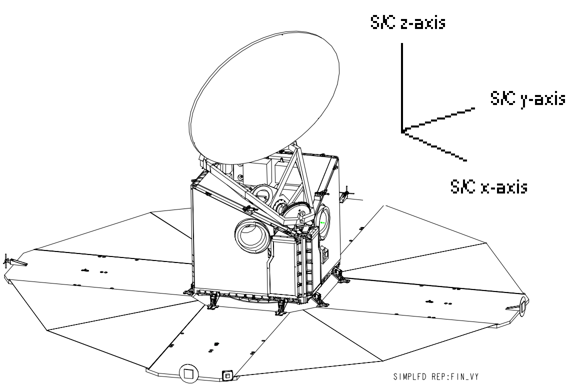

Figure 2: Odin with solar panels deployed

ACS. For atmospheric observation, 2 arcminutes (reconstructed) in scanning mode can be guaranteed to an 85% confidence level. Real-time atmospheric tracking accuracy must be within 6 arcminutes, also guaranteed to 85% confidence.

SPACECRAFT CHARACTERISTICS

The Odin spacecraft is a 3-axis, zero momentum, zero consumable system in a 600km sun-synchronous orbit. It weighs 250 kg and has a lifetime goal of 2 years. It has two possible geometric configurations: solar arrays stowed or deployed (Figures 2 and 3). Solar arrays will be deployed three minutes after separation from the upper stage on the condition that the sun-pointing error is less than 22.2º. The panels will remain deployed throughout the mission.

Inertias (kg m^2)	Stowed	Deployed
Ixx	33	44
Iyy	36	48
Izz	31	55

The heart of the spacecraft is the Odin System Unit (OSU) (Figure 4). This data handling unit is a 3rd generation development of the Freja and Astrid system units. The OSU handles the on-board telemetry (TM), telecommand (TC) reception, decoding and storage,

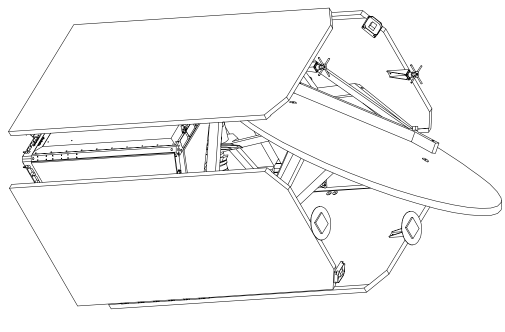

Figure 3: Odin with solar panels stowed

battery management, and redundancy switching. In the context of the ACS, the OSU's primary components are the Odin System Controller (OSC) and three dedicated interface processors: an Actuator Controller (AC), an Off-The-Shelf controller (OTS) for those sensors with complex TM interfaces and the 100MB mass memory (MM), and a House Keeping ∅ (HK∅) for those sensors with simpler TM interfaces. Through the OSU, the onboard TM exchanges data between sensors, actuators and the redundant Attitude Determination and Control Computer (ACDC).

The ACS hardware components are a combination of commercial off-the-shelf (COTS) equipment and project specific developments. These components are described below.

ACDC

Each ACDC is an electrically independent, individually powered 130x212 mm board running a 30kRad SAAB Ericsson Space AB Thor 32 bit microprocessor running at 6 MHz.

RWs

The four reaction wheels are standard Type A Ithaco (USA) RWs with 4Nms momentum capacity and 0.02 Nm torque capacity.

<u>ACS Acronyms</u>:
TC/TM : telecomand/telemetry
Rx/Tx : receiver/transmitter
OSU : odin system unit
OSC : odin system controller
AC : actuator controller
HK∅ : housekeeping ∅
OTS : off the shelf equipment controller
ACDC : attitude determination and control computer
FSS : fine sun sensor
CSS : coarse sun sensor
MG : magnetometer
ST : star tracker
GP : gyro package
MM : mass memory
MT : magnetorquer
RW : reaction wheel

MTs

The three air-core magnetorquers were developed in-house with ACR of Sweden. These three electromagnetic coils are integrated directly into the frame of the platform. The z-axis coil produces a dipole moment of 49 Am^2 at 400 mA. The other coils produce 46 Am^2 at 400 mA.

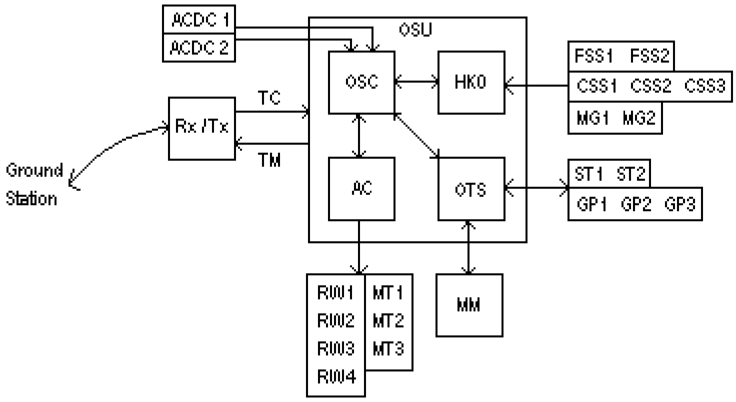

Figure 4: schematic of Odin System Unit

CSSs

The three coarse sun sensors were provided by Matra Marconi Space of France. They provide an accuracy of 3° with linear output between ±7°. The two CSSs on the solar panels provide sun presence sensing up to ±90°.

FSSs

The two fine sun sensors were built by ACR of Sweden to complement the CSSs. They have an accuracy of 1° within an area of ±30°.

MGs

The two 3-axis fluxgate magnetometers were manufactured by SSC in-house under an American license. They have an operating range of ±100μT. The large range accommodates possible large onboard bias.

GPs

Odin carries three Sagem gyros from France. Each gyro gives two axis integrated rate information to within 0.05 arcseconds. Drift stability is a few millidegrees/hour over a 10 minute period.

STs

The two Matra Marconi Space / Sodern star trackers from France have a long flight heritage. They point symmetrically 20° off of the telescope line-of-sight (S/C body x-axis) and have a total field of view of 7.5° x 10°. Stars are detected and tracked autonomously in the star trackers. Star identification and inertial fix calculations are done in the ACDC. The instrumental 3σ error with in-flight compensation is 7.5 arcseconds.

CONTROL MODES AND FUNCTIONAL DESIGN

Description of operational modes

The attitude control system modes fall into three general categories:

- Safe mode
- Standby mode
- Normal modes.

A contingency mode, Detumble, and a maintenance function, Momentum Management, are also included. A bootstrap program initiates the ACDC software upon launch vehicle separation and enters the Safe mode. The bootstrap program can be reexecuted if a reboot is ever required.

Safe mode

The Safe mode acts as the base mode. It secures a sun pointing attitude to ensure good solar panel illumination. It also limits the attitude motion about the solar panel normal. A pseudo-reference based upon a sun vector and a B-field vector is used in attitude estimation. The mode is made simple and reliable by using only the coarse and fine sun sensors and the magnetometers for attitude measurement. The reaction wheels are the primary actuators.

There are three control gradations within the Safe mode: Large, Small, and Fine control. The Large control is an eigenaxis bang-bang type for large slew manoeuvres. The Small control is a single-axis bang-bang that is used as the intermediate step to the single-axis PID Fine control submode. Smooth PID control reduces the stress on the reaction wheels caused by the repeated on-off commands of bang-bang control.

Standby mode

The Standby mode acts as the base mode from which all Normal modes enter. It is entered from Safe mode by ground command or from any of the Normal modes in case of an error. Standby mode maintains full 3-axis inertial pointing and rate control. Standby mode takes one of two forms: Standby Magnetic for magnetometers and sun sensors, Standby Celestial for star trackers and gyros. Independent of how the attitude is determined, the control consists of Large, Small, and Fine gradations as in the Safe mode. The Standby control law and the Astro control law are essentially the same.

Normal modes

Scientific observation and data gathering takes place in the Normal modes. Specific observational programs are uplinked to the satellite in the form of Observational Mode Parameter Blocks (OMPBs). These programs consist of sequences of the six attitude manoeuvres listed below and time-tags for their execution. The primary sensors for these modes are gyros and both startrackers. However, attitude estimation can be performed for the cases of only one startracker or no valid startracker data. This is the case during Aeronomy observations when one of the startrackers is obscured by the earth. The primary actuators are the reaction wheels. As with Standby and Safe modes, the control has three gradations of control: Large, Small, and Fine (Figure 5).

Astronomy staring

Spacecraft points at a fixed location in inertial space and maintains that fix under the influence of external disturbance torques.

Astronomy staring with position switch

Spacecraft switches between two fixed inertial points: one for observation and one for calibration.

Astronomy mapping

Spacecraft targets a succession of adjacent inertial points based upon a predefined mapping area and pattern. The largest possible mapping area is 1.5° x 1.5°.

Aeronomy limb pointing

Spacecraft points at a specified altitude of the earth's limb and maintains that altitude under the influence of disturbances. Aeronomy observations can be made off of the orbit plane, as long as the antenna is protected from solar exposure that can cause thermal deformation.

Aeronomy scanning continuous

Spacecraft scans the earth's limb between 7 and 120 km at a maximum constant speed of 1°/min.

Aeronomy scanning stepwise

Spacecraft steps through up to 10 distinct altitudes of the earth's limb between 7 and 120 km altitude.

Detumble mode

The Detumble mode is a contingency mode that can be entered from any other mode if the spacecraft angular rates exceed 6.3°/sec in stowed configuration or 4.2°/sec in deployed configuration. The sole purpose of this mode is to reduce the spacecraft rates to an acceptable level. In this, the simplest of all the modes, only the magnetorquers and magnetometers are used. A bang-bang negative B-dot control law is used. The simple control objective is nominally to eliminate all spacecraft rates relative to the measured B-field. When the rates have been reduced to an acceptable level, the Safe mode is entered.

Momentum management

The Momentum Management function eliminates excessive spacecraft momentum by reducing the speeds of the reaction wheels to a target value specified for each mode. It is activated

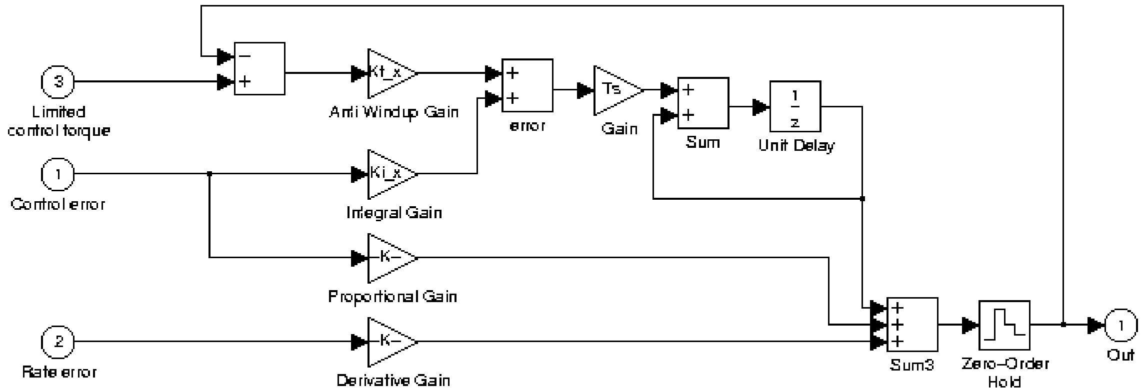

Figure 5: Aeronomy Fine control: PID with anti-windup

autonomously from any of the modes except Detumble if any of the RW speeds exceed the threshold value for the current mode. This function operates simultaneously with the mode that initiates it. The control law inputs are the measured B-field and the RW angular momentum vector calculated from RW speeds. The control law commands maximum possible magnetic dipole moment from the magnetorquers in the opposite direction of the RW angular momentum vector, that is, the control law calculates $\overline{m} = \overline{B}x\overline{N}$, where $\overline{N}$ is the largest achievable torque in the opposite direction of the RW angular momentum vector, $\overline{B}$ is the magnetic field, and $\overline{m}$ is the total magnetic dipole moment produced by the magnetorquers. The primary mode from which Momentum Management was initiated perceives this magnetorquer moment as a disturbance to be countered by reducing RW speeds. Since Momentum Management would produce an unacceptable disturbance during astronomical observations, a feed-forward loop is used to reduce RW speeds to the proper level before observations are begun.

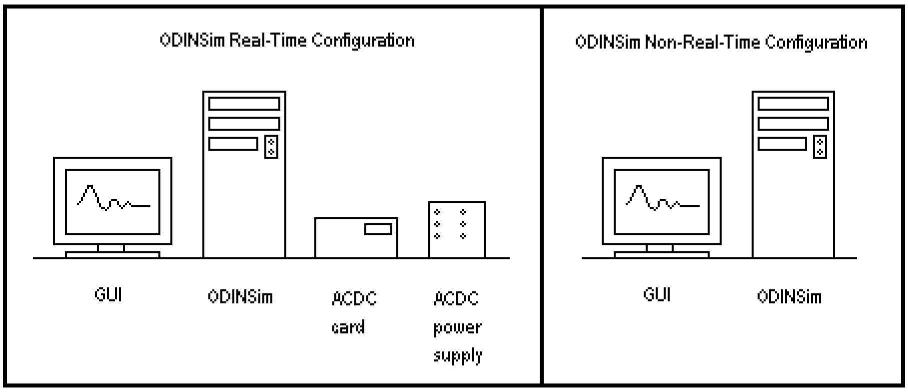

Figure 6: ODINSim configurations

ODIN ACS SIMULATION AND ACDC TEST

The testing of the ACDC flight software has two configurations: non-real-time and real-time (Figure 6). The non-real-time configuration runs the Odin simulation (ODINSim) against the compiled ACDC code. The real-time configuration runs ODINSim against the actual ACDC board through a direct link to the OSU simulation card. Each configuration has three parts: GUI, the ODINSim executable, and the ADA code, accessed either as an internal executable or as an external user (i.e. the flight ready hardware). The GUI is a window application written in Visual C++ using RPC protocol so that the GUI can be brought up at a remote terminal to run the simulator across a network. The ADA code is delivered by SAAB Ericsson Space (SESpace) in flight configuration having passed software integration tests. SESpace has not performed a full, closed loop dynamic simulation (SSC developed ODINSim specifically for this purpose). The ODINSim simulator is a thread-based application written in C++. It simulates the OSU, all sensors and actuators, rigid body dynamics, Keplerian orbit propagation, and an external environment. This environment consists of:

- magnetic field: 10^{th} order IGRF model
- sun: low precision formulas from Astronomical Almanac
- eclipse: cylindrical model

- albedo: models earth as 2^{19} flat areas for diffuse but not specular reflectance
- shading of CSS1 and CSS2 by 166 point 3-D description of spacecraft radiometer
- residual magnetic dipole moment approximated as a constant.

Gravity gradient torque and aerodynamic drag are not included. Reaction wheels, gyros, and rigid body equations of motion were identified as requiring continuous simulation and were therefore contained in a core model constructed in Matlab's Simulink which was then transformed to C code with the Real Time Workshop. In the simulation, continuous time is modelled with $\frac{1}{16} * \frac{1}{16}$ second quantization. The fastest discrete time step in the actual satellite is the gyro sample rate, 16 Hz. The ODINSim produces high fidelity simulation with the potential for even greater fidelity.

The acceptance testing of the ACDC with the use of the simulator has just recently begun. A rigorous test program is being developed. The program is delineated by the ACS modes. For each mode, an attempt is made to capture all potentially unacceptable behaviour. For example, a summary of the objectives of the Safe Mode tests are listed below:

- verify sun acquisition capability and pointing stability within the FSS area
- verify sun acquisition and pointing for all sky
- check safe mode momentum unloading function
- check safe/detumble and detumble/safe transitions

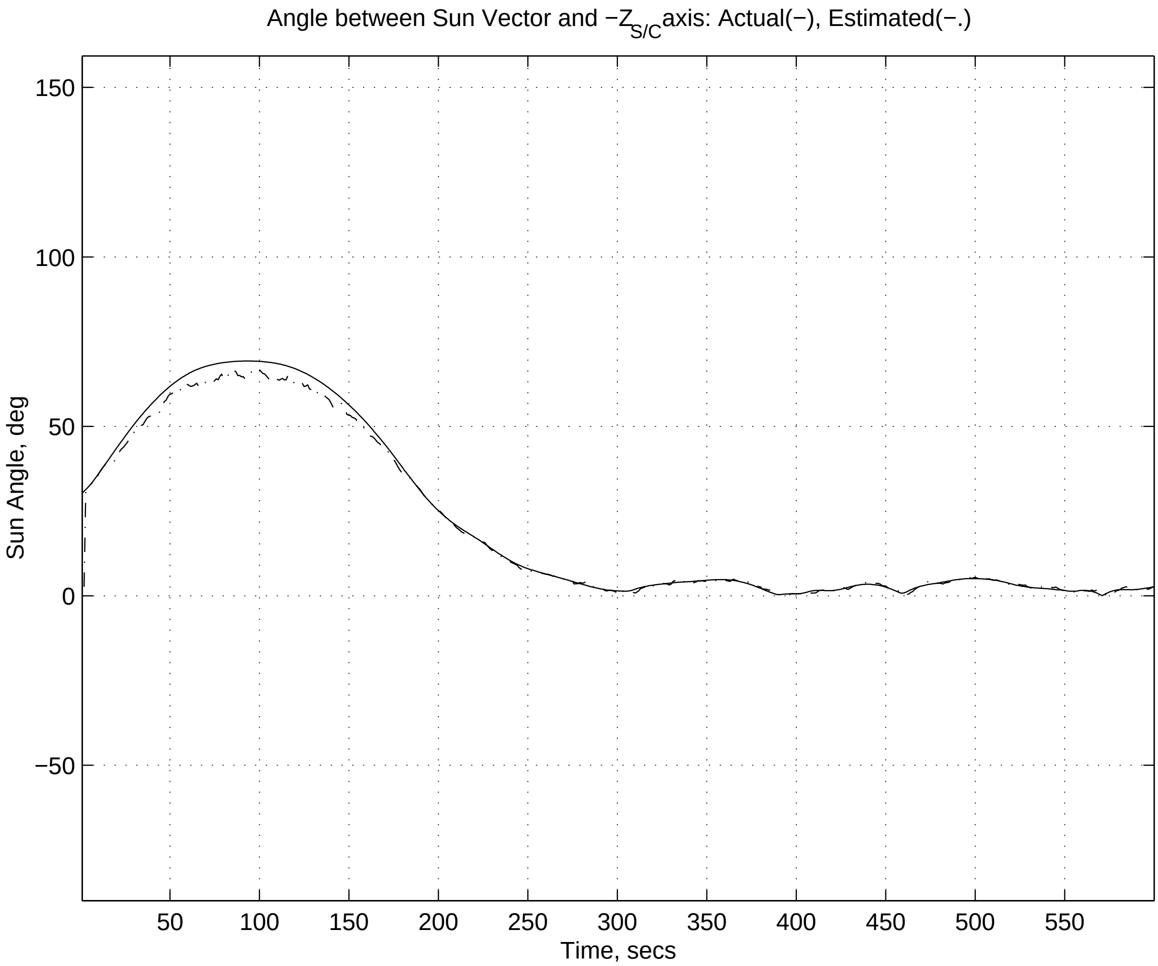

Figure 7: Tip-off simulation: angle from sun-pointing vs. time

- evaluate safe and detumble behaviour during eclipse
- miscellaneous cases: map rate estimation, erroneous sensor/actuator combinations, check response to direct ACDC commands, etc.

To date, the Safe Mode tests are nearly complete and the Standby Mode tests are under preparation.

Figures 7 and 8 show a simulation of the tip-off situation. The solar arrays are stowed. Tip-off rate is 1.5°/sec about an arbitrary axis. The satellite and final stage will separate 30° off of sun-pointing (to avoid eclipse of satellite by final stage). About 4 minutes (Figure 6) are required to attain sun-pointing. Safe Mode will keep the satellite within 5° of sun-pointing. Besides sun acquisition, Safe Mode attempts to minimise the rate about the z-axis with magnetometer data providing the 3rd axis of information. Rates of 0.5°/sec are acceptable.

The functional tests of the ACS, to be done by the Canadian Space Agency, will follow the ACS acceptance tests done by SSC. These tests consist of both open loop evaluations of the gyro and star tracker hardware performance and closed loop evaluations of the hardware/software system. The actual hardware contained in the closed loop tests are the OSU, ACDC, mass memory, interfaces to sensors and actuators, gyro packages, and star trackers. A real-time simulation of the ACS actuators, sensors, spacecraft body dynamics, and disturbance torques completes the closed loop system. The gyros and a star tracker optical head will be mounted on a two-axis motion table in front of a simulated starfield. The closed loop tests will emphasise astronomy, aeronomy, and standby modes.

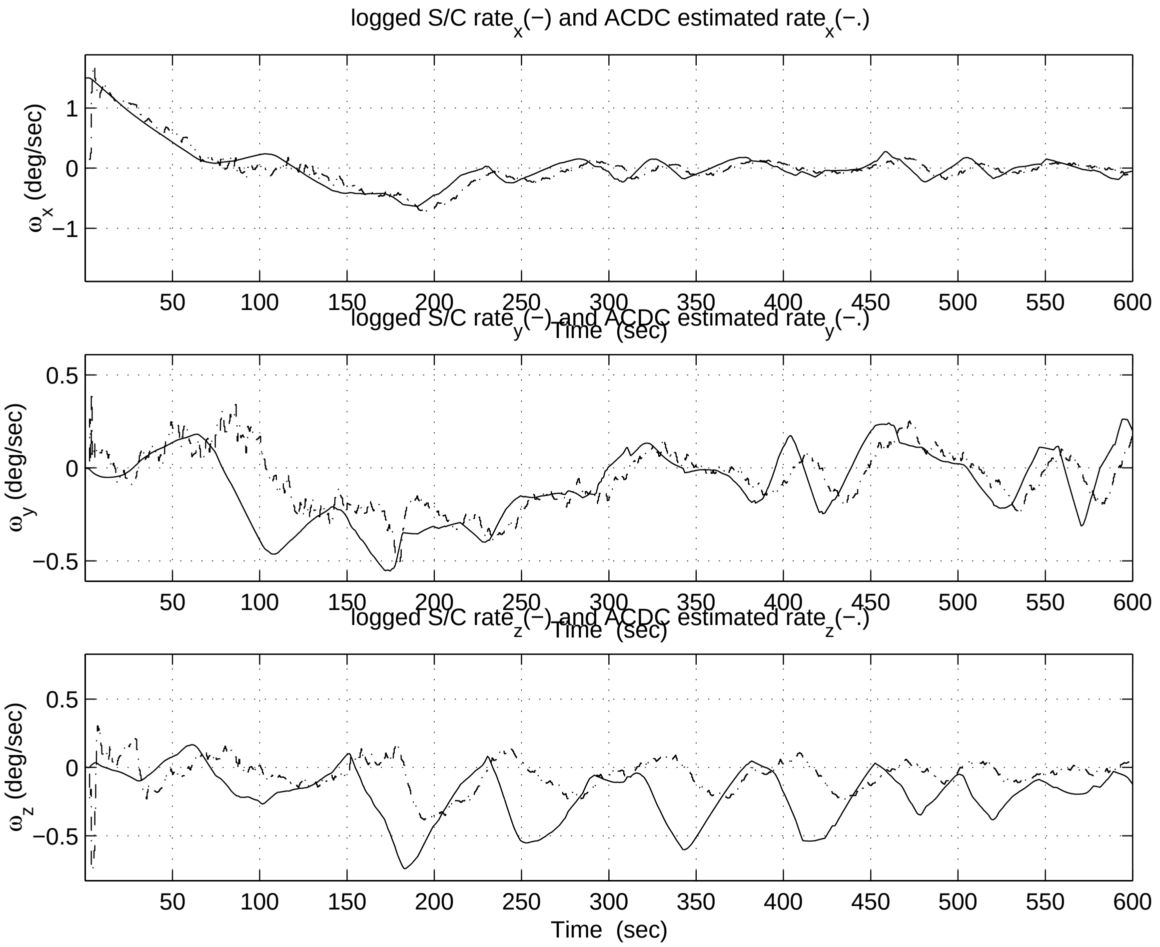

Figure 8: Tip-off simulation: satellite rates vs. time

FUTURE ADAPTATIONS

Both the ACDC software and the ODINSim simulator have been built with the intention of adapting them to future projects. Their code was designed to be modular and expandable. The ODIN ACS is going to be expanded to accommodate gimballed solar arrays and an orbit maintenance system in a small to microsatellite package. Recent developments in sensor technology, such as the autonomous Ørsted star tracker developed by the Danish Technical University and used on the Ørsted and Astrid 2 satellites, will also be adapted to the Odin derived ACS system.

CONCLUSION

The Odin satellite will carry an advanced attitude control system capable of astronomy staring to within 15 arcseconds, on and off orbit plane scanning to within 2.4 arcminutes, and several other useful inertially referenced normal modes. The ACS is defined in a modular and robust manner to accommodate future developments and expansions. A simulator has been developed for the Odin platform that can be reconfigured for future SSC style platforms. Testing of Odin's ACS is now underway. Odin's 3-axis stabilised, zero momentum attitude control system will be adapted and expanded for use on other platforms.

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