Small Demonstration Satellite-4 (SDS-4): Development, Flight Results, and Lessons Learned in JAXA’s Microsatellite Project

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Japan Aerospace Exploration Agency (JAXA)
SDS-4 Spacecraft Overview

**SDS: Small Demonstration Satellite**

- 48kg
- $500 \times 500 \times 450$ mm
  - $1400 \times 500 \times 450$ mm (SAP deployed)
- Zero momentum 3-axis stabilized
  - Pointing error < 0.5 deg (3σ)
  - Determination error = 0.052 deg
  - Stability over 5 minutes = 0.061 deg
- S-band
  - 16 kbps PCM-PM (HK downlink)
  - 1 Mbps QPSK (mission downlink)
  - 4 kbps (uplink)
- SSO altitude = 677km
- Launched in May 18, 2012
SDS-4 Block diagram

ADCS
- GPS Antenna
- Star Tracker
- 3-axis MEMS Gyro
- 3-axis Magnetic Sensor
- Multi-Interface Unit
- Reaction Wheels

OBC
- Core Module
- Extended Module 1
- Space Wire

System
- Monitor Camera
- Harness

Comm
- Diaplexer
- Tx Antenna
- Rx Antenna
- PCM-PM
- CMD
- ST
- QPSK
- TX
- RX
- AIS Receiver

Thermal and STR
- SAP Deployment Mechanism
- Temperature Sensors
- Structure
- Heaters
- Counter Weights

Mission
- AIS Antenna
- AIS Receiver
- Transponder(QPSK)
- Quartz Crystal Microbalance
- Flat-plate Heat Pipe

EPS
- Power Control Unit
- +24V Unregulated
- +5V
- +/-15V

Ni-MH Battery Assembly
- Extended Module 1
- Extended Module 2
- Network I/F
- Serial Digital I/O
- Discrete I/O
- Co-axial
ADCS components

**Sunlight Detection**
- Coarse Sun Sensor

**Attitude Determination**
- Static
  - Star Tracker
- Digital Sun Sensor
- Magnetic Sensor

- Dynamic
  - High Accuracy MEMS Gyro
  - Extended Kalman Filter

**Target Attitude Determination**
- GPS Receiver

**Attitude Control**
- PID Controller

**Momentum Unloading**
- Magnetic Torquer x 3

**Attitude Determination**
- Static
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SDS-4 Missions

*Space-based AIS*

- AIS (Automatic Identification System) for tracking ships
- Demonstrate technology for the future **space-based AIS system** and on-board AIS receiver.
- Understand AIS signal collision environment in orbit.

**Quartz Crystal Microbalance**

**Flat-plate Heat Pipe**

**Thermal Control Material Experiment**
Mission Results of Space-based AIS

◆ Results

1. Signals received from up to 336 vessels per minute
2. Range coverage of 5000km with a single antenna
3. Reduction of the signal reception rate in vessel congestion zones such as China and Japan (@ Sun Pointing Mode)
4. By antenna pointing maneuver, acquisition counts of signal increased doubly in congestion area considerably (@ Earth Pointing Mode)
Mission Results of Space-based AIS

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◆ 2nd Generation Satellite-AIS Receiver for ALOS-2

- 4ch AIS signal reception capability (simultaneously 2ch)
- Digital sampling and ground signal processing architecture.
- Newly designed deployable AIS antenna
LESSONS LEARNED
LL#1-1: System thinking

- **AIS receiver EMC problem**

  - Additional shields to:
    - On-Board Computer
    - Power Control Unit
    - AIS Receiver
    - Harness lines
    - Test cables
  - Aluminum conductive tape between structure panels

- AIS signals from ships
- SDS-4 system noise
- Interface point (below 170dBm/Hz)
- Bad signal-to-noise ratio (SNR)
LL#1-1: System thinking

- AIS receiver EMC problem

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  - On-Board Computer
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AIS signals from ships

SDS-4 system noise

Very weak

Unnecessary I/F and margins removed

Bad signal-to-noise ratio (SNR)

Bit error rate

Newly defined interface (End-to-end performance)

Good communication reduces unnecessary I/F and margins
LL#1-2: System thinking

- ADCS system level end-to-end tests

System real (night) sky test for attitude determination by a star tracker

System real Sun-mag (daylight) test for attitude determination by a sun sensor and magnetic sensor

Conduct end-to-end tests as much as possible
LL#1-3: System thinking

- Wheel polarity check

- Electrical I/F test with OBC
  - Visual polarity check: OK

- ADCS end-to-end test
  - Visual polarity check: Not conducted

- Final polarity check in end-to-end configuration
  - Visual polarity check: NG

Modified software was written and tested 5 days before shipping.

Don’t fractionate tests, instead conduct them in end-to-end configuration.
LL#2: in LEOP (Launch and Early Orbit Phase)

- Satellite motion just after separation from LV

1:39 am local time

uc_acs_mode: NOP
uc_acssubmode: MONITOR
衛星モード: スタンバイ
衛星 HOLD/RELEASE: HOLD
SAP1 OPEN/CLOSE: Close
SAP2 OPEN/CLOSE: Close

SDS-4
Power ON
Separation from LV
De-tumbling
SAP deployment
Sun search
Sun acquisition
LL#2: in LEOP

- 2:00 am (1 hour before the 1st pass) @ operation room
  - They are in tense, and getting too nervous
LL#2: in LEOP

- 2:00 am (1 hour before the 1st pass) @ operation room
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- 3:10 am: The 1st pass
  - “Most of the telemetry were OK!”, “But the 2nd pass will come in 5 minutes”
LL#2: in LEOP

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  - “Most of the telemetry were OK!”, “But the 2\textsuperscript{nd} pass will come in 5 minutes”
- 3:20 am: The 2\textsuperscript{nd} pass
  - “Let’s celebrate successful launch and operations”
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- **4:40 am**: 90 minutes later in the 3\textsuperscript{rd} pass
  - ADCS mode: de-tumbling
  - Digital Sun Sensor: Power off, FDIR (Fault detection, isolation, and reconfiguration) flag on,
  - Command uplink: Failed
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- 4:40 am: 90 minutes later in the 3rd pass
  - ADCS mode: de-tumbling
  - Digital Sun Sensor: Power off, FDIR (Fault detection, isolation, and reconfiguration) flag on,
  - Command uplink: Failed
- 6:10 am: 4th pass
  - Recovered by commands

✔ The sign of the malfunctioning were seen from the 1st pass

Relax BEFORE the launch, then concentrate on operations!

Don’t ignore even the slightest warning sign!
LL#3-1: FDIR, that is the problem

♦ FDIR of Digital Sun Sensor in LEOP

Error check for each sensor
  1. Upper / lower limit check
  2. Rate of change error check
     ✓ Constant value error
     ✓ Too high change rate error
LL#3-1: FDIR, that is the problem

- FDIR of Digital Sun Sensor in LEOP

Error check for each sensor
1. Upper / lower limit check
2. Rate of change error check
   - Constant value error
   - Too high change rate error

Sun acquisition mode

1. Upper / lower limit check
2. Rate of change error check
   - Constant value error
   - Too high change rate error

<FDIR 1>
DSS reset
counter = 1

1st pass

2nd pass

Error 1-1
Error 1-2
Error 1-3

<FDIR 2>
DSS power OFF

De-tumbling mode

3rd pass

4th pass

Recovered

Error 2-1
Error 2-2
Error 2-3

Error 3-1
Error 3-2
Error 3-3

Error 4-1
Error 4-2
Error 4-3
LL#3-1: FDIR, that is the problem

- FDIR of Digital Sun Sensor in LEOP

Error check for each sensor
1. Upper / lower limit check
2. Rate of change error check
   - Constant value error
   - Too high change rate error

- DSS was working perfectly
- Direction of the Sun was really constant
  - Attitude was too stable
  - Noise environment was quiet

- Too strict setting of FDIR threshold is rather dangerous

Space noise environment is quieter than on ground
LL#3-2: FDIR, that is the problem

◆ Attitude loss by resetting Kalman filter

Error check for Kalman filter

1. Too big difference between measured attitude and time propagated attitude

\[
\text{Estimated attitude} = K \times (\text{Measured attitude}) + (1 - K) \times (\text{Time propagated attitude})
\]
**LL#3-2: FDIR, that is the problem**

- **Attitude loss by resetting Kalman filter**

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</table>

\[
\text{Estimated attitude} = K \times (\text{Measured attitude}) + (1 - K) \times (\text{Time propagated attitude})
\]

- **Initial Kalman gain**
  - Initial Kalman gain
  - **K = 1**

- **Wheel FDIR**
  - Keeping constant rotational speed

**Static attitude determination method changed**
- **STT** ➔ **DSS + MAGS**

**Controller reacted to bad attitude estimation**
- Due to the bad attitude, sensor input was lost
- Inaccurate input
- Wheel upper speed limit

**Recovered**
- Pass 1
- Pass 2

**Initial values after reset is important**
LL#4: A backup plan

◆ Plan A

Specifications were insufficient
Newly developed

AIS antennas
Newly developed

AIS receiver
Newly developed

AIS data analysis software
Newly developed
LL#4: A backup plan

- **Plan A**
  - AIS test signal generator
  - AIS antennas
  - AIS receiver
  - AIS data analysis software
  - Newly developed

- **Plan B**
  - Buy a proven AIS signal generator

Without any proven components, how do you prove that the result is true?
LL#4: A backup plan

- **Plan A**
  - Specifications were insufficient
  - Newly developed
  - AIS antennas
  - Newly developed
  - AIS receiver
  - Newly developed
  - AIS data analysis software
  - Newly developed

- **Plan B**
  - Buy a proven AIS signal generator

Bugs were found in AIS receiver!

A backup plan should be executed in advance, otherwise it’s too late.

To concentrate on the new technology, use proven test environment.
LL#5: Squawk List

The more you find, the closer you come to the success!
More Lessons Learned

Make team rule for design changes and communication procedure.

To concentrate on the new technology, use proven test environment

If something is wrong, don’t proceed further. Stop and ask someone.

Accuracy of a DSS degrades in penumbra.

Initial values after reset is important

Don’t believe past heritage. Understand conditions of use and design concept.

Don’t think alone. Ask professionals.

Don’t fractionate tests, instead conduct in end-to-end configuration

A backup plan should be executed in advance, otherwise it’s too late

Space is quieter than on ground

Project policies should be told again and again.

Too strict setting of FDIR threshold is rather dangerous

It is important for system engineer to understand the mission background.

Good communication reduces unnecessary I/F and margins

Relax, then concentrate, and never give up until the last minute!

Leaders should produce an atmosphere for open discussions.

Don’t behave like busy even if you are really busy.

The more you find, the closer you come to the success!
Conclusion

- SDS-4, 48kg microsatellite, was launched in May 2012
  - 3-axis zero-momentum control
  - Achieved full success, now conducting extra experiments.
- Lessons learned will be applied to the post-mission phase of the SDS-4 and the next small satellite in JAXA.
Thank you for listening!

Visit our HP:
In-house development by young engineers

3.11 : Earth quake hits Eastern Japan

- Office room: Heavy damage!
- Flight hardware: NO damage!
- JAXA Personnel: No one injured!
Space-based AIS Experiment (SPAISE)

**AIS (Automatic Identification System)**

- All ships to carry automatic identification systems (AISs) capable of providing information about the ship to other ships and to coastal authorities automatically provide information - including the *ship's identity, type, position, course, speed, navigational status and other safety-related information* - automatically to appropriately equipped shore stations, other ships and aircraft.

![SPAISE operation image](image)
System Proto-Fright Test Flow

- Jun. 2011～: Electrical performance test before environmental tests (includes SPAISE Integrated Test #1)
- Jul. 2011～: Mass Property test, Solar Array Panel (SAP) deployment test, SPAISE Integrated Test #2, Fitness check for the Rocket Interface
- Aug. 2011～: System Vibration Test
- Sep. 2011～: System magnetic Test
- Oct. 2011～: SPAISE Integrated EMC Test #3
- Nov. 2011～: System Thermal Vacuum Test
- Dec. 2011～: Electrical performance test after environmental tests (includes SPAISE Integrated EMC Test #4)
- Jan. 2012～: Satellite Operation Test
SPAISE Integrated EMC Tests

- SPAISE mission required to make system noise low level for receiving AIS signal on orbit.
- The requirement is unspecified in design phase, so we conducted protection against noise by cut and try on EMC tests.
  - Requirement is so strict to system noise that we spent a total of around a month in Radio Test Building.
  - We accomplished the noise requirement by kinds of protection against noise.
Protection against system noise

- Protection against noise to satellite system
  - an additional shield to On-board Computer (OBC), Power Control Unit (PCU), AIS-RX, and part of the system harness line.
  - change the AIS heater line for shielded line
  - Aluminum conductive tape between structure panels
    - enhance the conduction between structure panels as a countermeasure to the SDS-4 bus system.

Conductive Fibers for Electromagnetic Shielding

Conductive Tape
Protection against system noise

- Establishment of Test Configuration
  - Suspend the SDS-4 on a crane and set it on a mounting made of polystyrene foam.
    - block the effect of a multi-pass arise from the satellite lifting mount
  - Power feeding by external battery
    - block the effect of test harness from Solar Array Simulator (SAS) line and external battery itself is shielded by shield box.
  - Change of AIS test signal transmitting Antenna.
    - dipole antenna was replaced to high directional log periodic antenna to block the effects of multi pass signal in test room
Operation Overview

- SDS-4 operations are divided into four phases by the implementation system and experiment contents.
  - Early Operation Phase: Satellite condition confirmation
  - Commissioning Phase: BUS and Mission component function checkout
  - Nominal Operation Phase: Experiment operation for full success
  - Post-mission Phase: Experiment operation for extra success

<table>
<thead>
<tr>
<th>Phase</th>
<th>Timeline</th>
<th>Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early operation phase</td>
<td>5/18, 2days</td>
<td>Power on, Separation, SAP deployment, Verification of COM, ACS and EPS, Orbit determination, Start to acquire IST and QCM data</td>
</tr>
<tr>
<td>Commissioning phase</td>
<td>~5/20, 1month</td>
<td>Establish inertially-fixed sun-oriented attitude, AIS-ANT deployment, All components checkout, Orbit determination by 2way doppler</td>
</tr>
<tr>
<td>Nominal operation phase</td>
<td>~6/18, 5months</td>
<td>Experiment operation to achieve full success, Evaluation of trend data</td>
</tr>
<tr>
<td>Post-mission phase</td>
<td>~11/16</td>
<td>Experiment operation to achieve extra success, Additional experiment operation, Outreach activities using satellite operation, Evaluation of trend data</td>
</tr>
</tbody>
</table>

At now
Early operation and Commissioning phase

- Early operation and Commissioning Phase
  - Two solar array panels (SAPs) deployment
  - Attitude determination and control in Nominal-SPM (Sun Pointing Mode)
  - All instruments checkout including mission instruments
  - SPAISE antenna deployment

Picture by MCMR

Power Budget@LEOP
Nominal operation and Post-mission phase

- **Nominal Operation Phase**
  - SDS-4 missions were conducted and achieved full success.
  - We evaluated the performance of bus components in orbit.

- **Post-mission Phase**
  - To enhance the mission and conduct new experiments.
    Ex) SPAISE experiments with attitude control for antenna-pattern

Structure Panel Temp. trend data

Additional experiment for SPAISE
Flat-plate Heat Pipe In-orbit Experiment (FOX)

◆ Mission Overview and Objective
  ■ FHP enables heat to be dissipated from the narrow clearance between the component and structure
  ■ To demonstrate and confirm FHP performance under a Micro-G environment

◆ Operation Result
  ■ The function and performance, by matching amount of heat transport and thermal conductivity among orbit data, analytical result, and ground test results are confirmed
In-flight experiments related to Space materials using THERME (IST)

◆ Mission Overview and Objective
  - To measure solar absorptance and the degradation characteristics of new thermal control material using “THERME”

◆ Operation Result
  - To confirm the effect of UV-shielded coating based on the variation in solar absorptance coefficient ($\alpha_s$)
  - To confirm that variation in $\alpha_s$ is due to ultraviolet degradation when compared with the ground test result.

![Graph showing the variation in solar absorptance coefficient ($\alpha_s$) over time.]
Quartz Cristal Microbalance (QCM) contamination sensor

- **Mission Overview and Objective**
  - To demonstrate the newly developed QCM: inexpensive, lightweight, compact and simple interface

- **Operation Result**
  - The in-orbit achievement is confirmed
  - Frequency variation affected by atomic oxygen is observed, and there is no trend toward deposition of contaminants.
SPAISE Extra Operation

- Acquisition count of signal increased at beginning of acquisition by maneuver operation.

Comparison to acquisition count of signal in a minute

<table>
<thead>
<tr>
<th>Time</th>
<th>TOTAL CRC OK</th>
<th>TOTAL CRC NG</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013/3/11</td>
<td>1021</td>
<td>2134</td>
</tr>
<tr>
<td>2012/8/21</td>
<td>620</td>
<td>1903</td>
</tr>
</tbody>
</table>