

# ESAIL D43.1

## Final report of RU control and telemetry

Work Package: **WP 4.3**

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## Table of Contents

<b>1. Introduction.....</b>	<b>3</b>
<b>2. Applicable documents.....</b>	<b>3</b>
<b>3. System overview.....</b>	<b>4</b>
<b>4. Telemetry system.....</b>	<b>5</b>
4.1 Electronic circuitry.....	5
4.2 Antenna .....	5
4.3 Communication protocol.....	6
<b>5. Control system.....</b>	<b>8</b>
5.1 Subsystem interfaces.....	8
5.2 Sensor circuitry.....	10
<b>6. Optical beacon.....</b>	<b>11</b>
<b>7. Conclusions.....</b>	<b>11</b>

## **1. Introduction**

This document describes the manufacturing and functional testing of the ESAIL Remote Unit (RU) Control and Telemetry (C&T) subsystem, whereas the design is presented in detail in the design description, AD-1. The purpose of the control subsystem is to control the various subsystems of the RU and to monitor the status of each subsystem as well as the overall RU status. The telemetry system is used to receive simple commands from the Main Craft (MC) and to transmit status data to the MC. An optical beacon is used to reveal the RU's position relative to the MC.

## **2. Applicable documents**

- AD-1: D41.2, Design Description of the Remote Unit.
- AD-2: D42.1, Final report of Remote Unit power system.
- AD-3: D41.4, Remote Unit test plan.
- AD-4: D41.1, Requirements specification of the Remote Unit.
- AD-5: D41.4, Remote Unit test results.

### 3. System overview

Besides the antenna, beacon and cabling, The C&T system occupies one Printed Circuit Board (PCB), placed inside the thermal box of the RU. This tailor-made PCB is stacked with the Power subsystem PCB (see AD-2) and the two reel motion controller PCBs, which together form the electronic system required to monitor and control the Remote Unit.

The final version of the C&T PCB is a four-layer FR-4 board, 98 by 98 mm, with mounting holes and cut-outs for the batteries used by the power subsystem, Fig. 1. This final system is very close to what is described in the design report, AD-1. Hence, the detailed schematics and Bill of Materials are omitted from this report. When any deviations from the original design have been made, it will be stated in the text.

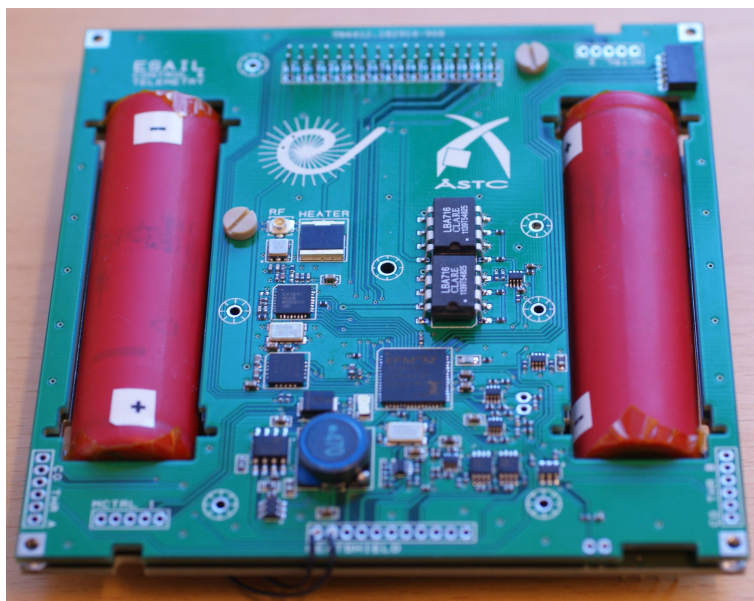


Figure 1: Final Control and Telemetry system PCB with all components mounted.

All components are mounted on the top side of the board while the back side is kept clear of components so that it can be stacked close to the Power PCB, visible underneath the C&T PCB in Fig. 1. The two inner layers are used as ground and power (3.3 V) planes.

The final PCB contains approximately 150 surface-mount components, 140 different signal nets and 300 vias. The total mass is 30.1 g and 25.7 g with and without components, respectively.

## 4. Telemetry system

The Radio Frequency (RF) telemetry system allows the Remote Unit to receive commands and send data to and from the Main Craft. All parts of the telemetry system, apart from the antenna, are placed inside the thermal box.

Communication takes place on the 869 MHz frequency band. This frequency band was chosen as a good trade-off, since higher frequencies would make the circuitry less power-efficient and lower frequencies would require unsuitably large antennas.

### 4.1 Electronic circuitry

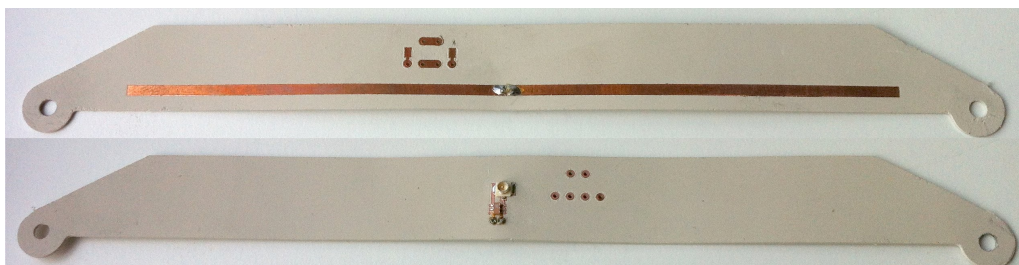
A monolithic low-power RF transceiver chip is used to handle the RF communication. The chip, SX1211 from Semtech Corporation, also handles address-based packet filtering and Cyclic Redundancy Check (CRC) error detection. The chip buffers all data received, and triggers an interrupt when a transmission is completed. This allows the Microcontroller to be put in low-power sleep modes and wake up only when a valid and intended data packet has arrived.

The radio chip requires two dozens of passive components (see AD-1), but with the current PCB layout, the entire RF subsystem only occupies an area of 20 x 10 mm.

Since the RF circuitry is placed inside the thermal box, the operating temperature is kept within tolerable limits (see AD-1 and AD-4). A climate chamber was used to test if a change in temperature would cause a frequency drift that, in turn, would cause the transmitting and receiving node to operate at slightly different frequencies and lead to a reduction of the received signal strength. No change in the received signal strength could be detected when one transceiver was kept at room temperature and the other was cycled from 10 °C to 60 °C. Furthermore, during the Sun simulator tests (see AD-3 and AD-5) the thermal box temperature was cycled from 20 °C to -30 °C without any measurable change in received signal strength. It is therefore concluded that the electronic circuitry is functional (and without any significant frequency drift) over the full temperature range.

### 4.2 Antenna

The dipole antenna, Fig. 2, was milled from a Rogers Corporation RO3210 ceramic-filled laminate reinforced with woven fibreglass. This substrate was chosen partly due to its high dielectric coefficient ( $\epsilon_r = 10.2$ ), which reduces the antenna size, and partly due to its high thermal and mechanical stability.



*Figure 2: The final 869 MHz antenna, front and back side. The photodiodes used for sun inclination measurements are not installed at this point.*

A thin coaxial cable with U.FL connectors are used to connect the antenna to the C&T PCB. After the U.FL connector, a ceramic chip balun converts the unbalanced signal to a balanced one, which is fed directly to the antenna. The PCB also holds the two photodiodes used for sensing the RU's inclination relative to the sun.

The antenna measures 165 x 19 mm in total and has mounting holes for a good mechanical connection to the heat shield's leading edge.

The manufactured antenna, with balun, was characterized with a vector network analyser and its S11-parameter was found to be approximately -20 dB at 869 MHz, Fig. 3.

Explicit measurements of how the resonant frequency shifts with temperature has not been made, but during tests in the sun simulator chamber the antenna was exposed to temperatures from -80 °C to +60 °C and no losses in the received signal strength could be seen, AD-5.

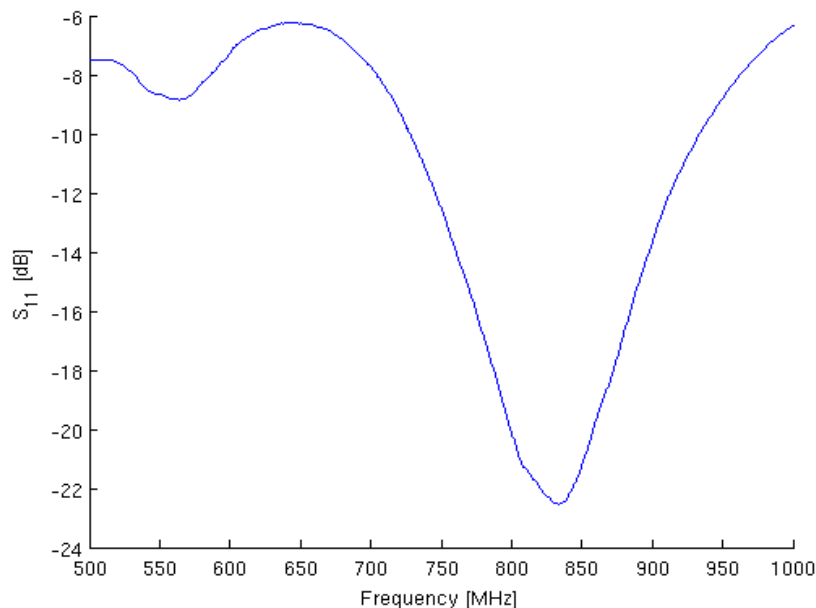


Figure 3: Measured S11-parameter of the RU antenna.

The total weight of the final antenna is 5 g. Including the PCB estate of the circuitry and cabling used, the total mass cost of the telemetry system is approximately 10 g. This is close to the design value of 12 g in AD-1.

### 4.3 Communication protocol

All RF messages are packet-based. The data structure for an RF packet is shown in Fig 4.

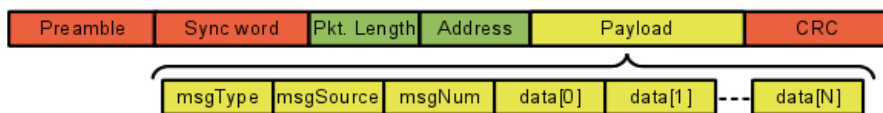


Figure 4: Packet structure for radio transmission

In order to send a data payload sequence (yellow), a packet header (green) and RF synchronization bytes and checksum (orange) must be added. The packet header is handled by the microcontroller whereas the synchronization and checksum bytes are automatically added to (and upon reception, stripped from) the packet by the SX1211 radio.

Furthermore, each payload contains a short header. The msgType byte describes the type of payload (ping, control request, status response, data request, etc). The msgSource byte contains the address of the transmitting entity and msgNum is used to keep track of which response belongs to which request, if several transmissions are queued.

Since all nodes share the same channel, some kind of channel access method is needed. For the small-scale RU tests, a novel method is used where the MC initiates all transmissions

over the medium. The MC acts as a master and the RUs act as slaves. This makes the protocol rather deterministic and easy to implement.

A small network consisting of one master and three slaves was tested in a laboratory environment. Transmissions occurred at a rate of approximately 6 Hz (one packet reception and one packet transmission per second for each slave) and, over 10 hours, the network showed a packet loss of less than 0.1%.

Although the polled master/slave channel access method is reliable and does provide worst-case latencies that are lower than the requirements, a large-scale system with more nodes would benefit from a more intricate channel access method. Two suitable alternatives would then be Time-Division Multiple Access or Frequency-Division Multiple Access.

### 5. Control system

The control system monitors the status of all subsystems and measures temperatures at several places, both inside and outside of the thermal box, AD-4. If any on-board anomalies are detected, the control system responds by by shutting down subsystems, activating heaters, etc.

The control system is based on a low-power EFM32 ARM Cortex-M3 microcontroller from Energy Micro AS. The EFM32 was chosen due to its very low power consumption and highly efficient sleep modes.

The MCU itself draws approximately 4-5 mA from the 3.3 V bus when running at 16 MHz with peripherals enabled, and does not occupy much more than 12 x 14 mm on the PCB, including decoupling capacitors and external oscillators, Fig. 5.

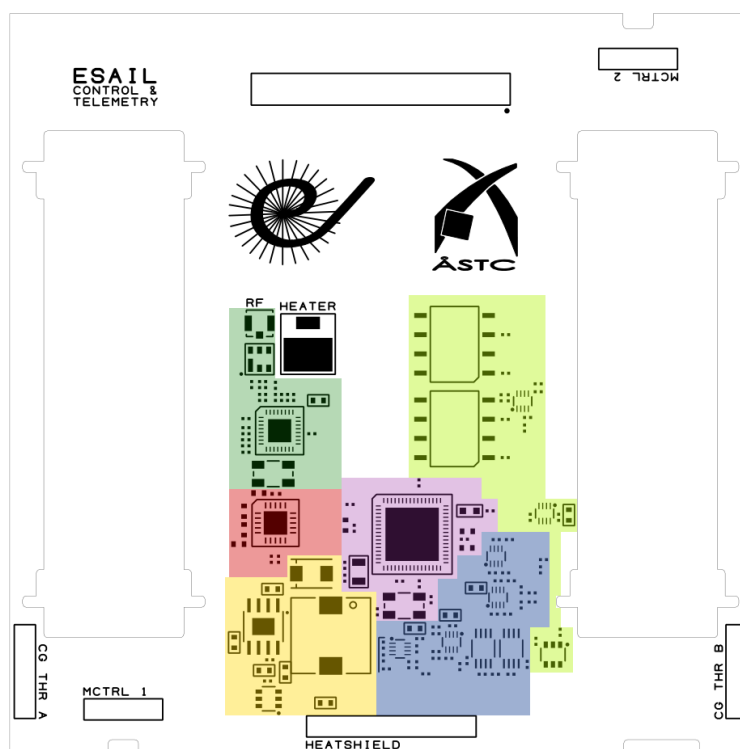


Figure 5: Final Control and Telemetry PCB floor plan showing circuitry for the radio (darker green), motion controller (red), optical beacon (yellow), sensors (blue), controller (purple) and cold gas thruster (lighter green).

#### 5.1 Subsystem interfaces

Since the purpose of the control system is to monitor and control the various subsystems of the RU, some signal and power interface circuitry is required. The following sections only briefly describe the circuitry used for each subsystem. An interested reader could, in conjunction to this text, use the schematics and descriptions in AD-1 to gain a deeper understanding of the systems.



### **Reel motor driver interface**

The reel motor motion controllers are COTS circuits from Faulhaber GmbH. Communication is entirely digital and follow the RS-232 standard with logic levels at  $\pm 15$  V. During prototyping, it became clear that the 3.3 V TTL signals from the MCU did not work with the high voltage levels required by the motion controller, and a level shifter from Maxim IC, MAX3222, was added to the final C&T system.

Due to the high idle current of the motion controller, 60 mA at 12 V, its supply voltage is toggled on only when the motors are active. The supply voltage is toggled by the power subsystem and controlled by the MCU over the I2C bus.

The total area required for the reel motor interface is 15 x 15 mm.

### **Cold gas thruster interface**

The low side of each cold gas thruster valve is connected to a MOSFET that is normally off. A positive pulse from the MCU turns this on so that the valve is connected to ground. The high-side of the valve is connected to an opto-relay that switches between the two different voltage supplies.

An RC network connected to a comparator is used to create a logic '1' pulse approximately 1 ms after the FET has been turned on. This signal triggers the opto-relays, and the voltage across the valve is switched from 12 V to 2.5 V.

The area occupied by the final cold gas interface circuitry is roughly 20 x 30 mm.

Since the cold gas thruster unit used in the RU model was a not electrically functional dummy, a stand-alone gas valve was used to test the pulse-/switch circuitry. The test was successful at room temperature but it is possible that large changes in temperature might cause the RC network to change time constant and provide a 12 V pulse that is too short. Therefore, the R and C should be chosen so that it delivers a long enough pulse over the full temperature range.

### **FEEP thruster interface**

Since the FEEP thruster-equipped RU was not built, the interface to the FEEP thruster's Power and Control Unit (PCU) was not included in the final C&T system.

A programmable voltage supply is available from the power subsystem, and should be used as an input to the FEEP thruster's high-voltage converter. The voltage is set by the MCU over the I2C bus.

### **Power subsystem interface**

Connection between the C&T and the power subsystem is made via a 34-pin connector at the top edge of the board, Fig. 1. The two boards are soldered to each other with a pin header to ensure a good electrical and mechanical connection.

Most of the commands required to control the Power subsystem is sent over an I2C bus. Some commands, like that to enable the radiator, uses only a binary signal, and the jettison mechanism requires both a binary signal and an I2C transmission to be triggered.

The initial design required a 50-pin connector, but after prototyping it was seen that a few redundant signals could be removed, or handled over the I2C bus. Out of the 34 remaining pins, more than half are used for the different voltage buses and high-current signals required by the various subsystems.

Functional testing of the interfaces was made after the RU prototype was assembled, and no problems were found. Due to the limited time available between delivery and RU testing, and since the control system could not be re-programmed after the final steps of the assembly process (when the MLI blanket was closed), the Maximum Power Point Tracking of the power subsystem was not fully tested. These parts have, however, been tested and verified as a part of the power subsystem testing, AD-2.

## 5.2 Sensor circuitry

The C&T subsystem sensors are used to monitor the RU’s inclination relative to Sun and the temperature both of the heat shield and at several places inside the thermal box, AD-4.

Two photodiodes are used as Sun inclination sensors. The photodiodes are placed on the antenna PCB, Fig. 2, and are reverse-biased so that the output photocurrent is proportional to the illuminance. A shunt resistor creates a voltage drop that is amplified by an operational amplifier, and the amplified signal is sampled by the MCU Analogue-to-Digital converter (ADC).

For reading the temperature of the heat shield, two platinum Resistive Thermal Devices (RTDs) are used. Each RTD is connected to a Wheatstone bridge and the output is amplified by an instrumentation amplifier. The signal is then fed to the ADC in the MCU.

Inside the thermal box, where the temperature swing is much lower than that of the heat shield, simple NTC thermistors are used. They are placed in a half-bridge configuration where the output is amplified by an operational amplifier and then passed to the MCU ADC.

The analogue circuitry for the sensors requires approximately 20 x 20 mm of PCB area. Total mass is approximately 5 g, including cabling, which is according to the design value.

Measurements in a climate chamber showed that temperature readings were within the required tolerances. The RU's ability to measure the inclination versus the sun was verified at room temperature, but more data should be collected in order to calibrate the system over the wide temperature range, AD-1, that the heat shield can be exposed to.

## 6. Optical beacon

The optical beacon is used for revealing the RU's position relative to the main craft. The beacon itself consists of a single High Brightness Light Emitting Diode (HBLED) that resides outside the thermally controlled box, placed on the short boom close to the jettison mechanism.

Since the diode is only turned on intermittently and for short periods of time (less than 100 ms), a rather high current can be used without risk of overheating.

A driver circuit, National Instruments's LM3404, placed on the C&T PCB, supplies the HBLED with a constant current of approximately 500 mA when the beacon is turned on, which corresponds to a power consumption of 2 W. When the LED is turned off, the driver circuit is put in a shut-down state and the system consumes only 0.7 mW.

The driver circuit requires rather large passive circuits and occupies 20 x 15 mm of PCB area. The total mass of the beacon is approximately 7 g including cabling, which is almost half of the estimated mass (12 g) in AD-1.

## 7. Conclusions

A control and telemetry system for the ESAIL Remote Unit has been designed, manufactured and functionally tested at both component and system level. The performed tests have not revealed any design flaws or problems, and it is therefore concluded that the control and telemetry system presented in this document satisfies the requirements stated in AD-4.

The prototype control and telemetry system is, however, heavier than designed (AD-1). This is largely due to the fact that the PCB was made larger than originally intended, so that it provides structural support to the thermal box frame. Mass savings can be made if the PCB is made smaller (an area and mass reduction of 50% is feasible) or, preferably, if the control and telemetry system can share one single PCB with the power system.

An even greater mass saving, of more than 20 g, can be made if the (currently COTS) reel motor circuitry was re-designed and placed on the same PCB as the the C&T system. This would cause a series of positive synergistic effects, since the height of the thermal box can be reduced which, consequently, leads to smaller shading wings. It would also reduce the amount of heat radiation from the thermal box, allowing for a thinner and lighter MLI blanket.