ESAIL D42.1
Final report of RU power system

Work Package: **WP 42**
Version: **Version 1.0**

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(List of participants:)

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1. Introduction

This document provides results of the ESAIL Remote Unit (RU) Electrical Power System finalized design and testing after being integrated into a complete RU prototype. The design of the RU Electrical power system has been described in a separate project deliverable D42 , WP 4.2 [1]. The changes from the original design due to various requirements updates and initial prototyping and testing results are also provided in the following chapters.

2. Overview of the development work process

2.1 First prototype manufacturing and testing

The first prototype of the RU EPS electronics was manufactured, based on the initial RU technical requirements specification and design concept. A prototype PCB was ordered from Brandner PCB OÜ, Paide, Estonia. The prototype board has 4 layers and is compliant to all design requirements except the final board dimensions and location of mounting holes which were not finalized at the time of manufacturing. A separate microcontroller board was designed and manufactured for providing all necessary digital interfaces for initial testing of the manufactured prototype.

The board was then populated with all components and block level verified. There were a few design errors found during initial evaluation but none of them were requiring any significant design changes. All electrical design requirements were fulfilled on the first prototype after minor modifications.

The picture of the first assembled prototype board is shown on figure 2.1.

The picture of the microcontroller board for block level verification is shown on figure 2.2.

An additional sample of the prototype board was manufactured and assembled for initial integration tests together with other RU electrical components at ÅSTC, Sweden.

Fig. 2.1 Photo of the first prototype of the RU Power system PCB

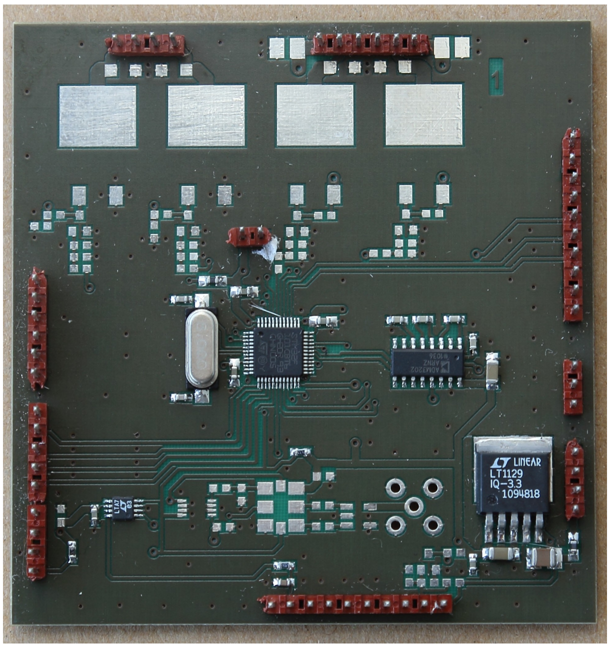


Fig. 2.2 Photo of the verification board

A special test and verification firmware was written for the verification board for control and monitoring functionality of the RU power board prototype.

All voltage regulators were tested individually with simulated test loads,. MPPT was tested with a simulated current source representing a typical solar cells array output at different sunlight intensities. The MPPT did not work properly in initial tests, but after a misconfiguration of voltage divider resistors at the voltage comparator (U2) inputs was identified and fixed, the MPPT was operating as expected. R19 and R6 values were fine-tuned to ensure operation of the MPPT in the specified input levels range. The digital potentiometer U6 was used to adjust the working range of the MPPT. All residual output voltage ripple levels were also checked. Due to very high efficiency no abnormal temperature increase was observed on any circuit components on the PCB. A quick check of the radiated high frequency noise was also performed. Although some noise was observed close to the regulator components under high switching currents and frequencies but its effects were local enough to not cause any harmful interference to the other subsystems of the RU.

Operation of the voltage and current monitor ADC (U12) was verified together with all current sensors at the voltage regulators and MPPT outputs.

High side switches U14, U17, U18 and U20 were also tested using simulated test loads.

2.2 Changes between first and second prototype

After verification of the first prototype board a decision was made to build a second prototype board based on a small number of possible improvements determined from the first prototype verification results. At the same time a refined design concept of the overall RU mechanical design became available making it feasible to include a refined PCB outline and mounting holes locations into the second prototype design. Based on the recommendations from the RU control unit design it was possible to remove the 2.5 V voltage regulator U10. Another digital potentiometer U22 was added to reduce the number of analogue control signals between RU power board and RU control board. As after the 2.5V regulator removal two ADC inputs were no longer used they were reconnected for 3.3 V current consumption (VIn5) and second battery cell voltage measurements (Vin4). Another current-sense amplifier (V10) was added for 3.3 V regulator output current measurements.

Due to the refined design requirements an number of pins of the connector P1 was reduced from 50 to 34. This was possible because of some of the reel motor control signals and temperature sensor outputs were no longer needed to be routed through the RU power board. Updated wiring diagram of P1 connector is shown on fig. 2.3.

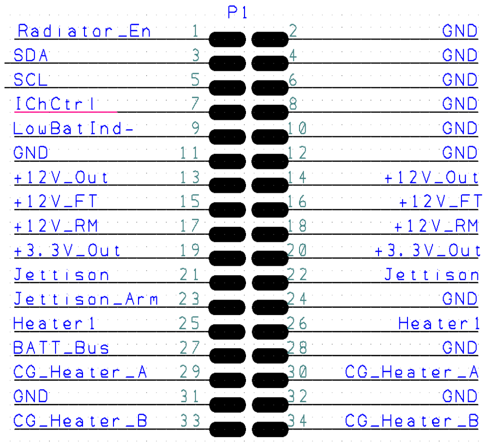


Fig. 2.3 Updated wiring diagram of P1

Updated control and monitoring functionality via I2C bus is provided in Table 2.1.

Ref.	Circuit	I2C addr. (Hex)	Function	Direction
U6	AD5259	18	MPPT power point adjust	Output
U22	AD5259	4C	Battery charge current adjust	Output
U19	AD5259	4E	+12 V output voltage adjust	Output
U15	TCA6408A (P0)	20	Jettison control	Output
U15	TCA6408A (P1)	20	Heater1 control	Output
U15	TCA6408A (P2)	20	CG Heater_A control	Output
U15	TCA6408A (P3)	20	CG Heater_B control	Output
U15	TCA6408A (P4)	20	+12 V Reel motor enable	Output
U15	TCA6408A (P5)	20	ADC enable	Output
U15	TCA6408A (P6)	20	+12 V enable (inverse pol.)	Output
U15	TCA6408A (P7)	20	+12 V FEEP thruster enable	Output
U12	AD7291 (VIn0)	2F	VBat monitoring ADC	Input
U12	AD7291 (VIn1)	2F	ICh monitoring ADC	Input
U12	AD7291 (VIn2)	2F	+12 V voltage monitoring ADC	Input
U12	AD7291 (VIn3)	2F	+12 V current monitoring ADC	Input
U12	AD7291 (VIn4)	2F	VBat2 monitoring ADC	Input
U12	AD7291 (VIn5)	2F	3.3 V current monitoring ADC	Input
U12	AD7291 (VIn6)	2F	3.3 V voltage monitoring ADC	Input
U12	AD7291 (VIn7)	2F	Solar panel voltage monitoring ADC	Input

Table 2.1 Updated control and monitoring functions via I2C bus

The complete electrical schematics diagram and PCB layout drawings of the second prototype board are provided in appendixes 1 and 2.

2.3 Second prototype manufacturing and testing

The second prototype PCB was manufactured by the same manufacturer and technology as the first prototype. It was assembled locally using hand soldering technology. The new board was tested the same way as the first board. Some temperature and vacuum cycling tests were also included this time as a part of initial verification against space environment.

In extreme temperatures (at -25 deg/C and +60 deg/C) all critical system parameters were checked and found to be within design limits.

The photo of the assembled second prototype board together with the control electronics board is shown on figure 2.4.

For RU control electronics firmware integration a calibration table was created for each digital potentiometer and ADC input. Typically 2...4 calibration points were recorded for each analogue control and monitoring function.

The recorded calibration information is summarized in table 2.2.

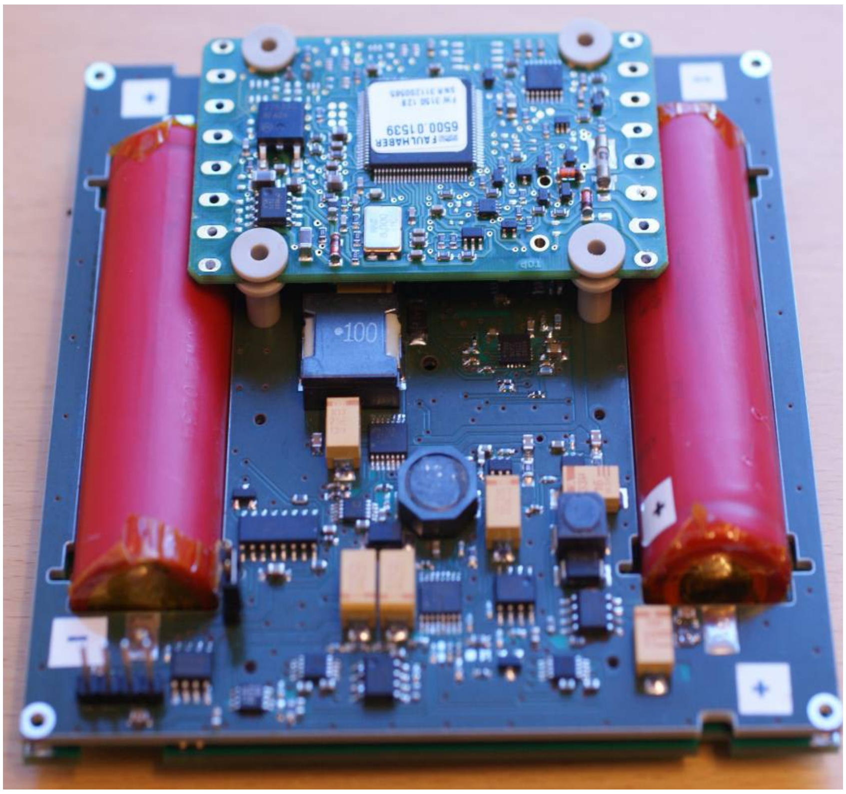


Fig. 2.4 Photo of the RU power system second prototype board

Ref.	Function	Measured parameter value	Digital value (Dec)	Comment
U6	MPPT DPOT	21.98 V 20.66 V 20.15 V 16.24 V	0 90 100 200	MPPT working level adjustment
U22	IChg DPOT	130 mA 390 mA 483 mA	0 50 255	Maximum battery charging current adjustment
U19	+12 V adjust	11.85 V 12.06 V 15.72 V	255 240 50	+12 V output voltage adjustment (needed if FEEP thrusters used)
U12(0)	VBat monitoring	7.65 V 8.02 V	3387 3539	Battery voltage monitoring
U12(1)	Ichg monitoring	130 mA 390 mA 483 mA	474 1309 1617	Battery charge current sense measurement
U12(2)	+12 V monitoring	11.85 V 12.06 V 15.72 V	2944 2988 3901	+12 V DC/DC converter output voltage
U12(3)	+12 V current monitoring	0 920	12 3074	+12 V DC/DC converter output current
U12(4)	Vbat2 voltage monitoring	0 3.88 V	2 3074	Second battery voltage
U12(5)	+3.3 V output current monitoring	275 mA 540 mA	1835 3015	+3.3 V regulator output current
U12(6)	+3.3 V output voltage monitoring	3.29 V	3284	+3.3 V regulator output voltage
U12(7)	Solar panel voltage monitoring	16.24 20.15 20.66 21.98	2872/2902 3561/3593 3669/3686 3905	Due to MPPT input voltage hysteresis the voltage on A/D converter input varies

Table 2.2: RU power subsystem analogue circuits calibration information

2.4 Assembly of the solar panel

The solar panel was assembled according to the same procedure that has been successfully used for EstCube-1 and AAUSat satellites (space-proven technology). Some modifications were made to allow upscaling the previous technology and to allow connecting the solar cells into a large continuous string, not small substrings, as previously. All of the most critical procedures were performed in an unrated cleanroom, if the heatshield had to be taken out of the cleanroom, it was re-cleaned before next procedures to prevent dust-contamination of glue layers that could cause degassing problems.

First the heatshield was thoroughly cleaned with reagent-grade ethanol and all surface imperfections were removed. After cleaning the heatshield was covered with strips of 2” pressure-sensitive polyimide tape. Polyimide (often known according to the DuPont brand name as Kapton) is a good electrical insulator and is very stable in extreme chemical, thermal and vacuum conditions; therefore it is a standard material for spacecraft assembly.

The tape-covered heatshield was put into a pre-vacuum chamber for degassing and was later inspected for bubbles under the tape. All of the defects were removed and the polyimide tape was removed and re-applied when needed. The end result was a tape-covered heatshield with no visual imperfections.

The sidepanel was cleaned again to ensure a good polyimide surface. Next a grid of polyimide tape was made on the surface of the panel, leaving recesses for the solar cells to fit in. After that GaAs 30% efficient triple-junction solar cells from AZUR SPACE were taken and copper strips were soldered on their bottom conductive surfaces.

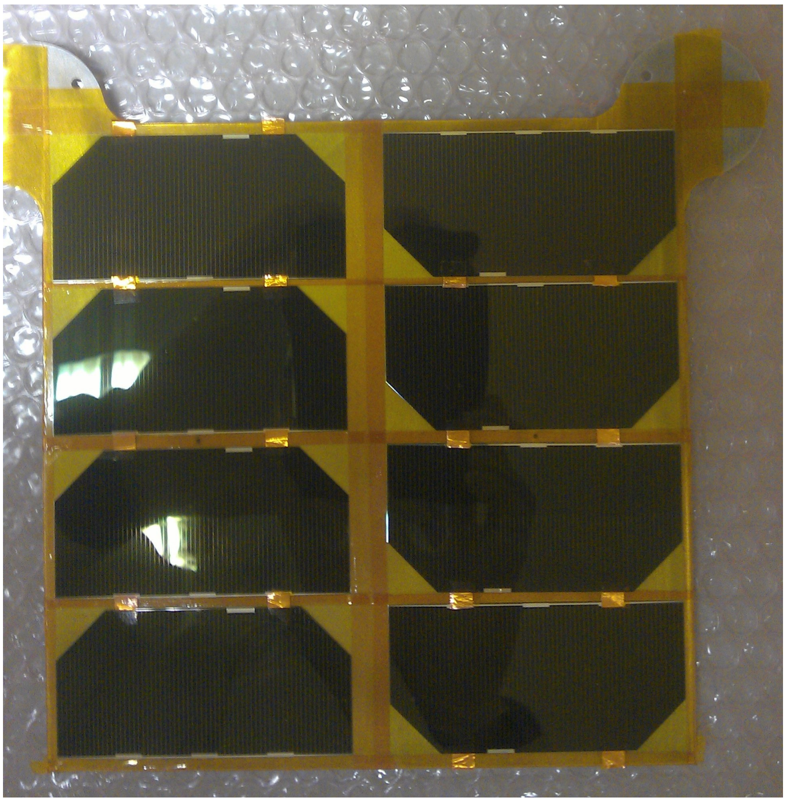


Fig. 2.5 The heatshield with polyimide tape applied and the ployimide mesh forming the recesses for solar cells (with solar cells inside, copper strips to bottom electrodes have been soldered). After this the RTV silicone was applied (the left string was rotated 180 degrees in the final design).

After this the recesses in the polyimide tape were filled with previously degassed RTV 9161 silicone from Dow Corning and solar cells were placed on top. After this weights were placed on the solar cells and the assembly was degassed in a vacuum chamber.

After degassing the assembly was put into a temperature-controlled chamber and the silicone was cured at 60 °C. After curing excess silicone and polyimide tape was removed and the whole panel was cleaned again with reagent-grade ethanol.

As the next step, the copper strips connecting the surface electrodes of the previous elements of the solar cell string with the next ones were soldered and electrically functioning strings were formed. The separate strings were connected together by soldering polyimide-insulated copper wires.

As the final step the electrical connections were tested and wires were bonded to the heatshield surface using ScotchWeld 2216 binary epoxy form 3M to avoid damage that could be caused by a loose wire being pulled.

After completion the panel was cleaned with reagent-grade ethanol and inspected visually under a microscope for defects and all of the cells were tested for nominal short-circuit current and open-circuit voltage. Later the whole string was tested as whole for the same parameters and was determined to be in working order.

The photo of the finalized (assembled, cleaned and electrically wired) solar panel is shown on Fig. 2.6.

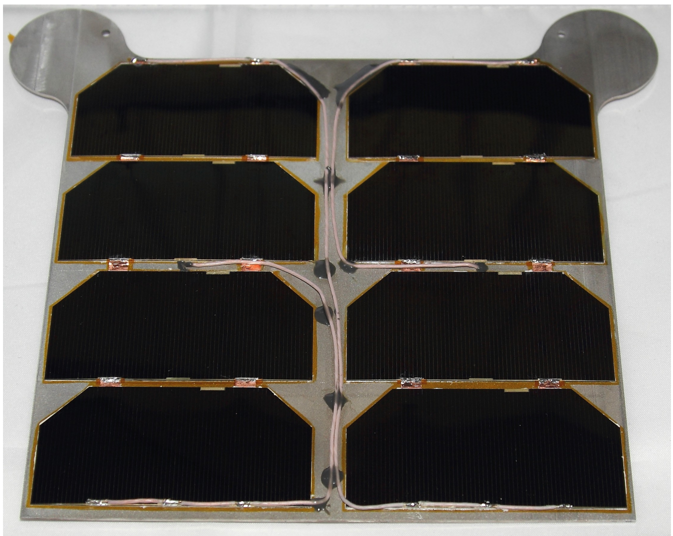


Fig. 2.6. Photo of the finalized solar panel

2.5 Integration

Both RU power PCB and fully assembled solar panel were sent to ÅSTC, Sweden for final RU system integration and preparation for testing. No major problems were encountered by the integration team regarding the RU power system and solar panel design. The required software functionality for RU power system operation and monitoring was also integrated into the RU control board firmware by ÅSTC team.

Additional temperature sensors were installed at various locations within the RU for more accurate temperature monitoring during system testing.

3. Integration testing

A set of tests were carried out by ESAIL project team at DLR test facilities in Bremen, Germany.

The following tests were performed on the fully integrated RU:

- Thermal tests in Sun simulator equivalent to 0.9 AU distance , 0 deg incident angle and 4 AU distance, 60 deg angle)
- Vacuum compatibility
- Vibration
- static loading
- Auxteher pull test

Complete test results are provided in a separate test report prepared by ÅSTC team [2].

During 0.9 AU thermal tests the battery charging stopped shortly after test was initiated. The solar panel output ant temperatures recorded during this test is shown on figure 3.1.

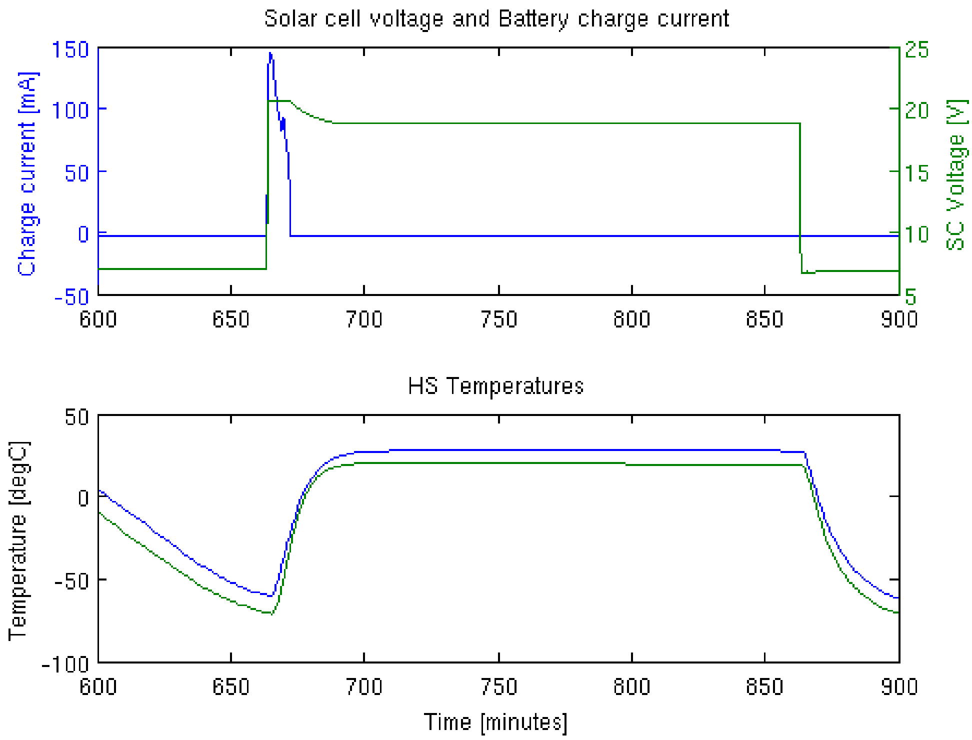


Fig. 3.1 Solar cells output and temperatures vs. time during 0.9 AU Sun simulator test.

Further investigation revealed a damage of at least two solar cells, most likely due to extremely large temperature gradient on a solar panel due to incomplete illumination of the solar panel in the corners. A photo of the damaged solar panel is shown on figure 3.2. For investigation purposes the solar cells array was electrically biased which causes cells to "glow". The distribution of the light over solar cells makes it possible to assess the extent of the damage [3].

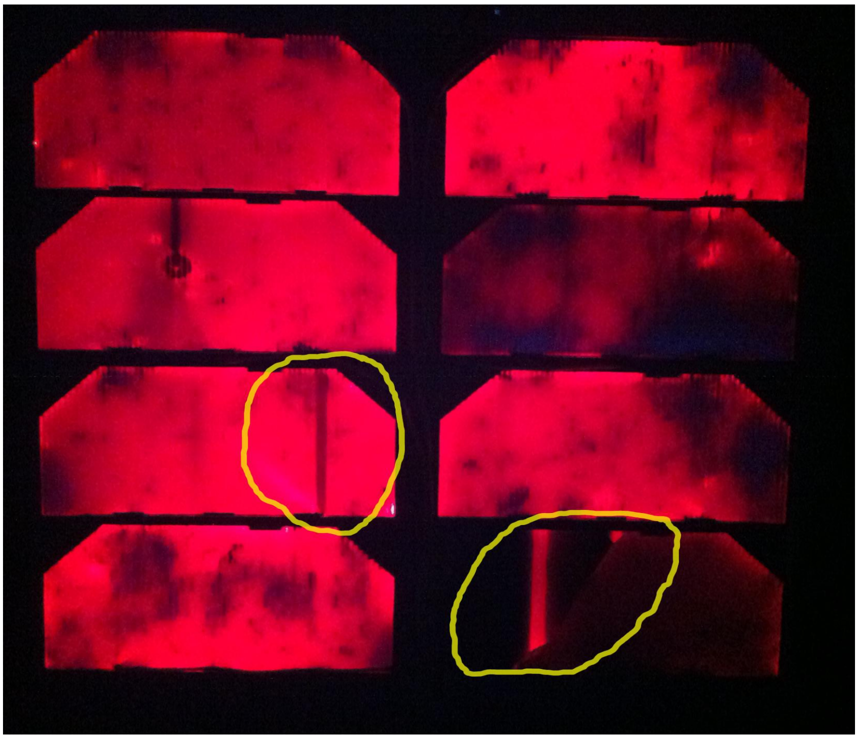


Fig. 3.2 Damaged areas of the solar cells

All other RU power subsystem electronics circuitry was later verified and found to be fully operational. Similar problem has been reported by various other cubesat development teams when testing their solar panel assemblies. In ESAIL case the test setup did not fully represent the real esail mission space environment where very high temperature gradients should not occur. However, this (negative) result should be taken into account when designing future electrical solar sail space missions either by avoiding any partial shading of the solar panel or improving the solar panel design to survive large temperature gradients.

4. Conclusion and recommendations for the next projects

A complete electrical power generation and distribution subsystem prototype was developed as a "proof of concept" study within ESAIL FP 7 project. The final prototype corresponds to TRL levels between 4 and 5 according to ESA terminology about technical readiness of a spacecraft components. Electrically the RU power subsystem was fully functional and its performance was within design requirements. For eventual future electrical solar wind sail projects the RU-s must be manufactured in relatively large numbers (about 100 … 300 units per spacecraft).

Although the PCB of the subsystem was hand soldered during prototyping its design makes it possible to use high volume manufacturing technologies like pick-and-place assembly and reflow soldering process. As all manual adjustments within the power subsystem are eliminated the whole board assembly can be calibrated and tested by using computerized equipment thus reducing the need for expensive and time consuming manual work.

Some new electronics components have become available during the project execution time which may improve the current design. For example a dedicated MPPT controllers from ST Microelectronics, SPV1020 and SPV1040 can be used as very efficient integrated MPPT blocks for energy harvesting from solar cells.

SPV1040 circuit is currently tested on board of recently launched EstCube-1 student satellite and is showing very promising results. Power harvesting efficiency of 90% was measured during evaluation tests for this circuit.

The solar cells assembly technology, very similar to what was used for ESAIL solar panel is also used on EstCube-1 satellite. It is worthwhile to note that EstCube-1 satellite has passed significantly higher vibration test levels than specified for ESAIL project.

The mass of the final prototype board was close enough to the original estimate. The empty PCB weight was slightly lower, (27 g vs 34 g), but components were slightly heavier than in the original estimate (12 g vs 10 g). It may be possible to reduce the overall mass of the power system further by using more lightweight PCB substrate and reducing the component count by using components with higher level of integration. The expected possible mass reduction could be in the range of 10...20 g.

5. References

1. ESAIL project deliverable, “ESAIL D42 Remote Unit Design Description. Power system”
2. ESAIL project deliverable D41.4 “ESAIL Remote Unit Test Results”
3. Doug Malchow, “NIR Trends: Maximizing Solar Cell Yield and Efficiency with Machine Vision”, Photonics Online
4. Erik Ilbis, “ESTCUBE-1 Electrical Power System – Design, Implementation and Testing”, Bachelor's thesis, University of Tartu, Institute of Physics 2013

6. List of abbreviations

ADC – Analog-to-Digital Converter

ESA - European Space Agency

MPPT – Maximum Power Point Tracker

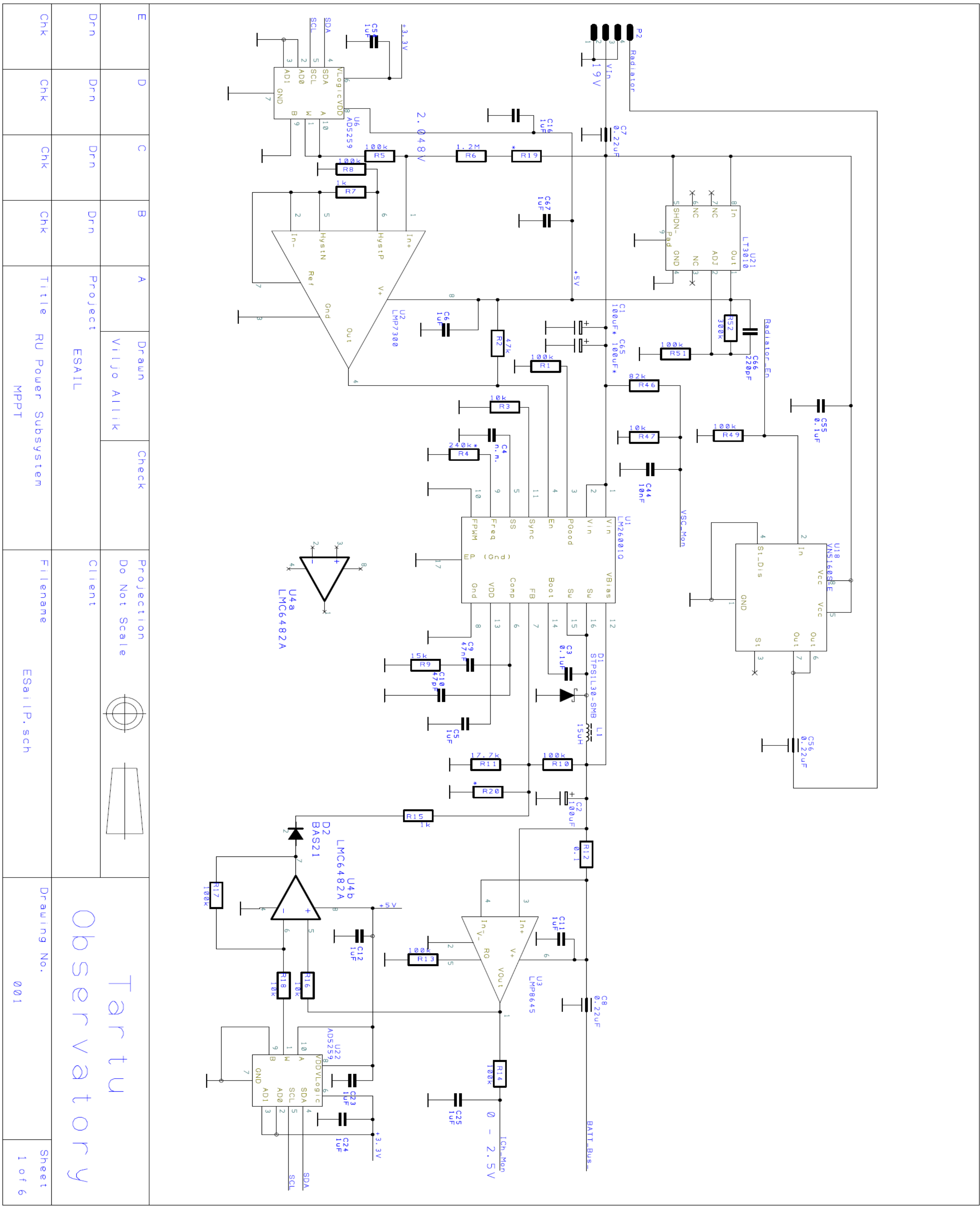
PCB – Printed Circuit Board

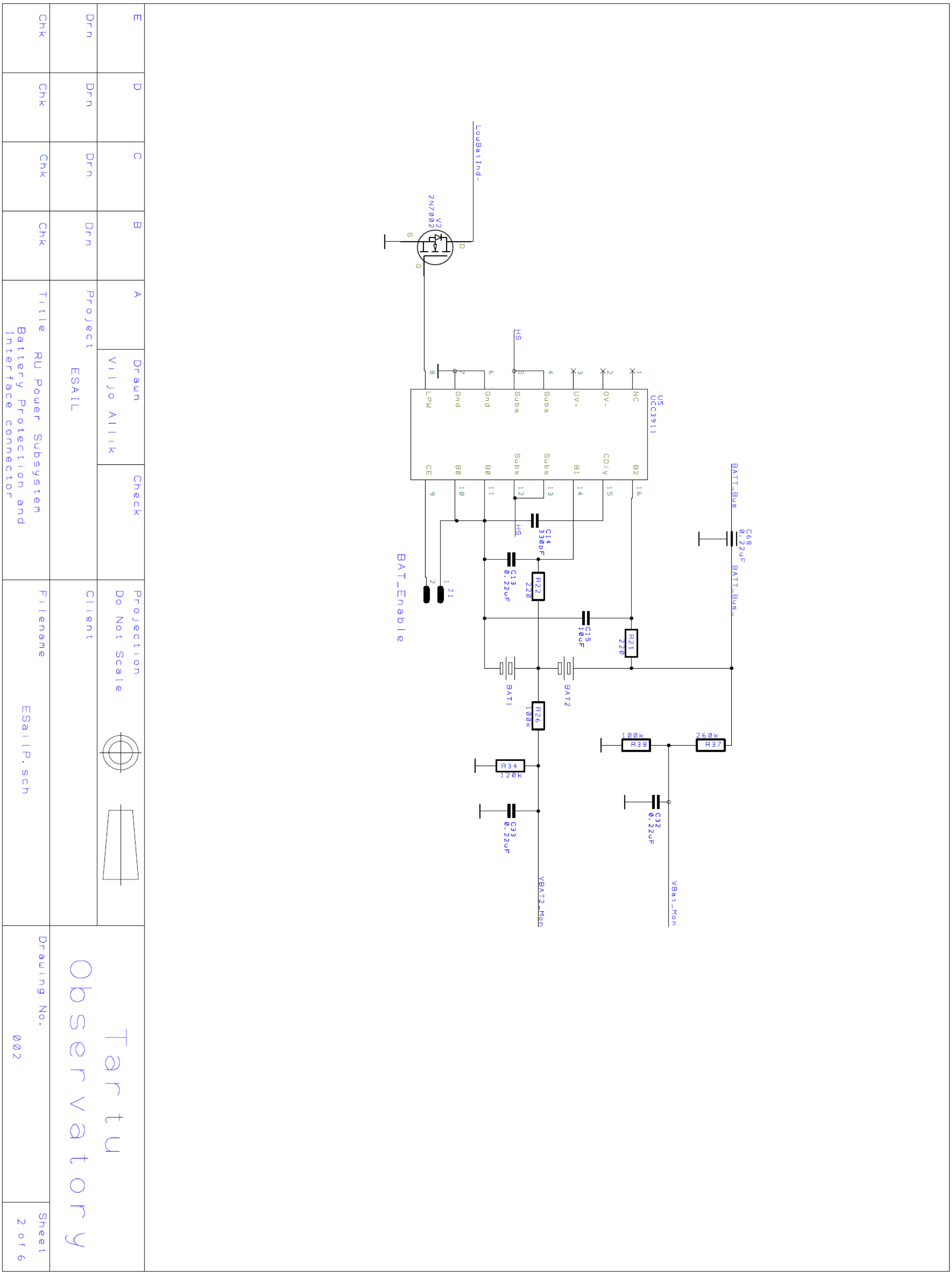
RU – Remote Unit

TRL – Technology Readiness Level (as defined by ESA)

Appendixes

Appendix 1: Final schematics of the RU power system

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B2
CDly
BATT_Bus
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0.22uF
C14
330pF
C13
0.22uF
R22
220
C15
10uF
R21
220
BAT1
BAT2
R26
100k
R38
100k
R37
260k
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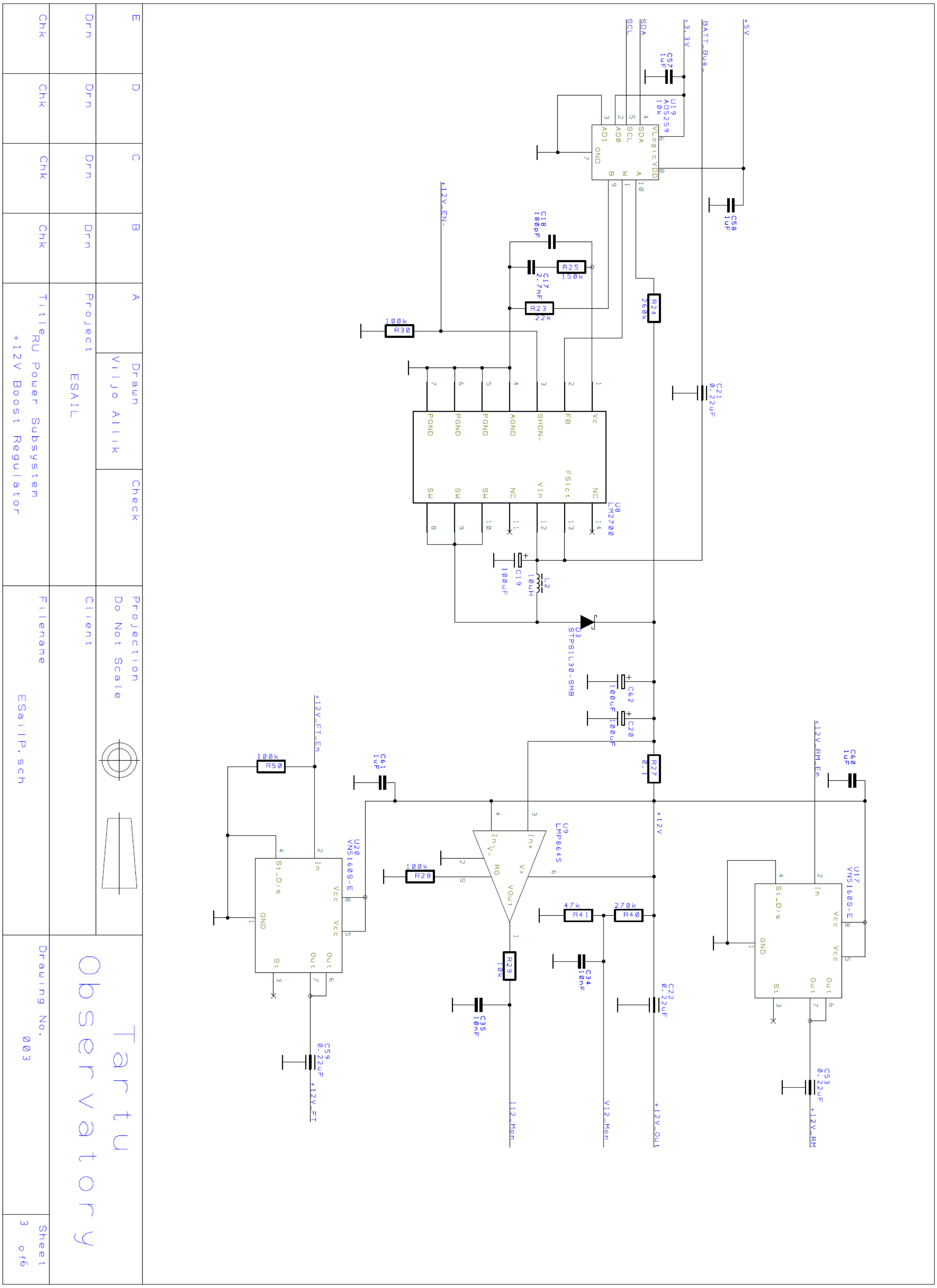
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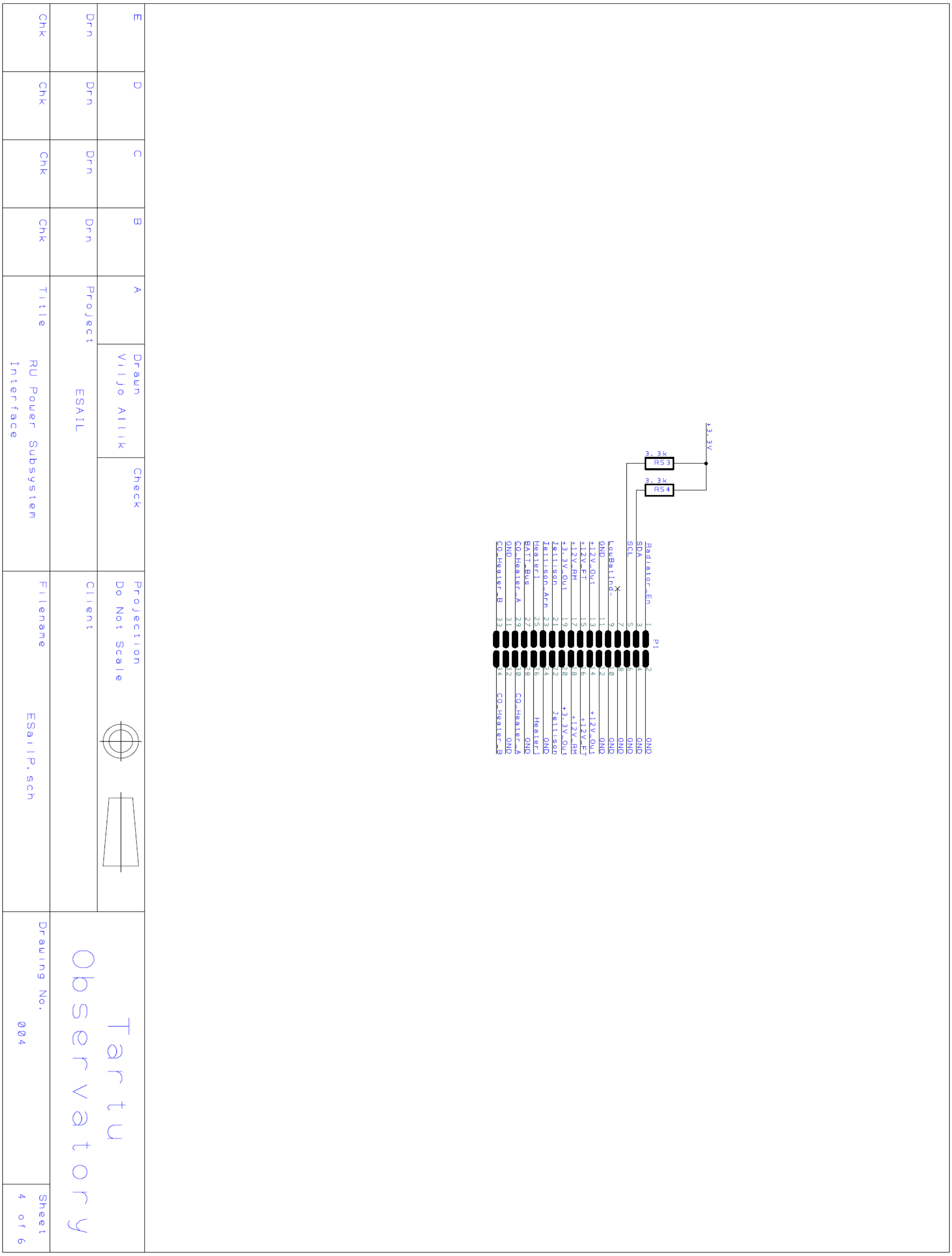
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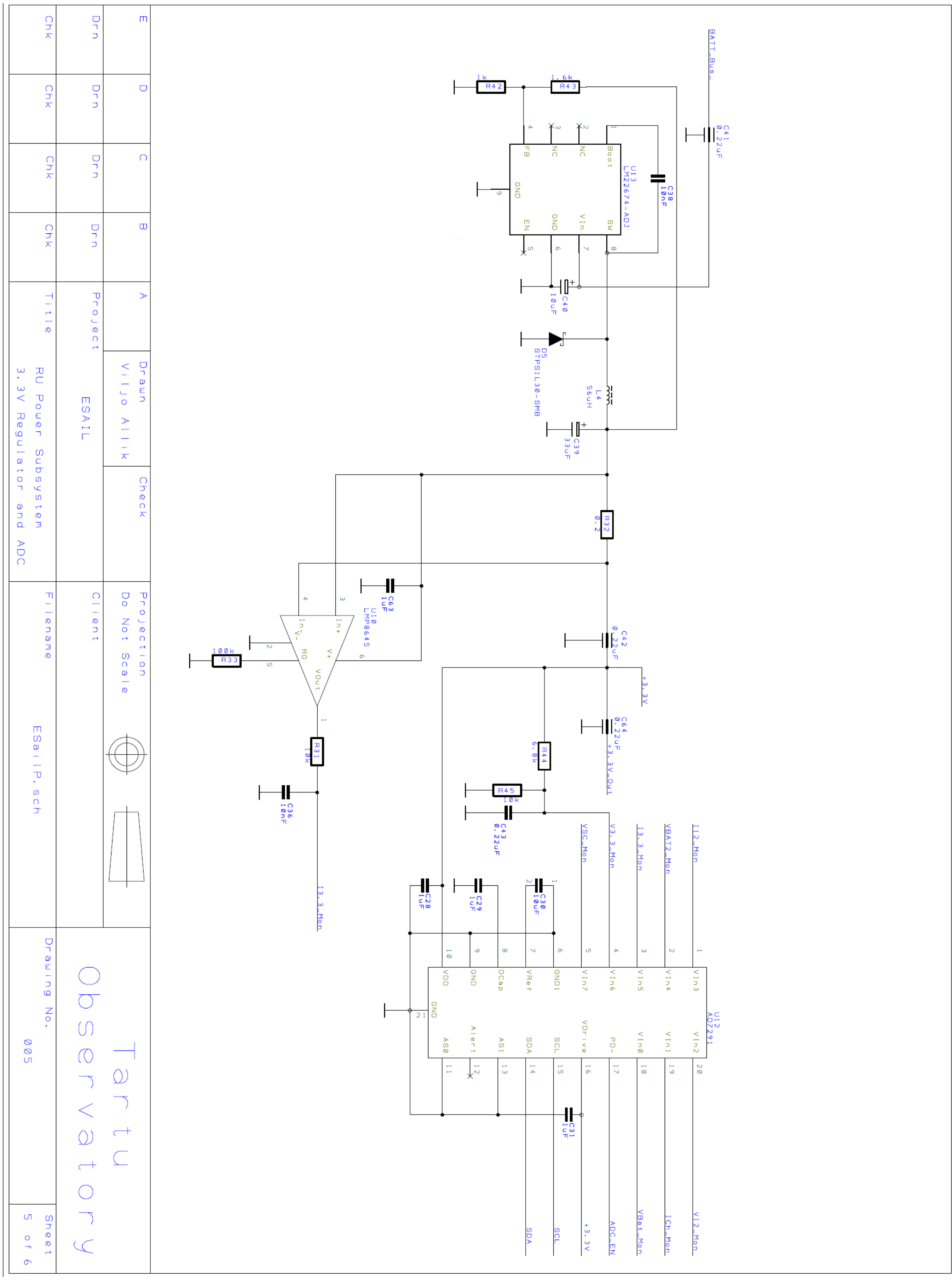
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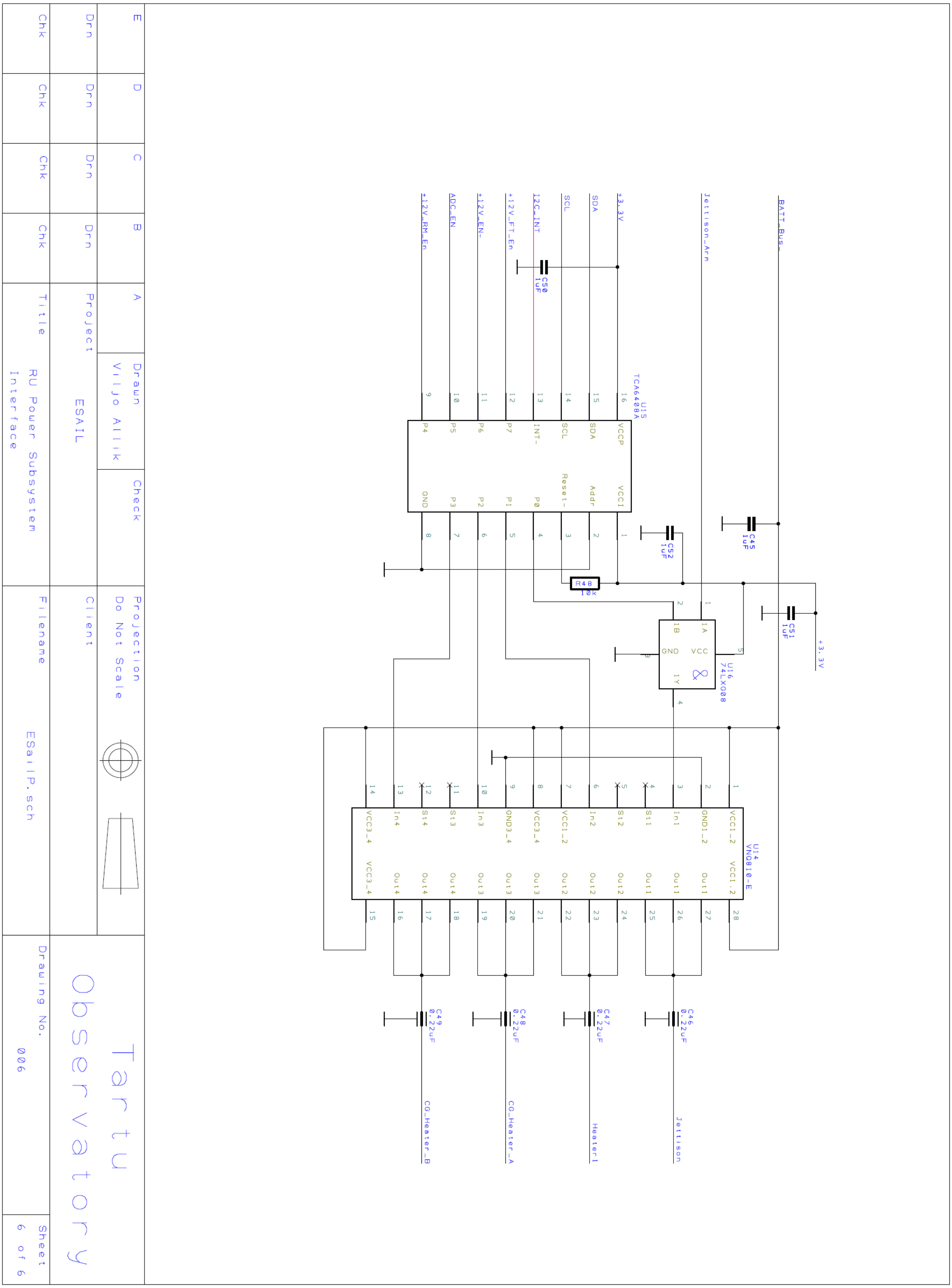
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C52
1uF
C45
1uF
C51
1uF
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U14
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C47
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C46
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CG_Heater_A
Heater1
Jettison

Appendix 2: Final version of the RU Power system PCB layout drawing (ground planes removed)