# Executive Summary

# Autonomous Planetary Payload Support

**DTI EXPORT CONTROL RATING: 9E001/9A004**
**Rated by: Carl Warren**

*Prepared by:* *Michael Williams* *Date:* *17/6/2014*

*Checked by:* *James Sadler* *Date:* *17/6/2014*

*Authorised by:* *Marie-Claire Perkinson* *Date:* *17/6/2014*

Astrium Limited
Gunnels Wood Road, Stevenage, Hertfordshire, SG1 2AS, England

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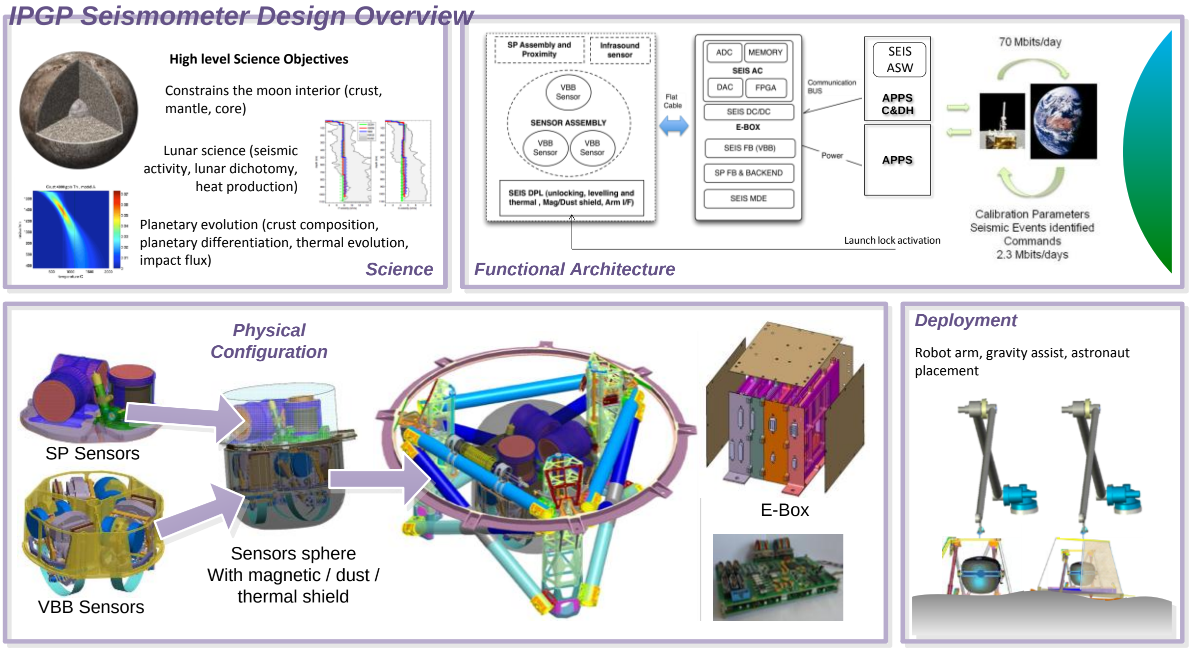
# 1 INTRODUCTION AND OVERVIEW

This document forms the Executive Summary, created in response to the Statement of Work entitled “Autonomous Planetary Payload Support System”, [Programme Reference: C213-001PA – SRE-PA/2009-041/SOW/SV, Issue 1.1 dated 17th February 2011]. In issue 2 of this Executive Summary, the additional work performed under a Contract Chance Note to update the parametric model for the mars environment and an INSPIRE-type mission is also detailed.

The APPS study work focusses on the critical technologies required to provide both servicing and support functions to a seismometer payload located on the lunar surface. Although the baseline payload (and by extension the reference mission) has specific requirements, the technology focus of the study allows the outputs to be of broader application to exploration missions to the moon and beyond.

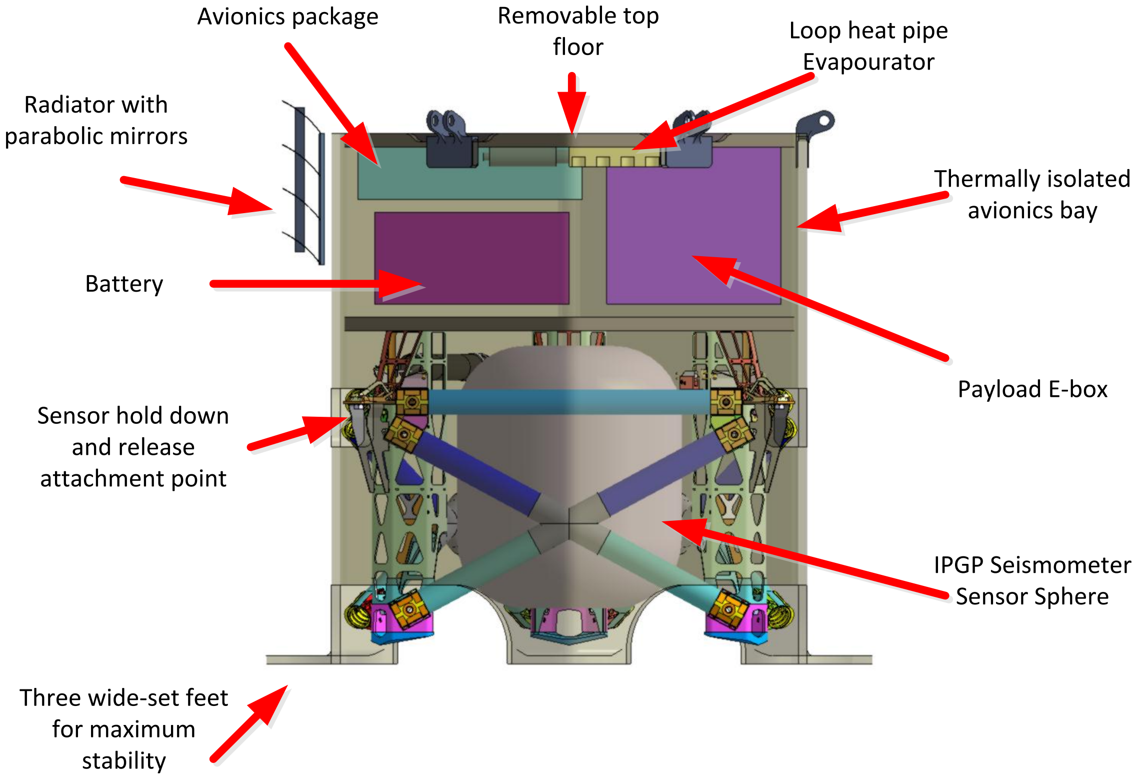
The IPGP SEIS instrument is summarised below. To assess the flexibility and scalability of the concept, ‘Delta’ payloads were also specified. These were a fluxgate magnetometer and an instrumented mole based on the DLR HP3.


IPGP Seismometer Design Overview

The proposed APPS design is summarised diagrammatically overleaf. The main design features are:

- Total system mass of 24.8 kg including margins and payload mass (requirement of 15 kg)
- Envia Si-anode Li-Ion battery (430 Whr/kg) and EMCORR 34% PV cells
- Combined OBC and X-band transceiver based on Atmel RTC and QinetiQ DUX in combination with simple phased array antenna allowing direct-to-earth communications
- Ultra low power system controller allowing lowest possible quiescent power and energy usage
- Thermal control using 1000:1 turn-down loop heat pipe and doubly insulated battery
- Operational concept allowing transceiver and OBC to be zero-clocked and switched off for maximum power efficiency

## *Inside the APPS*



Avionics package

Removable top floor

Loop heat pipe Evapourator

Radiator with parabolic mirrors

Thermally isolated avionics bay

Battery

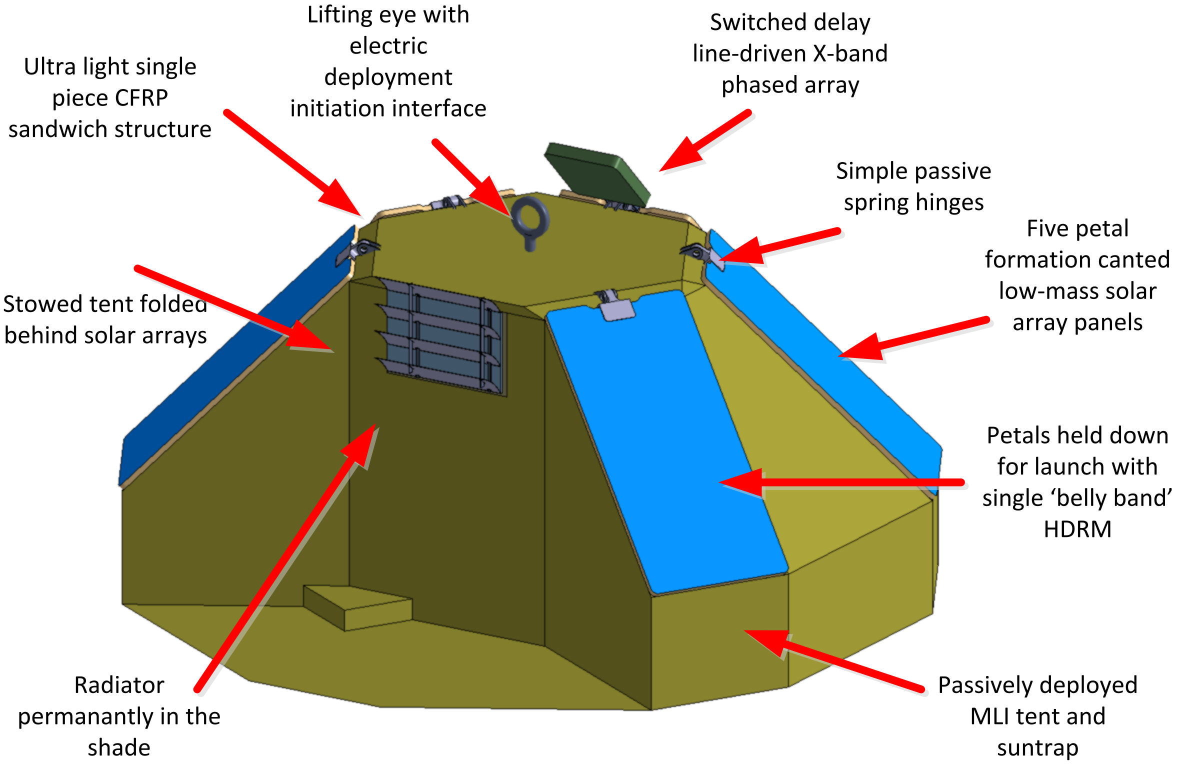
Payload E-box

Sensor hold down and release attachment point

IPGP Seismometer Sensor Sphere

Three wide-set feet for maximum stability

## *Overall Configuration*



Lifting eye with electric deployment initiation interface

Switched delay line-driven X-band phased array

Ultra light single piece CFRP sandwich structure

Simple passive spring hinges

Five petal formation canted low-mass solar array panels

Stowed tent folded behind solar arrays

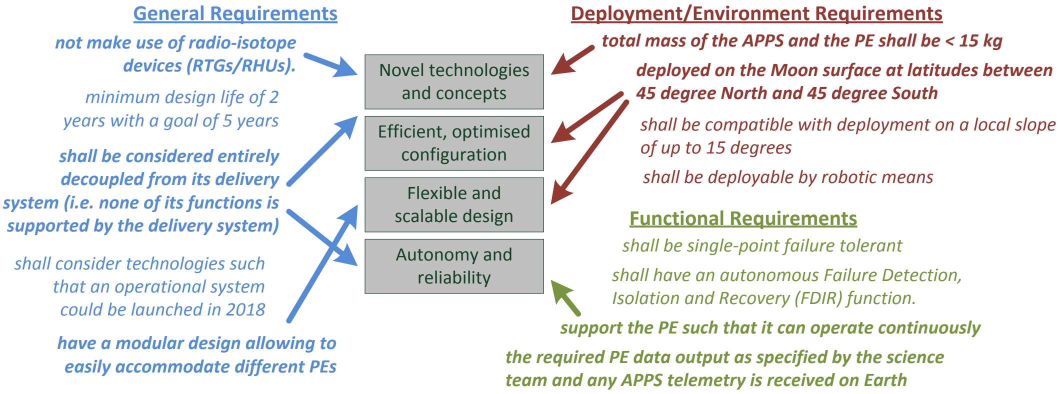
Petals held down for launch with single ‘belly band’ HDRM

Radiator permanantly in the shade

Passively deployed MLI tent and suntrap

## 2 DRIVING REQUIREMENTS

The driving requirements imposed on the APPS system were as a result of mission, payload and environmental constraints and requirements, and to ensure that the system design was flexible, scalable and autonomous. The most driving are summarised below.



General Requirements

*not make use of radio-isotope devices (RTGs/RHUs).*

*minimum design life of 2 years with a goal of 5 years*

*shall be considered entirely decoupled from its delivery system (i.e. none of its functions is supported by the delivery system)*

*shall consider technologies such that an operational system could be launched in 2018*

*have a modular design allowing to easily accommodate different PEs*

Deployment/Environment Requirements

*total mass of the APPS and the PE shall be < 15 kg*

*deployed on the Moon surface at latitudes between 45 degree North and 45 degree South*

*shall be compatible with deployment on a local slope of up to 15 degrees*

*shall be deployable by robotic means*

Functional Requirements

*shall be single-point failure tolerant*

*shall have an autonomous Failure Detection, Isolation and Recovery (FDIR) function.*

*support the PE such that it can operate continuously*

*the required PE data output as specified by the science team and any APPS telemetry is received on Earth*

Of the requirements, the most directly driving is the total system mass below 15 kg. This (along with a non-nuclear power source) requires a paradigm shift in technology use and operations.

## 3 TECHNOLOGY OPTIONS AND TRADE-OFFS

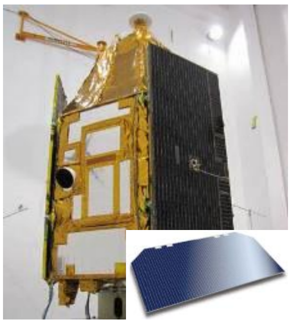
During the APPS technology review, many technologies and concepts were considered for implementation. The major options are described below. Where appropriate, these were also traded at a technology level. The criteria for each trade is subtly different, however they are broadly based on mass (20%), TRL (15%), Risk (40%), Flexibility (20%) and cost (5%). It should be noted that not all technologies in each field are mutually exclusive in their implementation. In the following section, selected technologies are marked in **bold.**

### Power Generation Technologies

Several power generation technologies were considered, and are shown in the figure below. Both **thin film and rigid photovoltaics** were initially selected in the trade due to their high performance and TRL. Thin film was subsequently discounted due to the large surface area required. Both flight proven PV cells (28% efficiency) and next generation quad-junction cells (34% efficiency) were investigated.

Thermophotovoltaics and thermoelectric generators were also considered but their low efficiency and preference for high temperature operation made them unfavourable. Although nanoantennas show considerable promise for the future, immature rectifier technology mean this technology is high risk.

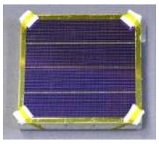
*Photovolotaics*

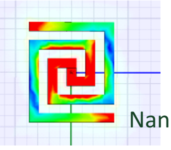


Thin film PVs

Thermoelectric Generators (TEGs)

Thermo-photovoltaics





Nanoantennas

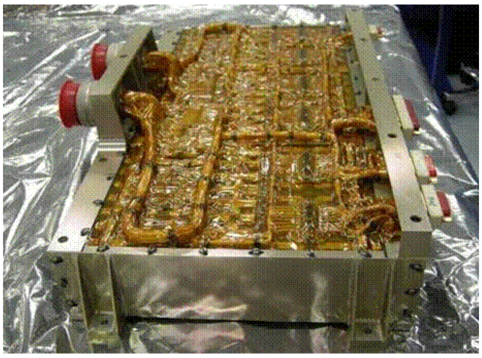
### Power Storage Technologies

Power storage is a critical technology for the APPS. Along with conventional spacecraft Li-Ion technologies, emerging battery chemistries (Si-anode Li-Ion and Li-Sulphur) were also considered. The former offers the highest currently demonstrated density of 400 Whr/kg, although this is only at a prototype level with packaging not suitable for space. However the very high energy density makes **Si-Anode Li-Ion technology** most preferable overall. Similarly, the latter has a high performance, but poor life-cycle performance and lack of development progress over recent years making it less favourable.

Regenerative fuel cells also show considerable promise with potentially high specific energies (up to 350 Whr/kg), however their high complexity make them risky and unsuitable for small scale use in APPS.

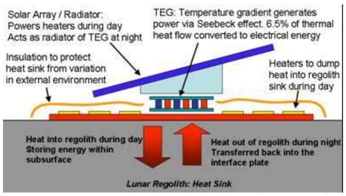
The properties of the lunar regolith make an in-situ energy storage method potentially feasible, where energy is stored in the subsurface during the day and recovered during the night (both for heat and electrical power via TEGs). Although this method could have a competitive specific energy (<200 Whr/kg) remote deployment could be complex and highly risky.

Conventional Li-Ion batteries

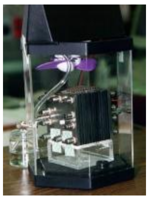


Si-anode Li-Ion batteries

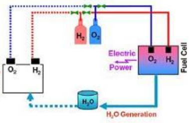
Li-Sulphur batteries



Lunarthermal

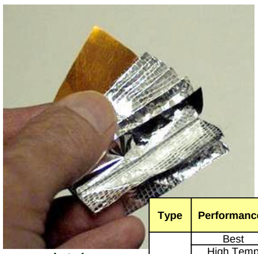


Fuel cells



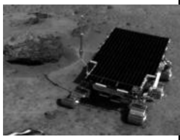
### Thermal Insulation Technologies

Thermal insulation is essential for efficient use of night-time power to keep vital subsystems within temperature limits. A well-established insulation technology is **multi-layer insulation**, used extensively on spacecraft in a vacuum environment. This is the de facto standard and the technology selected in this case due to its high TRL, low mass and high performance.



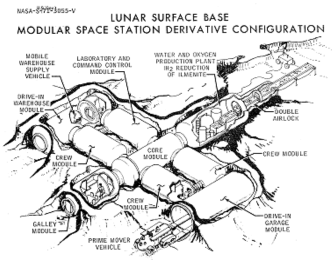
*Multi-layer Insulation*

| Type | Performances | Linearized Effective Conductive (W/m2K) |
|---|---|---|
| 20 layer | Best | 0.0048 |
| | High Temp | 0.0056 |
| | Medium | 0.0116 |
| | Worst | 0.0193 |
| 10 layer | Large | 0.0622 |
| | Small | 0.1554 |



*Aerogel*

*In-situ regolith insulation*



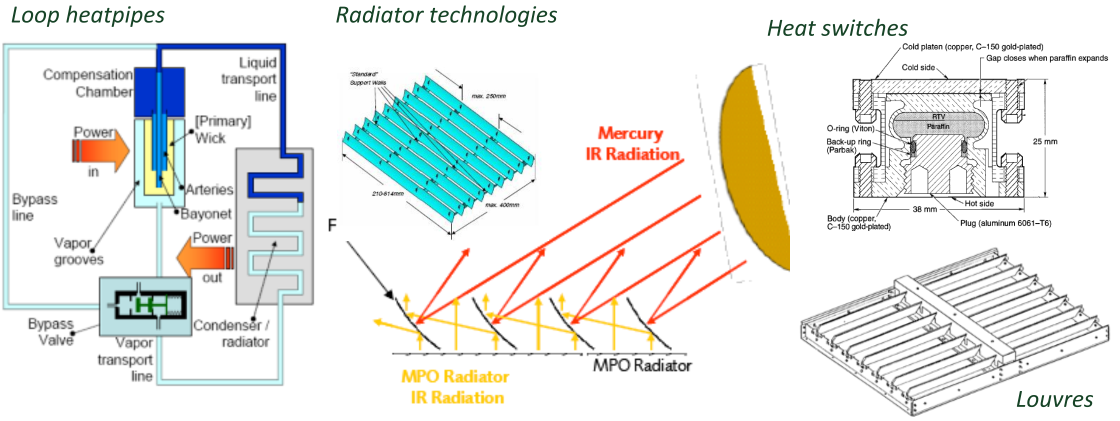
Another promising technology is aerogel, whose extremely low density makes it an excellent insulator and high performance in an atmosphere have resulted in its use on several NASA Mars missions. However it is bulky and required additional additives to make it IR opaque, resulting in a considerable increase in density and therefore a similar areal mass to MLI but with a considerably higher thickness. It is suggested as a technology also to be considered where a highly dependable performance is required.

### Variable Heat Rejection Technologies

The daytime and night-time lunar temperature can vary by up to 250 degrees C, and so a variable heat path between the APPS and external environment is most likely needed. Varios technologies were considered which provide this functionality, with varying levels of performance and TRL.

The highest performance technology is the **loop heat pipe**, where a fluid carries thermal energy from source to radiator or via bypass loop. The bypass functionality allows a very high turn-down (up to 1000:1) and allows the APPS radiator to be small, minimising night-time heat leakage. The LHP is the selected technology due to performance, despite being more complex and risky. Simpler but less performant is the passive heat switch with a turndown ratio of 100:1. Although extremely simple operationally, the heat switch does not provide heat transport with resulting APPS configuration constraints.

A simple approach used on Rosetta is to vary the radiator view-factor to space with louvers, where the orientation of venetian-style blades are varied. Although high TRL, their relatively high mass and moderate turn-down performance make them less favourable.



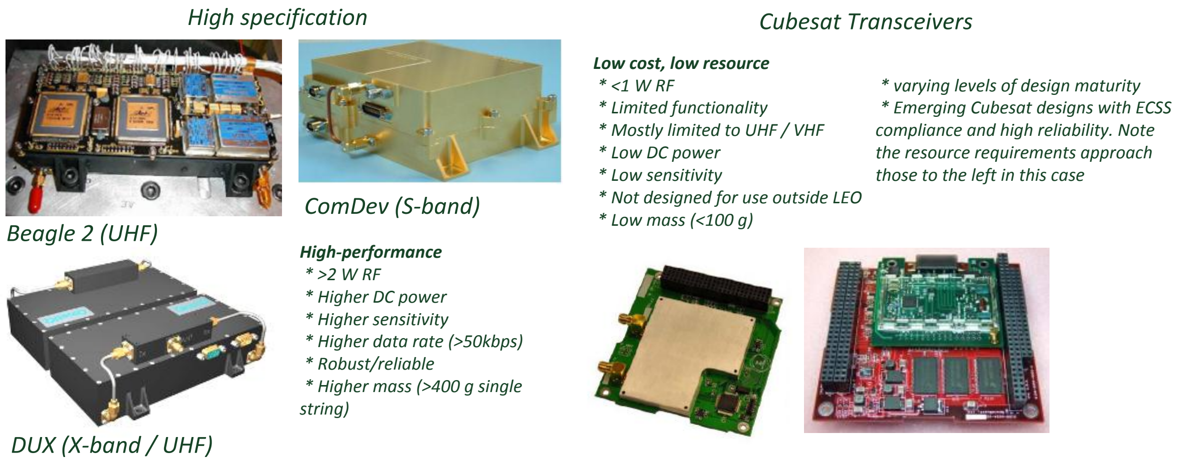
Both the Apollo ALSEP and BepiColombo implement **parabolic mirrors** to reduce the impact of reflected IR radiation on radiator performance. This low mass technology increases the view factor of the radiator to deep space and is therefore a strong candidate for implementation on APPS.

### Transceiver Technologies

The considerable data volume requirement for APPS (SEIS generates 1250 Gbit per lunation) means that a high performance comms system design is required, whilst maintaining a low resource usage. Both direct-to-earth and orbiter comms architectures are considered, meaning both UHF (orbiter) and S/X band technologies are candidates for implementation.

A range of compact transceivers designs exist. A prime candidate is the Beagle 2 UHF transceiver, whose low mass and high performance (both RF power and functionality/capability) make it more than adequate for that required for orbiter communications. However it contains obsolete parts and requires a design update. An evolution of this technology is the DUX (dual UHF, single X-band) development, which builds on the B2 design. This unit design considered for ExoMars is familiar to the team, high specification and flexible (both UHF and X-band single string variants could be considered) but has high DC power and mass requirements (30 W transmitting, 1.8 kg for DUX design). It is a variation of the **DUX** design that is selected for implementation.

Similarly, various S-band units exist such as the ComDev S-band transceiver, with a performance similar to the DUX (2 W RF, 400 g single string). However S-band is less favourable for several different reasons.



*High specification*

***High-performance***
** >2 W RF*
** Higher DC power*
** Higher sensitivity*
** Higher data rate (>50kbps)*
** Robust/reliable*
** Higher mass (>400 g single string)*

*Cubesat Transceivers*

***Low cost, low resource***
** <1 W RF*
** Limited functionality*
** Mostly limited to UHF / VHF*
** Low DC power*
** Low sensitivity*
** Not designed for use outside LEO*
** Low mass (<100 g)*

** varying levels of design maturity*
** Emerging Cubesat designs with ECSS compliance and high reliability. Note the resource requirements approach those to the left in this case*

CubeSat designs embrace a similar challenge to APPS, where both power and mass are constrained. Therefore several cubesat transceiver options are considered. The performance and reliability are generally considerably constrained, but they present extremely low mass options. They are generally VHF/UHF and so are suitable for orbiter comms only, and low receiver sensitivity and data rates make them unfavourable. It should be noted that Cubesat S/X band transceiver designs are emerging that bridge the gap with high performance options, with ECSS compliance, high reliability and compact efficient designs.

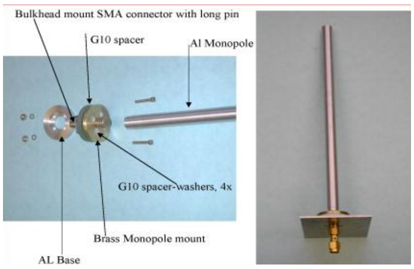
### Antenna Technologies

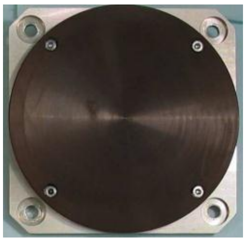
Antenna selection goes hand-in-hand with frequency band and transceiver selection, and architecture and technology-level selection is undertaken at a combined transceiver and antenna level for APPS, focussing on system-level performance achieved by sensible combinations.

For a UHF-based orbiter communications strategy, various technology options exist and the selection is based partly on accommodation options available, as well as antenna gain performance. Due to the low frequency, UHF antennas tend to be large. The **UHF monopole** has a favourable gain pattern (horizon biased where most orbiter contact time is accumulated) and is low mass, however it will likely require deployment. The alternative employed on Beagle 2 is the microstrip patch, which can be integrated with the structure but requires a larger surface area.

At higher S/X-band frequencies the simple patch or array of patches is preferred, although an end-fire helix is also to be considered, depending on which antenna geometry is most suitable. Due to the movement of the earth in the sky (libration and declination effects) and a range of potential local slopes the DTE antenna must either be sized to envelope this movement or have a steering capability. The former is easily achieved but reduces the achieved gain, and the latter can either be achieved by a mechanical or electronic steering mechanism. The former could be a 2 DoF design as used in the MER X-band link (high performance but expected to be high mass) or an operationally complex once-pointed antenna accounting for the deployment orientation.

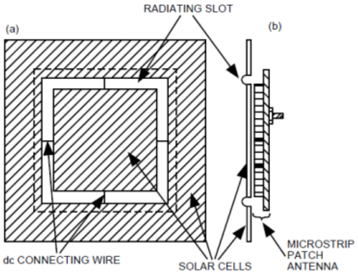
MER Monopole

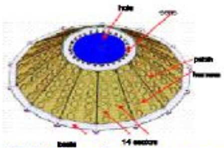




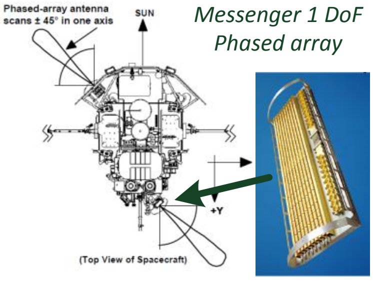
S-band Patch

UHF Microstrip Patch

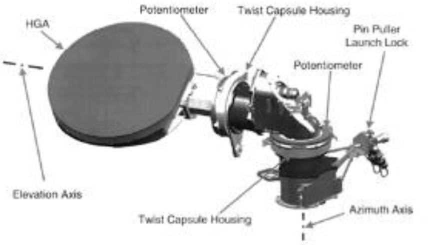




GAIA phased array radiating cone



Messenger 1 DoF Phased array



MER 2 DoF X-band steered antenna

An electrically steered antenna could be implemented by a phased array. Such technology is implemented on ESA's GAIA and NASA's Messenger, with varying degrees of complexity. A phased array for use on APPS need not be as complex however and the selected X-band implementation is a **single-feed PIN diode phased switching phased array**. The advantage of this implementation is that as opposed to other active phased arrays, only a single amplifier is required. The electronic steering allows the variation in orientation due to terrain and earth movement to be counteracted.

### Data Handling Technologies

Many technologies are interesting for the APPS design, from substrates, packaging technologies, memory technologies to integrated system-on-chip designs and complete DHS packages. This makes a straight trade-off a challenge due to the different levels of integration and capability (even at the processor level), and so a more qualitative process was required.

A key driver for the DHS is to be low power – a system operating at 1 W continuously (already a challenging low power to achieve) will have a significant impact on the total energy requirement. The selected technology should be power efficient.

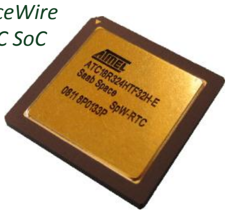
Various system-on-chip architectures have been surveyed with various integrated functionality, from the simple ERC32 CPU to Atmel devices and the SCOC3. A good compromise between performance/functionalities and power is the **Atmel Spacewire RTC** SoC whose extensive range of interface controllers and functionality is perfectly suited to APPS, being designed as an instrument interface controller. It also has a high TRL.

As on-board mass memory is required, a low power memory technology implementation must be found. An emerging low-power compact technology is **NAND Flash** memory, recently space qualified and under implementation for space. This technology is significantly more compact than other types of volatile solid state memory.

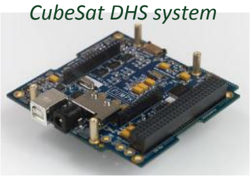
Technologies described above are designed or specially selected and qualified for space use. Another approach is to use terrestrial technology. Smart phones have almost all functionality required of the APPS DHS and are remarkably low power (as required to maximise battery life). It is possible that a smartphone could be used with minimal additional supporting technology required, as the radio could also potentially be used. This option has been explored by both NASA and SSTL, the latter having now launched. There is however concerns on having to rely on the Android operating system and system reliability over a long period (or complex FDIR of several units are required to achieve an acceptable level of reliability). Another extremely compact solution is the Gumstix CoM, but with similar drawbacks.

The use of efficient packing technologies would certainly be considered wherever possible.

*SpaceWire RTC SoC*



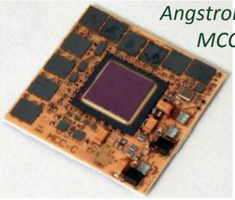
*CubeSat DHS system*

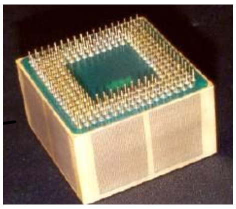


*Gumstix Computer-on-module*

*Smartphone (Google Nexus One)*

*Angstrom MCC*





*3DPLUS MCM*

*NAND FLASH memory module*

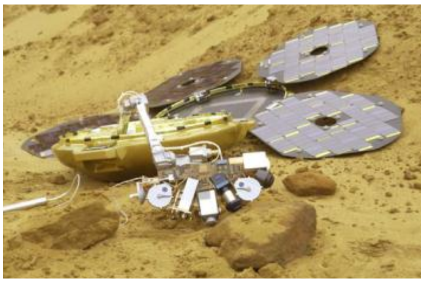
**Structure and Mechanism Technologies**

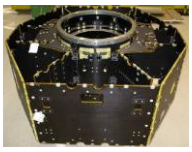
As structure is typically 20-25% the mass of a system, mass-efficient technologies and concepts could offer a significant advantage for the APPS. A variety of mechanisms for deployment of the system or subsystem elements were considered during the technology survey, including:

- Tape-spring deployment using curved steel or CFRP for array, antenna deployment
- Rolled tube deployment to raise an array and/or antenna
- Inflatables for APPS 'throw and forget' or deployment of UV-hardening dome structures
- Automatic sun tracking or Thermally Controlled Deployment using bimetallics or similar
- Catapult or self-righting structure for APPS 'throw and forget'
- **Pre-stressed beams** for array deployment, sunshield deployment or others

These were used in proposed configurations described in the next section. Standard spacecraft structures often use panels and brackets, which can be mass inefficient for compact designs. The use of **composites and monolithic structures** was proposed minimising bracketry and secondary structure.

*Beagle 2 clamshell and petal arrays*





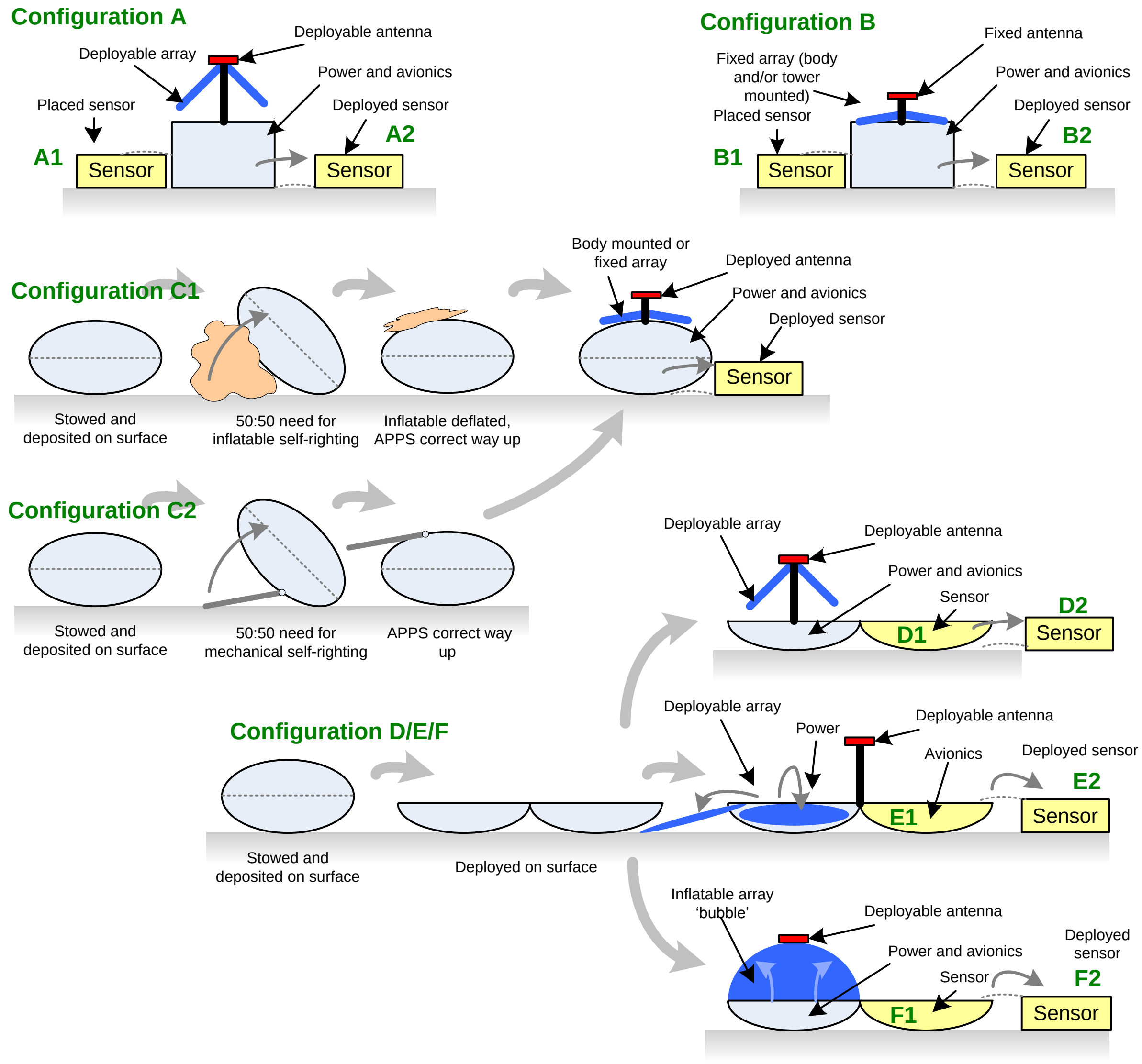
*Airbags*

*Carbon Fibre structures*

*Pre-stressed deployables*

## Configuration Options

The following figure shows a variety of configurations considered for the APPS:

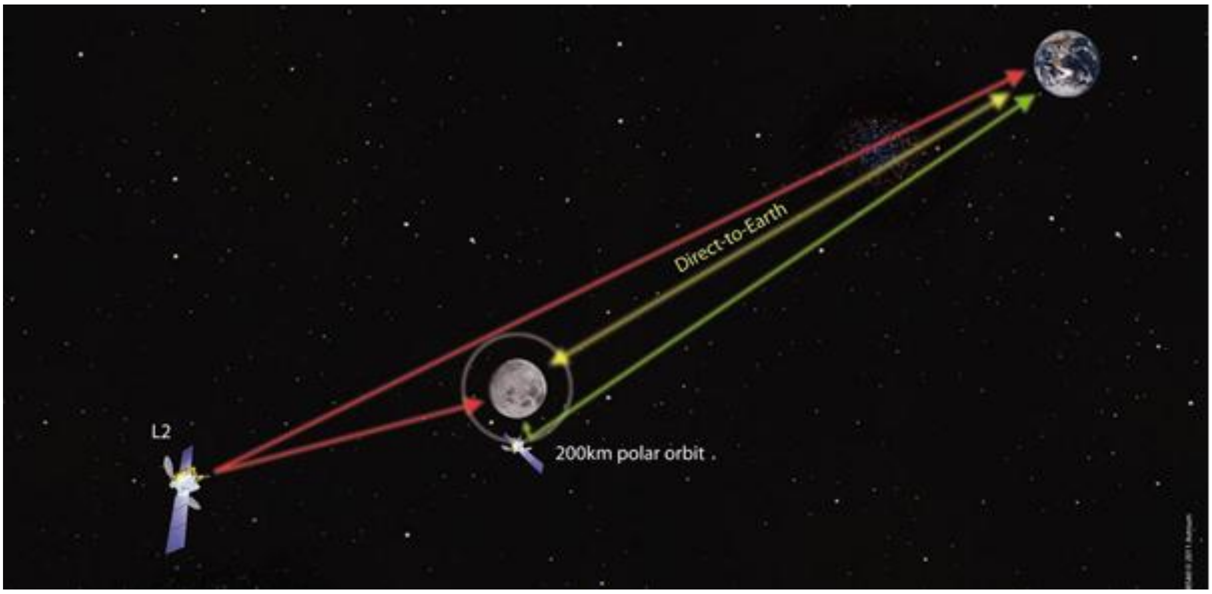


Configurations C-F were proposed to allow the deployment of the APPS with minimum deployment complexity, where catapult or ‘egg-laying’ approaches were possible. However they are expected to have significant drawbacks for the APPS design and are not favourable. These options could use a variety of mechanisms previously outlined. Configurations A and B use an **APPS carefully placed onto the surface**, with either separately placed or deployment sensors, with **fixed arrays** preferred due to simplicity and low risk.

## Communications Concept

Three APPS communications architectures are proposed to allow command, control and science telemetry transmission with/to Earth. The approximate performance of each option was calculated for a range of communications technologies and a trade was undertaken at system level to determine the most appropriate approach. The following figure shows the options: **Direct-to-Earth (DTE)**, polar orbiting relay and L2 relay.

At a mission level there are advantages and disadvantages for each option. For example, an orbital relay reduces the performance burden on the APPS as the link is less demanding, but additional costly space hardware is required. The DTE option provides greater operational flexibility but is more technically challenging to implement with minimal resources. However, it was shown that **DTE communications** can be realised with a 12 m ground station and without overly constraining the APPS design (long communications sessions require larger amounts of energy and pose a thermal challenge) and so this option was selected.



## 4 THE PROPOSED APPS DESIGN

Section 1 gives an overview of the APPS design. This section covers the detailed design and justification in detail.

The selected APPS architecture is driven mainly by the thermal design challenges and the aim to maximise structure efficiency. The large variation in day and night temperature and consequently the challenge of maintaining night time heat and dissipating daytime peak energy make the thermal configuration of central importance. Both a selection of technology options with a wider temperature range and additional battery insulation to isolate it from thermal extremes allow for an optimised design.

The APPS configuration allows a single structure for both avionics and sensor and a single interfaced point. The combined approach also saves on thermal hardware mass. The sensor can also benefit from additional heat from the avionics, low-pass filtered by the structure to ensure sensor thermal power spectral density requirements are not violated. This approach was selected over separate sensor and platform units.

Central to the electrical design was power efficiency. This resulted in the selection of a combined transceiver and OBC module to avoid duplication of processing hardware. This could be achieved by combining the DUX transceiver and a system-on-chip to provide a low power data handling and comms core. The main power saving is achieved by use of a low power system controller allowing an operational profile where the processor and transceiver are powered down the majority of the time. To achieve this the controller must be extremely reliable.

**Physical Configuration and Mechanical Design**

The selected system configuration concept comprises the following aspects:

- A stacked configuration with the sensor package at the base and the service package above
- Complete mechanical and thermal separation of the sensor package from the service package, except for the linking electrical harness
- A deployable thermal shield protecting the planetary surface up to 800mm dia around the sensor package from direct view of deep space or the sun.
- A deployable thermal shield protecting the APPS body from direct solar illumination and sun trapping behind the deployable array panels
- Multiple deployable but non steerable arrays of rigid solar cells
- A single deployable patch antenna with an adjustable-before-placement elevation
- A thermally isolated, service avionics and power bay with a dedicated heat dissipating radiator on the anti-sun side of the APPS.
- A simple and robust interface with the robotic arm placement system on the top face of the APPS that permits accurate placement and orientation
- A simple and robust lower interface that provides hold down to the transportation system throughout the transportation phases to the planet, release from the transportation system and support from the planetary surface, covering a range of soil types from loose dust to rock, without toppling over

The main structure and mechanical design aspects are summarised graphically on the next page.

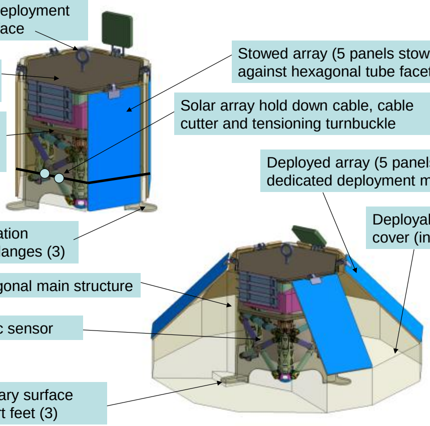
The stacked configuration is used as positioning separate units would be challenging or less efficient due to the interconnecting harness, required lifting frame to position both together, increased number of hold downs, doubling of thermal hardware and large service module size required to house solar arrays anyway. The array configuration (stowed against the APPS sides) was found to match well the required APPS size and leaves the top deck free for other hardware. A single low mass deployment mechanism is also possible. This is also suitable for a range of latitudes from equatorial to 45 degrees north/south without design change.

The structure concept is based on strong and light CFRP sandwich monolithic hexagon and floors and is modular for AIT. It also requires minimum fixings making it mass efficient.

Solar array hold down/release mechanism uses a tensioned cable and panel snubbers. On cutting the cable, the sprung (or potentially motor driven) hinges would drive each panel into the correct position. This configuration is efficient for releaseing 5 panels as required by the design.

The MLI sunshield is folded and stowed beneath the solar arrays and is deployed using pre-stressed beams. The antenna is deployed into a pre-defined orientation as it is fixed to the central solar array.

The sensor is released from the APPS after delivery to the surface. A three point, pre-loaded, cup/cone hold down and release system holds the sensor in place and release is achieved using a pyro or hot wire knife.



Robotic deployment arm interface

Avionics panel

Sensor support panel

Transportation interface flanges (3)

Stowed array (5 panels stowed against hexagonal tube facets)

Solar array hold down cable, cable cutter and tensioning turnbuckle

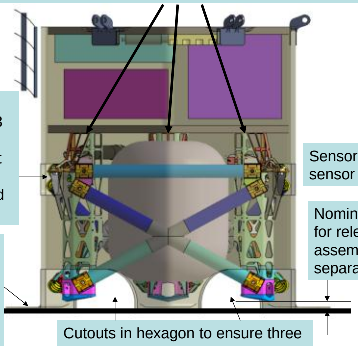
Deployed array (5 panels with dedicated deployment motors)

Deployable MLI cover (in outline)

Hexagonal main structure

Seismic sensor

Planetary surface support feet (3)



Three point cup/cone support from sensor support panel. Clamp force provided by bolt or kevlar cable. Release provided by ultra low shock pyro nut or hot wire knife

Cut outs in hexagonal tube (3 locations) to ensure no contact with sensor when released (dropped on 15 deg slope)

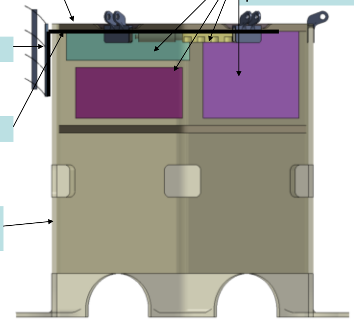
Broad feet (3 locations) to ensure stable support on loose / soft / uneven surface

Sensor supported from sensor panel

Nominal 20mm drop for released sensor assembly to ensure separation

Cutouts in hexagon to ensure three point support on planetary surface

Planetary surface



Service module panel

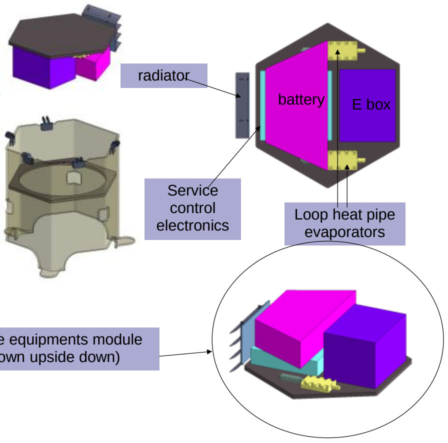
Service panel equipments (all mounted to service panel

Finned radiator

Loop heat pipes

Hexagonal tube

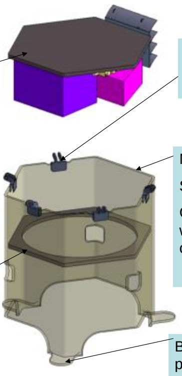
**Service Equipment Layout**



Service control electronics

Loop heat pipe evaporators

Service equipments module (shown upside down)



Service equipment support floor bolted to tube via 12 edge inserts
Sandwich panel: CFRP faces 0.25mm thick with 10mm thick kevlar core

Solar array deployment motor / pivots (5 off) bolted to hexagonal tube

Monolithic Hexagonal tube:

Sandwich construction

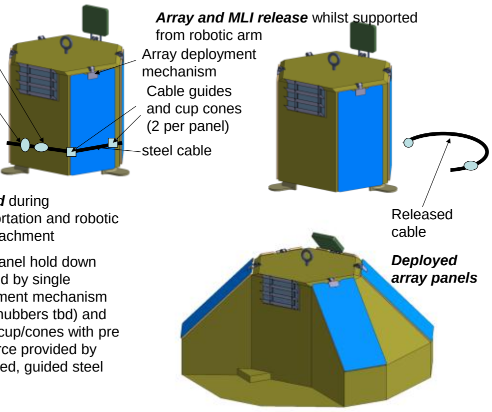
CFRP faces 0.25mm thick with 6.3mm thick kevlar core

Sensor support floor bolted to tube via 12 edge inserts

Sandwich panel:

CFRP faces 0.25mm thick with 10mm thick kevlar core

Bolted aluminium alloy feet providing transportatrion interface and planetary surface interface



Cable cutter

Turn buckle

Array deployment mechanism

Cable guides and cup cones (2 per panel)

steel cable

***Array and MLI release*** whilst supported from robotic arm

***Stowed*** during transportation and robotic arm attachment

array panel hold down provided by single deployment mechanism (plus snubbers tbd) and pair of cup/cones with pre load force provided by tensioned, guided steel cable

Released cable

***Deployed array panels***

### Electrical Power System Design

The architecture for the APPS EPS has been selected to minimise mass by maximising efficiency. To this extent the APPS EPS provides two voltage buses; a 16 V regulated bus and an 11 V unregulated bus. The 16 V regulated bus is provided to those users requiring a stable voltage supply (±160 mV), such as the payload, OBC and DUX units. The 11 V unregulated bus is provided to those users able to tolerate a wider voltage range (±2.2 V), such as the heaters.

Power is generated by APPS using EMCORE's quad-junction IMM 34% efficient cells, selected for APPS on the basis that they are the most efficient cells currently available, they have also been subjected to some level of radiation testing and development plans have suggested that the cells would be qualified for use in space by 2016. Five identical solar array panels are arranged radially from the central structure at 60° intervals and angled at 45° to the horizontal. In order to maximise the fill factor of the solar panel it is assumed that a small-cell variant (20 x 40) would be available. The radial arrangement of the solar panels maximises the available solar power throughout the lunar day.

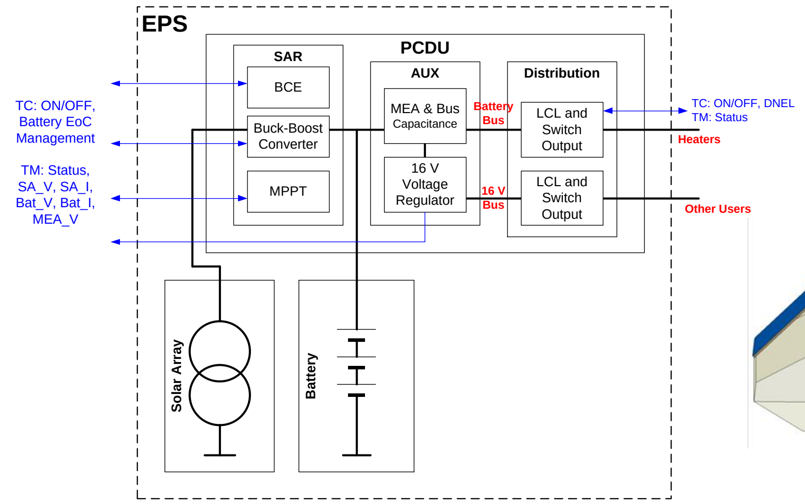
To convert the solar array voltage to the power bus voltage, hot redundant Buck-Boost Regulators (B2R) are connected to each panel. B2R topology was selected on the basis that it maximises flexibility within the solar cell arrangement which maximises the packing factor of the panel and, therefore, reduces solar array mass. The temperature of the solar panels ranges from -120°C to +150°C which causes a significant variation in solar array voltage. The temperature variation is also very slow taking 7 days to transition from -120°C to +150°C. MPPT functions actively hunt for the optimum operating input voltage and can be implemented in a number of ways, such as a "trail and error" FPGA algorithm or by a full voltage sweep of the array. In order to save power the MPPT function would not be required to operate continuously

The power distribution architecture is another critical area affecting the APPS mass. The heater-style output architecture shown overleaf shares the LCL consumption overhead as well as the protection and telemetry feature between the users. Sharing the LCL consumption overhead makes the users more efficient, but it does reduce the visibility of the individual user telemetry since only an LCL provides current telemetry. This restriction is believed to be an adequate compromise based on the mass saving within the battery. Both power buses distribute power using the same architecture, but the regulated power bus utilises Re-switching LCLs (LCL-Rs) in place of traditional LCLs since power to the system controller can never be accidently removed, thus, should a failure occur that triggers the LCL to switch OFF, the LCL is automatically reset back ON after a short duration

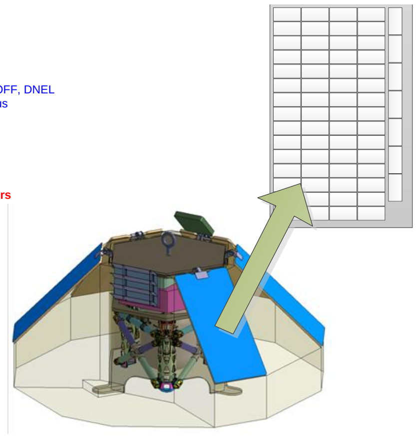
The APPS EPS distributes two voltage types (16 V regulated and 11 V unregulated), but the platform users require a wide variety of voltages (+5 V, +3.3 V, -15 V, etc.). In place of central producing these intermediate voltages, the users will employ Point-of-Load (PoL) converters at the desired location. PoL converters are small, chip based devices that minimise power distribution losses (higher losses with lower voltages) and remove the need for the PCDU to generate a wide variety of reference voltages.

Energy storage for APPS is performed by a Li-ion battery utilising a silicon anode. This chemistry, as demonstrated by Envia, has a very high energy density (400 Wh/kg) and very good capacity retention. Lithium-Sulphur (Li-S) chemistry, despite its higher potential energy density (~650 Wh/kg), was not selected for APPS on the basis of TRL. Li-S current suffers from very poor capacity retention, losing 75% of its capacity after 100 cycles and about 6% of its stored energy by self-discharge after 14 days. A battery mass of 4.8 kg has been predicted for APPS based on a cell mass of 50 g and 10% additional mass for support structure. This is comparable with the 40 g/cell for current Li-ion cells and the overhead percentage for the Beagle-2 battery which was specifically designed to minimum battery mass.

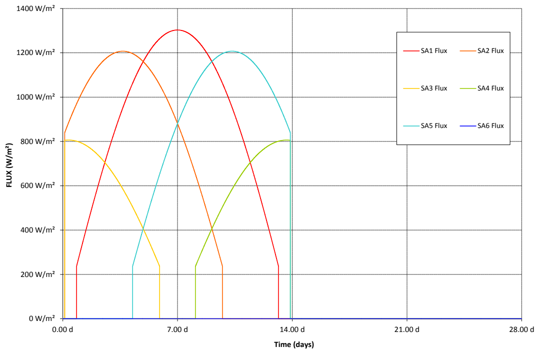
EPS Architecture



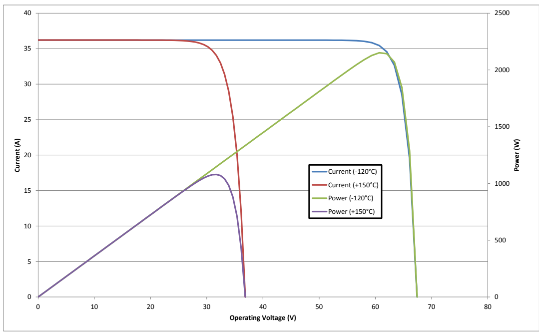
Possible cell configuration



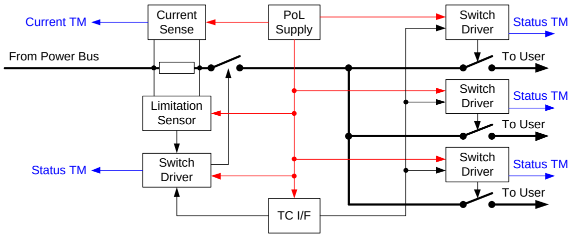
Array flux over one lunation



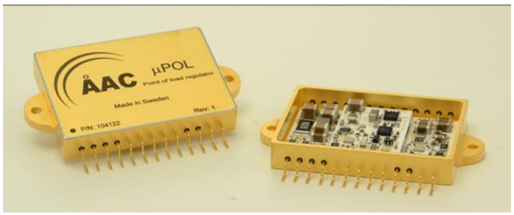
Variation in operating point over temperature

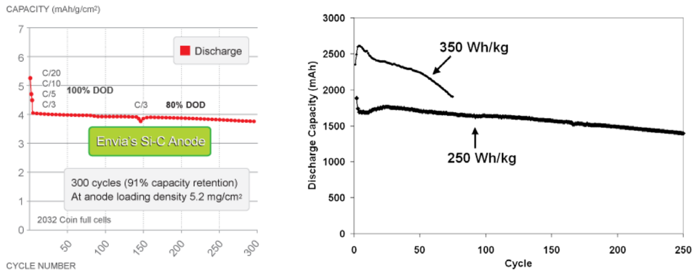


Heater-style power distribution



Point-at-load convertors





Lithium-ion with Si-anode (left) and Lithium Sulphur (right) cycle performance

## C&DH ELECTRICAL ARCHITECTURE AND DESIGN

The centre of the APPS is the integrated avionics package. This package must control the APPS and the payloads it serves for the duration of its operations. The system is a highly integrated electrical platform which has the following functions

- Data handling and storage
- Communications
- System control and FDIR (soft)
- Instrument interface

The main design requirements for the C&DH system are to be as low power as possible when in a quiescent state, power down as completely as possible whenever functions are not in use, maintain low level HK functions, be highly integrated and maintain flexibility for payload interfacing. The overall functional architecture is shown overleaf.

At the heart of the design is the combined OBC and comms module, where the ATMEL RTC system-on-chip is combined with an updated X-band transceiver based on the Beagle 2 design. The integrated LEON2 processor provides processing for the proposed payloads and the running of the Transceiver baseband software. The LEON device can be slow-clocked to reduce its already nominal low power consumption of 1 W down to levels of tens of milliWatts. The RTC also has a host of integrated interfaces such as SpaceWire, CAN, ADC, DAC, RS-422, GPIO meaning that additional support hardware is minimised and the APPS system is highly integrated. Directly interfacing to the RTC is a pair of redundant 32 GBit NAND Flash memory modules. The omission of a fast SDRAM buffer allows a low power consumption of ~115 mW.

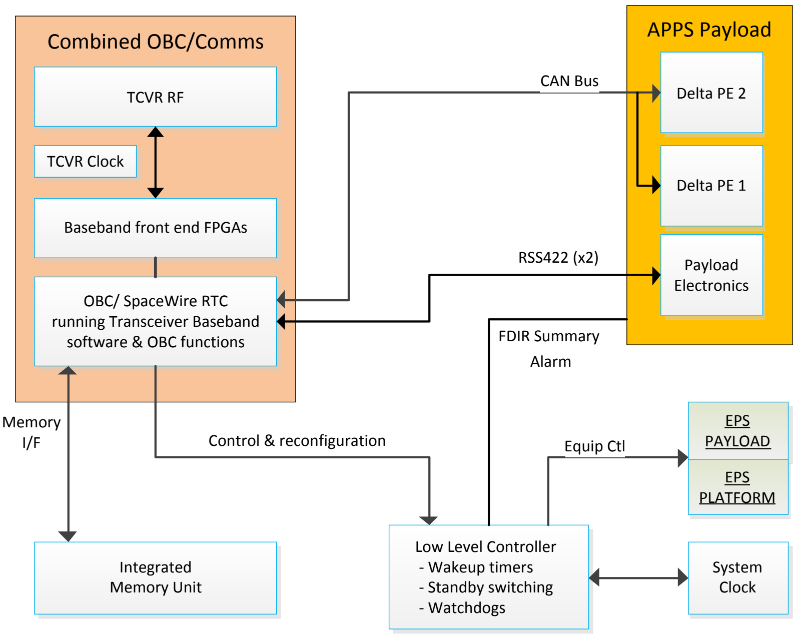
The transceiver design is updated, with the baseband front end FPGAs being combined into a single unit (encoding, syncing, CRC, frame buffer handling), with other functionality being transferred to software, handled by the RTC. Various other updates are recommended to the design, such as the use of chip stacking. The X-band RF section as updated for the DUX is however already highly optimised and requires minimal additional development.

At the heart of the design and operation of the DHS is the system controller. This functional element allows the majority of functionality (processor, receiver transmit and receive sections) to be powered down or off when not required to save energy. This allows a considerable amount of energy to be saved during the night-time. The System Controller is implemented using an array of timers which are programmed from the OBC and clocked by the triple redundant System Clock. The timers have programme registers in which a time interval is entered – once the time register value exceeds the time counter the switch outputs are triggered thereby controlling the necessary equipments, whether they are payload or platform equipments

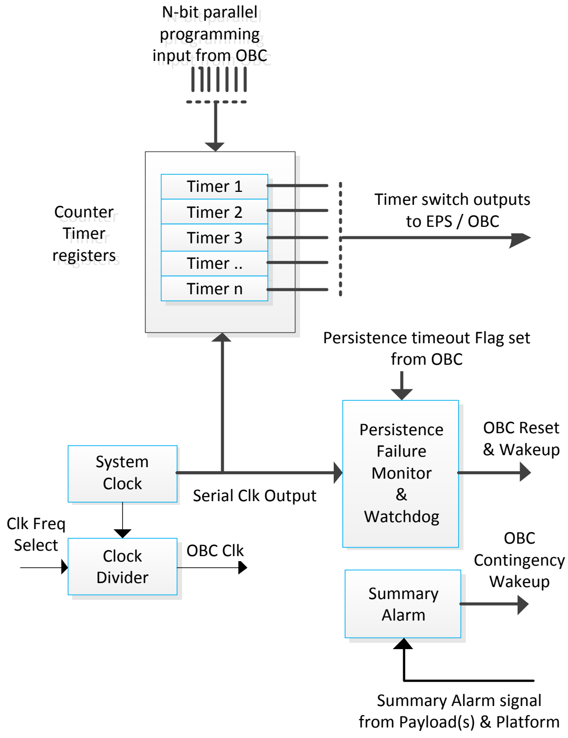
Persistence Failure Monitor allows rapid recovery of OBC function in the event of a timer wakeup signal or OBC anomaly in which the OBC is not woken at the programmed time. The OBC must set a persistence flag periodically that expires after a set length of time. If the persistence flag fails to be set the OBC reset and wakeup signal restarts/reinitializes the OBC thereby supporting recovery.

System time is implemented using a low power crystal oscillator. Timing accuracy is achieved by post processing to remove voltage, temperature and long term drift errors to achieve approximately 10ms total error over one lunar night.

Data Handling and Communications System Architecture



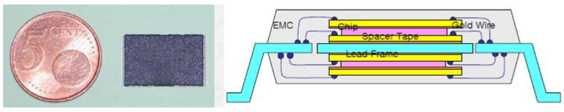
Low level controller architecture



DHC operational modes

| Mode | C&DH target power consumption (mW) | Application & comments |
|---|---|---|
| Full Power | 1000 | Interfacing to Payload and Payload processing<br>Communications (power increases to ~30W for periods or ~10 minutes depending on data volumes)<br>Periodic Housekeeping TM acquisition |
| Low Power Mode 1 | 50 | Baseline for SEIS Payload<br>Keeps the system 'ticking over'<br>FDIR basic functions operating |
| Low Power Mode 2 | 400 | (as for Low Power Mode 1 plus…)<br>Continuous Payload TM acquisition (sampling at kHz rate)<br>Continuous TM acquisition into Mass Memory |
| Safe Mode | 100 (TBC) | Contingency recovery mode<br>Payload off<br>Transceiver in Receive mode |

NAND Flash non-volatile memory



**Phased Array Antenna Design**

The phased array antenna allows the local slope and earth movement to be accounted for over the mission duration, and the additional RF loses are more than offset by the increased boresight gain. The main design features are shown in the figure below.

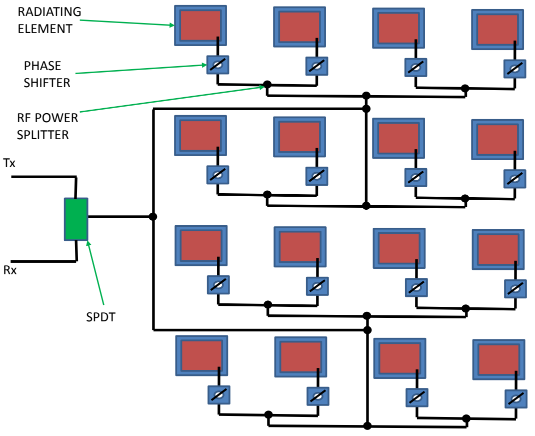
A 4x4 element microstrip phased array is proposed. The radiating element design is a dual frequency circularly polarised microstrip element. It comprises a Tx element above a slightly larger Rx element. The antenna is designed to operate in either Tx or Rx only, which simplified the design. A switch is used to select the mode.

The phase shifter consists of a series cascade of three phase bits. The GaN FET switch SPDT switching elements need to be assembled inside a hermetic package, using this substrate. All 3 bits can be located inside a single package. This package can be assembled on the underside of the main PCB which contains the 4x4 patch array. An increase in bits is offset by the additional losses.

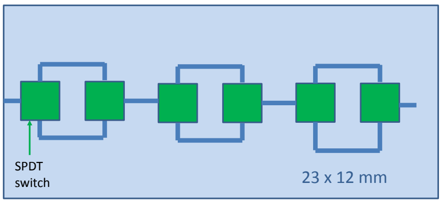
The antenna interfaces to the APPS via RF Tx and Rx lines, and a 15-pin serial interface for control.

Even with conservative margins, a performance of 13.1 dB for Tx is achieved. The total antenna package including Aluminium frame is predicted to be less than 160 g, making it an extremely light package.

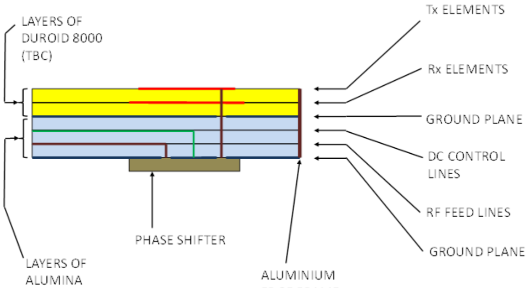
RF Layout Showing Corporate Feed Network

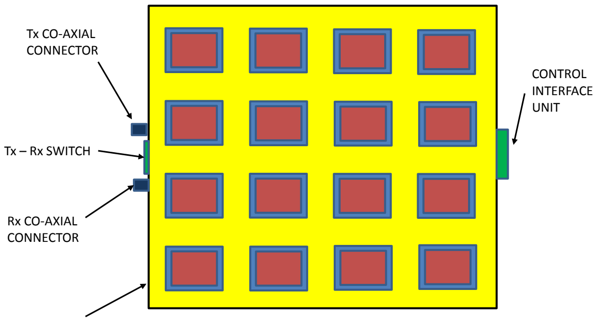


3-Bit Phase Shifter Design



Section through the Multi-Layer PCB





View on Radiating Side of Antenna

| | Tx | Rx |
|---|---|---|
| Directivity on boresight (dBi) | 19.6 | 18.2 |
| Phase shifter loss (dB) | 3.0 | 3.0 |
| Transmission line loss (dB) | 0.8 | 0.8 |
| Tx - Rx switch loss (dB) | 0.5 | 0.5 |
| Phase error loss (dB) | 0.5 | 0.5 |
| Gain on boresight (dBi) | 14.1 | 12.6 |
| Scanning loss (dB) | 1.0 | 1.5 |
| Minimum EOC Gain (dBi) | 13.1 | 11.1 |

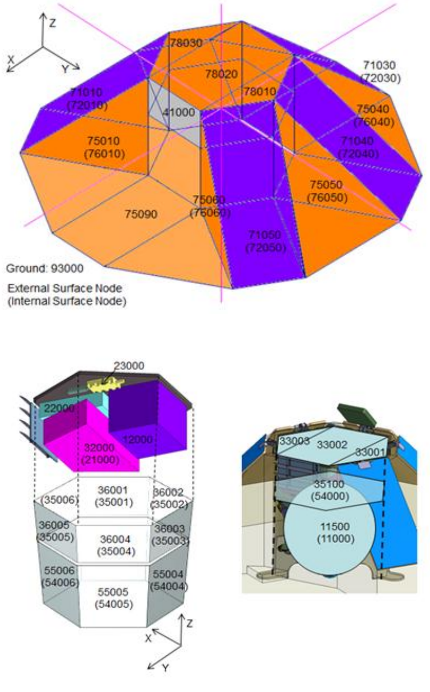
Predicted Antenna Performance

## Thermal Design

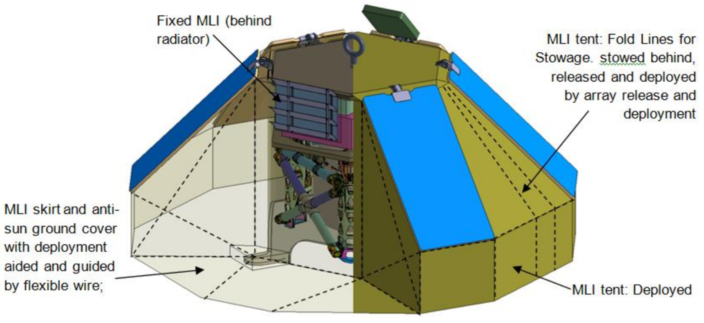
The main drivers for the thermal design were to control the temperature of electronics and payloads during periods of solar illumination and periods of darkness, maintain payload interface temperature stability and to provide a low thermal control energy consumption due to impact on the power subsystem. To minimise the energy required by the thermal system, full utilisation of equipment thermal ranges was desired, and active thermal control implemented.

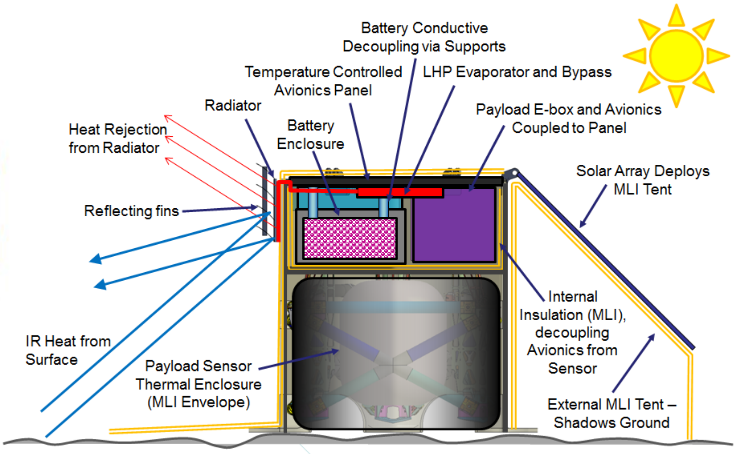
The design is shown in the figure below. The avionics zone is coupled to the radiator via a loop heat pipe and is surrounded by MLI. The payload sensor is disconnected physically from the APPS and is also surrounded in MLI. A sunshield surrounds the complete system, providing a cover for the regolith (as required by the sensor) and an enclosed environment.

A key tool in the APPS thermal design was the thermal model. This was implemented in ThermXL and modelled conductive and radiative interactions, and the interface between the APPS and the ground, space and sun, along with time dependant thermal dissipations and active thermal control.



APPS Thermal model





As part of the thermal design process, several key subsystem trades were performed:

- APPS communications operations concept
- Heater control
- MLI vs Aerogel and insulation concept
- Heat rejection and control thereof

The communications subsystem causes a large peak in dissipated power which can drive the thermal design. A trade was undertaken to determine whether longer, lower power sessions were more thermally efficient than short high power sessions. Due to the low-pass filter effect and the system thermal capacity, it was found that the latter had less of an impact on the thermal performance of the system, and was therefore baselined.

During the night time, ohmic heaters were found to be required. Although more complex operationally, heaters with closer set points were found to minimise the heater power demand as heat was not wasted. The faster time constant also minimised the impact on the sensor thermal stability.

Due to the need to conserve as much energy as possible, the APPS thermal insulation configuration was a critical aspect. Both aerogel and MLI were initially considered. Many APPS exterior surfaces are flexible and/or deployable and so MLI could not be considered in these cases. A sensitivity in MLI performance of +/- 50% was undertaken, and it was found that although the APPS was insensitive to battery and rigid wall MLI performance changes, the top surface was a major driver. Although aerogel (which has very stable characteristics) could be used on the APPS top surface, a 75 mm thickness would be required to meet the equivalent MLI performance and so was discounted. Interestingly, the night time nominal dissipation was very well matched to the thermal design, and only if a ‘survival’ mode (where the payload is switched off) would drive the need for increased top surface MLI performance.

Heat rejection is achieved using a single radiator, orientated vertically away from the equatorial sun. To avoid impinging IR radiation from the lunar surface, shaped low emissivity reflectors cover the radiator surface, as used on BepiColombo and Apollo ALSEP. However during the night time, this radiator must be decoupled from the avionics to avoid excessive heater power levels, where even with heating from the ground, 2.5 W of heater power would be required. A major thermal trade undertaken was the selection of a loop heat pipe system or a wax heat switch. Although the heat switch is essentially passive, the lack of heat transport capability makes accommodation challenging and increases radiator size by 50% and considerably more heater power is required at night. Therefore the loop heat pipe is selected.

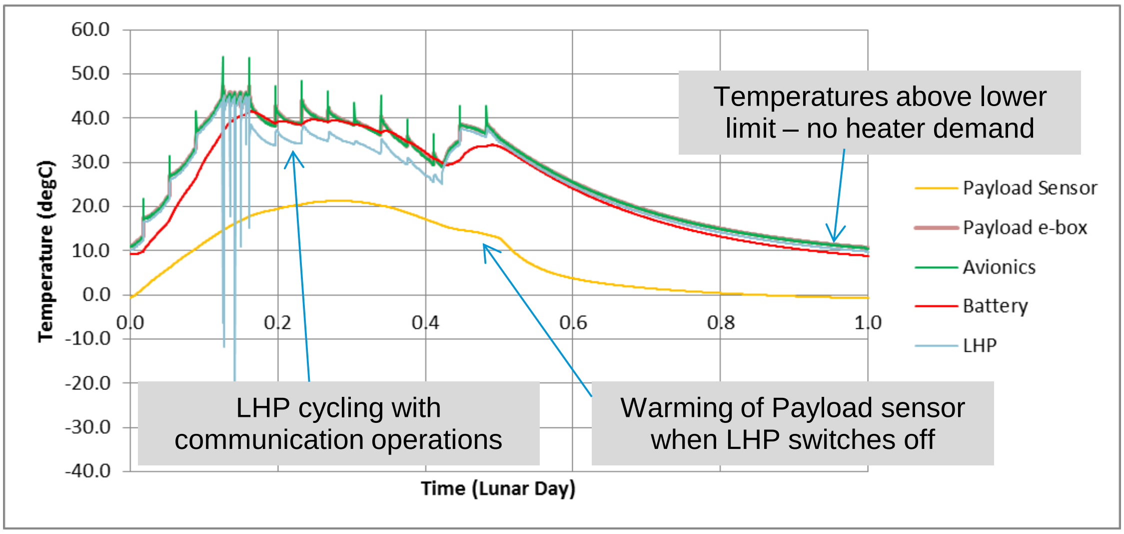
Another important consideration on the moon is the effect of dust, making surfaces blackened and increasing absorptivity and emissivity. This is critical for both MLI and radiator performance. A sensitivity analysis was performed and it was shown that an 11% covering of dust would result in a 50% increase in radiator area to compensate for higher heat loads. However using a LHP, there is minimal impact on heater power demand. It should be noted however that the level of dust deposition is an unknown factor.

The plots overleaf show the predicted APPS thermal performance over a complete lunation. The peaks due to communications are clearly visible, however the avionics stays below the required 60 degrees at all times (50 degrees for the battery). Due to the insulation concept, no night time heater power is required in the nominal case. The survival case shows the thermal performance when the payload is off. In this case, 1.25 W total heater power is required (also accounting for 0.5 W additional margin for MLI performance variation), with heater cycling every 30 minutes. It is also noteworthy that in this case the LHP does not switch on in the daytime.

The thermal impact on the sensor was also calculated, in relation to the thermal power spectral density requirement. Although marginally non-compliant, it was deemed to be acceptable by the scientists.

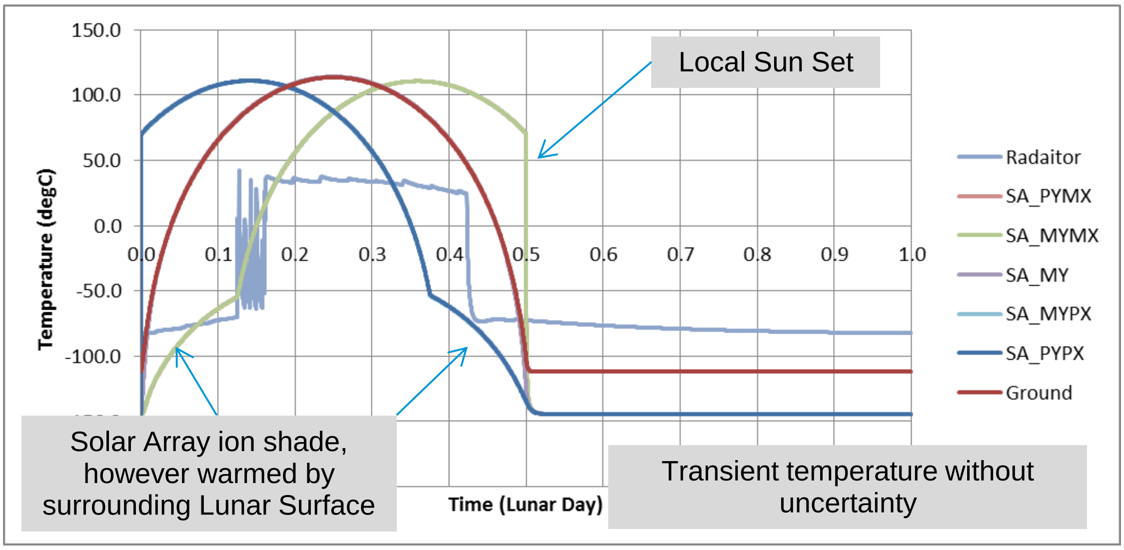
Further work is recommended on minimising the thermal performance sensitivity to MLI performance.

## Nominal Operation


Temperatures above lower limit – no heater demand

LHP cycling with communication operations

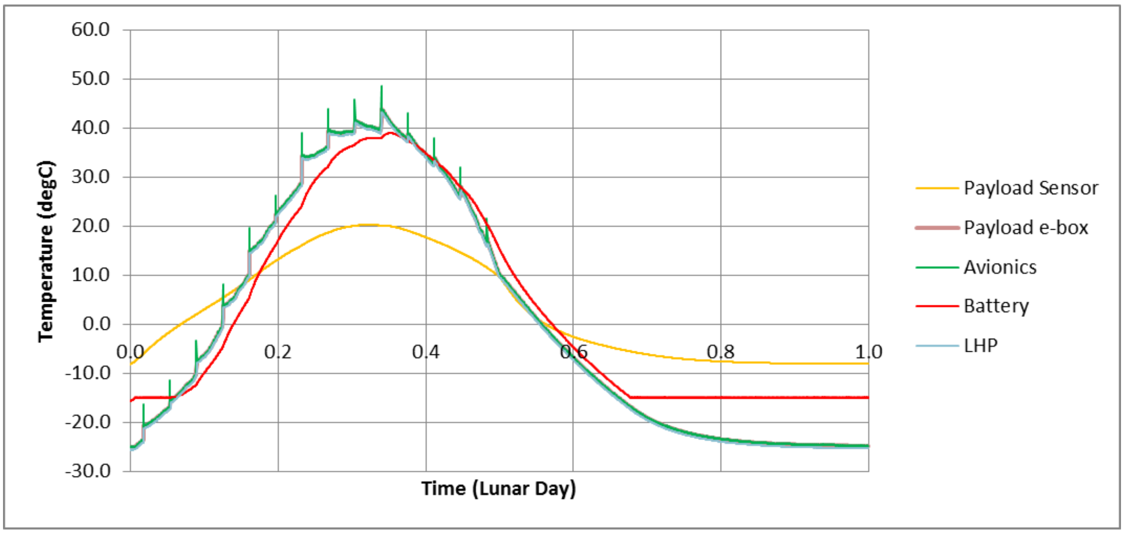
Warming of Payload sensor when LHP switches off


Local Sun Set

Solar Array ion shade, however warmed by surrounding Lunar Surface

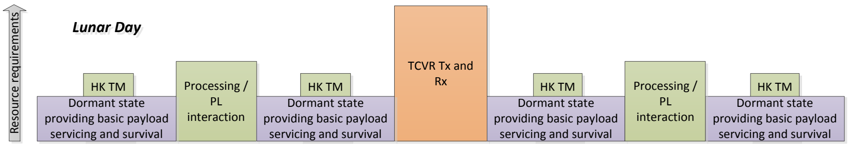
Transient temperature without uncertainty

## Survival Mode



### Functional Design and Operations

A key design aspect of the APPS is the operational concept, where all non-essential systems are shut down when not in use. The application of a high-reliability system controller at the core of the APPS allows this to be achieved, offering significant energy and hence mass savings. The operations proposed for the APPS are shown below, where in between periods of activity, the platform lies in a dormant and low-power state.

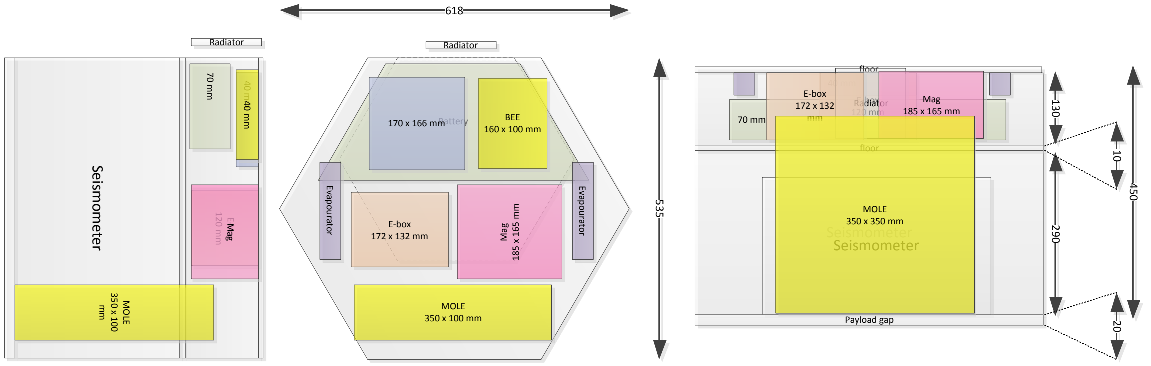


Using a single-string design in the APPS wherever acceptable helps to drive the system mass down, however certain areas still require redundancy to minimise the risk of mission loss. The complete integrated OBC comms module is proposed to be a cold redundant unit, allowing a combination of simplicity in architecture and high internal integration. The low level controller also contains a triple redundant system clock. The PCDU and mass memory also have internal redundancy, and both solar arrays and battery are string failure tolerant.

### Delta Payload Accommodation

To assess the scalability of the APPS concept, additional 'delta-payloads' were specified and the design adapted to accommodate them. The impact on the APPS design is shown below, with an example of the updated configuration to accommodate both the additional magnetometer and mole. More information on Delta-PE accommodation can be found in Do5.

| | Mass | | | | | Configuration | | | | Dimensions | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Scenario | Payload | EPS | Structure | Thermal | Total inc system margin | battery | Solar Array | Data volume | TCS | structure height | structure width |
| Baseline | 8 | 6.4 | 3.7 | 1.3 | 24.8 | 29p3s | 5 x 18s4p (18 | 16.08 Gbit | 0.00 W heater | 404 mm | 360 mm |
| SEIS + Mole | 10.4 | 7.2 | 4.5 | 1.7 | 29.5 | 32p3s | 5 x 19s5p (24 | 16.09 Gbit | 0.02 W heater, 125% radiator size | 404 mm | 517 mm |
| SEIS + Mag | 9.8 | 10.8 | 4.1 | 1.6 | 32.7 | 50p3s | 5 x 21s5p (25 | 23.34 Gbit | 0.00 W heater, 210% radiator size | 404 mm | 438 mm |
| SEIS + Mole + Mag | 12.2 | 12.3 | 4.8 | 2 | 38.2 | 56p3s | 5 x 20s7p (30 | 23.35 Gbit | 0.00 W heater, 225% radiator size | 450 mm | 535 mm |

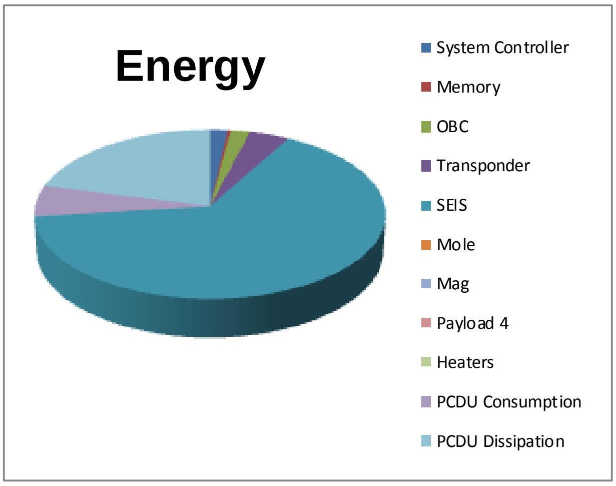


**Budgets**

The following tables give the top level mass and energy budgets for the APPS baseline scenario.

| APPS | | | |
|---|---|---|---|
| **Subsystem** | **Current Best Estimate (kg)** | **Design Maturity Margin (kg)** | **Total CBE + DMM (kg)** |
| APPS | 1.5 | 0.4 | 1.9 |
| Power Subsystem | 5.4 | 1.1 | 6.4 |
| Harness | 0.4 | 0.1 | 0.5 |
| X Band Communications Subsystem | 0.1 | 0.0 | 0.1 |
| Structure and Mechanisms | 3.4 | 0.3 | 3.7 |
| Thermal Subsystem | 1.2 | 0.1 | 1.3 |
| **PLATFORM / SERVICE MODULE TOTAL** | **12.0** | **2.0** | **14.0** |
| VBB Assembly | 1.5 | 0.2 | 1.6 |
| Short Period Assembly | 1.2 | 0.1 | 1.4 |
| HK | 0.0 | 0.0 | 0.0 |
| Magnetic Shield | 0.5 | 0.1 | 0.6 |
| Installation and Levelling | 1.8 | 0.4 | 2.1 |
| Electronics | 1.9 | 0.4 | 2.3 |
| Payload 2 | 4.8 | -4.8 | 0.0 |
| Payload 3 | 0.0 | 0.0 | 0.0 |
| **PAYLOAD / PAYLOAD MODULE TOTAL** | **11.6** | **-3.6** | **8.0** |
| **TOTAL** | **23.7** | | **22.0** |
| System Mass Margin | | 20% | 2.8 |
| **TOTAL (incl. System Margin)** | | | **24.8** |
| **Requirement** | | | **15.0** |
| **Mass Margin to Launch Vehicle Capability** | | | **-9.8** |

| **Energy** | Unit | Value |
|---|---|---|
| Total energy | Whrs | 1895 |
| System Controller | Whrs | 34 |
| Memory | Whrs | 6 |
| OBC | Whrs | 37 |
| Transponder | Whrs | 77 |
| SEIS | Whrs | 1231 |
| Mole | Whrs | 0 |
| Mag | Whrs | 0 |
| Payload 4 | Whrs | 0 |
| Heaters | Whrs | 0 |
| PCDU Consumption | Whrs | 113 |
| PCDU Dissipation | Whrs | 398 |



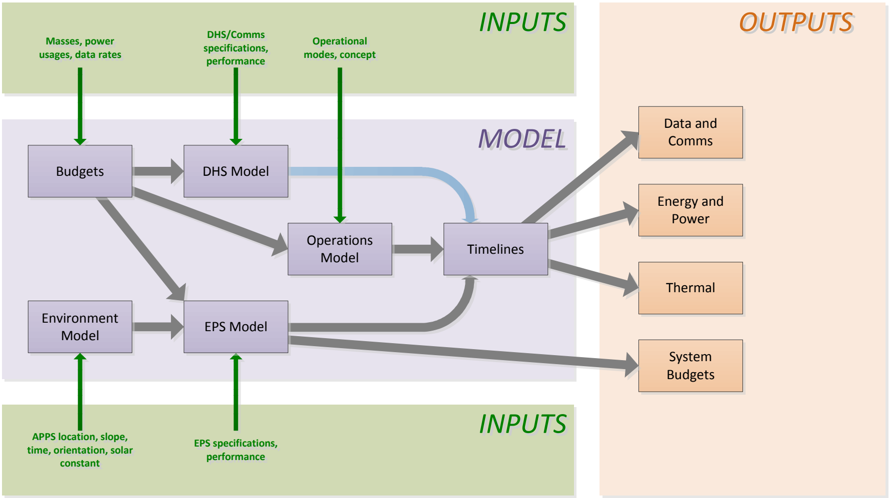
# 5 APPS PARAMETRIC MODELLING

Development and use of the Parametric Model was a key aspect of the APPS study. The tool allowed the efficient exploration of the APPS performance in a variety of scenarios and configurations, proving an essential tool in the design process, as well as assessment of the performance of both baseline and delta configurations. The primary objectives of the model were:

- Demonstrate APPS concept meets the requirements placed upon it with a high level of confidence.
- Enable assessment of the key sensitivities of the design, accounting for modelling uncertainties.
- Allow assessment of design scalability, specifically with respect to the payload interface.

It was also important to note however that the Parametric Model could not fully represent all complex behaviours and interdependencies. The purpose was to demonstrate key functionalities and interactions.

The following figure shows the basic model architecture:



The main model elements were as follows:

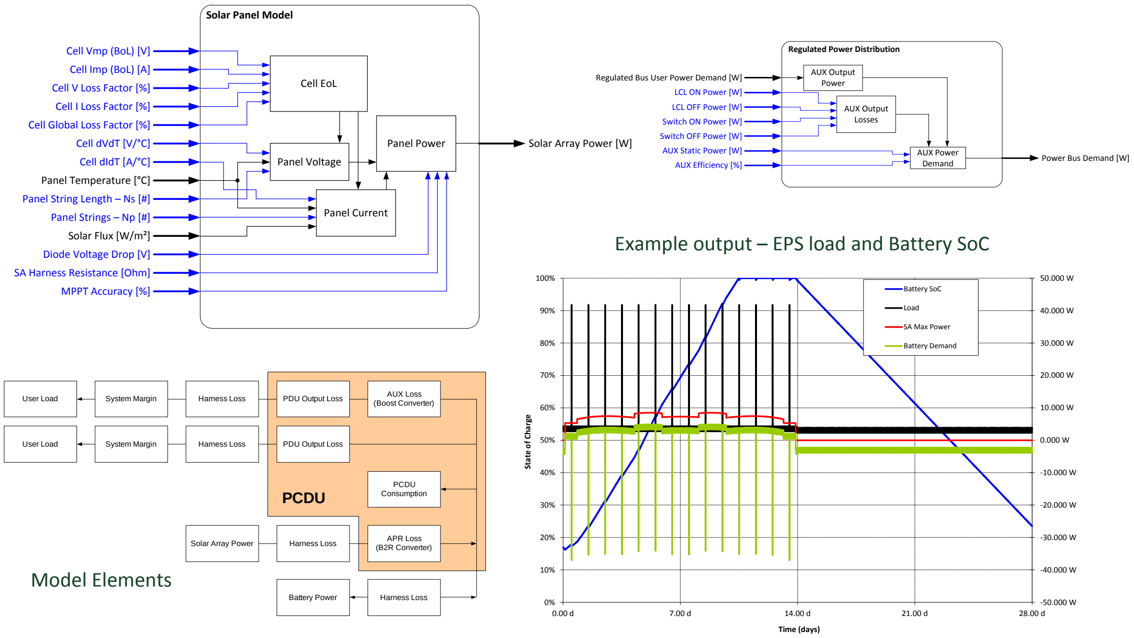
- APPS Operations Model. Including the operational modes and profile. This was central to the model and described the operational state of the system over time. This allows the model to be truly flexible and responsive to changes in operations and payload implemention
- Electrical Model. Models interaction of EPS with environment (power generation), battery charging/discharging and static and dynamic losses to accurately model the energy and power usage of the system – a central aspect of the APPS design.
- Thermal Model. Although the thermal behaviour of the APPS is extremely complex, the key interactions were distilled into a reduced model that described key interactions within the system. Estimates of the thermal impact of changing electrical loads are possible.
- Data handling Model. Simple algorithms allow data volume and communications volume to be estimated, along with several calculation tools.

## Electrical Model

The power model was of critical importance as energy management was central to the APPS design. An accurate and realistic model was required and was developed for both the APPS design and Parametric Model. The model had the following sub-elements:

- Power Generation (Solar Arrays)
- Power Conversion
- Power Distribution
- Energy Storage (Batteries)

To model power generation, a detailed model of solar array performance was generated, along with an environmental model with inputs covering APPS latitude, orientation, local slope solar flux such that all environments could be simulated. The model allowed a specification of any array string configuration and orientation (as well as several cell types). All array loss factors were also modelled (including dust). A parametric array mass calculation was also implemented based on panel size. The solar array model is shown schematically as an example below.



Both power conversion and distribution were modelled to include both static and variable losses to ensure that an accurate estimate of the system load under all conditions was modelled as both could have significant effects on energy usage. Sizing of the system (number of users) also allowed a parametric assessment of the PCDU mass.

Energy storage was modelled in detail to ensure an accurate battery mass could be calculated. Battery performance against load and temperature was modelled, along with voltage, allowing a battery under voltage to be detected.

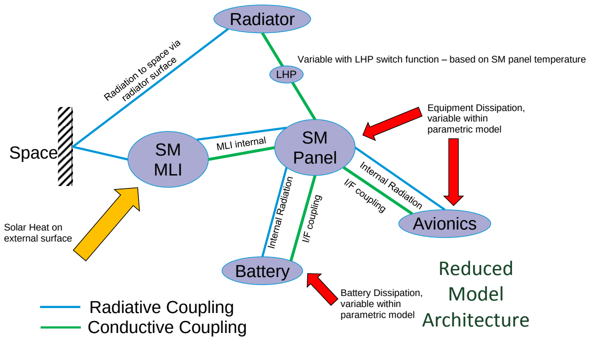
An assessment of the EPS model accuracy was undertaken, with the accuracy of the battery data being a recognised limiting factor. A recommendation for future work would be to better link thermal and electrical performance.

### Thermal Model

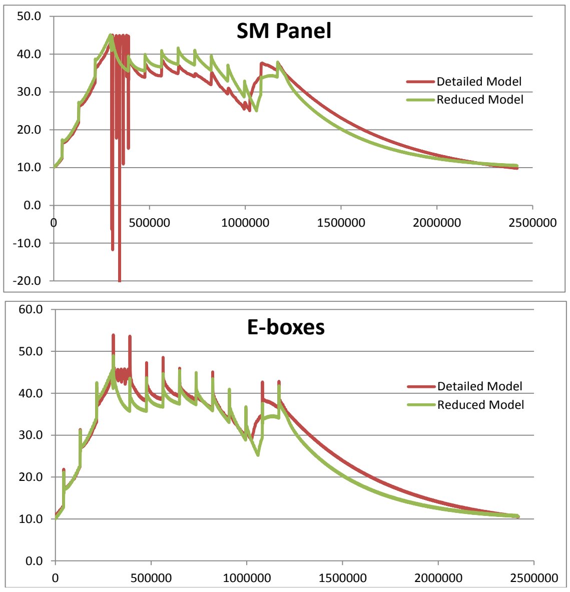
Creating a thermal sub-model proved to be a significant challenge, as the thermal behaviour of the APPS is extremely complex. The thermal model requirements were:

- Model the thermal behaviour of the APPS over time
- Be responsive to changes in the operational profile
- Allow a representative estimation of the required heater power
- Allow a representative estimation of the equipment temperature limits

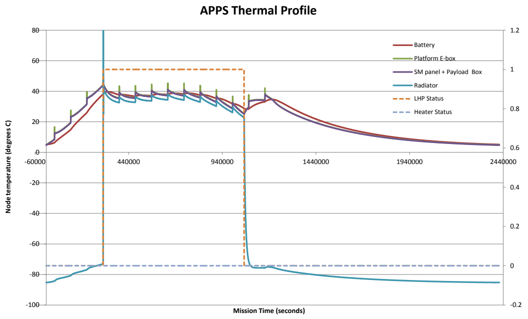
The Parametric model implemented a reduced ThermXL model which was correlated with the full model to ensure consistent performance, designed to implement the key thermal interactions with the electrical subsystem. The architecture and correlation with the full model are shown below.



Reduced Model Architecture



Correlation of the full APPS thermal model with the reduced parametric thermal model showing similar behaviour with some subtle differences



Parametric Model output plot

A key aspect of the thermal model was the loop heat pipe operation which operated automatically based on specified set points and thermal performance. Similarly, the heater switching was defined and a maximum heater power specified. This allowed a calculation of the heater power usage during the night time and therefore impact on the energy requirement.

Due to the complex nature of the modelling, the electrical and thermal models ran serially, with a potential iteration of the electrical model. However the fast running of either meant this was not an onerous task.

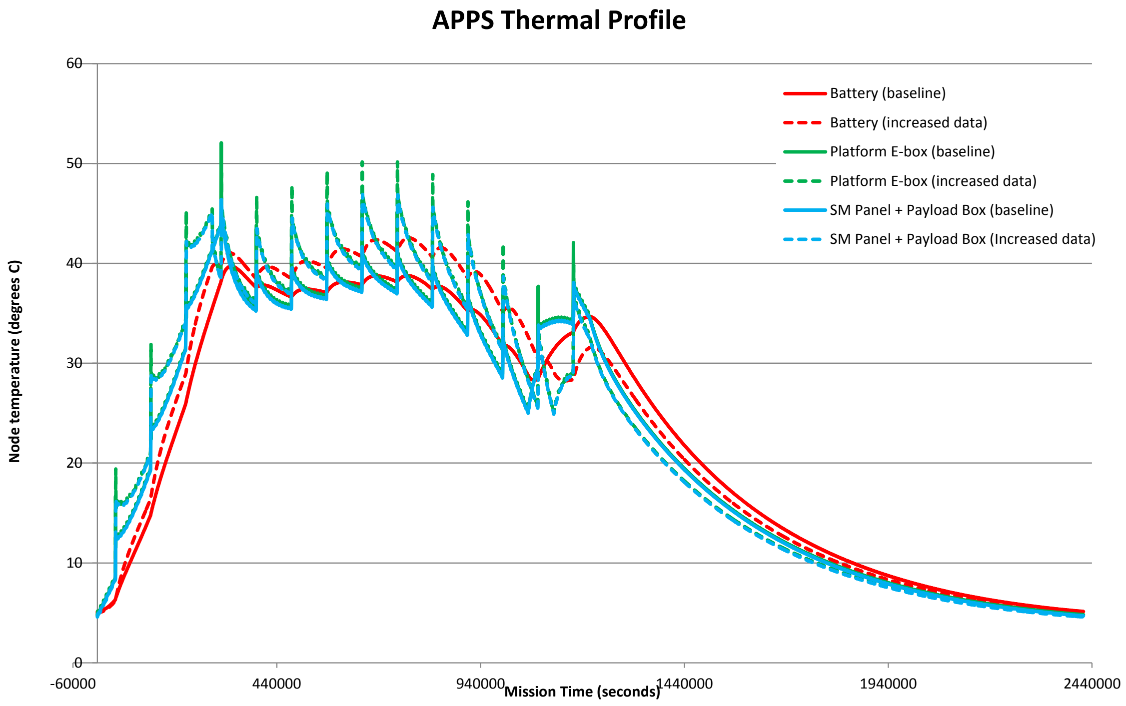
The thermal model was identified as a challenging aspect of the Parametric Model. Although the model could represent changes in equipment transient power profiles and estimation of heater power demand, the main limitation was that changes in geometry could not be modelled.

### Data Handling Model

Estimates of total data volume required and data transmission to ground could be made using the Data Handling Model. This simple model works by defining data ‘locations’ and allowing operational modes to generate or copy data between locations. This allows data processing (generating or reducing data) impacts to be estimated, along with HK data generation and true representations of total data transmitted to Earth.

### Model Results

The Parametric Model was demonstrated over a range of scenarios, including both the baseline payload and delta payloads, giving an estimate for the change in resource requirements and operational strategy required to implement additional payloads. The impact of EPS failures and increased communications sessions (along with other aspects) were also successfully demonstrated using the model. The example below shows the impact of increasing communications sessions (peak power)



### Parametric Model Conclusions

The tool developed in Microsoft Excel is responsive and relatively efficient whilst maintaining considerable power and flexibility. The model demonstrates considerable flexibility to operational scenario, where both the thermal and electrical model time domain performance shows response to any defined operational behaviour.

The model however had some limitations. The thermal model is tied to the physical configuration to some extent due to the complex radiative and conductive interfaces being too complicated to be represented in the reduced model. The electrical model is currently loosely integrated with the thermal model, and further work would allow this to be tightened, with thermal effects on electrical performance modelled in more detail. Sensitivity to some parameters (e.g. dust) could also be more explicitly accessible to the user.

# 6 TECHNOLOGY ROADMAPPING AND PROGRAMMATICS

During the APPS study, various technologies were recommended for implementation. As a result, some specific technology developments were suggested. An implementation plan for the APPS up to flight delivery was also developed.

### Technology Developments

The following table shows the recommended technology developments for the APPS, to take place before the start of Phase B.

| **Tech Dev.** | **Development time** | **Models** |
|---|---|---|
| Lifting Eye / Arm Attachment | 12 month | Mechanism BB + env testing |
| APPS Transfer-Phase Bayonet Hold Down | 12 month | Mechanism BB + env testing |
| Silicon Anode Lithium-Ion Battery Technology | 18 months | BB characterisation and qualification |
| Integrated X-band Transceiver and OBC Package | 24 months | BB + env testing |
| Ultra-Low Power Timer-based System Controller | 18 months | BB + env testing |
| X-band Phased Array Antenna | 18 months | EM + env testing |
| Low Sensitivity MLI Coatings | 12 months | EM + env testing |

Key developments from the above list were identified as the Integrated X-band Transceiver and OBC package and the Ultra-Low Power Timer-based System Controller. Several other developments were identified which would be undertaken as part of the procurement process with low risk, such as the sunshield and low power PCDU. It was also noted that the Silicon anode battery technology could not be developed within the space industry due to high costs, and that terrestrial development would be relied upon. The developed cells would then be space qualified. In this instance, the mass impact of switching to currently available Li-Ion cells was identified as 4.6 kg, or 18% of total mass.

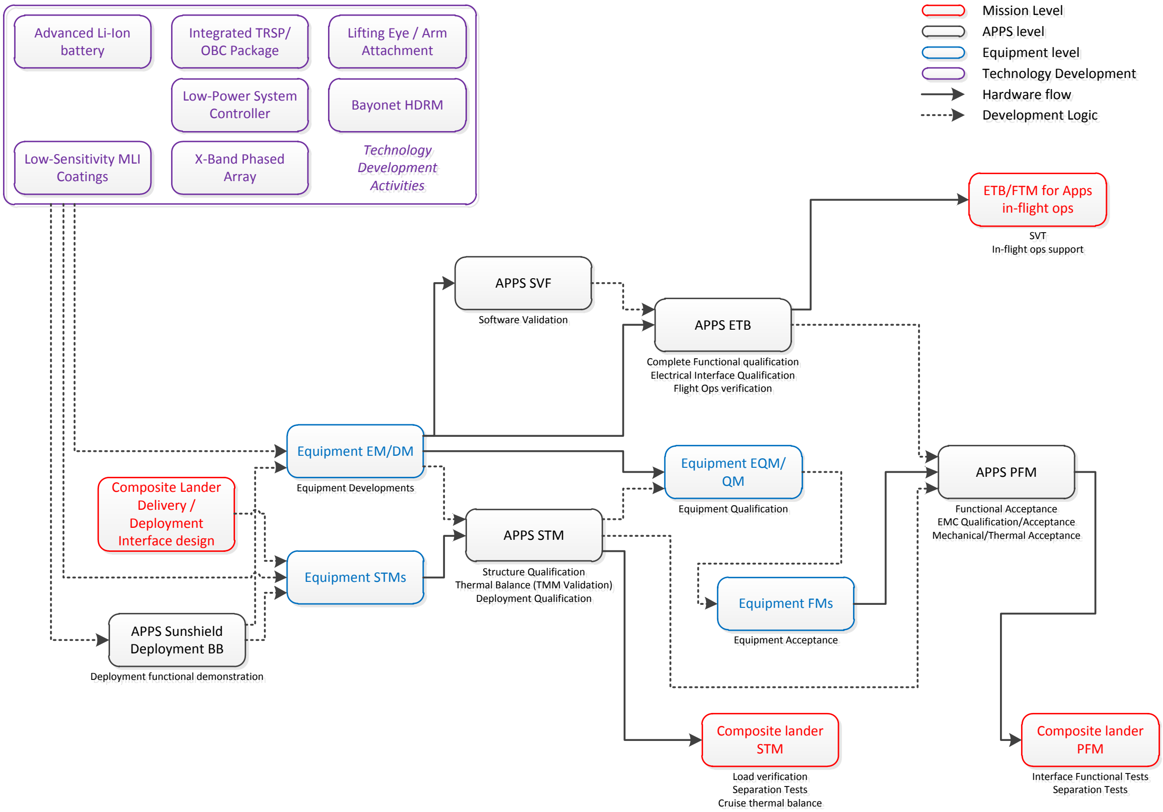
### Programmatics

The main issues driving the development plan and suitable risk reduction activities were identified as

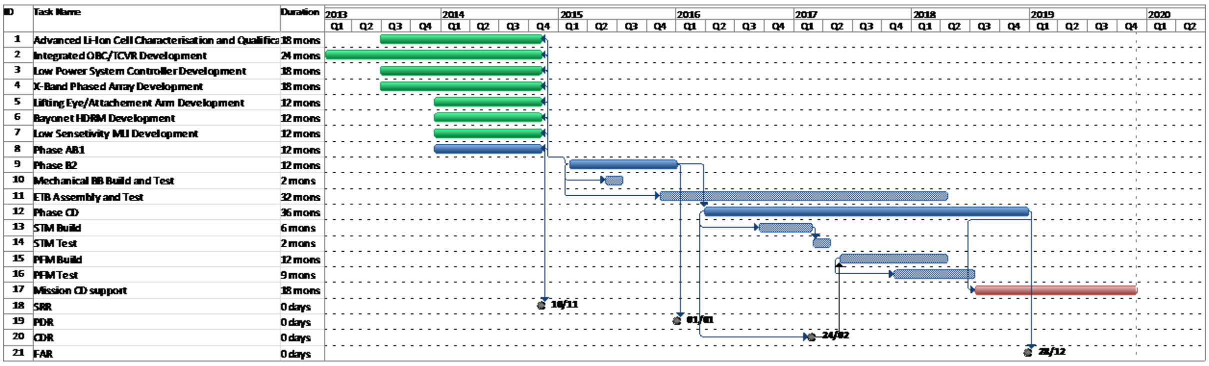
- **System control and FDIR**. The risk is reduced my maintaining a simple approach, minimising verification complexity
- **DTE comms link performance**. The risk is reduced by early characterisation of the performance in time to adapt the APPS design
- **Electrical System resource requirements**. Early characterisation of equipment performances allows both a maximally representative STM test and adaption of the design to account for variations
- **Battery technology performance**. Early identification of battery technology performance allows the design to be adapted or alternative technologies to be selected

- **Sunshield and Array Deployment Strategy and Performance**. The sunshield is a critical design element. Functional performance should be demonstrated early with a functional breadboard.

The suggested development approach is summarised below, showing the recommended model philosophy.



The proposed APPS development schedule allows the flight model to be delivered by the end of 2018:



| ID | Task Name | Duration |
|---|---|---|
| 1 | Advanced Li-Ion Cell Characterisation and Qualifica | 18 mons |
| 2 | Integrated OBC/TCVR Development | 24 mons |
| 3 | Low Power System Controller Development | 18 mons |
| 4 | X-Band Phased Array Development | 18 mons |
| 5 | Lifting Eye/Attachement Arm Development | 12 mons |
| 6 | Bayonet HDRM Development | 12 mons |
| 7 | Low Sensetivity MLI Development | 12 mons |
| 8 | Phase AB1 | 12 mons |
| 9 | Phase B2 | 12 mons |
| 10 | Mechanical BB Build and Test | 2 mons |
| 11 | ETB Assembly and Test | 32 mons |
| 12 | Phase CD | 36 mons |
| 13 | STM Build | 6 mons |
| 14 | STM Test | 2 mons |
| 15 | PFM Build | 12 mons |
| 16 | PFM Test | 9 mons |
| 17 | Mission CD support | 18 mons |
| 18 | SRR | 0 days |
| 19 | PDR | 0 days |
| 20 | CDR | 0 days |
| 21 | FAR | 0 days |

# 7 CCN ACTIVITY – PARAMETRIC MODEL UPDATE FOR MARS

**Introduction**

The APPS work was extended to allow the team to adapt the Parametric Model for a new target – Mars. The reference mission was INSPIRE – currently under investigation by ESA. The main tasks were to identify the new model requirements, update the model architecture and functionality and to demonstrate the model functionality. A comprehensive User manual was also required.

**Driving Requirements for INSPIRE and Mars**

Mars represents many challenges for mission design, with many tightly coupled system drivers like environment and power generation. These drivers also represent a challenge for system modelling, where the system behaviour is strongly linked with many parameters in a non-deterministic way.

Taken from previous experience on the INSPIRE mission, the team identified the main issues that the Parametric Model would have to tackle, defining the functional requirements:

- Model the impact of power-hungry DTE X-band comms (in terms of power and thermal)
- Determine platform survivability in a wide range of environmental conditions
- Represent the dynamic Mars environment in the model
- Represent a Mars-like platform in terms of the thermal and electrical design

Another significant change to the model specification based on previous experience was that a proper Thermal Mathematical Model (TMM) was required to be included, such that the complex (but critical) interface interactions between the thermal, electrical subsystems and environment could be represented and modelled.

**Updated Model Architecture**

A major component was the Environment model, which described the location of the sun and the temperature and solar flux over time. In order to allow a high fidelity model, the thermal and flux information is externally generated (for example from the Mars Climate Database) and inputted. The tool allows a range of environments to be generated and a dynamic environment to be simulated, for example a dust storm where the atmospheric optical depth changes with time. A similar approach was also used to allow a changing dust factor to be modelled. The effect of wind could also be represented, where day and night convective coupling levels could be specified and these values fed through to the Thermal model. These elements allowed highly realistic Mars environments to be replicated.

The operations model was updated to allow the definition of a set of generic ‘Users’, each with specified modes. A user would represent any active element on the platform, such as a unit, payload, etc.. The platform configuration would then be defined by ‘System’ modes, built from User modes to allow the state to be defined as a function of time. The state of the platform over the simulation was then easily defined by these modes.

A major addition to the model was the inclusion of a generic TMM, where a detailed thermal model of the platform could be defined using the ThermXL add-in. The parametric model merely provides a defined interface. This allowed the model to have the following functionality:

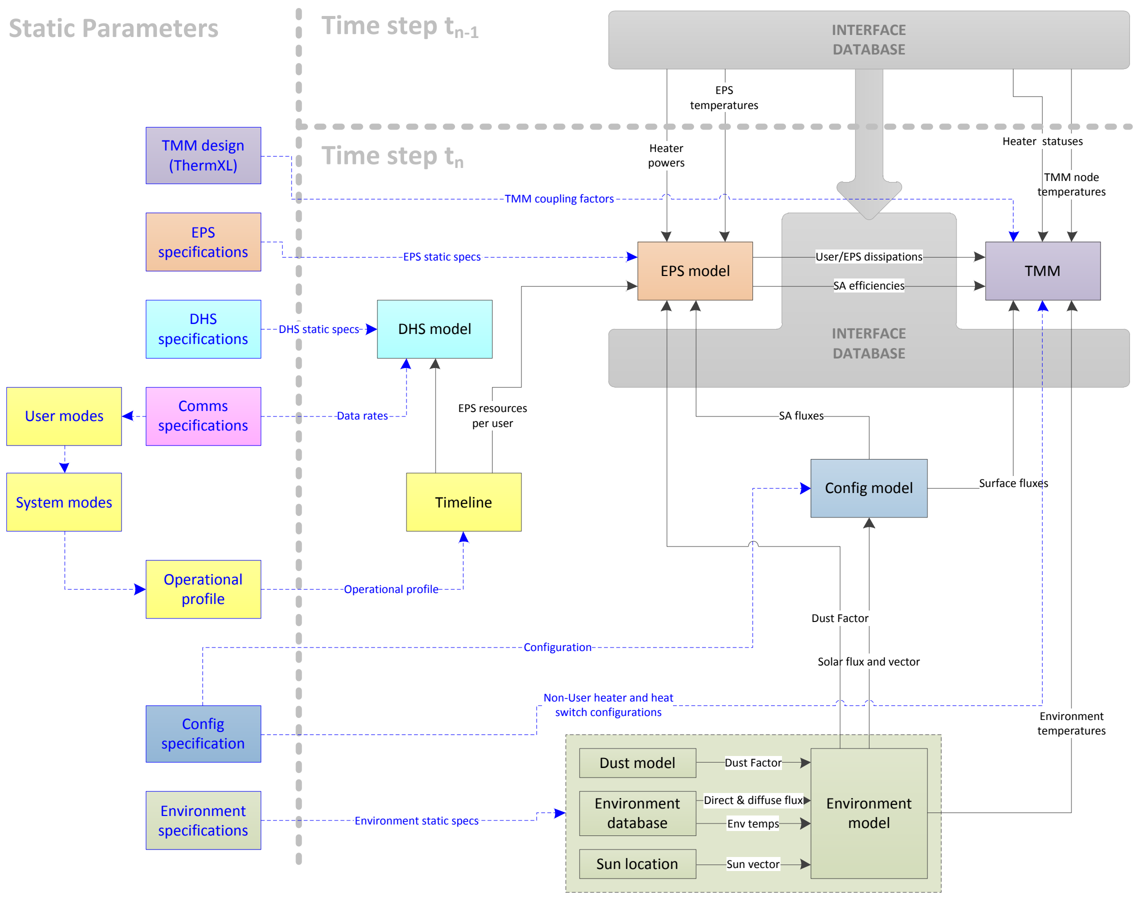
- Deterministic heater and heat switch behaviours, based on defined logic and providing actual estimated heater loading on the electrical model, rather than a priori estimates

- True temperature dependant EPS element behaviours (solar arrays, battery)
- Accurate predictions for equipment temperatures and excursions from allowed limits

The modelling of time also had to be redefined for Mars. The selected implementation allowed the model operator to specify the platform operational profile in Earth seconds but with each SOL lasting 24:40:00. The simulation length and time interval was also user defined, allowing multi-day simulations.

Data handling modelling was similar to the previous APPS model version. However the link model allowed both UHF-orbiter and DTE communications to be modelled with the data rate defined by detailed link budgets. Due to time constraints, these budgets were static. This would be an area for model improvement in the future.

The following diagram shows the model architecture, showing the complex interactions between elements that result in a powerful and flexible model.



In order to implement these additions, updates and changes and based on significant experience gained from the initial APPS study and from elsewhere, the model was completely rewritten for the Mars case. This model was largely implemented in Microsoft VBA, allowing it to run significantly faster than for the Lunar case.

## Model Performance

In order to demonstrate the model functionality, a set of reference scenarios were developed. These were used to show the model behaviour was as expected and to showcase the functionality and value of the model as a system design tool, and to verify that it would meet the top level requirements defined at the start of the CCN.

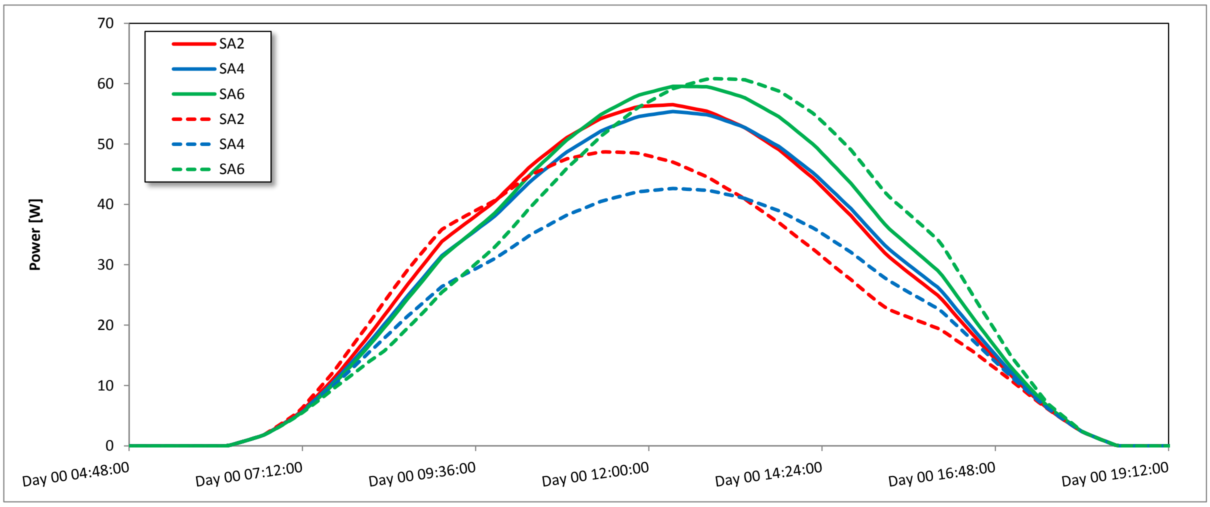
The following simulation cases were defined and run:

1. ***Nominal DTE communications – hot case***. Nominal case with long duration DTE communications during the day. Hot environment and low wind. Unity dust factor
2. ***Nominal DTE communications – cold case***. As above but with cold environment.
3. ***Global dust storm – static environment***. Low power case with no DTE communications. High dust factor
4. ***Global dust storm – dynamic environment***. Varying optical depth and dust factor with time to simulate transient dust storm
5. ***Stepped Solar array cleaning***. Demonstrate impact of progressive solar array cleaning when recovering from a dust storm and resultant deposited dust

In order to demonstrate the model, a reference platform design was specified. This represented an INSPIRE-like design, but was not connected to any previous design study output and was purely for demonstration purposes.

The model outputs were used to show the performance of the modelled system and the behaviour of the model. It could be used to verify that the design was meeting the requirements or to size the system. It could also be used for sensitivity analyses and 'what-if's.

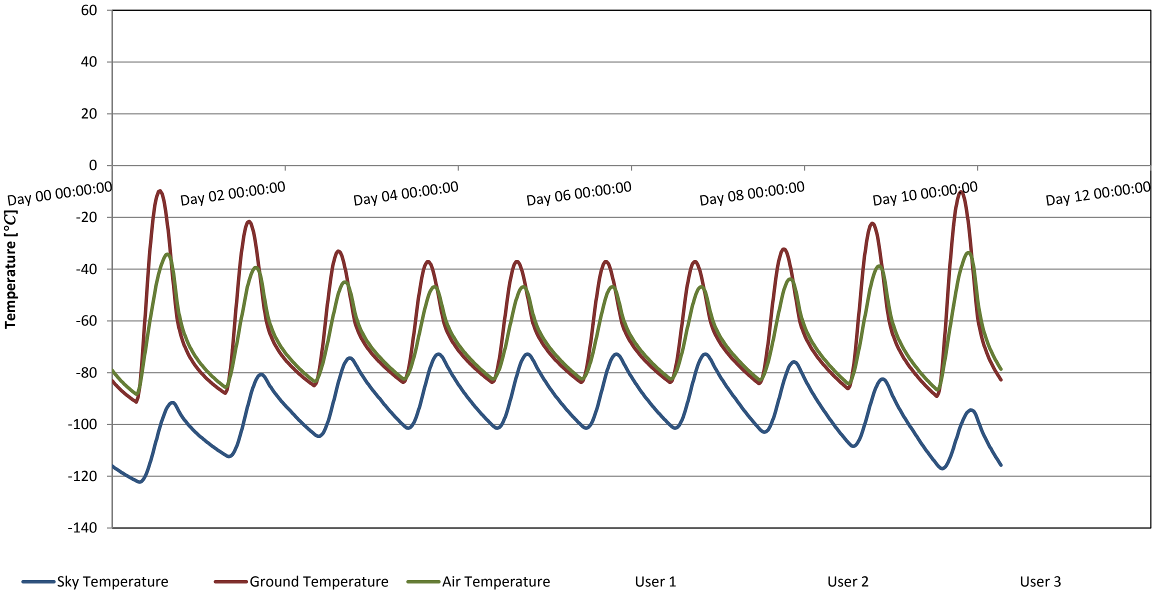
An example of this is below, where the effect of canting the arrays was explored.



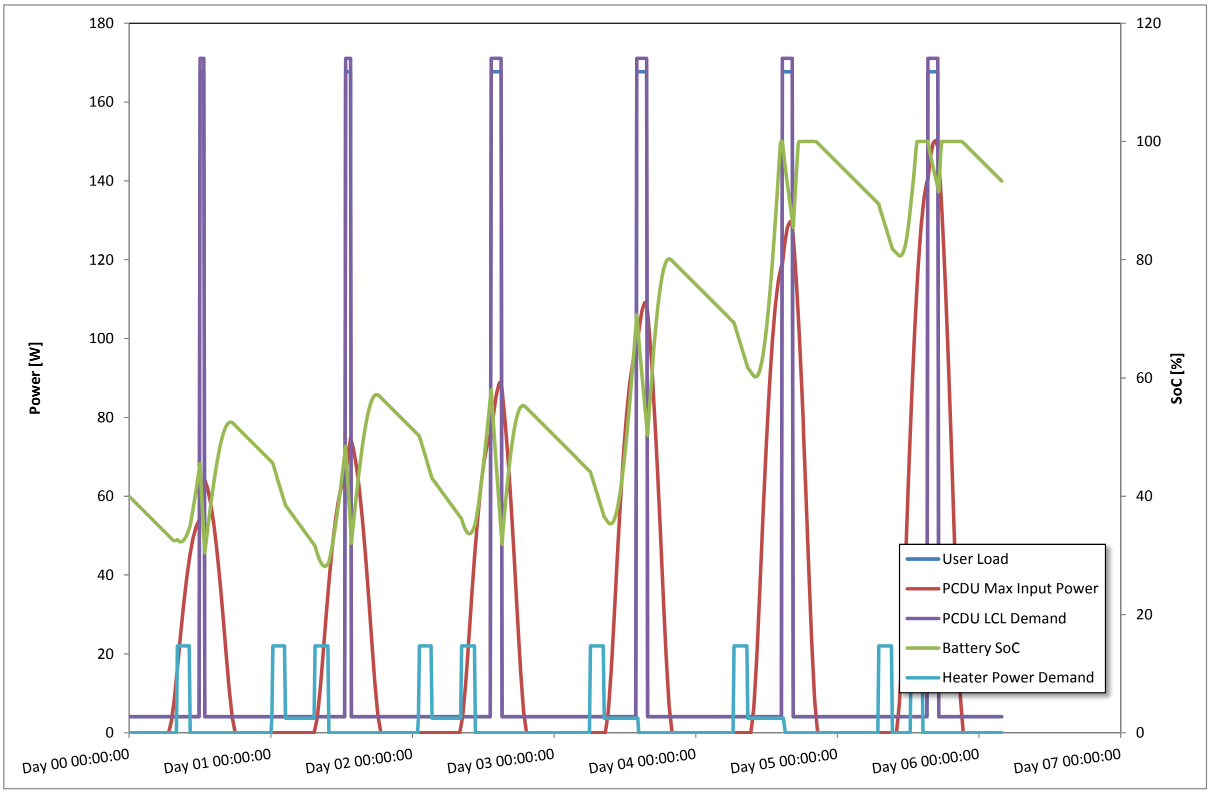
Nore that the power generated here is a function of several things, due to the detailed nature of the model:

- the orientation of the panels to the sun and hence the flux received
- the temperature of the panels due to the solar and environment heating

When modelling a transient dust storm, the optical depth change was modelled. This affected the environment temperature over the 6-day simulation. The modelled temperatures are shown below



The stepped solar array cleaning model allowed the effect of cleaning dust off the arrays over successive days using a high powered cleaning system to be explored. The effect on the energy balance is shown below, with the array dust factor being steadily decreased with each dust removal phase



## DOCUMENT CHANGE DETAILS

| ISSUE | CHANGE AUTHORITY | CLASS | RELEVANT INFORMATION/INSTRUCTIONS |
|---|---|---|---|
| A | - | - | Initial Draft Issue |
| 1 | - | - | First Formal Issue |
| 2 | - | - | Update to include CCN activity outputs |
| 2.2 | - | - | Includes ESA review comments |

## DISTRIBUTION LIST

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