Columbus Ka-band Terminal thermal control - a compact design for varying conditions

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The Columbus Ka-band Terminal (COLKa) will enhance and add new capabilities to the existing Columbus on-orbit and ground communications systems and create an additional bi-directional Ka-Band data transmission for the ISS. The terminal will be accommodated on a platform offering support panels and structure designed to withstand thermal and structural environments and form the interface between the communications system from MDSRL (MDA UK), the Columbus module and the launch vehicle/temporary on-orbit stowage location. The platform is delivered by Kayser Italia, under ESA contract. In order to ensure compliance with Columbus design and operations and with the boundaries of the already established interfaces the implementation is coordinated with and followed by the Columbus system authority. In the location where it is situated on the Columbus exterior the COLKa Terminal is exposed to pronounced changes in the thermal environment both during the orbit and between seasons. It forms a major challenge to meet the thermal requirements for the varying conditions while also respecting the constraints which are imposed by the ISS. It involves adapting the design to the launch of the COLKa Terminal and transfer by EVA crew to the position for integration, via the ISS airlock. The paper will give an overview of the different aspects of the thermal design and the planned verification programme.

I. Introduction

THE COLKa Terminal will provide bi-directional communications between the Columbus laboratory and the EDRS satellite communication system. It is made up of a steerable antenna, RF signal processing assemblies (LNAs, frequency converters, etc.), digital signal processing assemblies (digital modulators and digital demodulators), Command and Data Handling assemblies (PIAU), DC power conditioning assemblies (PDU), micro-wave filters, waveguides inter-connects, co-axial cable inter-connects, high speed digital cable inter-connects as well as of survival heaters and DC harnesses. With the Forward Service Link , low-rate data is relayed from the EDRS System Ground Segment to COLKa Terminal via the EDRS GEO satellite. The Return Service Link, also via the COLKa Terminal to the EDRS Ground segment via the EDRS GEO satellite, provides high-rate user data communications between the COLKa Terminal and the EDRS Ground Segment, such as video, sensor data, etc.

The COLKa Terminal, along with the COLKa Platform, is identified as the COLKa Flight Unit (FU). The COLKa FU will be installed on a pre-defined, external section of the ISS Columbus Platform. The COLKa FU will be connected to Columbus laboratory interfaces via six cable harnesses. Delivered by the Embarkation Contractor (i.e. KI), the COLKa Platform includes the support panels and structure designed to withstand thermal and structural environments, interfacing with the COLKa Terminal equipment, the Columbus laboratory and the launch vehicle/temporary on-orbit stowage location. It also provides radiation shielding and protection against space debris and micrometeorites for the installed Terminal equipment.

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II. Location on ISS

The location for COLKa FU installation is on the zenith-facing starboard side of the Columbus laboratory cylinder (Figure 1). The COLKa Platform is composed of an aluminium box housing the COLKa Terminal electronic boxes and including all the parts required to implement the mechanical and thermal interfaces to the Columbus laboratory, the IVA and EVA operations provisions (e.g. handholds, tether rings etc.) and the Columbus to COLKa harness. The main Terminal units will be accommodated in a closed box (Case) while the Antenna is mounted on the external Platform Top Panel (Figure 2).

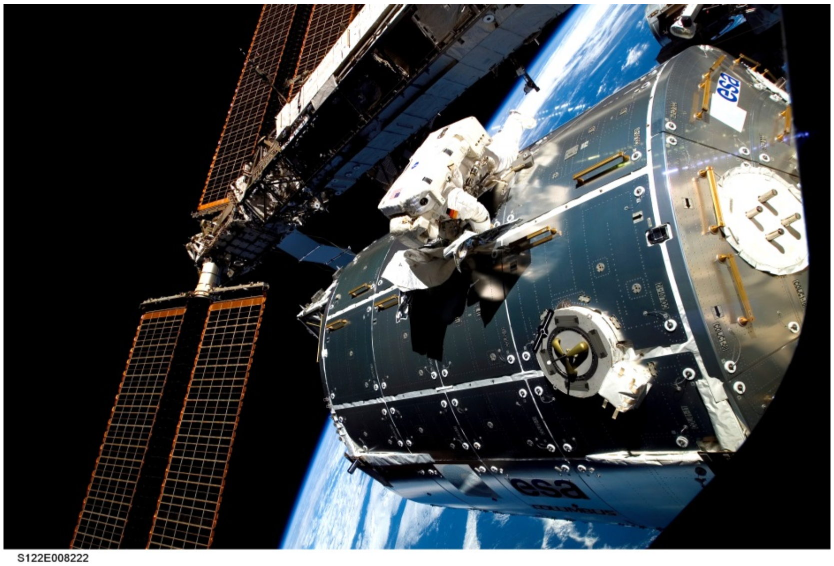

Figure 1. View on section of Columbus laboratory where the COLKa FU will be installed (ESA).

III. Mission Scenario

The COLKa FU will reach the ISS in a soft stowed set-up inside a pressurized launcher compartment. It will be transferred to the ISS cabin for temporary stowage until the final transfer to external space for the installation by Extra Vehicular Activity (EVA). Candidate launchers are HTV, Dragon (SpaceX) and Cygnus (Orbital). During launch and on-orbit phase inside the ISS cabin the COLKa FU is unpowered and is not mated to any electrical power source. Anyhow, the temporary stowage inside the manned cabin implies that the hardware shall meet all the environmental and safety requirements of the ISS cabin (e.g. toxicity, flammability, offgassing etc.). Toxicity and flammability requirements would complicate the use of heat pipes due to the properties of candidate working fluids, notably ammonia. Other alternatives requiring long development and qualification times were also discarded due to time schedule constraints. Consequently, there has been a strong incentive to find a design that can be based on standard thermal control equipment, e.g. MLI, paints and heaters.

Once transferred to ISS cabin, the launch bag containing COLKa will be stowed in a temporary location until the final installation. Before COLKa EVA transfer to the installation site, the six cables, that

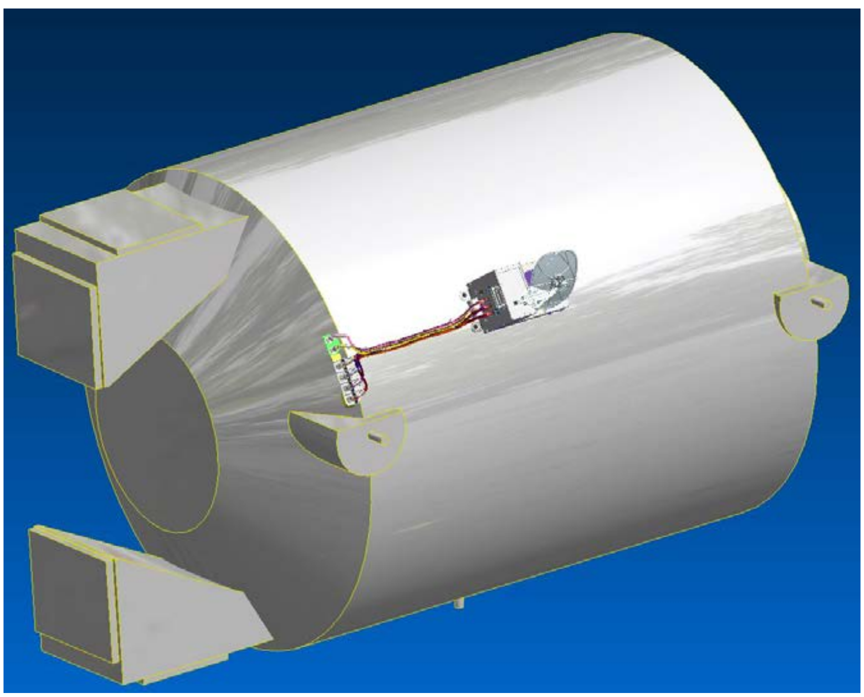

Figure 2. COLKa installation on the Columbus MDPS and harness routing (Kayser Italia).

are disconnected during launch, are mated to COLKa FU. Also the Antenna Locking Devices, which hold the antenna reflector and actuators during launch, are manually unlocked by the crew. Finally the COLKa FU is transferred to the Joint Airlock (Quest) together with two crew members, from which it will be transferred to the outside of the ISS.

The COLKa FU will be transferred following the EVA path to the Columbus forward zenith location. After reaching the installation site the crew will mount the COLKa FU by means of four Attachment Bolts to mounting points of the Columbus MDPS panels, pertaining to two different MDPS Panel. After mounting the COLKa FU to the Columbus, the crew will mate the six cables to the Columbus connectors bracket located in the starboard zenith side of the Columbus. Temporary blankets will cover the radiative panels of the COLKa FU during transfer and installation which would last up to six hours. Purpose of this temporary blankets is to minimize the heat losses of the hardware while it is unpowered and exposed to the deep space.

After installation completion, the COLKa FU is powered and functionally checked (commissioning phase) before full operations. After successful completion of the commissioning the COLKa FU start its operational phase.

IV. Thermal Requirements

A. Internal requirements

The thermal control shall take into account the design temperature of the various Terminal units which ranges from -20°C to +85°C and the heating power which ranges from no dissipation of some units in the stand-by mode to above 50 W of some units during transmission and receiving phase, with a total power above 200 W (nominal). Heating power increases above 240 W total in case of fault conditions. Anyhow, one of the main drivers of the thermal control design is relevant to the high power density heat dissipation on some units and the tight operational temperature range (i.e. 0°C ÷ 50°C) of some other units. There are also requirements on the maximum allowable daily, monthly and yearly, etc. temperature excursions. Another challenge of the thermal control design is represented by the high number of units, accommodated in a tight layout, which implied unavoidable proximities of units having remarkable differences of operational range and power dissipation. The tight set-up is caused by the overall dimensions constraints due to the launcher standard accommodation dimension and to the Airlock and relevant hatch dimensions.

B. Safety requirements

The COLKa hardware shall meet as well the touch temperature requirements, so that the external surfaces designed for unlimited contact shall have temperature in the range-43°C to 63°C. Surfaces where only incidental contact is foreseen shall have temperature in the range -118°C to 113°C. Exceptions are allowed for surfaces for which the heat flux to and from the surface can be shown to remain below specified limits.

C. Interface requirements

Other thermal requirements for COLKa, are the ones relevant to the thermal interface with the ISS and Columbus, specifying limits on heat transfer by conduction and on the reflected incident solar radiation and reflected incident IR radiation.

The COLKa external surfaces shall also withstand the plume impingement effects of the visiting vehicles that consist in pressure loads and a high heat flux for few seconds.

D. Environment

To take into account of the external thermal loads from the Sun and the Earth on COLKa, the data in Table 1 and Table 2 were used as input in the thermal model. HOT and COLD conditions were considered as well as extreme HOT and extreme COLD conditions. Extreme HOT and COLD values are expected to occur no more than 0.5% of the time. The thermal effects of the Sun on the ISS can be defined in terms of beta angle (i.e. the angle between the orbit plane and the sun vector, β) and flight altitude. Euler angles (yaw, pitch and roll) describe the ISS' flight attitude.

Table 1. Parameters adopted in the hot and cold scenarios.

	HOT:A	***HOT:B***	***COLD:A***	***COLD:B***
Solar constant	1423 W/m^2	1423 W/m^2	1321 W/m^2	1321 W/m^2
Albedo	0.27	0.35	0.27	0.22
Earth flux	273 W/m^2	241 W/m^2	217 W/m^2	241 W/m^2
ISS orbit height	278 km	278 km	500 km	500 km
Thermo-optical properties	EOL	EOL	BOL	BOL

Table 2 Parameters adopted in the extreme hot and cold scenarios

	Ext HOT:A	***Ext HOT:B***	***Ext COLD:A***	***Ext COLD:B***
Solar constant	1423 W/m^2	1423 W/m^2	1321 W/m^2	1321 W/m^2
Albedo	0.30	0.40	0.27	0.20
Earth flux	286 W/m^2	241 W/m^2	206 W/m^2	241 W/m^2
ISS orbit height	278 km	278 km	500 km	500 km
Thermo-optical properties	EOL	EOL	BOL	BOL

E. Thermal loads

Four main operating modes were considered for the thermal dissipation, besides the Survival (only heaters ON) and Passive (no power).

- Stand-by (155 W)
- Tracking (175 W)
- Transmitting/receiving (Tx/Rx) (200 W)
- Fault (245 W)

In the Passive mode the COLKa Terminal is completely unpowered. This mode would occur during installation and may occur as consequence of a major failure while COLKa is in the operational phase.

In the Survival Mode, the COLKa Terminal units are disabled (unpowered) while the heating control functions are operational and the heaters are powered.

In Stand-By Mode some electronic units are operating so to implement some functions, such as accepting commands from the Columbus, gather all telemetry from the units, transmit the telemetry frames to the Columbus and enabling the other units as requested.

In the Tracking Mode all the COLKa Terminal units are enabled and besides the functions listed for the Stand-By Mode the motor drive signals required to position the antenna are generated.

In Tx/Rx Mode all the COLKa Terminal units are enabled and the COLKa Terminal is continually tracking the EDRS GEO satellite and besides the functions listed for the Tracking Mode the receptions and transmissions functions are implemented.

Stand-By, Tracking and Tx/Rx are modes foreseen in a typical orbit of COLKa.

For the orbits when COLKa will be transmitting the typical mode durations are as follows; Tracking Mode duration is typically 3 minutes in the orbit, Tx/Rx Mode duration is variable and the maximum duration is about 25 minutes. For the remaining time of the orbit the COLKa Terminal will be in the Stand-By Mode.

V. Thermal Design

The COLKa FU thermal control is based on heat dissipation through thermal radiative surfaces to limit higher temperatures in hot cases and the use of heaters to limit lower temperatures in the cold cases. Thermal insulating blankets, made of MLI, cover the non-radiative surfaces so to limit the heat rejection towards Columbus and the other ISS elements and so to contribute at limiting the COLKa FU temperature variations.

The outer layer of the MLI blanket will be made of a UV radiation and atomic oxygen resistant outer layer (Beta Cloth). The conductive heat flow, towards the Columbus through the Attachment feet and Attachment Bolts, is limited by using thermally insulating washers between the Attachment Bolts Stud and the Attachment Feet and between the Attachment Feet and the Columbus MDPS panels.

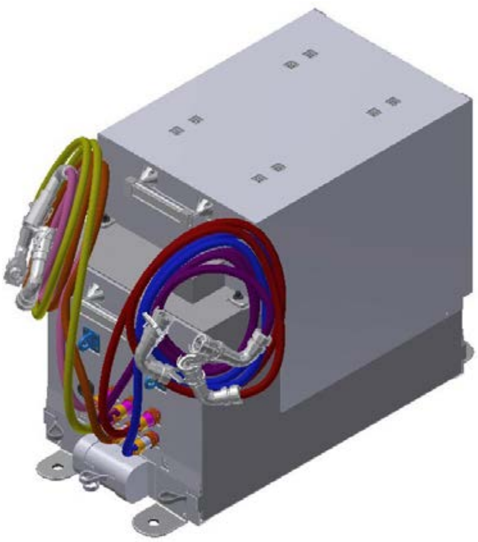

Figure 3. COLKa FU Transfer Set-Up (Kayser Italia).

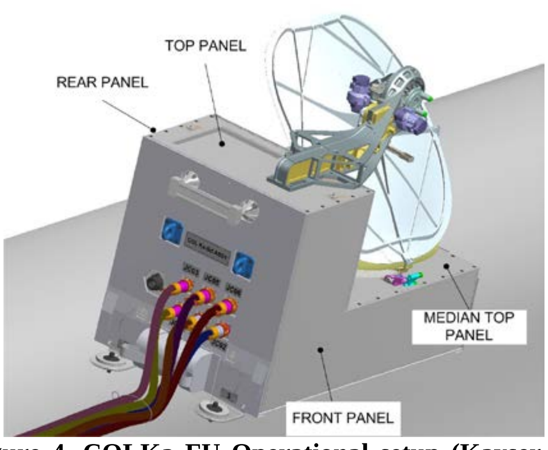

Figure 4. COLKa FU Operational setup (Kayser Italia).

A Temporary Blanket and a Temporary Cover with its Blanket are used during the EVA transfer and installation phase assuring that the COLKa temperatures stay within the allowable limits when COLKa is unpowered. Figure 3 shows the COLKa FU Transfer Set-Up, with the Temporary Cover and the Temporary Blanket installed. During transfer the external cables coiled and restrained to the hardware.

The Temporary Blanket and the Temporary Cover are removed by the EVA crew at the end of installation. The Operational Set-Up is shown in Figure 4 with the cables routed to the Columbus connectors bracket and the Antenna and radiative panels exposed to space.

The COLKa Platform Top Panel, Rear panels, Median Top Panel and Front Panel will be used as thermal radiation surfaces. These panels will dissipate the power generated by the electronic components and the heat received by the environment.

The following panels are radiative:

- Front Panel, Rear Panel with Silvered Teflon external surface and anodization around the edge
- Top Panel with some MLI on the starboard side and the rest of the surface either with embossed Silvered Teflon or anodization
- Median Top Panel with part of the panel was covered by MLI (close to the Median Port Panel). The central part of the panel was considered to be coated with anodized aluminium. The remaining parts were considered to be covered with embossed Silvered Teflon

The remaining panels Starboard Panel, Port Panel, Bottom Panel and Median Port Panel are covered by MLI with the exception of the small items (e.g. Handles and COLKa Attachment Feet that are clear anodized).

Inside the COLKa Platform the surfaces not used for electronic units mounting will have a high emissivity value, to maximize the internal heat exchange among the COLKa electronic units equipment and the case panels.

Dry contact is foreseen between the electronic units and the Platform case panels for the units having low heating

power densities while a thermal filler is used for the units having high heating power densities.
Heaters are used to control the temperature in the cold cases.

VI. Thermal Modelling and Analysis

The analyses are performed using the software ESATAN-TMS 2016.

ISS moving parts and time-varying thermo-optical properties can affect the thermal behaviour of the COLKa FU. For the present analysis, both the effect of the ISS and the interaction with the Columbus were taken into account (see Figure 5)

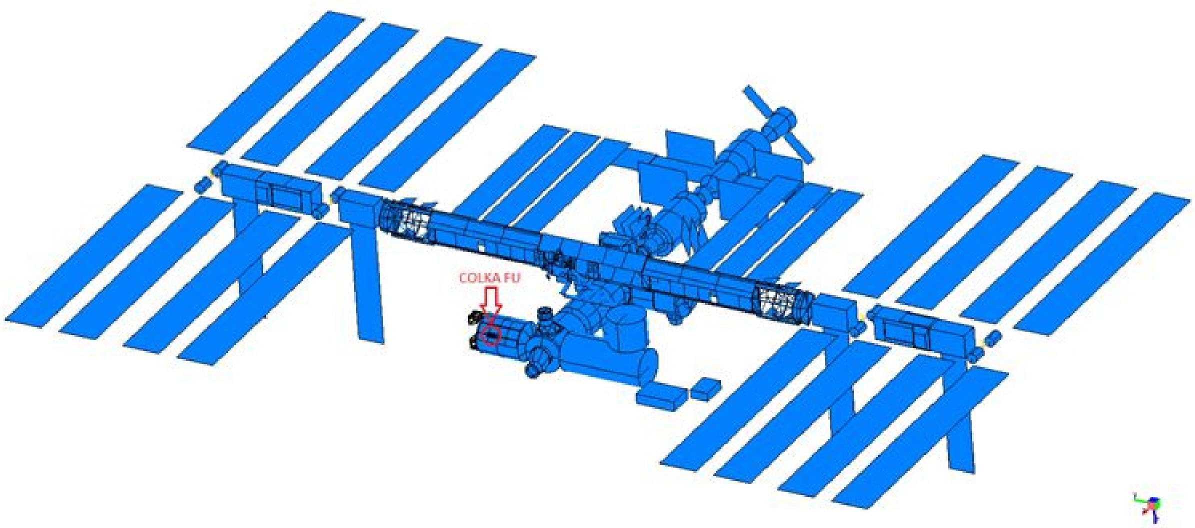

Figure 5. ISS and COLKa FU GMM (Kayser Italia/NASA/ESA)

Three different GMM were used to run all the scenarios analyzed for COLKa:

- Operational Set-Up, BOL properties.
- Operational Set-Up, EOL properties.
- Transfer Set-Up, BOL properties.

Figure 6 shows the GMM of the operational set-up.

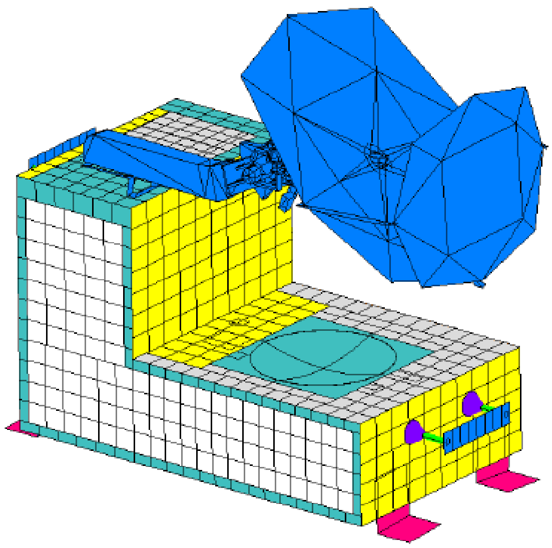

Figure 6. COLKa FU Operational Setup GMM (Kayser Italia).

The cases driving the thermal design are the following:

- Operational Active Mode (Stand-By + Tracking + Tx/Rx) Extreme Hot Case A.
- Survival Mode COLD A

Other important cases affecting the design are the following:

- Stand-by Mode Extreme COLD A.
- Transfer Mode Extreme COLD A.

In addition, the thermal analysis is used for

- Verification of the touch temperature requirements
- Verification of plume impingement requirements (pending)
- Verification of the thermal variations requirements

Finding the compromise between the needs of large radiative surfaces requested to meet the HOT scenarios and the needs to reduce the heat rejected during COLD scenarios considering the available heating power is the more challenging task of the COLKa thermal design.

Screening to determine the worst-case orbital parameters has identified the orbit with β = 0° and yaw/pitch/roll = 0°/-20°/0° (Figure 7) to represent the worst-hot and the orbit with β = -75° and yaw/pitch/roll = -15°/15°/-15° to represent the worst-cold conditions.

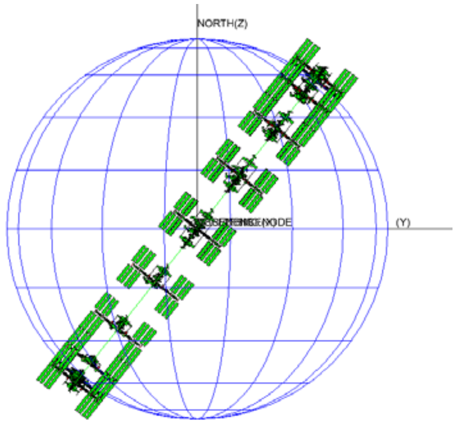

Figure 7. Hot-case orbit (Kayser-Italia)

Limiting the overview to the cases driving the thermal design, the results for the Active (communication) Mode, Extreme Hot Case A, are shown in Table 3. It shows that the only unit outside of the operating limit is the MODEM, but it is not judged as critical. It is worth remembering that the given design limit includes a margin of 10°C. Additional analysis with one heater failed ON has shown that, while the MODEM temperature continues to rise, it does not go higher than 8.5°C above the design limit, and there are work-around options to deal with such a failure case.

Regarding the Survival Mode, Cold Case A, it was analysed with the assumption that the sixteen survival heaters together provide 210 W of heater power. The result is shown in Table 4. With the available power both operating and non-operating temperature limits are met. However, the power for the heaters is provided by the two Thermal Control System (TCS) parts of the Payload Interface Adapter Units (PIAU), with each TCS powering eight heaters. The need and the strategy to deal with a TCS failure, or failure by Columbus to provide power to the TCS, is under evaluation and will form a major issue to be considered also for the verification programme.

VII. Conclusion

As for the worst-hot conditions, full compliance with the unit temperature requirements is seen as achievable with further optimization of the radiator areas. For the MODEM, the most obvious step would be to increase the radiative area of the Median Top Panel. For the worst-cold conditions, the analysis has shown that the available heater power, 210 W, is sufficient to maintain units above the minimum design temperature limits. Currently there is an effort done to understand the effect of a failure case with power available only from one TCS, 105 W. While presently installation of heaters on the panel is preferred, a beneficial effect is reached by installing the heaters directly on the units. Another option under consideration is the local use of Phase Change Material (PCM) devices to sustain a longer period with reduced period in the Survival Mode. The further consolidation of the thermal design and verification is in progress.

Acknowledgments

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References

[1]Lorenzini, F., Ganga, P., and Creati, F., "COLKA – Thermal Report," KI-COLKA-RP-026, 1/3, 2016.
[2]Lorenzini, F., Creati, F., and Ganga, P., "COLKA – Thermal Analysis," KI-COLKA-TN-143, 1/0, 2016.

Table 4. Communication mode, extreme HOT:A, maximum temperatures

COMPONENT	Max T° Design + 10°C margin Operating	HOT_A TXRX max T° (°C)	Delta T (°C)
Antenna Assembly	60	36.0	-24.0
Coaxial Switch L1 (4 pack)	65	36.8	-28.2
DOCON Prime (#1)	45	36.4	-8.6
DOCON Redundant (#2)	45	39.6	-5.4
EPC Prime (#1)	45	40.9	-4.1
EPC Redundant (#2)	45	38.1	-6.9
HPI & Switch Assembly	50	42.3	-7.7
Input Filter T1	50	36.5	-13.5
Dual LNA	45	35.8	-9.3
MODEM	40	42.6	2.6
Output Filter	45	37.5	-7.5
PCDU	45	39.5	-5.5
PIAU	40	36.5	-3.5
Test Coupler Input	50	36.7	-13.3
Test Coupler Output	75	37.8	-37.2
TWT (CC) Prime (#1)	65	60.3	-4.7
TWT (CC) Redundant (#2)	65	44.4	-20.7
TWTA Input Filter T2		34.9	
UPCON Prime (#1)	45	38.9	-6.1
UPCON Redundant (#2)	45	38.3	-6.7
WR34 Switch Ka1 C-Type	55	35.5	-19.5
WR34 Switch Ka2 C-Type (+1 transition +1 load)	55	36.0	-19.0
WR34 Switch Ka3 C-Type (+3 transitions +1 load)	55	38.9	-16.1
WR34 Switch Ka4 C-Type (+2 transition +1 load) (#1)	55	36.7	-18.3
WR34 Switch Ka4 C-Type (+2 transition +1 load) (#2)	55	35.9	-19.1

Table 3. Survival mode, COLD:A, minimum temperatures

COMPONENT	Min T° Design + 10°C margin Operating	Min T° Design + 10°C margin Non-operating	Survive COLD:A minimum T	Delta T WRT Operating T	Delta T WRT NON-Operating T
Antenna Assembly	-5	-10	18.8	-23.8	-28.8
Coaxial Switch L1 (4 pack)	-10	-15	12.8	-22.8	-27.8
DOCON Prime (#1)	0	-15	13.5	-13.5	-28.5
DOCON Redundant (#2)	0	-15	14.3	-14.3	-29.3
EPC Prime (#1)	0	-5	13.9	-13.9	-18.9
EPC Redundant (#2)	0	-5	14.4	-14.4	-19.4
HPI & Switch Assembly	-10	-10	17.8	-27.8	-27.8
Input Filter T1	5	-10	15.9	-10.9	-25.9
Dual LNA	0	-15	15.5	-15.5	-30.5
MODEM	10	-10	14.6	-4.6	-24.6
Output Filter	10	-10	16.6	-6.6	-26.6
PCDU	0	-10	13.5	-13.5	-23.5
PIAU	10	-10	21.3	-11.3	-31.3
Test Coupler Input	5	-10	20.3	-15.3	-30.3
Test Coupler Output	-10	-10	16.0	-26.0	-26.0
TWT (CC) Prime (#1)	0	-5	17.1	-17.1	-22.1
TWT (CC) Redundant (#2)	0	-5	16.2	-16.2	-21.2
TWTA Input Filter T2			5.8		
UPCON Prime (#1)	0	-15	17.9	-17.9	-32.9
UPCON Redundant (#2)	0	-15	17.9	-17.9	-32.9
WR34 Switch Ka1 C-Type	-10	-10	7.1	-17.1	-17.1
WR34 Switch Ka2 C-Type (+1 transition +1 load)	-10	-10	12.5	-22.5	-22.5
WR34 Switch Ka3 C-Type (+3 transitions +1 load)	-10	-10	11.4	-21.4	-21.4
WR34 Switch Ka4 C-Type (+2 transition +1 load) (#1)	-10	-10	16.1	-26.1	-26.1
WR34 Switch Ka4 C-Type (+2 transition +1 load) (#2)	-10	-10	15.7	-25.7	-25.7