LISA THERMAL CONTROL ANALYSIS IN CONTEXT OF THE BAYERNSAT MISSION

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This document deals with an analysis of the thermal control subsystem of a Lightweight Inter-Satellite Antenna (LISA). LISA is expected to be part of the small satellite mission BAYERNSAT. The mission goal is the establishment of a high frequency and data rate inter-satellite communication link to the geostationary satellite ARTEMIS as technology demonstration for telepresence operations.
LISA is designed as small phased array antenna. The mission constraints for LISA orbital performance comprise several low Earth orbits, the wide variety of antenna orientation vectors during operation is challenging.
LISA relies on passive thermal control mechanisms including MLI, sun shield foil and surface finishes. A detailed thermal model with about 1000 nodes is constructed and object to six load cases in order to examine worst case conditions and typical operational temperatures. The computational temperature and heat flux results are investigated and compared with mission requirements. For persistent solar loads in non-eclipsed orbits that contribute to requirement violations, a solution is outlined. Finally, a conclusion with design ameliorations is given.

1. INTRODUCTION

1.1. LISA and BAYERNSAT Framework

LISA (Lightweight Inter-Satellite Antenna) is developed by a cooperation of NTP (Netzwerk Technischer Partner, Neubiberg) and the Institute of Astronautics (LRT) at TU München. LISA will be employed as main high gain antenna on the technology demonstration mission BAYERNSAT (BS) that is initiated at LRT. BS is planned to be a small satellite mission of 50 kg and overall geometric measures of maximum 50 cm. Main payload elements are three cameras for high and medium resolution pictures of Earth. LISA shall be qualified to perform a high-frequency, high-data two-way inter-satellite communication link (ISL) to the geostationary satellite ARTEMIS.

1.2. Technology Demonstration

On-orbit telepresence is a new technology currently being developed for space telecommunication operations that targets at satellite communication with only short time delay. Most Earth-observation satellites have low Earth orbits (LEO) due to better visibility of ground structures and mission costs. LEO orbits generally allow a maximum of about eight minutes of satellite contact to a certain ground station. Only geostationary (GEO) spacecraft (S/C) have abilities to remain in contact with one ground station for the whole revolution time. So today's mission architecture has to either operate with a lot of ground stations or reduced accessibility times. A possible solution for the growing need of continuous access to a satellite is telepresence, i.e. to be “present” in a remote environment by the use of communication interfaces. A two-way ISL established between a LEO and a GEO satellite allows the latter to operate as relay satellite. This principle enables the ground operator to receive Earth observation data nearly instantly and to send executable commands in exchange. In respect to future Earth observation and unmanned S/C repair missions, knowledge of on-orbit telepresence can be a vital technology progress and economic advantage.
LISA project goal is a stable data connection between ground station ⇔ ARTEMIS ⇔ LISA on BS. The ground station shall be enabled to command BS camera focusing (and other operational commands) and obtain satellite Earth observation data within the shortest time possible. ARTEMIS has accessibility to BS for most of the orbit revolution time, (depending on both orbital planes,) and stays in contact to its ground station for the whole time. This distinguishes its use as relay satellite for establishing a long-lasting communication link.

1.3. Thermal Analysis Objective

LISA on BS should be able to operate in a wide envelope of low Earth orbits and orientations of the active aperture surface. A basic design requirement for LISA is thermal stability in a large temperature spectrum. The mission goal projects a BS lifetime of at least six months. This document describes a passive thermal control concept (TCC) for LISA by means of numerical simulation.
A thermal analysis (TA) of BS is conducted to validate the overall satellite bus and payload performance, to find out critical design positions for detailed analysis and to generate boundary conditions for LISA TA.
A high-detail transient investigation of LISA by means of numerical simulation determines antenna thermal performance for different orbital environments.

2. LISA / BAYERNSAT DESIGN SUMMARY

2.1. Satellite Bus Structure

The satellite platform of BAYERNSAT consists of two integral panels and the frame. The other four sides of the cube have sandwich structures mounted on the frame. All structural parts are made of 7075 aluminum alloy. The sandwich panel adjacent to LISA is the antenna panel. An overview of BS structural layout is depicted in FIG. 1. The sandwich panels are not illustrated here to detail the interior elements. LISA is mounted to BS via a steering mechanism.

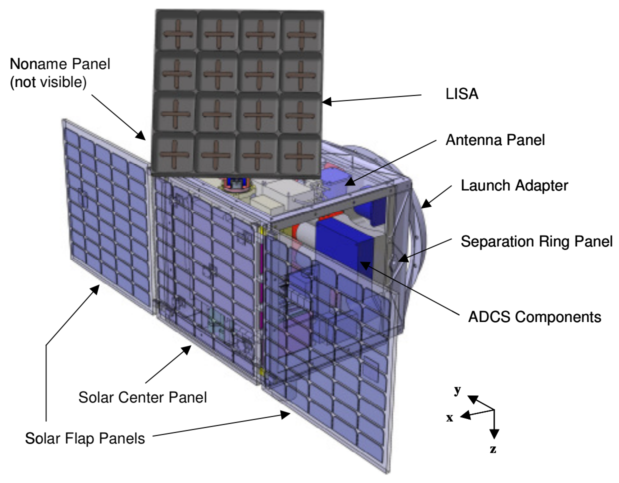

FIG. 1: BAYERNSAT design

2.2. Antenna Design

LISA configuration is an open waveguide radiator array that is fed by a beam forming network (BFN) in microstrip technology. High aperture efficiency and very low connection losses are advantageous. The radiator array consists of 16 waveguide element cavities that are arranged in a 4 x 4 matrix. The dimensions of the aperture in the x-y plane are 399.5 mm x 399.5 mm with a height of 50.0 mm. The radiator housing encases two printed circuit boards (PCB); the aperture is illustrated in FIG. 2.

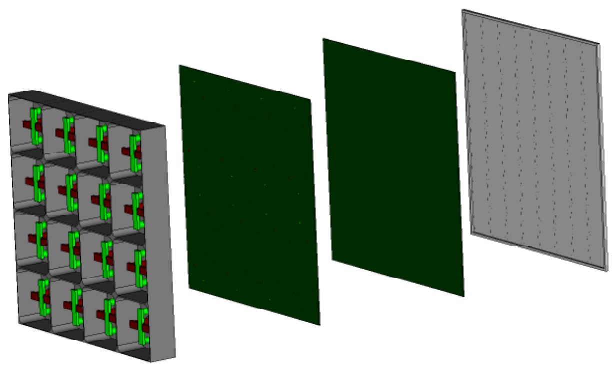

FIG. 2: LISA assembly exploded view

2.3. LISA Thermal Requirements

LISA thermal environment may vary widely between aperture area in direct sun exposure to eclipse with deep space orientation and negligible incidental heat loads. Additionally, LISA thermal capacity is small (as total mass < 4kg) while the surface-to-volume ratio is high. This normally leads to wide temperature variations during orbital revolutions. Temporal temperature changes however shall be minimised. The thermal heat loads on LISA surfaces vary mostly due to the orientation of LISA aperture towards ARTEMIS. ARTEMIS is a moving target itself, the view angle from BS between ARTEMIS and solar vector is crucial. Some orbits therefore have high solar loads, others low. If LISA reaction to changing boundary conditions is not sensible, heat load maxima and minima will result in a smoothed temperature pattern. The projected temperature range then will be small; this constitutes in performance augmentation and wider margins to extreme temperatures.

Internal heat dissipation is low, but concentrated in the distribution network.

2.4. LISA Thermal Control System Design

LISA relies on passive thermal control mechanisms. The TCC aims at maximum possible independant operation and minimum environmental coupling. Solar and Earth heat loads shall have low influence on LISA.

The aperture surface of the antenna array is protected from irradiating IR and UV radiation by a sunshield. The sunshield is made of a Germanium coated reinforced black Kapton blanket. It is applied by the use of velcros and fixed with adhesives.

The back plate is covered with 10 layers of MLI. The MLI overlaps at the edges for about 20 mm and is fixed with velcro strips at the radiator side walls.

About 30 mm of the side wall is bare for radiating heat into deep space. The total unprotected radiator surface of LISA then is four times 30 mm x 400 mm. Cut aluminum surface properties are assumed, as no special surface treatment is intended. Aluminum has small UV absorptance and IR emittance and therefore contributes to a small extent to overall heat flux budgets. FIG. 3 depicts the waveguide array and the thermal design features.

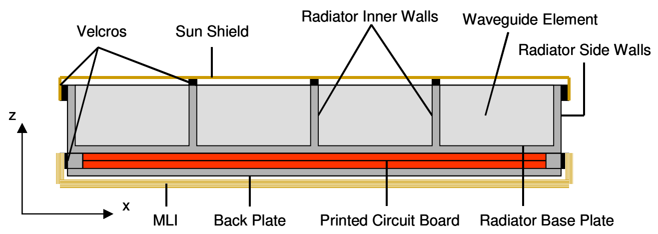

FIG. 3: LISA thermal design

2.5. LISA Pointing Mechanism

LISA back plate is mounted to the antenna adapter and via bearings to a 2-degree of freedom (2DoF) steering mechanism that establishes the connection to the BS satellite bus. The motion perimeter comprises ±180 in azimuthal and 0 - 90 deg in elevation direction. The total pointing directions specify a half-sphere. The device is situated at the satellite interior for protective reasons and geometric size constraints. The electrical conductor that feeds BFN and radiator is situated in the vicinity.

The mechanism is responsible to fulfill LISA orientation requirements. The numerically calculated radiative exchange factors (REF) between BS and antenna parts therefore have to be modeled variably. This analysis only regards the elevation angle movement for simplicity.

3. MISSION REQUIREMENTS AND CONSTRAINTS

3.1. Orbit

An orbital envelope has been defined. The Earth observation payload determines a LEO between about 390 km lowest altitude (mostly due to aerodynamic drag influence in lower orbits) and 780 km altitude (dependant on LEO launcher abilities). The orbital inclination is set between 53 deg (the whole of Germany should be visible) and 98.5 deg. Circular orbits are favoured.

An important parameter for thermal loads on low Earth orbits is the beta angle. It defines the angle between orbital plane

(ORP) and solar vector. Low Earth orbits with a precession rate that does not match the Earth revolution round the sun show a beta angle drift. Right Ascension of Ascending Node (RAAN) and inclination i determine the beta angle β over time and therefore the sun-exposure-to-eclipse ratio. The critical beta angle defines the transition between eclipse and eternal sunlight orbits.
For this analysis two candidate orbits are defined. The LEO chosen has the lowest altitude and inclination of the orbital envelope. It embraces long eclipse phase duration for low and no eclipse phase for high beta angles. IR and albedo loads are highest due to Earth proximity. The SSO is characterised by lower Earth albedo and planetary IR loads. Additionally, the BS shading of LISA reaches high percentages. TAB. 1 summarises the orbital parameters for the analysis.

Orbit	Altitude [km]	Inclination [deg]	RAAN [time]	Beta Angle [deg]			Eclipse time [%]	
				Critical	Max	Min	Max	Min
SSO	774.0	98.5	14:30	±63.1	+42.3	+28.9	29	33
LEO	395.0	53.0	variable	±70.3	±76.4	0.0	0	39

TAB. 1: Candidate orbits for LISA thermal analysis

3.2. Operational Modes

LISA has to fulfill several operational modes with different orientation requirements and internal heat dissipation.

- Telepresence Mode:
  Telepresence Mode (TPM) requires an established ISL between LISA (BS) and ARTEMIS, therefore LISA waveguide aperture orientation is fixed to ARTEMIS. The satellite bus with its cameras mounted on nadir panel is oriented to Earth. Both orientation requirements are executable at the same time due to the steering mechanism. TPM is the only configuration with electric fluxes dissipated to internal heat. Long TPM phases with aperture orientation towards sun vicinity are expected to be hot orbits.
- Non-operational Modes:
  Non-operational modes (NOM) include charge mode or safe mode. LISA is not obliged to point in a certain direction and internal dissipation is 0 W. The aperture pointing can be partly adjusted by thermal requirements.
- Hibernation Mode (HM)
  This mode configuration is chosen for eclipse duration. Main focus is on the avoidance of significant heat losses. The BS payload camera panel is strictly oriented towards Earth, as the video cameras are the most temperature-sensitive part. LISA is in stored flat position and contributes to heat loss minimisation of BS through shielding the antenna panel. There still is a rotational degree of freedom round the z-axis, but it has no thermal influence

The orientation requirements are summarised in TAB. 2. The orientation given in brackets describes the second pointing direction. It normally is in conflict with the first orientation constraint, thus executed as far as possible. LISA basic position is flat stored on the antenna panel.

Mode	LISA orientation		BS orientation	
	z-axis	x-axis	Nadir panel	Solar panels
Telepresence (TPM)	ARTEMIS	n/a	Earth	n/a
Non-operating (NOM) (SSO CC, charge mode)	flat stored position		(Earth)	sun
Non-operating (NOM) (LEO worst CC)	(deep space)	sun	Earth	n/a
Hibernation (HM)	stored flat position		Earth	n/a

TAB. 2: LISA operational modes

TPM requires adequate visibility of Earth structures. The payload video cameras need an incident sun angle of more than 15 deg to recognise and resolve Earth structures in an adequate way. Further requirements for TPM include i.e. charged batteries. Additionally, TPM is futile if BS position is beyond oceans or clouds are covering the surface. These constraints limit the time intervals.
In respect to applicable operational modes, the Earth can be divided into three zones depicted schematically in FIG. 4. These zones and BS position are dependant on orbit parameters. The partition right of the red marker delineates a solar elevation viewed from ground of 15° or more needed for TPM. The left side behind the blue dash denotes the Earth region in eclipse with satellite objective of hibernation. At the intermediate partition between red and blue dash, BS and LISA are in sun exposition. Non-operational modes are feasible for all positions in sun exposure (right of the blue dash).

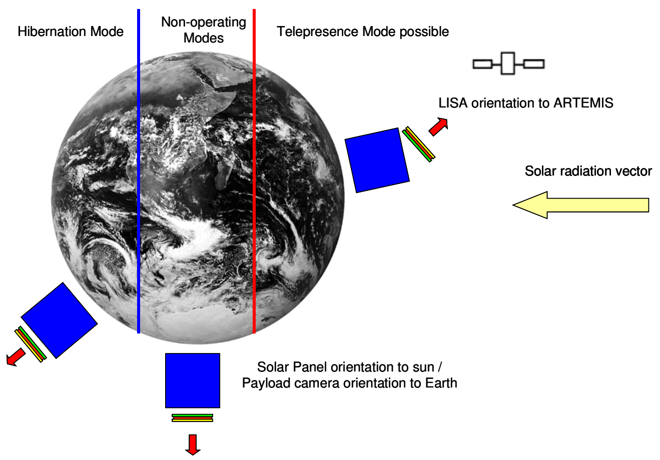

FIG. 4: Modes dependant on orbital position

3.3. Thermal Requirements

The temperature spectrum for qualification of LISA parts is between –100 °C and +100 °C. The allowable calculation temperature range for LISA therefore is between –80 °C and +80 °C due to calculation uncertainties.

4. BAYERNSAT THERMAL ANALYSIS

4.1. Thermal Model

The thermal model consists of 36 diffusive nodes and one space boundary node. Ten nodes form the structural parts, five are thermal hardware elements. Radiator panels are modeled as one node; MLI-covered panels are separated in two nodes. 21 payload elements are modeled. Small interior structural parts like holders and carriers are ignored in the radiation calculation.
The estimated global mass of BS is 40 kg, the global thermal capacity 30.8 kJ/K. These assumptions constitute a conservative approach. The thermal model is depicted in FIG. 5 to FIG. 7.

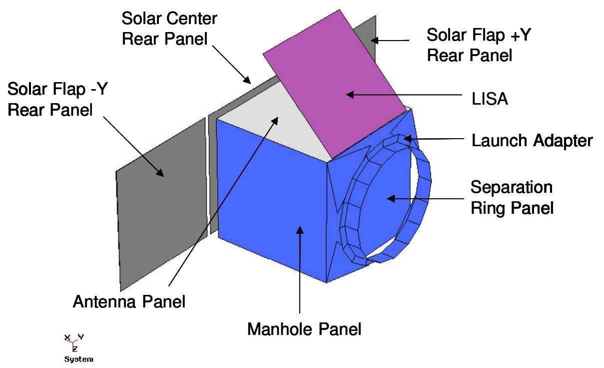

FIG. 5: Thermal model, exterior view

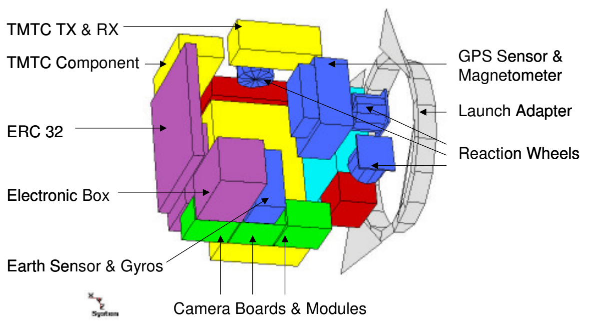

FIG. 6: Thermal model, internal view 1

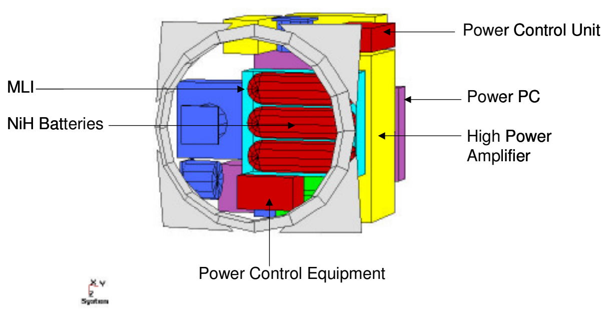

FIG. 7: Thermal model, internal view 2

4.2. BS Temperatures

For the above mentioned LEO, typical hot and cold operational orbits are presented.

4.2.1. Cold Case

The BS structural parts temperatures vary between -5 °C and –20 °C. The S/C boundary temperature for LISA analysis therefore is chosen to be –20 °C. The thermal behaviour is depicted in FIG. 8.

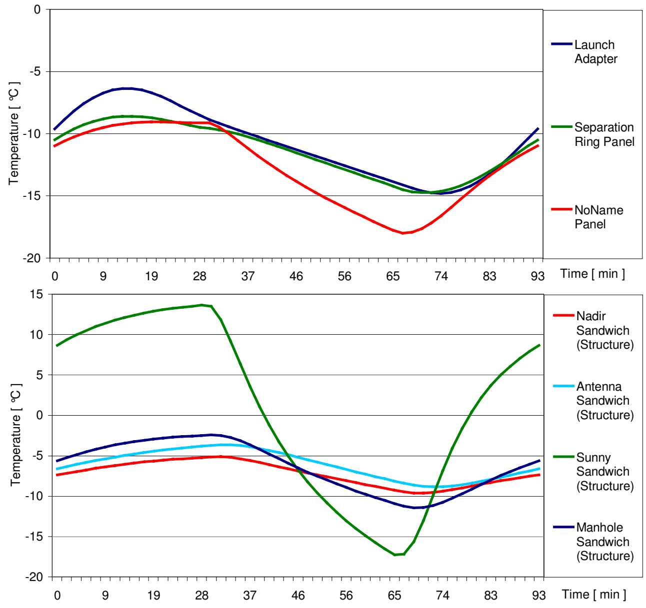

FIG. 8: BS cold case temperatures

4.2.2. Hot Case

The maximum temperatures are around 30 °C, so this value is chosen as boundary for hot LISA environment.

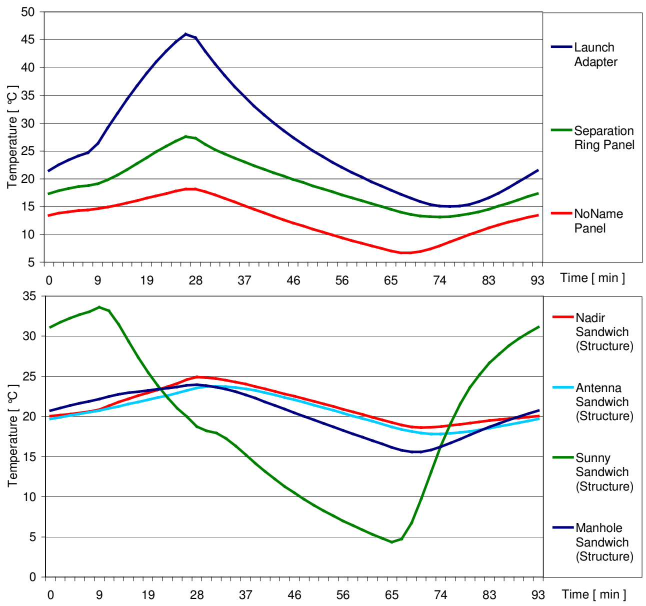

FIG. 9: BS hot case temperatures

4.3. Results Overview

The results of the preliminary BS thermal design are both promising and challenging. Most components of the satellite lie within the range of the accepted temperatures. Sensitive parts like batteries and camera modules have to be considered in detail.
TPM is mainly responsible for temperature augmentations.
Reasons are the dissipated power in the internal satellite elements and its pattern only vaguely known, and the orientation and operation requirements are quite different in cold and hot cases.

5. LISA THERMAL MODEL

This chapter specifies the thermal model that is adequate to simulate the thermal performance of LISA.

5.1. Software Code Architecture

The TMM architecture is based on the main programme LISA.D and various subordinate routines with special tasks. The hierarchical modular structure is outlined in FIG. 10.

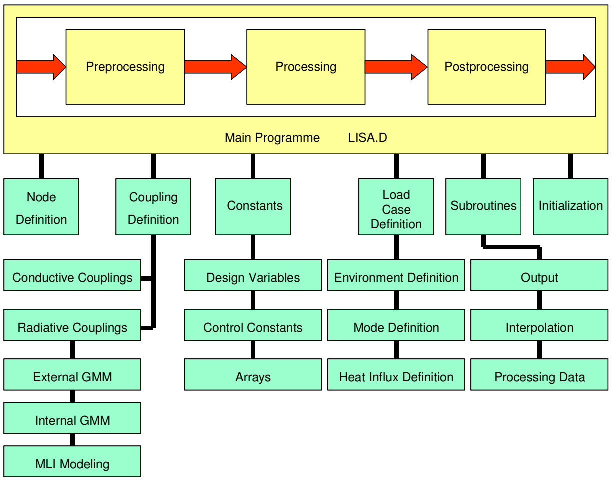

FIG. 10: Thermal model software architecture

5.2. Model Nodal Breakdown

The TMM defines about 1000 thermal nodes. The complete LISA thermal model consists of three nodal categories:

- Diffusive nodes are subject to temperature change and have a thermal capacity. The determination of their temperature behaviour is part of the solution. LISA TMM contains about 920 diffusive nodes.
- Boundary nodes have fixed temperature behaviour but influence diffusive node behaviour. Two boundaries are determined, space and BS.
- Virtual nodes are helpful for computational algorithms such as determination of MLI efficiency and for output data. This analysis includes about 100 virtual nodes.

5.3. Geometric Mathematical Model (GMM)

The GMM objective is to determine radiative exchange factors (REF) of surfaces and combine view factors with thermo-optical material properties. The GMM contains two submodels:

- The interior model relates internal waveguide elements to radiator housing and sun shield. LISA contains in total 16 waveguide elements. The sun shield assumed to be completely opaque.
- The exterior model couples LISA to space and BS satellite bus. Orbital simulations to determine surfacial heat loads are performed with this model. BS boundary is modeled as a cube. This model delivers time-dependant REF arrays.

The node notation of interior and exterior model is consistent. The GMM is depicted in FIG. 11 and FIG. 12.

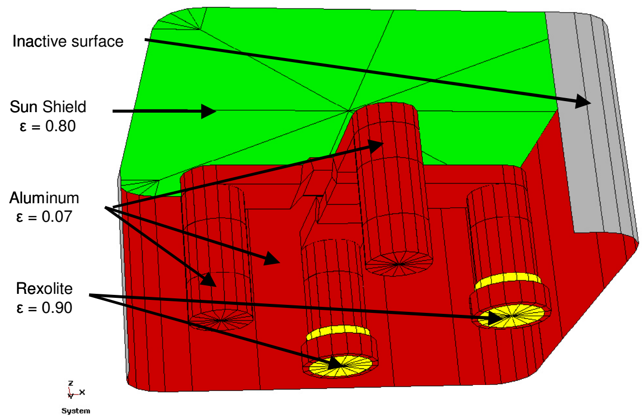

FIG. 11: GMM, internal view, thermo-optical properties

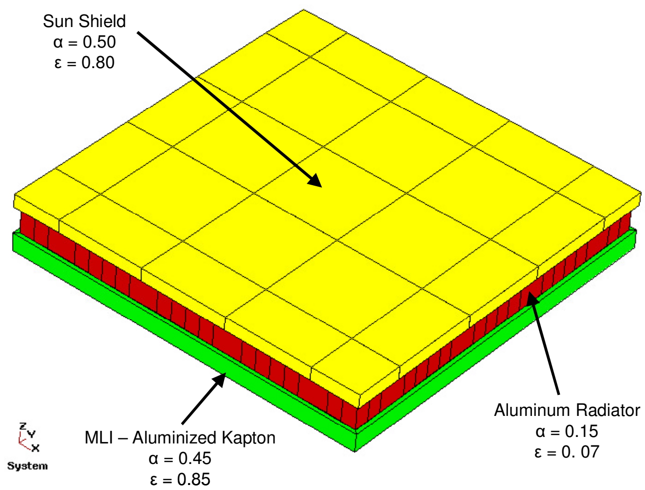

FIG. 12: GMM, external view, thermo-optical properties

5.4. Thermal Mathematical model (TMM)

The TMM comprises linear heat transfer couplings, GMM REF and thermal capacities. In some cases, linear heat transfer is difficult to predict.

5.4.1. Contact Conductances

Contact conductances between adjoining materials are a function of material pairing, contact surface quality such as roughness and waviness, contact pressure and stiffness. Minor deviations may play major roles. As a consequence, contact conductances are hardly predictable. A possibility is to employ empirical values.

5.4.2. MLI Modeling

Multi layer insulation aims at minimising heat fluxes especially between S/C components and space environment. Heat Transfer through MLI is composed of radiative and conductive heat fluxes that both have to be taken into account. Additionally, temperature gradients through a package can be quite high. The MLI modeling approach consists of the definition of two opposing surfaces linked only by radiation. The internal heat flux has a temperature-dependant effective emissivity.

5.4.3. Velcro Modeling

A special sort of velcro qualified for space is used. They attach the Germanium Kapton SSF and the MLI package to the aluminum radiator and back plate. The small contact area

(2.5% of the velcro dimensions are assumed) between both strips results in excellent insulating qualities.

5.5. Solving Process

The orbital- and time-depending heat loads and REF are obtained by executing the GMM.

The orbital data is prepared for every 12 to 15 deg in the orbital plane, in total 30 positions are calculated. Values between these positions are interpolated linearly. Two vertices are inserted for terminator transition, the time gap between both in the twilight phase is assumed to be 20 s.

6. THERMAL ENVIRONMENT

6.1. Boundary conditions

The thermal environment comprises Earth and solar radiation and space boundary conditions. LISA operational modes define the positioning in space. The orbit and orientation requirements then determine load cases by defining heat loads on the various surfaces. TAB. 3 illustrates cold case (CC) and hot case (HC) environment.

Environmental parameter	Wavelength	Unit	HC	CC
Incident solar flux	UV	[W/m^2]	1420.0	1320.0
Earth albedo	UV	[-]	0.35	0.20
Earth black body equivalent temperature	IR	[K]	260.0	245.0
Space temperature	IR	[K]	4.0	4.0

TAB. 3: Thermal environment

6.2. Heat Dissipation Pattern

As outlined in previous chapters, LISA is operating and transmitting data in TPM only. The distribution network functions as electric conductor between LISA and S/C. Electrical resistance produces internal waste heat that is dissipated mostly in the BFN between the PCBs. Antenna design constraints are responsible for the heat dissipation distribution pattern illustrated in FIG. 13.

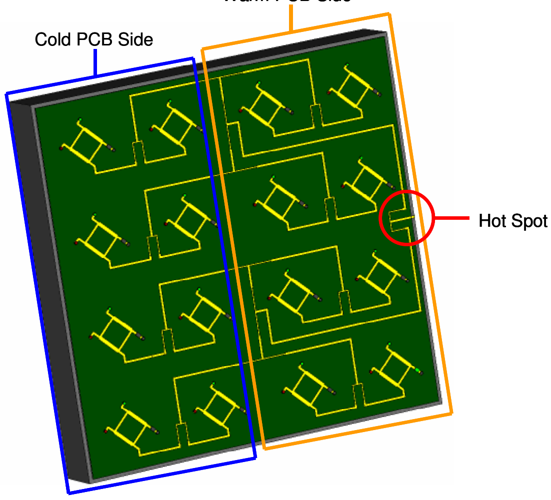

FIG. 13: Heat dissipation pattern

7. ANALYSIS CASES AND RESULTS

This paragraph describes orbital parameters and results for both worst cold and hot case (CC / HC) and two more frequent operational case (OC) orbits.

7.1. Worst Hot Case

7.1.1. Load Case

The worst HC combines maximum heat loads on LISA aperture with persistent TPM. The antenna panel acts as radiator and is hot (30 °C). The HC consists of a LEO orbit with a beta angle that exceeds the critical beta angle of 70.3 deg. The maximum beta angle of 76.44 deg assumed here requires coincidence of solstice and RAAN of 180 (0) deg in a coordinate system with gamma (vernal) point orientation. The low altitude of 395 km contributes to maximum IR influx. ARTEMIS pointing vector is aligned with the sun vector. Winter solstice in coincidence with hot planetary temperature and high solar and albedo loads are assumed.

LISA operational mode is TPM for the whole orbital revolution of 92 min 28 s. Nearly all LEO 395 km orbits have non-eclipsed phases of more than 10 revolutions.

The orbit is illustrated in FIG. 14; orbital plane (ORP) and BS rotation are illustrated with red arrows, the equatorial plane (EQP) with a green dash.

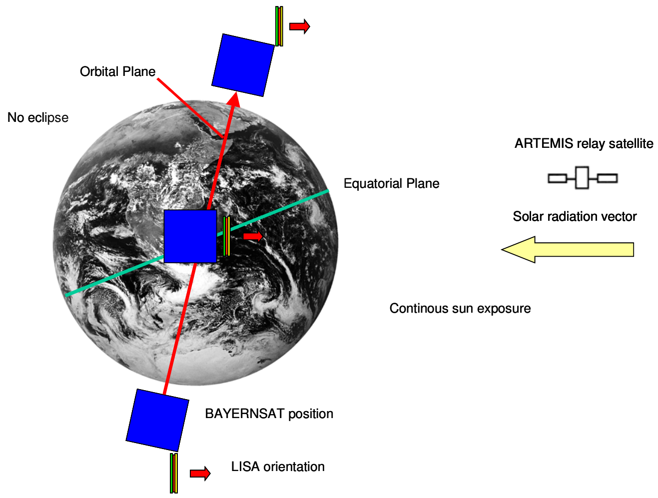

FIG. 14: Worst hot case orbit

7.1.2. Temperature Results

The values of LISA temperatures given in FIG. 15 are not dependant on BS orbital position. Radiator housing (base plate, radiator walls) and back plate reveal constant temperatures of about 67 °C – 69 °C. They fulfill the maximum hot calculation temperature requirements of 80 °C. The printed circuit board however violates that requirement by achieving temperatures of 93 °C at hot spot position. The average PCB temperature however is about 69 °C, the warm side attains 76 °C.

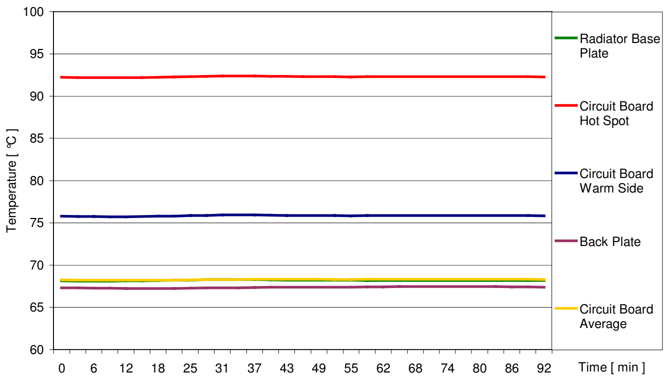

FIG. 15: Worst HC temperatures

The temperature declines quickly when the orientation of the radiator surface is turned to deep space and irradiating solar radiation is reduced, as it is outlined in FIG. 16. The cool down results reveal a possible solution to limit maximum temperatures in enduring hot orbit conditions.

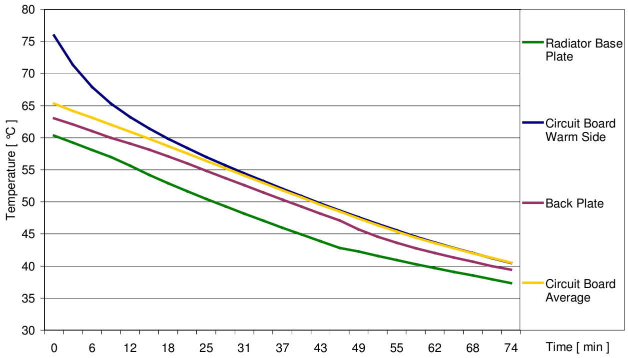

FIG. 16: HC temperature decline

7.2. Worst Cold Case

7.2.1. Load Case

The worst CC is a 775 km SSO with a short eclipse phase of 30 min 54 s, total revolution time is 100 min 21 s. An afternoon orbit is chosen with a local time of 14:30 at the ascending node, the beta angle is 37.0 deg.
BS is in chare mode during sun exposition, so the solar panels are oriented in sun direction. LISA is always in flat stored position; the aperture is oriented towards deep space orthogonal to the sun vector. No direct solar radiation reaches the front sun shield, and BS satellite body shields nearly all albedo and planetary IR irradiating on the back side and the edges. In eclipse, BS cameras are oriented towards Earth, so LISA receives only a small fraction of IR loads there. Environmental conditions are cold planet temperature, low albedo and solar loads. BS temperature is -20°C.
FIG. 17 illustrates the orbit. The ORP is depicted as ellipse because it is inclined 37 deg to the drawing plane.

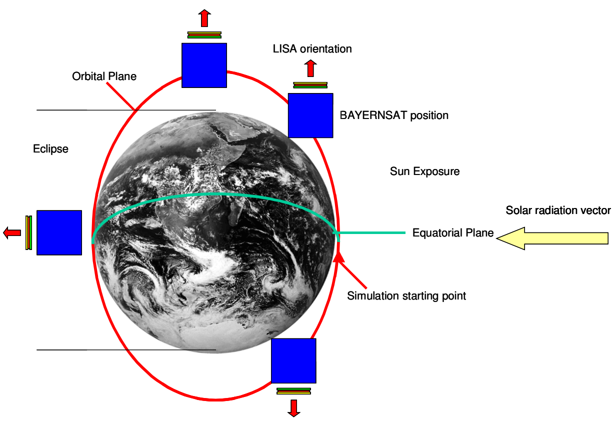

FIG. 17: Worst CC orbit

7.2.2. Temperature Results

The average temperatures for internal LISA elements are depicted in FIG. 18. Temperatures lie within a 3-degrees-range from -69 to -66 °C.

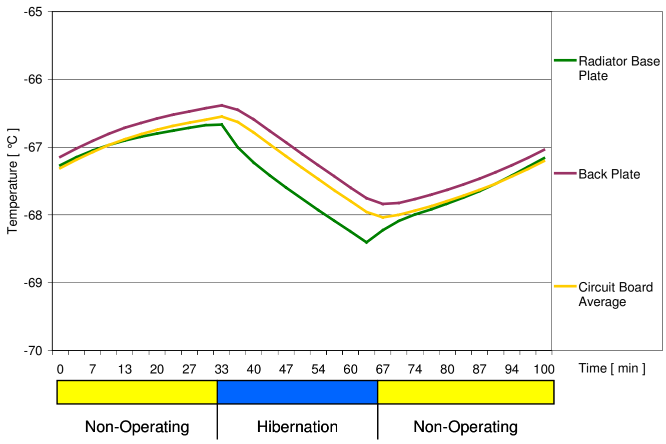

FIG. 18: Worst CC temperatures

7.3. SSO Hot Operational Case with Charge Mode

7.3.1. Load Case

The orbit assumed for this OC is a SSO with RAAN of 14:30 h local time at vernal equinox. The beta angle is 37.0 deg, the eclipse phase is short (30 min 54 s), being 31 % of 100 min 21 s revolution duration.
The TPM takes about 40 min 8 s or a 144 deg orbital segment. This is considered to be the maximum for ground visibility reasons. The rest of sun exposition time (29 min 19 s) is utilised for charging operations, LISA is in basic position and oriented to deep space (orthogonal to solar vector).

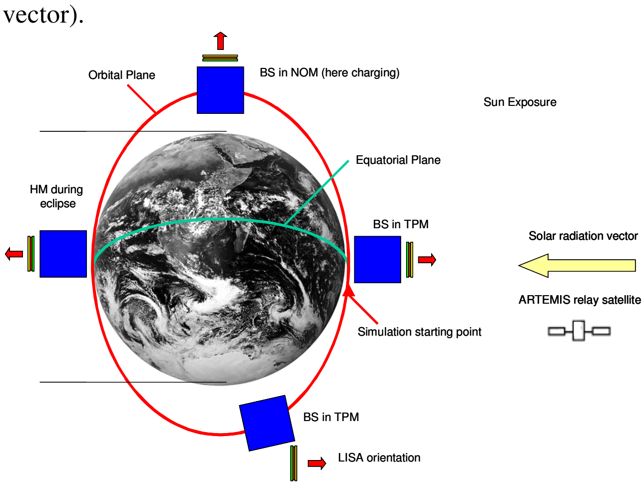

FIG. 19: SSO Hot OC orbit

7.3.2. Temperature Results

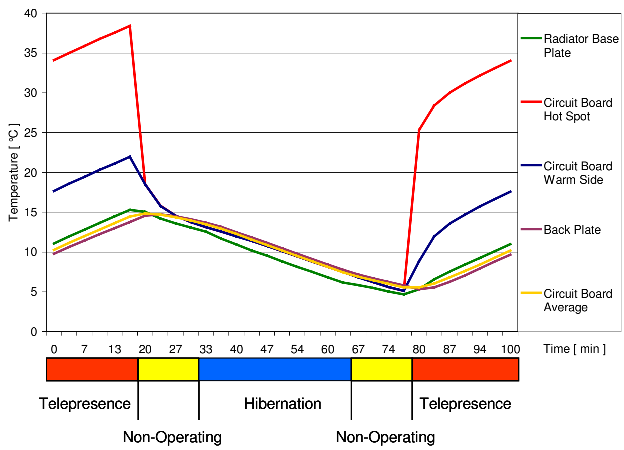

FIG. 20: SSO Hot OC temperatures

7.4. LEO Cold Operational Case with Telepresence

7.4.1. Load Case

The LEO cold OC is a 395 km altitude orbit with a beta angle of 0 deg. These orbital parameters represent the highest eclipse-to-sun-exposure ratio of all feasible orbits. The eclipse lasts for 36 min 7 s of total 92 min 28 s revolution time.

LISA aperture orientation vector is orthogonal to the solar vector, therefore no direct solar radiation reaches the front sun shield. BS shields a considerable fraction of the albedo and planetary IR, but less than in a LISA continuous flat stored position.

Environmental cold conditions for sun, albedo and planetary radiation influx are assumed. TPM operates for about 7 minutes towards the end of sun exposure period.

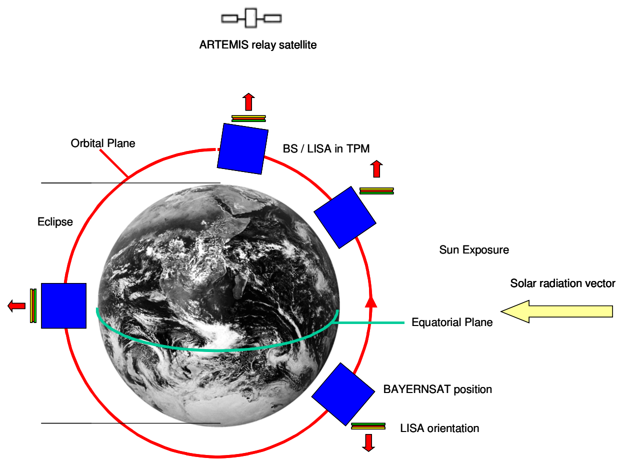

FIG. 21: LEO Cold OC orbit

7.4.2. Temperature Results

The short TPM results in a hot spot temperature rise of about 25 °C in only seven minutes. The internal parts react with an average temperature increase of about 1 °C. The warm PCB side temperature rises by about 7 °C. General temperatures are about -50 to -55 °C

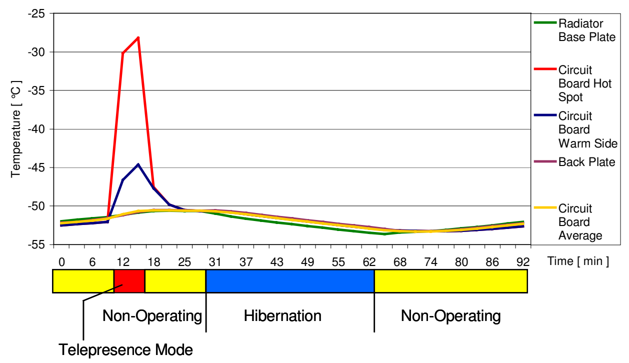

FIG. 22: LEO Cold OC temperatures

8. DESIGN RECOMMENDATIONS

8.1. BFN Hot Spot Requirement Violation

The hot spot in the beam forming network is a result of high dissipation in a small area. The PCB material is not able to distribute the heat quickly, but the distribution network electrical conductor material might enhance distribution. The temperatures in the hot spot achieve high violating temperatures only if:

- The orbit receives large amounts of energy (especially solar loads by sun shield absorption);
- The preceding orbits left behind LISA average temperatures about 45 °C;
- TPM lasts for about 30 minutes or more.

The printed circuit boards of LISA (especially the hot spot area) has to be coupled well to radiator base plate and back plate. Possibilities are the application of thermal interface fillers or gaskets. They can be applied to the specified region and let apart not influenced PCB areas. A stiff back plate also enhances heat transfer.

8.2. General LISA Temperatures Conclusion

Cold case temperatures require long times to be attained, but cold orbits are numerous. According to the general small orbital temperature changes, LISA temperatures are assumed to be rather cold than hot. The only exception to that is the PCB hot spot. In conclusion, overall LISA temperatures are determined to a larger extent by the aperture pointing than by internal dissipation.

In general, LISA thermal behaviour is in agreement with the requirements. For the critical HC, a possible solution is to withdraw the antenna from direct solar irradiance when clouds cover Earth structures. Only small adaptations in the surrounding of the BFN hot spot are necessary for qualification.

9. LITERATURE

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