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LISA – LIGHTWEIGHT INTER-SATELLITE ANTENNA

R. Lundin, J. Letschnik, U. Walter
Institute of Astronautics, Technische Universität München
Boltzmannstrasse 15
D-85748, Garching / München
+49-89-289-16003
office@lrt.mw.tum.de
Germany

N. Nathrath, M. Trümper
NTP, Netzwerk Technische Partnerschaft
Lena-Christ-Strasse 22a
D-85579, Neubiberg / München
+49-89-602305
ntp.truemper@gmx.com
Germany

M. Lang
Institute for Lightweight Structures, Technische Universität München
Boltzmannstrasse 15
D-85748, Garching / München
+49-89-289-16111
Lang@llb.mw.tum.de
Germany

ABSTRACT

Project LISA (Lightweight Inter-Satellite Antenna) was initiated to develop a space-qualified antenna for inter-satellite communication in S-band. This antenna will be constructed of Composite Fiber Reinforced Plastic (CFRP) in order to obtain thermal stability without major displacements due to thermal loads. This technology will also enable to build an antenna operating at higher frequencies such as Ka-band, because in space industry there is growing need for long-term and high data rate communication links to satellites in Low Earth Orbit (LEO) via inter-satellite links (ISL). To accomplish this, a steerable antenna is needed to constantly point to the communicating satellite, for instance a geostationary relay satellite. Since electronically beam steering is limited to steering angles up to about 60°, LISA will be mounted to a two-degree-of-freedom (2-DoF) mechanical device which enables steering of even more than 90°[1].

The project strategy is to construct an antenna of aluminum (engineering model) to be used as a baseline and a reference model for the final antenna made of CFRP material (flight model). This will allow verifying the performance of the CFRP antenna by comparing it to that of the aluminum model. Since both models are developed to be used in space environment this strategy allows verifying the results of antenna measurements. The long-term goal of this project is to proceed with this design for higher frequencies (Ka-band) in order to achieve very high data rates. In this paper the concept for LISA, with its requirements, will be presented together with the first design features and results.

1. INTRODUCTION

The BayernSat [2] project started in March 2004 at the Institute of Astronautics to develop a micro-satellite. The dimensions of BayernSat will be 50 x 50 x 50 cm and it will have an overall weight of about 50 kg. The primary objective of BayernSat is to verify and demonstrate a two-way ISL via a geostationary data relay satellite to a ground station [3], see FIG 1.

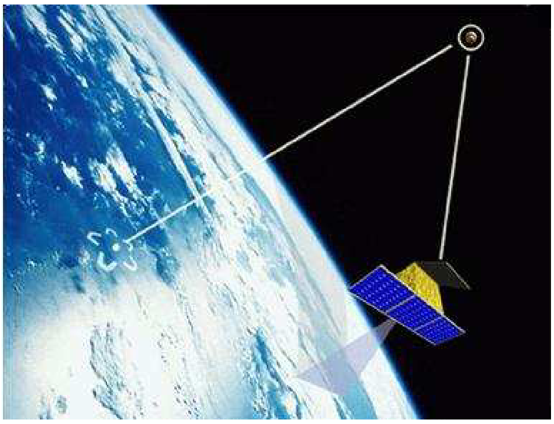

FIG 1: Mission concept of the satellite project BayernSat

Such a relay link will strongly enhance the acquisition time to a LEO satellite compared to a classical, direct link between the satellite and a ground station [4]. For BayernSat the link will be used to uplink control commands for a steerable onboard color video camera and to downlink its pictures to ground via the relay satellite. The signal roundtrip time of this communication link should be less than 0.8 seconds in order to provide a transparent feeling, i.e. an almost immediate movement response of the camera to the steering commands from a user on ground. The principle of transparent activities of remote targets is also referred as “telepresence activities” and a lot of non-space related research has been done in this field, for instance in the research project called “Realistic Telepresence and Teleaction” [5] funded by the German Research Community (DFG), but only little space related work, such as ROKVISS [6]. This paper focuses on a light-weight inter-satellite antenna, LISA, that will enable the communication link between BayernSat and ESA’s geostationary data relay satellite ARTEMIS.

2. LISA REQUIREMENT

LISA is designed to establish a forward and return ISL between BayernSat and ARTEMIS. The operational frequency band for LISA is defined by the forward and return link frequencies allocated for ARTEMIS. This implies that LISA has to be designed to conform to these external requirements. The links involved in this communications architecture system is defined in FIG 2 below.

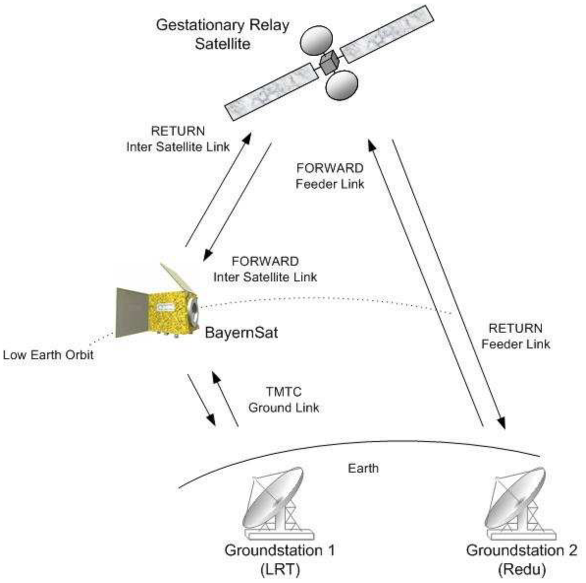

FIG 2: Communication architecture for LISA

It is the intention to develop a lightweight space qualified antenna based on composite materials. Furthermore, the antenna should exhibit thermal stability over a long time. To date many antennas are manufactured from aluminium which deform significantly under strong thermal loads. Therefore, LISA will be constructed from a more thermally stable material.

It is designed to work in S-band and to have small mass and dimensions. In order to meet the growing need for telepresence requirements over a long time period in LEO a steerable high gain antenna is needed to constantly point towards ARTEMIS during the accessible time. ARTEMIS tracking can either be achieved with an electronically steerable antenna or with a passive antenna mounted on a mechanical steering device. However, when tilting a beam off the antenna’s normal direction electronically the gain decreases with the cosine of the tilt angle. Since for small antennas every contribution to the link budget counts, LISA was chosen to be passive and to be mounted to a mechanical 2-DoF steering device.

Payload mass is precious in space due to costly launch masses as well to the fuel needed for the satellite’s attitude corrections in space. Therefore it is favorable to construct a lightweight antenna of composite material. Size also matters for satellites, since it is restricted by launchers. In particular secondary payloads are strongly regulated in size and configuration. Therefore the size of the antenna should also be kept to a minimum without violating the system requirements.

The harsh space environment restricts the number of applicable materials. Materials proven to work on Earth in high-frequency applications might not be suitable for space. Space antennas are often made of aluminum which make them light-weight and fairly durable. In order to verify the advantages of LISA made from CFRP an otherwise identical antenna (engineering model) will be made of aluminium. Both antennas will be space-qualified so their performance can be compared directly to each other.

3. LISA DESIGN

Initial LISA studies covered all possible types of antennas, such as a short backfire, slotted waveguide, parabolic disc, patch array, and open waveguide antenna. The decision fell on the open waveguide antenna. It has a very high aperture efficiency providing high gain for the small antenna size and it covers a relatively broad frequency range for up- and downlink frequencies. Furthermore, its development is rather straight-forward; no major manufacturing obstacles could be identified. Another reason for this choice is that it can be down-scaled to work in the Ka-band without a design change. The final LISA dimensions will be a compact 40 x 40 x 6 cm antenna with a height of only 6 cm. A mechanical design of LISA is depicted in FIG 3.

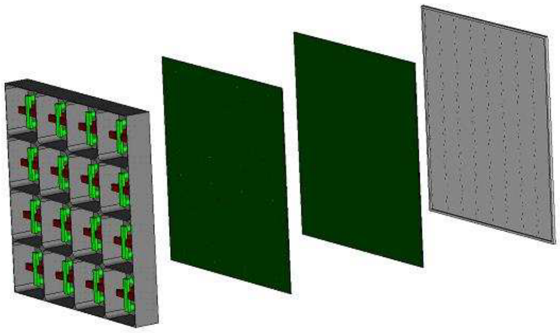

FIG 3: The mechanical layer structure of LISA

LISA's top layer is an arrangement of 4 x 4 = 16 cavities with dipole radiation elements in a cross pattern to circularly polarize (left hand circular polarization) the transmitted signal. Below this layer two RT Duroid™ layers enclose the RF distribution network for the radiating dipoles. These two layers will be sandwiched by the top cavity layer and a back plate to seal the antenna.

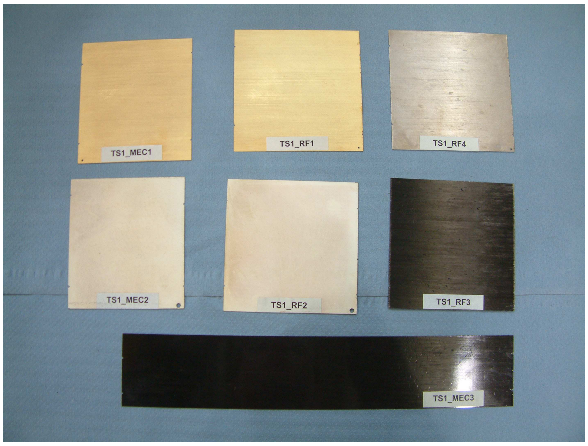

FIG 4: CFRP test samples with and without different metallic coatings (black samples without any coating) [7]

The flight model will not just be a CFRP copy of the aluminum engineering model. Rather the radiating dipole elements will be kept to be of aluminum integrated into CFRP cavities. To ensure the electrical performance of the CFRP antenna, the cavities will have a metallic coating, see FIG 4. While the back plate will be made of CFRP the RF distribution network will be identical to that of the aluminium model.

4. TECHNICAL SPECIFICATIONS

An ISL with LISA via Artemis will be the main path for all communications with BayernSat. The acquisition of this signal will be managed at the ESA ground station facility in Redu, Belgium. However, for telemetry and telecommand also an omni-directional antenna will be used for backup purposes and to constantly track BayernSat when visible from the ground station at the Institute of Astronautics (LRT).

4.1 Frequency Range

The frequency range for the ISL provided by ARTEMIS is given in FIG 5. It includes a receiving and transmitting range. Therefore, LISA's bandwidth is required to overlap both ranges.

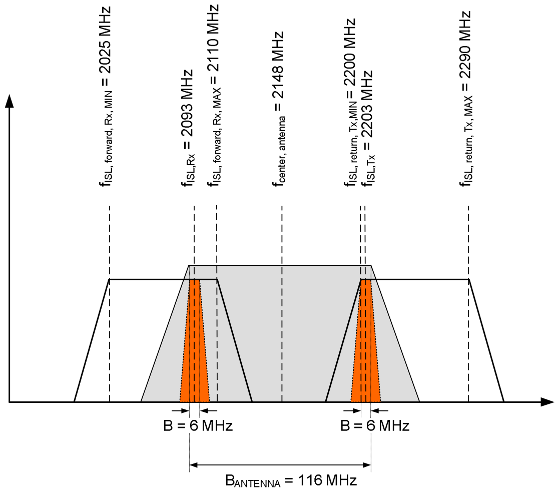

FIG 5: Frequency plan for LISA

The center frequencies in TAB 1 constitute the required total bandwidth for LISA and define the bandwidths for the receiving and transmitting channel, respectively. This implies that LISA will operate in the frequency band 2090-2206 MHz which gives a required LISA bandwidth of 116 MHz (5.4% of the center frequency). Furthermore, LISA will have a left hand circular polarization (LHCP) and a center frequency of 2148 MHz.

Link	ARTEMIS Forward S-band ISL	ARTEMIS Return S-band ISL
Polarization	LHC	LHC
Channel Definition	$f_{ISL,Rx}$	$f_{ISL,Tx}$
Center Freq. (MHz)	2093,0	2203,0
Bandwidth (MHz)	6	6

TAB 1: Receive and transmit center frequencies chosen for LISA

4.2 Co-polar and Cross-polar Radiation Pattern

In view of the ISL conditions the co-polar radiation pattern must have rotational symmetry. Any iso-level cut through the co-polar main lobe pattern of the antenna must display a roughly circular shape with a maximum relative angular deviation from a circle of ≤ 10 percent.

Since LISA is designed to work with LHCP the cross polarization will be equal to the right hand circular polarization (RHCP). The peak level of the cross-polar component of the antenna must be less than 20 dB compared to the peak level of the co-polar component in the boresight direction. The cross- and co-polar radiation pattern simulations are depicted for two different cuts in FIG 6 and FIG 7. From these graphs it can be realized that the requirement for the cross-polar radiation level is fulfilled.

4.3 Antenna Gain

The antenna gain is defined in boresight direction relative to a LHC polarized isotropic radiator. The goal for LISA is to achieve 17 dBi, at least 16 dBi, for the frequency band of LISA as specified above. The first side lobe should be kept 20 dB below the maximum gain level in boresight direction. As seen in FIG 6 and FIG 7 this requirement is fulfilled for the 45° cut but not for the 0° cut. However, rather than to attenuate the first side lobe which would imply a non-uniform illumination of the radiating antenna elements which in turn would complicate the design of the RF distribution network significantly, it was decided to preserve the simplicity of the antenna construction.

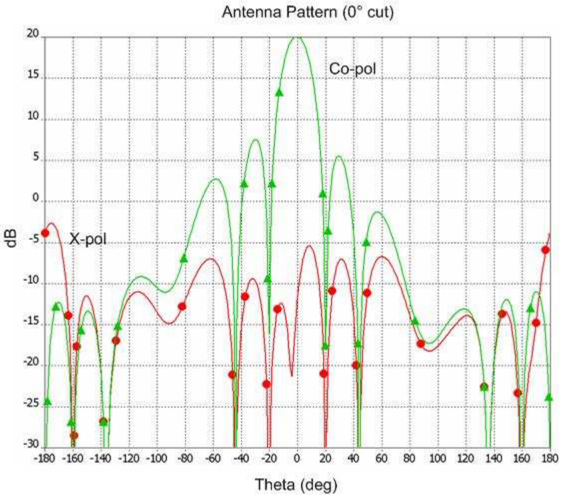

FIG 6: Antenna pattern at 0° cut

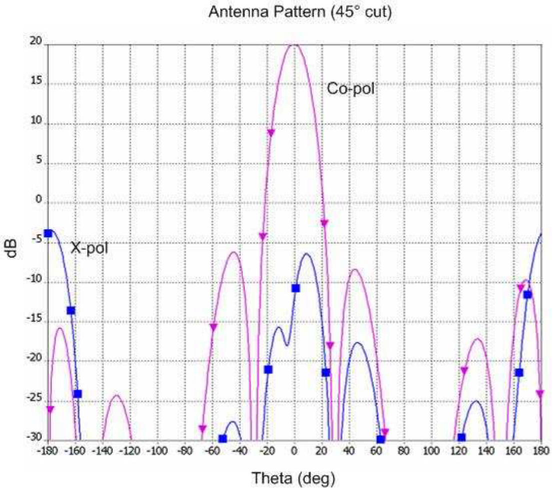

FIG 7: Antenna pattern at 45° cut

5. Current Status and Results

A two-cavity (1 x 2) breadboard model (BBM) of LISA has been manufactured and a test procedure is now undertaken to verify the electrical and structural performance of LISA. This BBM aims to reveal possible design defects that need to be solved before manufacturing the 16-cavity (4 x 4) aluminium version of LISA.

To predict the thermal performance of this antenna, actions have been taken to generate a Geometric Mathematic Model (GMM) using the software tool Thermica. The first step is to develop a detailed model of one cavity with radiating elements as seen in FIG 8. The model will then be extended to include all 16 cavities with more than 1600 nodes for the LISA GMM. The thermal analysis of LISA will be completed by a Thermal Mathematic Model (TMM) generated by ESATAN. This will be the basis for a possible passive thermal control system to LISA and it may avoid "over-designing". The mechanical 2-DoF also gives the opportunity to influence the thermal load situation during in-orbit operation.

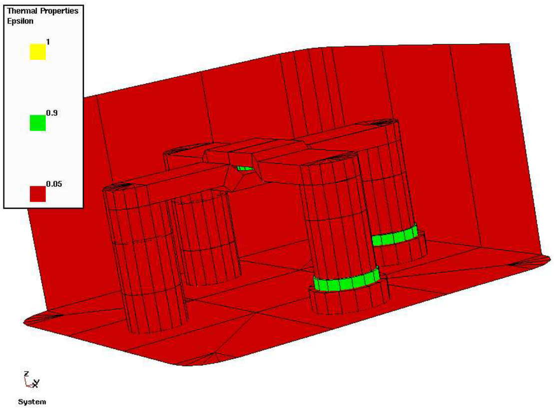

FIG 8: GMM for one LISA cavity

A preliminary structural analysis has been performed to monitor the effects of mechanical and thermal loads during launch and in-orbit operation. During launch static loads of 30 g in all directions are anticipated and in orbit thermal loads are assumed to be in the order of ±100℃. As an example, the deformation vector plot for the aluminium version of LISA is shown in FIG 9 where the maximum displacement is found to be about 0.5 mm.

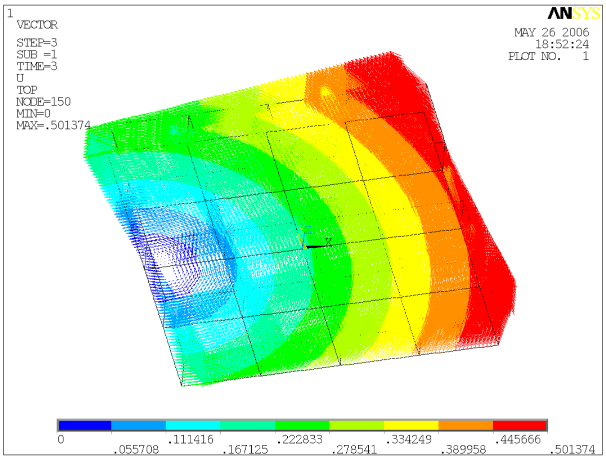

FIG 9: Deformation vector plot of LISA under 30 g static load in the most critical direction

First simulations of thermal stresses in orbit show larger deformations on the aluminum structure than the static loads during launch. A picture of the simulated deformations due to thermal loads during in-orbit operation is presented in FIG 10. The result of the first simulation of the displacements caused by thermal loads in orbit shows maximum deformations of about 4 mm. However, these thermal stresses are based on a crude assumption of the thermal environment for LISA and have to be further examined and may also be reduced by a thermal control system. Thermal loads in orbit might continue to be a problem for the aluminum model of LISA. This urges to construct the flight model from CFRP.

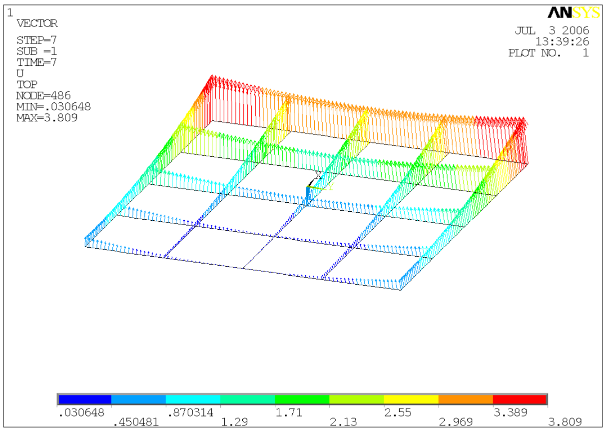

FIG 10: Deformation vector plot of LISA under assumed thermal loads in the most critical direction

A modal analysis has also been carried out to monitor the eigenfrequencies of the structure both at launch and in-orbit conditions. There will be a possibility to influence the eigenfrequency behavior of LISA during launch through the hold-down mechanism design. These first

results will further help to optimize LISA with respect to thermal stability and structural endurance.
First methods to manufacture the CFRP version of LISA have been investigated. This also includes CFRP surfaces with coatings of different materials and thicknesses. The electrical performance of the LISA BBM and the CFRP samples will be tested in a test facility at Munich University of Applied Sciences (FHM).

6. OUTLOOK

A compact, lightweight and thermally stable LISA antenna would lay the basis for inexpensive ISL communication in S-band, in particular for real-time telepresence applications. Moreover, LISA is designed to work in a down-scaled version also in Ka-band to meet the increasing need of high data rate ISL's. These frequencies are also supported by ARTEMIS.
A problem which might be encountered by downscaling is the need for increased accuracy of the antenna structure. Therefore, it is most desirable to find an adequate manufacturing method for CFRP and also to control the critical thermal loads occuring during in orbit operation of the antenna.

7. ACKNOWLEDGEMENTS

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