DEVELOPMENT OF A COMPACT KA-BAND ANTENNA POINTING MECHANISM FOR INTERSATELLITE LINKS ON SMALL SATELLITES

M.Pfeiffer(1), J. Harder(1), U. Walter(1)

(1)Institute of Astronautics, Technische Universität München, Boltzmannstraße 15, 85748 Garching, Germany, Email: m.pfeiffer@tum.de

ABSTRACT

The Institute of Astronautics (LRT) at Technische Universität München is currently developing a lightweight, high data-rate, intersatellite-link antenna (LISA) in the Ka-band for application on small satellites. The driving design constraint to the pointing mechanism is a compact envelope of the satellite. For this reason a non-gimbal two-degree-of-freedom pointing design was chosen. Two-low loss Ka-band wave guide rotary joints have to be introduced for the signal transmission from the antenna into the satellite.

This paper will present the design solutions and constructional details for a precise pointing and the implementation of the Ka-band rotary joints.

1. INTRODUCTION

The main research fields of the LRT are the development of technologies for telepresence and their application on small satellites. Telepresence comprises all technologies that allow an operator the feeling of being immersed in the whereabouts at another location [1]. For telepresence on small satellites a geostationary relay link has been identified [4] to increase link time and accessibility. For this purpose a compact, lightweight intersatellite-link antenna (LISA) has been developed by the LRT. The first step in this development has been a S-band antenna first with a coarse breadboard of a 2 degree of freedom (2DOF) antenna pointing mechanism (APM) [2]. After the successful ground testing of the S-band antenna it was decided to advance towards a mechanical steerable Ka-band antenna (see Fig. 1) system [3]. With the development of this all-encompassing antenna-system the LRT is gathering first experiences in a most complex and challenging research field: the design of space mechanisms.

2. DESIGN REQUIREMENTS

Independently of the any attitude motion of the satellite the APM must be capable of pointing the antenna to a given relay satellite. The overall antenna properties and design requirements are listed in Tab. 1. The LISA antenna itself comprises 8×8 horns made of copper. As the antenna shall allow a communication link over a half orbit, the APM must allow a continuous coverage of at least a hemisphere. Furthermore the APM shall allow a flat storage of the antenna on the satellite structure during launch (see Fig. 2)

Table 1 Antenna properties

LISA Ka-band, mechanically steerable		
Size	[mm]	400x400x200
Weight	[g]	5000
Frequency RX/TX	[GHz]	23.205/27.350
Half Power Angle	[°]	0,75
Polarization	[-]	LHC/RHC
Gain	[dBi]	37
Max. moment of inertia	[kgm²]	0.5
Application	[-]	LEO/GEO
Lifetime	[yr]	15

Due to the small antenna aperture of 400×400 mm and the high frequencies, the main lobe is limited to approximately 1.5°. Quite naturally, tracking a relay satellite involves a slow motion within a limited angular range a precise continuous pointing is necessary for a good link quality.

The APM shall permit a lifetime of 15 years for a LEO/GEO application.

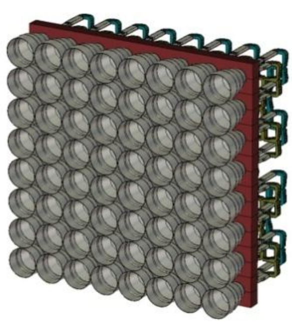

Figure 1: LISA Ka-band antenna with structural plate

Proc. '13th European Space Mechanisms and Tribology Symposium – ESMATS 2009', Vienna, Austria 23–25 September 2009 (ESA SP-670, July 2009)

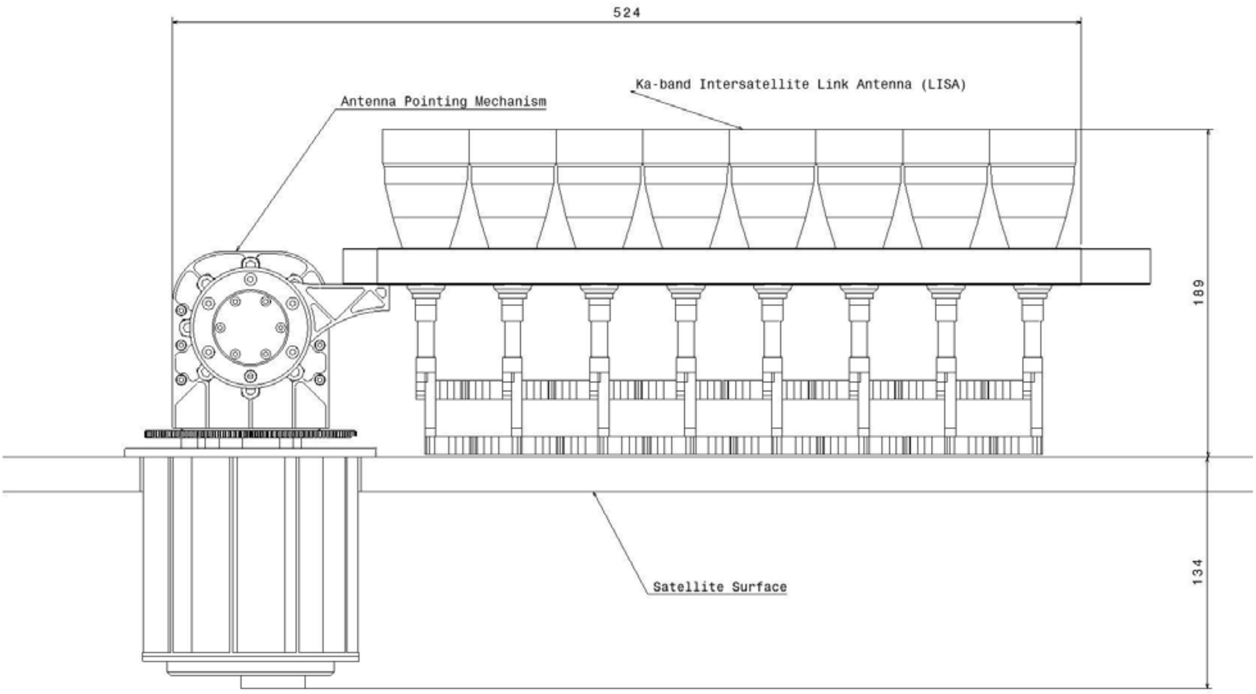

Figure 2: Flat storage of LISA on the satellite structure

2.1 Pointing Requirements

The required angular ranges, velocities and pointing accuracies are summarized in Table 2. The desired maximum angular acceleration shall be at least 2.5 °/s² for both DOF. Pointing shall be accomplished with a predetermined profile.

Table 2: APM angular pointing requirements

		minimum	goal
ε	[°]	0 - 180	-5 - 185
α	[°]	0 - 360	unlimited
ε'	[°/s]	0.05 - 3	0.05 - 5
α'	[°/s]	0.05 - 3	0.05 - 5
ε''	[°/s²]	2.5	5
α''	[°/s²]	2.5	5
$\Delta\varepsilon_{err}$	[°]	< 0.2	< 0.1
$\Delta\alpha_{err}$	[°]	< 0.2	< 0.1

The goal for the APM is to minimize pointing errors in order to relax the requirements for the satellite's attitude control system. For an error of 0.2° in both azimuth and elevation the total de-pointing equals 0.28°. This leaves a total misalignment margin of 0.46° for the satellite's attitude control system.

2.2 RF Requirements

For a constant communication link the APM must be capable of transmitting the continuous wave (CW) Ka-band signal with a minimum loss through the mechanism at any operational time.

2.3 Thermal Requirements

For non-operational phases the temperature of the APM shall remain within the limits of -40°C to +80°C and for operational phases it has been proposed to stay within -20°C to +40°C.

2.4 Lubrication Requirements

All ball bearings and moving parts within the APM must be lubricated in order to guarantee performance over lifetime. Bearings within the space qualified stepper motors are used as is and will not be modified.

3 DESIGN CONCEPT

First it was planned to modify the existing S-band APM design [2] for the Ka-band application. This low accuracy, slide bearing equipped S-band APM comprised an azimuth stage, driven by a spur gear and planetary gear-equipped stepper motor. The elevation drive was placed along the azimuth rotational axis. This elevation drive comprised a ball screw nut mounted on a stepper motor, which translated a spindle and tilted the elevation mounting plate. The antenna signal should be forwarded into the satellite via coaxial cable.

This design had to be adapted to the RF requirements and increased accuracy demands of the LISA Ka-band antenna. Due to the high RF power of approx. 35 W (CW) or more in the Ka-band a coaxial cable was no longer a viable option. For a continuous signal transmission a custom developed 2-channel TX/RX- Ka-band rotary joint has been proposed and designed by NTP (Netzwerk Technischer Partner, Munich). It must be centered along the rotational axis of both the azimuth and elevation and allows a low loss transmission of the antenna signal in transmit and receive. For this reason the Ka-band APM (see Fig. 3) is built around the rotary joint with a special focus on the careful guidance of the rotary joint parts and antenna pointing accuracy.

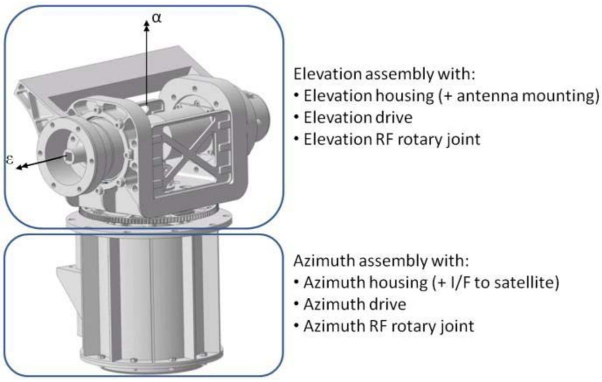

Figure 3: Complete view of APM with degrees of freedom

4 DESIGN SOLUTION

The APM (see Fig. 3) comprises two main assemblies. One for the elevational motion, the other for the azimuth. The elevation assembly is supported in the azimuth housing that is connected to the satellite surface (see Fig. 2). These assemblies, including drive, RF rotary joint and housing for the elevation and the azimuth, will be described in the following.

4.1 Elevation Drive

As the entire elevation stage (altogether with RF rotary joints and drive components) rotates around the azimuth axis a compact drive is desired. The choice was made for a stepper motor with a 100:1 ratio type harmonic drive. For higher reliability the motor will have two cold redundant independent windings. The motor shaft is directly connected to the wave generator of the gear via a glued flange. Axial forces of the harmonic drive are compensated for by the stepper motor bearings. The motor torque was chosen with respect to the gear‘s no-load torque, unknown friction losses and lubrication behavior with a 30% safety margin on the acceleration torque due to inertia and the gear's no-load running torque.

The elevation drive shaft is mounted by two FAG 71800 spindle bearings in back to back configuration.

4.2 Elevation RF-rotary joint

As the RF-rotary joint (developed by NTP, see Fig. 4) is one of the key-features of the APM it requires a special focus. An example of the rotary joint's mounting is depicted (Fig. 5).

The 90° bent knee-like part of the rotary joint is fastened in the elevation housing. The antenna signal enters the APM from the left side. This part of the rotary joint is attached to a hollow shaft, which encloses the rotary joint bearing. The hollow shaft itself is mounted by two preloaded thin-section bearings in back to back configuration in the elevation housing. It co-rotates with the RF-entrance, the antenna and the mounting platform and allows the relative motion in the elevation axis. In order to achieve a maximum RF performance during pointing, a careful concentric alignment of the rotary joint parts must be maintained. This is the task of the depicted needle bearing (Fig. 5). It prevents tilting between the moving and stationary part of the RF-rotary joint.

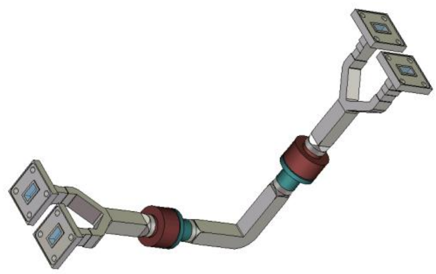

Figure 4: RF-design of the Ka-band rotary joint (developed by NTP)

4.3 Elevation housing

The elevation housing comprises both the elevation drive and the RF-rotary joints. These are concentrically aligned within the housing. The bent RF-rotary joint is additionally congruent with the azimuth axis. The housing is made of aluminum 7075 for high yield strength and stress corrosion resistance with separately attached side walls for increased stiffness.

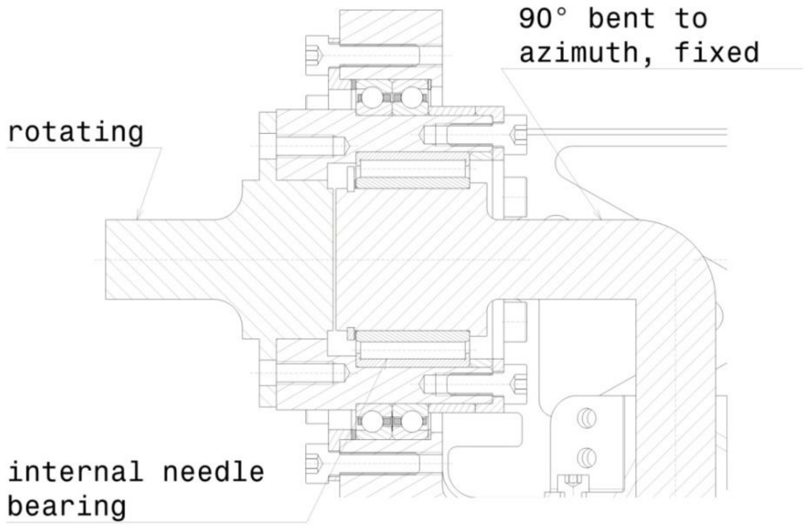

Figure 5: Detail of the elevation RF-rotary joint (simplified)

The antenna itself will be attached to a mounting plate, which allows the pointing around the elevation axis. This elevation mounting plate is connected to the elevation drive by a spring spacer coupling for a radial force free torque transduction.

4.4 Azimuth Drive

The azimuth axis is driven by a stepper motor identical to the elevation drive. Thus the overall gear ratio of the azimuth is identical to the elevation drive. The rotation around the azimuth axis is achieved by a 5:1 ratio spur gear and a 20:1 ratio planetary gear. The spur wheel of the first stage is directly attached to the elevation housing. The bevel is driven by another stepper motor (identical to elevation motor) with an integrated low-backlash planetary gear. The adjustment of the spur gear is critical to the azimuth pointing accuracy and must be carefully investigated.

Due to the open exposure of the spur gear a dry lubrication with sputtered MoS_2 will be applied to the gear teeth in order to ensure performance over the lifetime.

4.5 Azimuth RF-rotary-joint

The mounting of the azimuth RF-rotary joint is analogue to the elevation rotary joint (Fig. 5). In this case the 90° bent knee rotates together with the complete elevation assembly around the azimuth axis. The final rotary joint part, which leads out of the APM into the satellite, is fastened to the azimuth housing.

4.6 Azimuth housing

The azimuth housing comprises the complete elevation assembly, the RF exit to the satellite and mounting interface to the satellite structure. Analogue to the elevation housing this essential part of the APM is made of aluminum 7075. Fig. 6 shows the configuration of the azimuth assembly.

The complete elevation assembly is fastened to a hollow spindle, which is mounted in the azimuth housing. The azimuth drive is adjustably attached to the side of the azimuth housing in order to allow a minimization of the spur gear's backlash.

Unlimited rotation around the azimuth axis is provided by the integration of a slip ring assembly. This slip ring provides electrical power and control signals to the elevation assembly.

The elevation assembly is mounted on top of the azimuth spur wheel and the hollow spindle. This spindle carries the slip ring for the electrical signal throughput and is mounted by two angular ball bearings.

4.7 Lubrication

Lubrication of moving parts is most essential for the function of the APM. It is planned to examine three different means of lubrication. The first option is to treat all ball bearings within the APM with Braycote 601 EF as a baseline. Additionally it is planned to investigate the usage of Dicronite DL-5 as a dry lubrication, although the performance appears only viable for low load applications and highly depends on supplier quality [5]. As the supplier of Dicronite claims that DL-5 can be applied together with any wet lubricant, the third option is to investigate the usage of Braycote 601 EF together with Dicronite DL-5 as a backup lubrication.

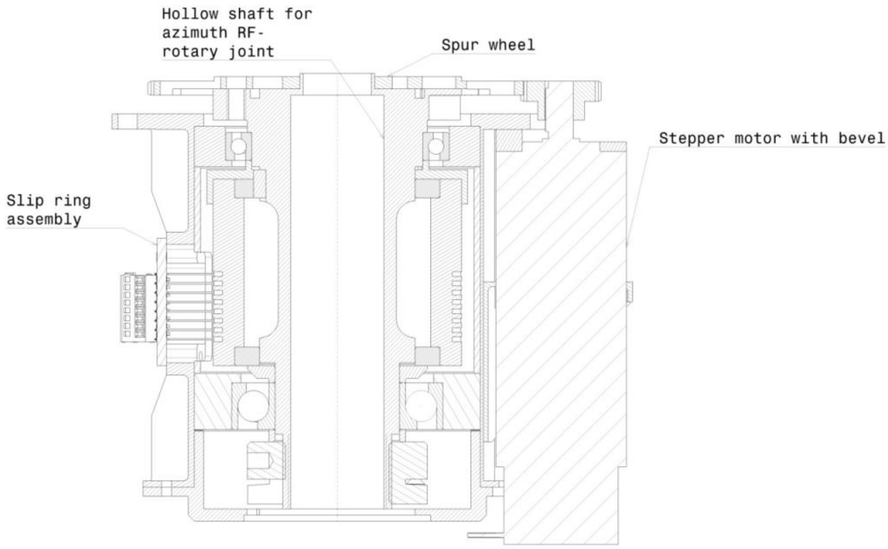

Figure 6: Azimuth housing with slip ring assembly (rotational joint not shown)

5 END STOPS AND POSITION REFERENCE

Pointing of the antenna can be performed both in an open or closed loop, depending on the usage of encoders, which can be attached to a second motor shaft. Both stepper motors are designed such that step errors should not occur. A position reference must be included for the case of occurring step errors that allows a precise reset back to a predefined reference position.

Positive experience has been gathered with light-barriers during a recent sounding rocket experiment flight campaign. Therefore it is planned to examine the usage of such sensors in the APM for end stop and reference purposes. The idea is to have a slotted disc rotating with the respective DOF that will trigger the light-barrier. For the azimuth DOF only a position reference for resetting purposes will be necessary as the rotation will not be limited to a maximum value.

6 ENGINEERING MODEL MANUFACTURING AND TESTING

The APM as introduced is currently in manufacturing and will be assembled by July 2009. This engineering model (EM) will not comprise a functional version of the RF-rotary joint. Additionally a fly-wheel test-rig is being built that will be used for motor and lubrication performance testing. This test-rig comprises an off-loaded fly-wheel with the antennas moment of inertia around the elevation axis and a low temperature torque sensor. It contains identical bearings for the antenna mounting platform and elevation drive as incorporated in the APM.

The APM EM will be functionally tested in order to determine whether the pointing requirements are met. All lessons learned during the manufacturing and assembly of the APM EM will then be translated into a refinement of the current design.

With the fly-wheel test rig the following tests will be performed under a pointing load scenario:

1. Torque Measurement under varying lubrication, no vacuum:

- Elevation drive torque, varying Braycote 601 amount, low temperature (-20°)
- Elevation drive torque, Braycote 601, at various low temperatures (-20°C to +40°C)
- Elevation drive torque, Dicronite DL-5, at various low temperatures (-20°C to + 40°C)
- Elevation drive torque, Braycote 601 and Dicronite DL-5, at various low temperatures (-20°C to +40°C)

2. Bearing lifetime under varying lubrication, vacuum, ambient temperature:

- Bearings unlubricated
- Bearings with Braycote 601 lubrication
- Bearings with Dicronite DL-5
- Bearings with Braycote 601 and Dicronite DL-5

The goal of those tests is to understand the behavior of the lubrication in connection with the construction.

7 CONCLUSION

The original goal of this APM development was in first place to create a small and compact mechanism for a Ka-band intersatellite link antenna. Soon it became clear that not only the small main lobe of 1,5° of the antenna is a design driver for the APM but also the RF-rotary joint, which has been designed by NTP for the application in this APM.

The APM is constructed with the RF-rotary joint as the main feature. The support of the rotary joint parts poses a high accuracy requirement, which has a direct influence on the overall link performance.

Lubrication has been identified as one of the main critical aspects in the APM. Due to the low rotation speed and the viscosity of the planned grease the impact on friction losses and bearing lifetime are still unclear. The usability of Dicronite DL-5 for the load scenario and application must be examined as well as the possibility of applying both lubricants simultaneously.

ACKNOWLEDGEMENTS

This work was supported by DLR research grant no. FKZ 50YB0602 and FKZ 50YB0802. Special thanks also to all the project partners and students involved in the LISA project.

LIST OF ACRONYMS

2DOF	2 degrees of freedom
APM	Antenna Pointing Mechanism
CW	Continuous Wave
DOF	Degree of Freedom
EM	Engineering Model
GEO	Geostationary Orbit
I/F	Interface
LEO	Low Earth Orbit
LHC	Left Hand Circulation
LISA	Light-weight Intersatellite Link Antenna
LRT	Institute of Astronautics
MoS_2	Molybdenum Disulfide
NTP	Netzwerk Technischer Partner
RF	Radio Frequency
RHC	Right Hand Circulation
RX	Receive
TX	Transmit

REFERENCE

[1] Stoll E., "Ground verification of telepresence for on-orbit servicing", Dissertation, TU München, 2009

[2] Czech M. , Stoll E., Walter U., "Development of a low cost, medium accurate 2-axes pointing mechanism for small satellites", Proc. Deutscher Luft-und Raumfahrtkongress, Aachen, Germany, 2006

[3] Harder J., Stoll E., Schiffner M., Pfeiffer M., Walter U., "A compact light-weight high data rate antenna system for remote sensing orbiters and space exploration", Acta Astronautica (2009), doi:10.1016/j.actaastro.2009.05.001

[4] Raif M., Letschnik J., Pauly K., Walter U., "BayernSat - How to utilize relay satellites for real-time data acquisition on small satellites", Proc. 4th IAA Symposium on Small Satellites for Earth Observation, Berlin, Germany, 2004

[5] Anderson M.J., Cropper M., Roberts E.W., "The tribological characteristics of dicronite", Proc. 12th ESMATS, Liverpool, United Kingdom, 2007