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Development of Technology for Lightweight Beryllium Cassegrain Telescope for Space Applications and Lessons Learnt

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Abstract— This paper gives an overview on the development of a light weighted Cassegrain telescope with a 200 mm optical aperture as one key element of the Laser Altimeter which will fly on the BepiColombo mission to Mercury (BELA). The Receiver Telescope (RTL) collects the light pulse transmitted to Mercury and reflected from the planet's surface. Mercury's challenging thermal environment, the thermo-mechanical stability of the telescope and the stringent instrument's mass budget require the implementation of an innovative design solution to achieve the requested optical performance over an extended temperature range.

Index Terms—Cassegrain, Beryllium, Light weight.

I. INTRODUCTION

One of the main objectives of the BepiColombo mission to Mercury is a systematic scan of the planet's surface. The BepiColombo Laser Altimeter (BELA) onboard of the Mercury Polar Orbiter (MPO) scans the surface by transmitting a Laser pulse to the planet's surface and collecting the light pulse reflected by the planet's surface. The measured Time of Flight (TOF) of the light pulse is proportional to the distance between planet surface and instrument. Figure 1 provides an overview of the BELA instrument.

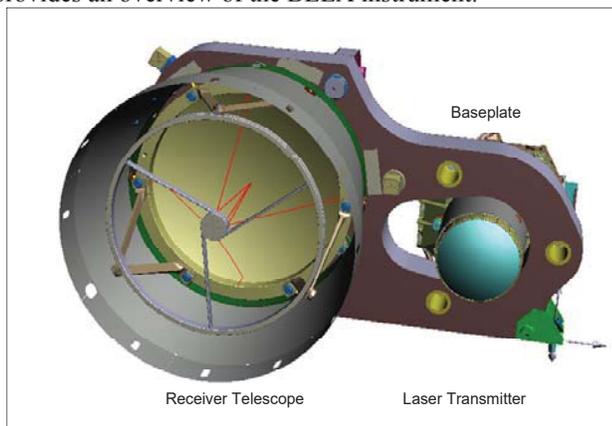


Fig. 1: BELA Instrument

The instrument development is a joint project between Switzerland as responsible for the receiver and baseplate unit and Germany as responsible for the transmitter part of the instrument. RUAG Space is the industrial prime for the receiver part of the scientific instrument which is a joined effort of Swiss industries under the leading role of RUAG and University of Bern as co-Prime Investigator.

Mercury's challenging thermal environment, the thermo-mechanical stability of the telescope and the stringent telescope's mass budget ($m < 600\text{g}$) require the implementation of an innovative design solution to achieve the requested optical performance and optical quality over the requested temperature range of -50°C up to 115°C . Taking into account the challenging boundary conditions Beryllium has been evaluated as most promising base material for the telescope. Beryllium, however, requires the development of a complex technology to manufacture parabolic mirrors with the required optical quality. The requested mirror geometry jeopardizes the application of already existing standard manufacturing processes. In several manufacturing trials RUAG developed in close cooperation with an industrial team of 4 suppliers a new manufacturing approach for the BELA RTL to manufacture a 200 mm optical aperture Cassegrain telescope with a focal length of 1250mm with a total weight of less than 600 grams.

II. RECEIVER TELESCOPE DESIGN

The RTL is designed as an all Beryllium telescope (except for specific attachment hardware like the bipods to the Baseplate, bonding pads, bolts, etc., as well as the field stop aperture) to achieve the required low mass while providing sufficient stiffness. The RTL (Fig. 2) comprises a parabolic primary mirror M1 with a field stop aperture fixed on the mirror's rear side (not shown in Fig. 2), a hyperbolic secondary mirror M2, M2 Bipods providing an isostatic M2 mount, M1 Bipods to fix the RTL to the instrument's sandwich base plate and a Multilayer Insulation also omitted in Fig. 2.

The central part of the telescope is the primary mirror M1 which collects the incident light and focuses it on the secondary mirror M2. Beside the optical tasks M1 also provides the structural interface for mounting the supporting Bipods. The mirror specification is given in Table 1. It is worth to mention that M1 is the heaviest part of the complete RTL. Its geometry is optimized with respect to stiffness and weight. In fact the thickness of the parabola had to be reduced to 2mm to meet the overall mass budget.

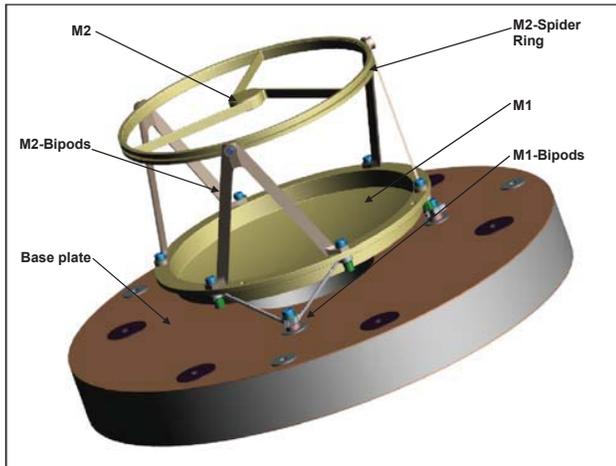


Fig. 2: 3D-View of RTL

M2 is manufactured as the central part of a ring construction to establish a good thermal conductance leading to an almost uniform temperature distribution in M2 and to simplify the telescope alignment. The parameters of this hyperbolic mirror are listed in Table 2. The M2 spider ring is bonded to the Beryllium made M2-Bipods designed to be soft in radial direction and stiff axially and tangentially to ensure the required isostaticity and to minimize the temperature differences between M1 and M2. The M2-Bipods are bolted together with Titanium M1-Bipods to M1. The M1-Bipods provide a thermally decoupled isostatic interface between RTL and sandwich base plate.

The secondary mirror's rear side is equipped with a cross hair within a highly reflective surface to support alignment during telescope and instrument integration. The telescope's field stop is fixed to M1's rear side. It is bonded to the M1 after alignment in lateral and axial position to define the line of sight of the telescope.

Thermal radiation into the satellite environment is reduced by wrapping the telescope into multi layer insulation blankets comprising an aluminized and a standard Kapton foil.

Table 1 Primary mirror characteristics

Parameter	Value	Remark
Active diameter \varnothing_e	$\varnothing_e = 204\text{mm}$	
Radius of curvature R	$R = 317.0531$	Concave (CC)
Conical constant	$\kappa = -1 \pm 0.05\%$	Parabolic

Table 2 Secondary mirror characteristics

Parameter	Value	Remark
Active diameter \varnothing_e	$\varnothing_e = 27\text{mm}$	
Radius of curvature	$R = 41.8976$	Convex (CX)
Conical constant	$\kappa = -1.6653 \pm 0.025\%$	Hyperbolic

III. MANUFACTURING

The choice of Beryllium as base material for the mirrors implies a more complicated manufacturing process to achieve the optimum optical performance of the mirrors. Beryllium is a brittle and poisonous material which requires special handling and hermetically sealed machines. Beryllium reacts very fast with a vast number of liquids like cleaning agents which limits strongly the manufacturing process.

For the manufacturing of the optical surfaces Single Point Diamond Turning (SPDT) has been selected as method of choice. Applying SPDT techniques on Beryllium, however, show, that due to the brittleness of Beryllium itself the achievable surface roughness is far away off the required stray light performance for RTL. Moreover this SPDT causes small chips of Beryllium to chip off the turned surface. Consequently a coating of the Beryllium substrate supporting SPDT is required. Usually Beryllium mirrors are coated with a thin electroless Nickel or Ni-Phosphor layer which allows for SPDT and which is polished afterwards to optimize the shape and surface roughness. The geometry of the large M1 parabola proved to be an unsolvable challenge to the Nickel coating process. In a lot of coating trials performed on a form, fit and function compatible stainless steel mirror no acceptable pore-free Ni layer could be achieved. More over this the shape of the mirror substrate was strongly deformed due to Ni layer internal stresses. Additionally the requested large optical surface leads to significant wear of the diamond device during the turning process. An exchange of the tool is most likely reducing the achievable optical quality of the mirror.

Another material option well suited for SPDT techniques is pure Copper (Cu) well proven in various applications as Laser optics for example. The advantage of good manufacturability, however, is partly compensated by the fact that Copper coating onto Beryllium is neither a standard nor a qualified process for space applications. Further more Cu tends to immediately corrode in the presence of oxygen, sulphur and humidity reducing the quality of the optical surface and leading to reduced adhesion capabilities for optical coatings. A suitable protection of the Cu-layer is mandatory on which the final optical reflection coating can be applied to safeguard the optical performance during lifetime of the mirrors. Hence,

a suitable coating process needed to be developed for the manufacturing of the RTL Beryllium components. The instrument's performance and the thermal environment during operation require a highly reflective coating of the RTL components to avoid excessive heating of the mirrors and to ensure a good signal to noise ratio of the receiver. For the telescope a pure Gold (Au) coating has been selected.

The manufacturing process of the RTL was developed in close cooperation with four suppliers:

- SWSTech AG Manufacturing of Beryllium substrates
- Surcotec SA All coatings based on Physical Vapour Deposition (PVD)
- Collini AG Galvanic Coating
- Kugler GmbH Single Point Diamond Turning (SPDT).

The most critical issue within the manufacturing process is the adhesion of the applied Cu-layer on the Beryllium substrate. The Cu-layer needs to survive thermal cycling between lowest and highest qualification temperature as well as the stresses induced during machining of the optical surfaces. First tests with a PVD Cu-layer on a test specimen showed an unacceptable homogeneity of the Cu layer itself as well as bad adhesion to the substrate. A galvanic Cu coating showed good adhesion and homogeneity performances on test samples. The incompatibility of the Cu electrolyte with Beryllium itself requires an intermediate adhesion layer to seal and passivate the Beryllium. This sealing adhesion layer is applied onto the Beryllium substrate using PVD techniques. The Cu-layer itself can then be applied onto the mirror using an adapted and tailored electro-plating process. Both sides of the mirrors, front and rear side, are coated with a thick Cu layer (up to 250 μm) to compensate for bimetallic effects caused by the different materials i.e. Be and Cu. Due to the thickness of the layer several trials to manufacture the optical mirror surface are supported until the final layer thickness of 50 μm is reached.

The optical surface is manufactured on high precision turning machines after careful measurement of the mirror geometry and especially the Cu-layer thickness to ensure that the Beryllium substrate is never toughed during the turning process. For safety reasons and to avoid any unwanted contamination of the workshop with Beryllium dust the machines are operated in temporarily installed protection tents. Tests on breadboard mirrors showed that front side and rear side have to be manufactured in an alternating sequence to avoid any deforming of the mirror contour due to residual stresses in the Cu-layer after the turning process. Thermal annealing in between the turning steps up to the maximum qualification temperature helps to minimize the residual stress in the Cu layer. The quality of the contour of the mirror is directly impacted by the turning speed i.e. the mirror revolution rate turned out to be essential. Although Beryllium provides a high stiffness the limited thickness of the mirror parabola (2mm) leads to significant contour deformations of the parabola due to centrifugal forces. In several trials on

bread board level the optimum turning speed as a compromise between surface distortion and cutting speed was evaluated.

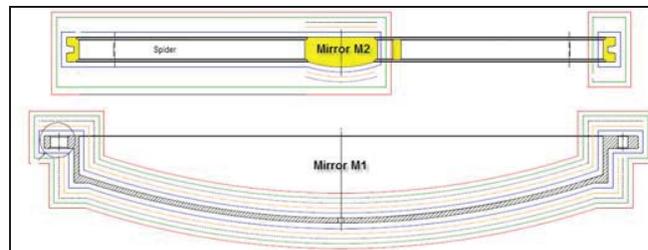


Fig. 3: Mirror coating stack

Table 3: Coating Table

Layer	Coating / machining
1	adhesive layer
2	Cu
3	Diamond machining of Cu Ra < 1nm
4	protection layer
5	optical coating



Fig. 4: Single Point Diamond Turning of M1



Fig. 5: Single Point Diamond Turning of M2

After finishing of the optical surface a fast protection of the Cu layer against corrosion is mandatory. The protection effect of the optical coating i.e. Au is not sufficient. Molecules are

still diffusing through the thin reflection coating layer and cause corrosion of the Cu leading to deterioration of the reflectivity and, in the worst case, to a coating peel off. A thin metallic glass layer deposited directly on the Cu surface after the SPDT process seals the Cu layer reliably. The required reflectivity is achieved using a thin Au coating on top of the protection layer. All manufacturing steps and integration steps have been trained first on stainless steel components being compatible with the later flight model in form, fit and function. Fig. 6: shows the assembly RTL bread board.

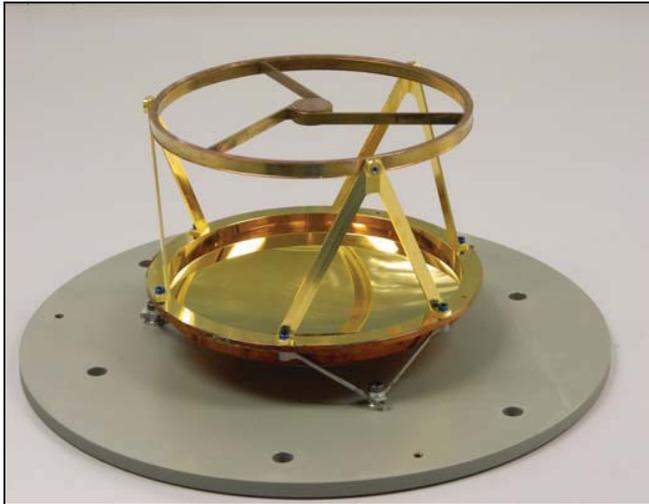


Fig. 6: Stainless steel bread board of the RTL

IV. LESSONS LEARNT

The complete manufacturing chain has been qualified taking into account the environmental constraints like Operation and Non-Operational Temperature Range, Radiation and Humidity as well as manufacturing aspects like masking techniques for the galvanic plating process or mechanical treatment of the Cu layer. Small contaminations of the Beryllium substrate cause serious adhesion problems of the Cu layer during mechanical treatment. Acetone cleaning agents for example lead to pitting effects of the Beryllium if not removed properly immediately after cleaning of the substrate. Visible oxidization of the Beryllium material leads to adhesion problems of the basic adhesion layer after Cu coating. Small contaminations of the Cu electrolyte can also impact the overall quality of the Cu layer as shown in Fig. 7: with coated steel samples. Defects like pin holes jeopardize the optical quality and performance of the mirror. A chemical removal of the Cu layer from the Beryllium substrate is not possible due to the high reactivity of Beryllium in case the removal agent contacts the Beryllium substrate through a microscopic defect in the sealing layer. Further more the galvanic coating of a thick Cu layer (250 μm) turns out to be a big challenge, too. The low growth speed of the Cu layer on top of the substrate leads to a several days period of the part within the Cu bath with precisely controlled process parameters.



Fig. 7: Problems during coating development (left: unexpected Cu growth, right: poor adhesion)

Some areas of the mirrors cannot be coated with a Cu layer because some areas of the raw substrate are needed as reference area to define the position and the thickness of the Cu layer during SPDT. Ultra sonic measurement techniques to measure the thickness of the Cu layer are not compatible with the layer thickness. Consequently a perfect masking of the reference areas is mandatory also driven by the fact that no chemical removal of excessive Cu is possible. While the geometry of M1 and the position of the reference area (rear side of mounting flange) supports masking with O-ring seals this method cannot be applied for the secondary mirror. Varnish or tape masking areas do not prevent the Cu layer to grow on top of the masking material. The masking becomes part of the Cu layer and impacts the adhesion of the Cu layer. Therefore a different manufacturing approach is applied for the secondary mirror. Fig. 8: summarizes the main steps of the M2 manufacturing. In step one the raw mirror substrate is manufactured which only provides the real geometry for the front and back side mirror and the reference area. The reference area is located in a groove along the circumference of the stiffener ring which can be satisfactorily masked with a tape. After Cu coating of the complete substrate (see Fig. 8:, left image) the secondary mirror unit is re-manufactured to the correct final geometry removing the excessive Cu layer except front and rear side mirror and to establish excellent Cu layer boundaries (Fig. 8:; right image). Finally the substrate is recoated with an additional adhesion layer to seal again the bare Beryllium for the SPDT activities.



Fig. 8: M2 Manufacturing Steps: Left: raw part Cu plated, right: final raw part

The Achievement of an acceptable optical performance especially for the primary mirror is very demanding due to the low mirror substrate thickness of 2mm. The above mentioned deformation of the mirror substrate during the manufacturing process leads to an astigmatic optical aberration. This effect can easily be amplified by inadvertent torquing of the Bipod interface bolts. The optical surface areas close to the mounting

flange are mostly affected and contribute significantly to the astigmatism of the mirror.

Figure 9 shows the measured surface deviation of the preassembled M1 unit including both Bipod sets.

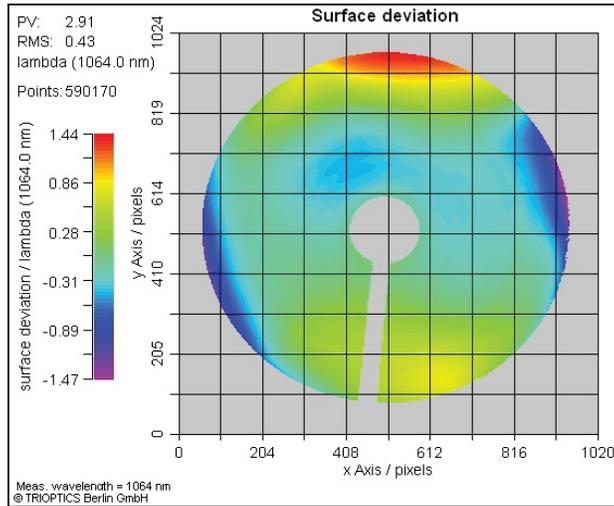


Fig. 9: Measured surface deviation of M1 assembly

The manufacturing of the secondary mirror is much less critical as Fig. 10: shows.

The main task of the RTL is to collect most of the Laser pulse back reflected by Mercury's surface and to focus the incident light onto the detector of the instrument i.e. the RTL's spot size must be smaller than the sensitive area of the detector. Therefore the integration sequence of M2 accounts for an optimized spot size. First M2 is aligned w.r.t. M1 for the optimum Wave Front Error (WFE) and afterwards the RTL's spot size measured with a focal point camera is optimized by fine adjusting M2. After alignment M2 is bonded to the M2 Bipods in this position. Fig. 11: shows the final WFE of the RTL after settling which corresponds to a spot size of ~200 μm (diameter 90% encircled energy). The wave front error of the overall telescope is governed by the WFE of M1 while M2's contribution M2 is small.

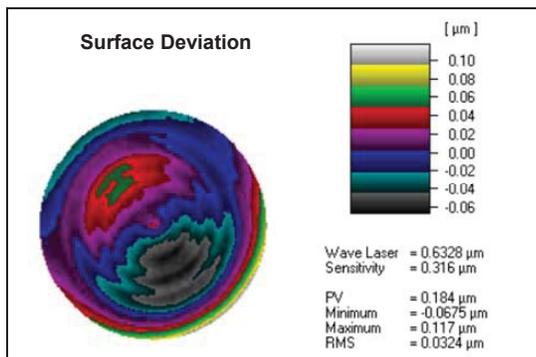


Fig. 10: Surface deviation measured for M2 after diamond turning

Table 4 provides an overview on the achieved optical performances and masses. With the achieved spot size of ~200 μm a Cassegrain telescope with a total mass below 600 g for the BepiColombo Laser Altimeter compliant with the instrument's performance requirements could be manufactured.

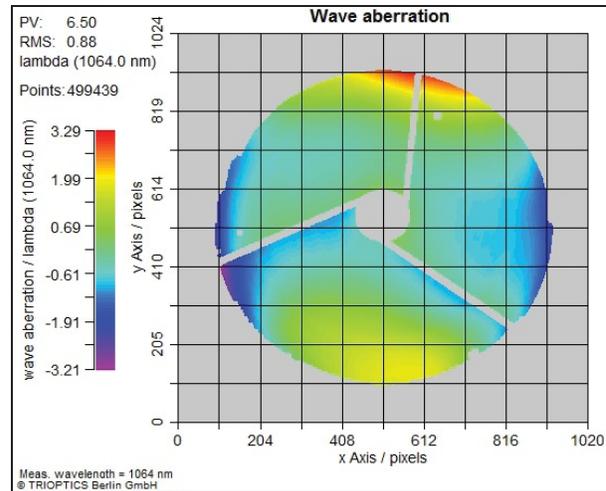


Fig. 11: RTL Wave Front Deviation after settling vibration run

Table 4: Achieved Performances

Component	Mass [g]	WFE (achieved) rms
M1 Assembly	485.1	0.76 λ
M2	74.4	0.064 λ
RTL	593	0.88 λ

V. CONCLUSION

In this paper some aspects of the development of the BepiColombo Laser Altimeter Receiver Telescope to be flown on the BepiColombo mission to Mercury were briefly discussed. Beside optical performance requirements the allocated mass budget turned out to be one of the most demanding challenges. Selecting optical grade Beryllium as base material for the central structure of the Cassegrain Telescope a lot of new processes and manufacturing technologies had to be developed and adapted to comply with the performance requirements of the BELA instrument. A dedicated coating layup was developed to support SPDT techniques on parabolic Beryllium mirrors with an aperture of 204mm. Applying this techniques finally a Beryllium telescope with an overall WFErms of 0.88 λ, a spot size of ~200 μm (diameter 90% encircled energy) and an overall mass of 593g could be manufactured.