A Simple S/X Dual-Band Coaxial Feed for Satellite Communication

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1. Introduction

The concept of equipping a geostationary satellite with an amateur radio transponder originated at Qatar satellite company Es`hailSat [1] during the design phase its new satellite, Es`hail 2. Es'hailSat currently operates one satellite, Es'hail 1, launched on August 29, 2013 as EUTELSAT 25B [2], for television, radio, and various other communication purposes in the Middle East, North Africa and Central Asia regions. To facilitate installation of an amateur radio transponder in a new satellite, a representative of AMSAT-DL was invited to Doha to introduce to the Qatari government, which strongly supports amateur radio, AMSAT projects and suggest parameters for an amateur radio transponder. From the efforts of the Qatari government and especially Deputy Premier, HE Abdullah bin Hamad Al Attiyah – A71AU, president of the Qatar Amateur Radio Society, the amateur radio payload for Es'hail 2 was approved. The project was announced at the ITU Symposium and Workshop on Small Satellite Regulation and Communication Systems in Prague, Czech Republic, March 2015 [3]. Satellite production was assigned to Mitsubishi Electric Corporation (MELCO) [4] with an expected Q1 -2017 launch date aboard a Space Exploration Technologies Corporation "Falcon 9" rocket.

2. Transponder parameters

Detailed information on the satellite transponder, its parameters and a review of basic earth-station requirements have been published [3]. Table 1 from this publication is reproduced here:

Transponder		Freq. Band	Polarization	Central Freq. (MHz)	Transponder Bandwidth
NB	Uplink	S-band	RHCP	2400.175	250 KHz
	Downlink	X-band	LVP	10489.675	
WB	Uplink	S-band	RHCP	2405.5	8 MHz
	Downlink	X-band	LHP	10495	

Table 1. Transponder frequency allocation.

For successful uplink operation, a 10-watt transmitter driving a parabolic reflector antenna with D >75 cm is recommended. A downlink receiving system with G/T > 13.98 dB/K is

recommended. To achieve this parameter, a parabolic dish antenna of at least $D \geq 80$ cm diameter and LNA with noise figure less than 1.5 dB should be used. The terrestrial communication coverage region is shown in Fig. 1.

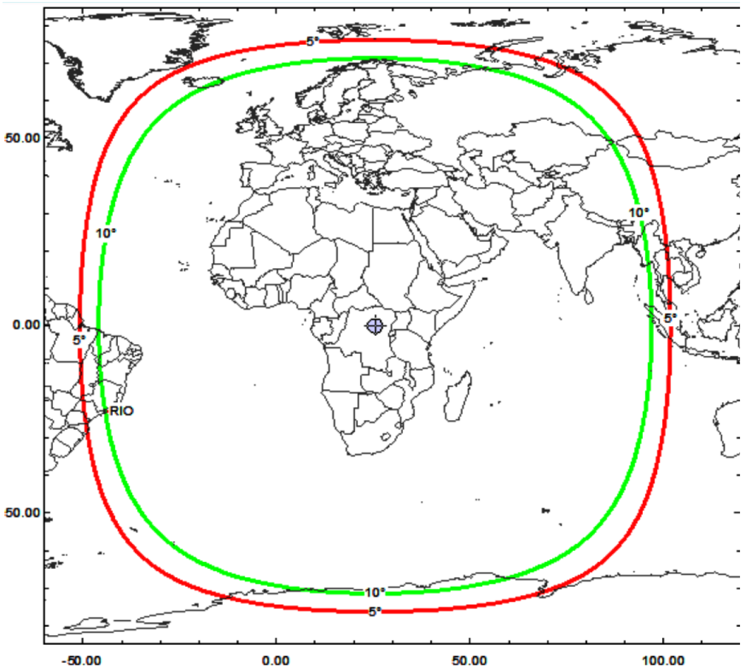

Fig. 1 - Estimated coverage region. Fringe regions requiring ground antenna elevation angles of 5 and 10 degrees are indicated by red and green lines, respectively. Reproduced from [3].

3. Design goals

As mentioned in the preceeding section, a parabolic dish reflector with similar diameter for X and S bands can be used. The goal then is to design a dual-band, high efficiency feed for a reflector of the given size. To simplify feed design, configuration with a prime focus feed was prioritized. Offset reflectors are less suitable, since their *f/D* ratios are often above 0.7. Such reflectors require feeds with gains of about 12 dB and higher which, in turn, requires an increase in the feed aperture diameter. For example: a feed with 12 dB gain and aperture efficiency of 80%. Such feed must have a diameter lager than $\lambda\sqrt{2}$. When the feed is in dual-band configuration, a lager aperture diameter narrows the upper band radiation pattern, resulting in lower antenna efficiency on the upper band. To achieve good overall efficiency, similar radiation patterns should be present on both bands. Goals for design are:

1. Antenna working frequencies: S band, fS = 2404.775 ± 4.725 MHz
   X band, fX = 10494.275 ± 4.725 MHz
2. RHCP polarization for S band
   LP polarization for X band
3. Good efficiency on both bands – similar radiation patterns
4. Good impedance parameters, *S11*, *S22*
5. Good port-to-port isolation *S21* (at least 80 dB) to allow duplex operation
6. Simple mechanical configuration, easy to produce

4. Design Concept

A coaxial waveguide configured as a feed is often used for dual- or even triple-band antenna feeds as long the spacing between the working frequencies is adequate. To study design examples of such structures, see pertinent IEEE or NASA publications [5], [6]. Two conductive coaxial cylinders functioning as circular and coaxial waveguides comprise a dual-band feed. The higher frequency band signal propagates through the smaller diameter, inner cylinder functioning as a circular waveguide excited with its principal TE11 mode. The lower frequency band signal propagates through the space between the inner and outer cylinders functioning as a coaxial waveguide working above its cutoff TEM frequency. See Figure 2.

This configuration has some important advantages:

- both phase center positions lie almost in the same aperture plane for both bands,
- excellent port to port isolation
- ease of assembly.

A coaxial waveguide feed is appropriate for our purposes since our working frequencies comply with the frequency spacing condition $f\text{X} \gg f\text{S}$. Coaxial waveguide radiation properties, crosspolarization suppression, size dependence etc., have been adeptly described by Olver et al. [7].

4.1 Waveguide Dimensions

Basic dimensions of a coaxial waveguide configured as a feed are shown in Figure 2.

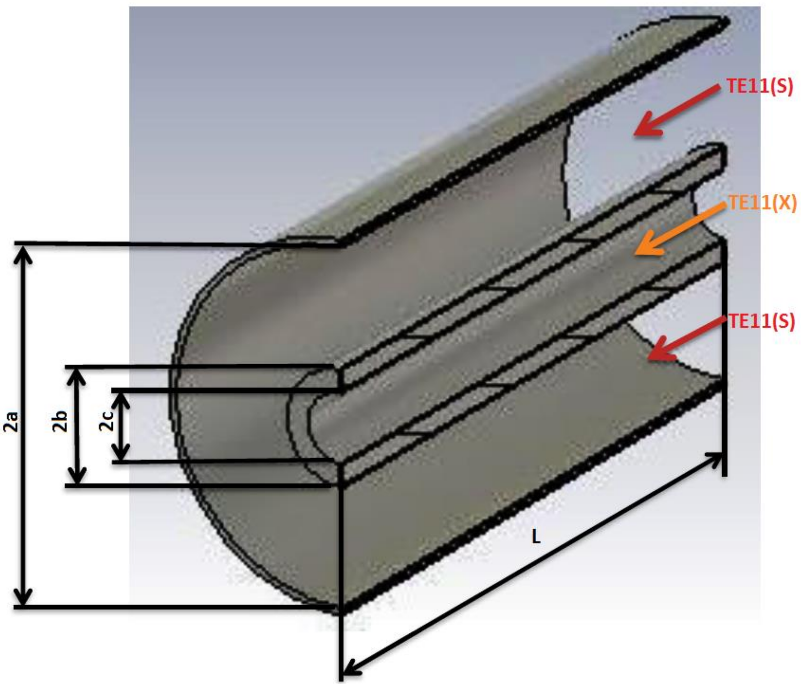

Fig. 2 - Dual-band coaxial waveguide dimensions.

Both sections of the feed are excited with standard TE11 modes. Dimensions of waveguide components were selected based on commonly available aluminum cylinders. The inside diameter of the X-band waveguide, $2c$, has been chosen to be 20 mm. Minimum and maximum frequencies for this cylindrical waveguide can be calculated from published formulae [8]. Critical frequencies for X-band TE11 and approaching the higher mode TM01 are:

$$fX_{TE11} = 300/3.412c = 8.79 \text{ GHz} \tag{1}$$

$$fX_{TM01} = 300/2.613c = 11.48 \text{ GHz} \tag{2}$$

So the condition for single-mode operation is satisfied: $fX_{TE11} < fX < fX_{TM01}$

To accommodate one ring choke for the X-band waveguide, the wall thickness of the inner cylinder is made 6.5 mm. *b* is then calculated to be 16.5 mm. The radius *a* was chosen to be 56 mm. Using these dimensions we can calculate the basic S-band TE11 mode frequency range:

$$fS_{TE11} = \frac{300}{1.873\frac{\pi}{2}(a+b)} = 1.41 \text{ GHz} \tag{3}$$

and for next higher mode, TE21

$$fS_{TE21} = \frac{300}{1.023\frac{\pi}{2}(a+b)} = 2.57 \text{ GHz} \tag{4}$$

Again, the condition for single-mode operation is satisfied: $fS_{TE11} < fS < fS_{TE21}$

4.2 Transmitter to Receiver Port Isolation *S21*

Successful communication via the satellite transponder requires full-duplex capabilities of earth stations which reinforces the important role of good Tx to Rx isolation. Also, transmission power may negatively affect LNA performance causing intermodulation and sensitivity or reliability problems. For example, assume a radiated Tx power of 10 Watts, an antenna diameter 90 cm with *f/D* ratio 0.36 and a feed gain of about 10 dB. Based on our published calculations [9], the maximum reflected power from a parabolic reflector back to the feed can be as high as +30 dBm. However, this insignificantly downgrades the *S22* parameters, since reflected power has the opposite polarization and a different phase. The main portion of this power is dissipated as heat in the Wilkinson power divider`s balanced resistors.

Equation (1) clearly demonstrates that the X-band waveguide functions as an effective attenuator, since for the S-band it acts as a waveguide below its critical frequency. The value of attenuation can be calculated using adapted formula (5) from [8]

$$ATT_{WG} = 0.1819 fX_{TE11} \sqrt{1 - \left(\frac{fS}{fX_{TE11}}\right)^2} \;, \quad (\mathrm{dB/mm, GHz}) \qquad (5)$$

For our values $fX_{TE11} = 8.79$ GHz and $fS = 2.405$ GHz, waveguide attenuation $ATT_{WG} = 1.53$ dB/mm. For 170 mm it is more than 260 dB, obviously a theoretical value. In the real world, due to RF connectors and cable leakage we can expect a value of about 100 dB, which is still very good.

4.3 Feed Optimization

Feed parameters such as radiation patterns and impedance match are optimized using a parametric model with CST MW Studio software [10]. A cylindrical waveguide for the X-band in the first design was fitted with a coaxial-to-waveguide transition that employs a simple $\lambda/4$ excitation probe, ensuring linear polarization excitation of the TE11 mode. Another option for waveguide excitation is to use a waveguide adapter – circular to WR75-size waveguide. Two kinds of adapters have been designed to date, a narrow band adapter designed by Jeffrey Pawlan [11] and a wideband adapter respectively. The simulated radiation pattern and impedance match *S11* for the X-band are shown in Figures 3 and 4.

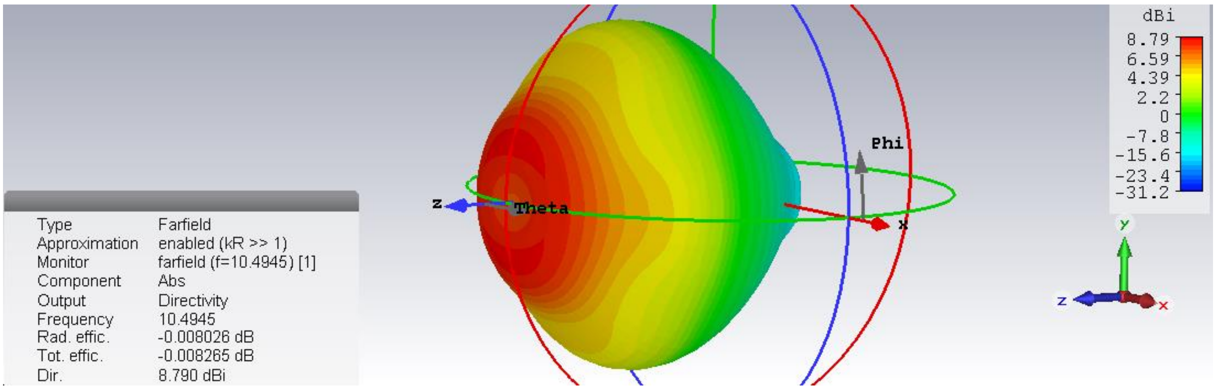

Fig. 3 - Calculated 3D X-band radiation pattern.

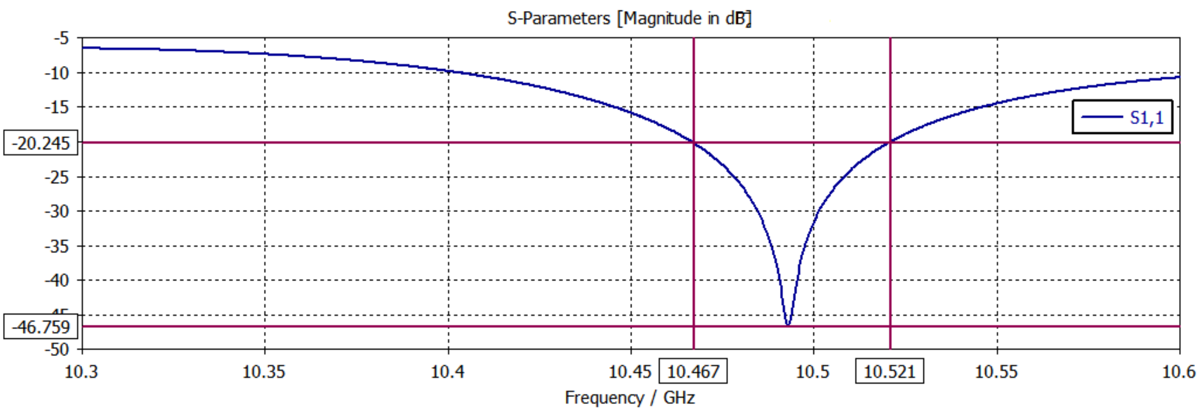

Fig. 4 - *S11*- calculated impedance match of the X-band port. The port employs a $\lambda/4$ excitation probe, created from the center pin of a SMA connector.

Four probes are used to excite the S-band coaxial waveguide. Probes are fed signals with 0°, 90°, 180° and 270° phase shift. This creates circular polarization. See Fig.5.

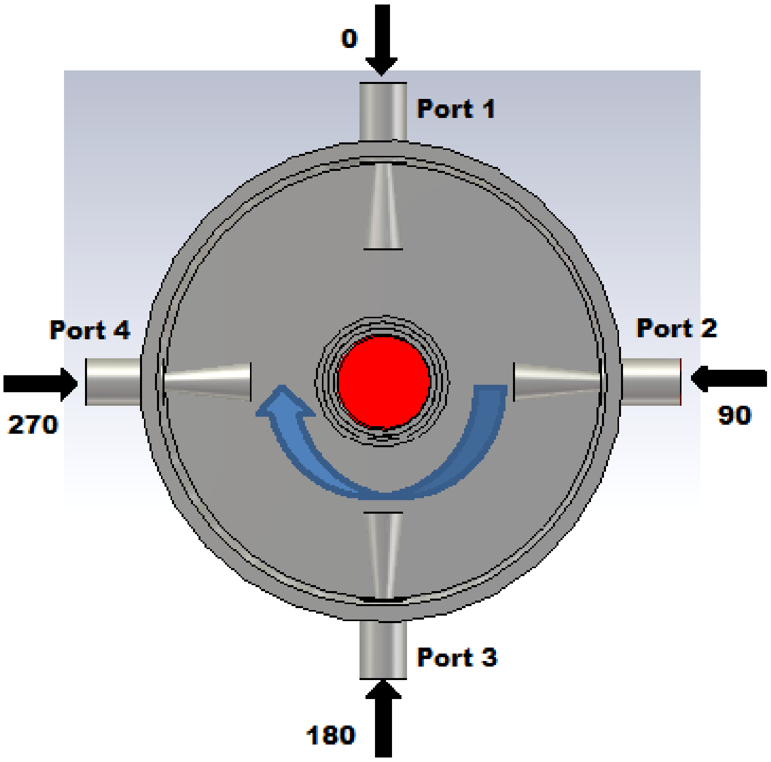

Fig. 5. - Feed boresight axis view. Four probes are fed with phase shifted signals exciting RHCP in this figure. To change the sense of rotation, excitation signals of two opposite ports must be exchanged.

An E-MECA Wilkinson power divider was used for our first measurements. Phase shifts are facilitated by coaxial cables of appropriate lengths. See Fig. 6.

Fig. 6 - An E-MECA 4-way power divider with coaxial phasing cables. A single SMA connector for the X-band is visible below the power divider.

The simulated S-band radiation pattern and axial ratio are shown in Figures 7 and 8.

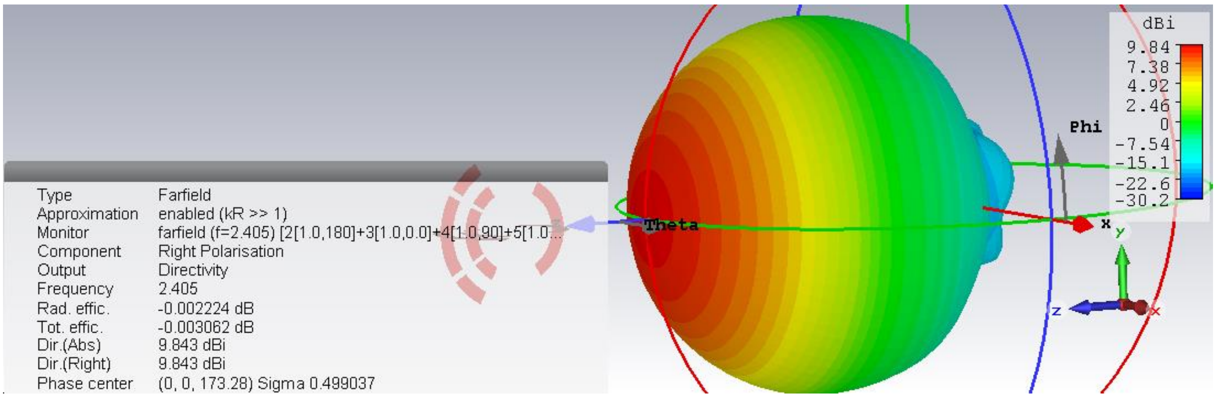

Fig. 7 - Calculated S-band 3D radiation pattern. RHCP is displayed.

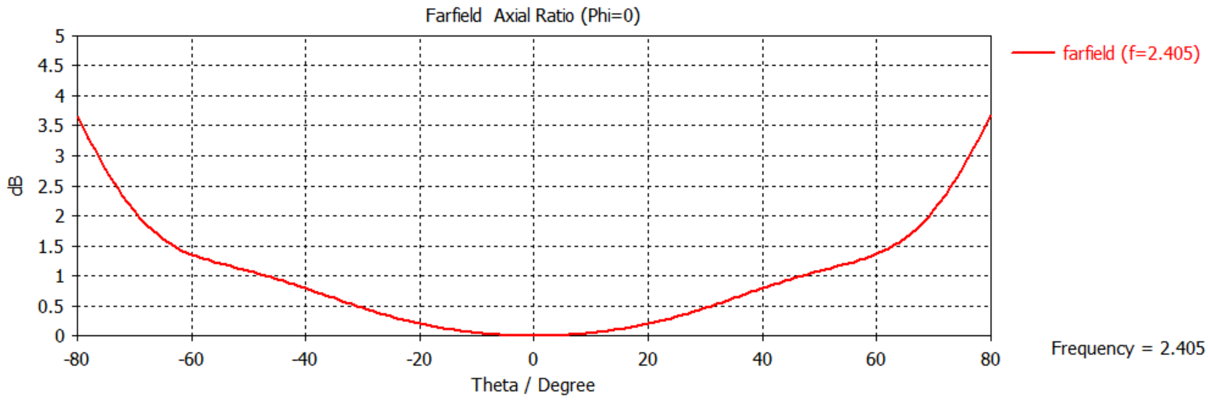

Fig.8 - Calculated S-band axial ratio for Phi = 0 deg.

S22 parameters for each port are shown in Figure 8.

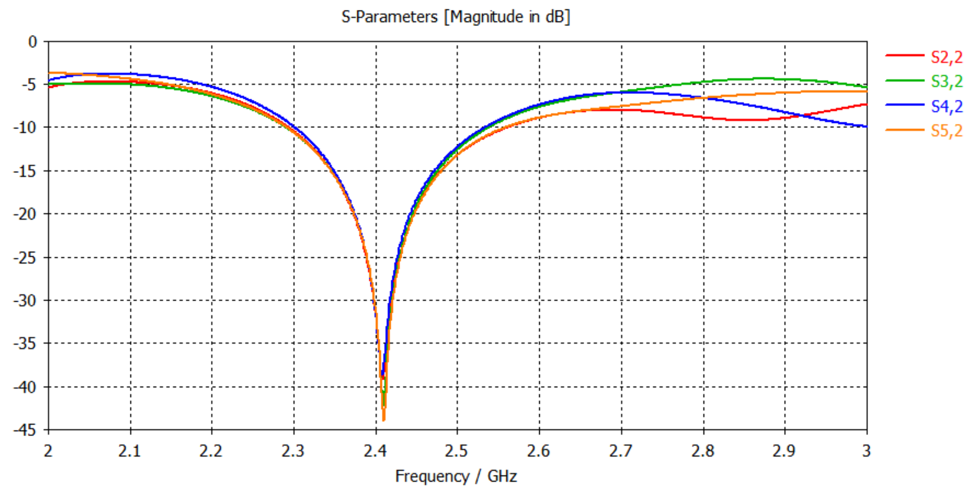

Fig. 9 - Calculated *S22* parameters for S-band. Ports are excited with 0, 90, 180 and 270 deg. phase shifted power.

5. Actual Measured Performance

Two feed prototypes based on computer models were fabricated for the purpose of verifying calculated performance parameters. See Fig. 10.

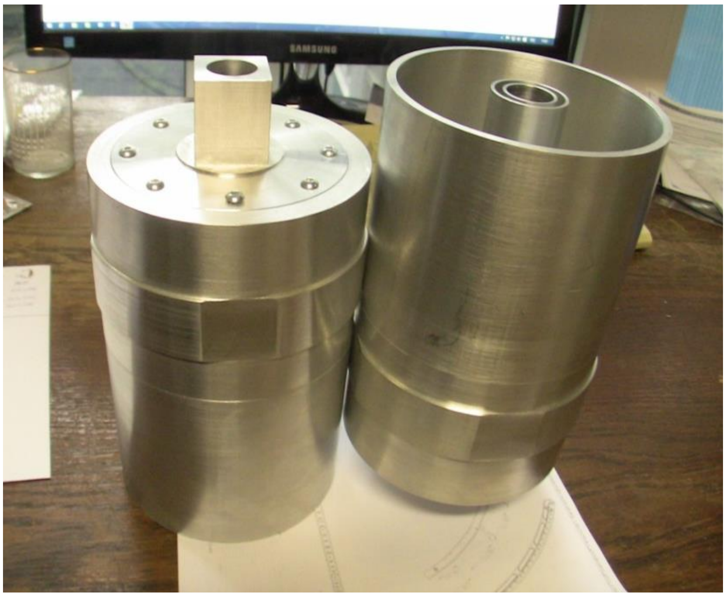

Fig. 10 – Feed prototypes during fabrication process.

During final assembly, one feed was fitted with an E-MECA, 4-way Wilkinson power splitter, and the second feed with a similar product from MICROLAB. Both splitters can handle up to 10 W of power. The phase shift of both splitters was verified by Franta-OK1CA, using an ANRITSU MS2028C vector network analyzer. The same instrument was used to check and adjust the phase feeding cables. Feeds were tested at the laboratories of Czech Technical University in Prague. See Fig. 11. The measurement setup was the same as used for our previous project which is referenced here [12].

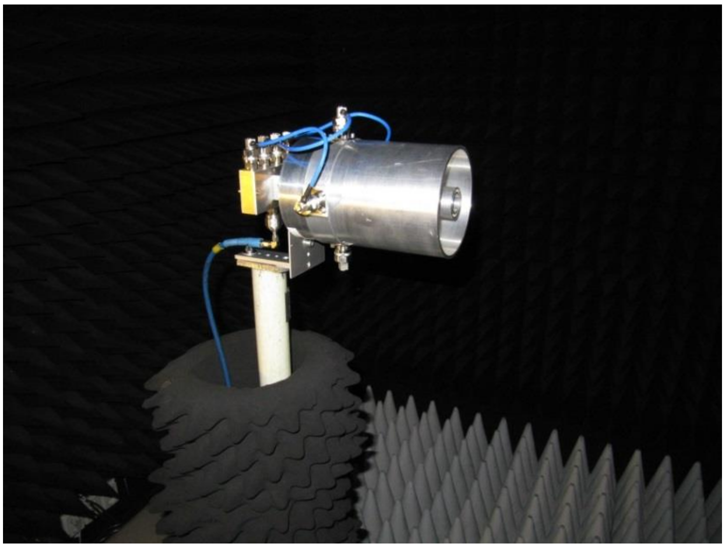

Fig. 11 - Feed under test in anechoic chamber.

An RF Spin antenna, DHR20, was used for radiation pattern and polarization pattern measurements on X- and S-bands. A spiral circular polarization antenna, SCSA-27, was used for radiation pattern measuremenst on the S-band [13].

5.1 X-Band Performance

Radiation patterns for feeds 1 and 2 are shown in Figs. 12 and 13.

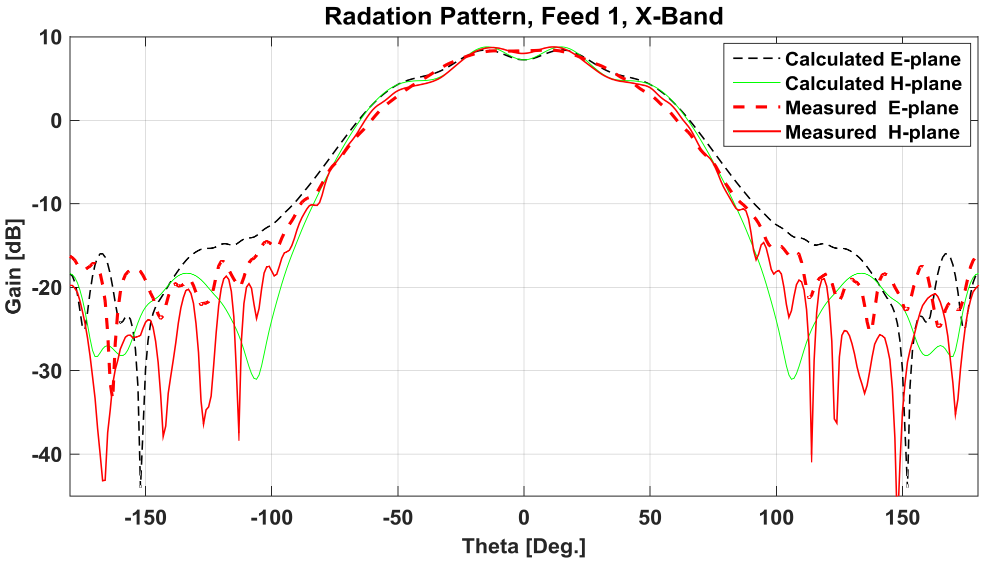

Fig. 12 - Feed 1, calculated and measured radiation patterns on X-band, linear polarization.

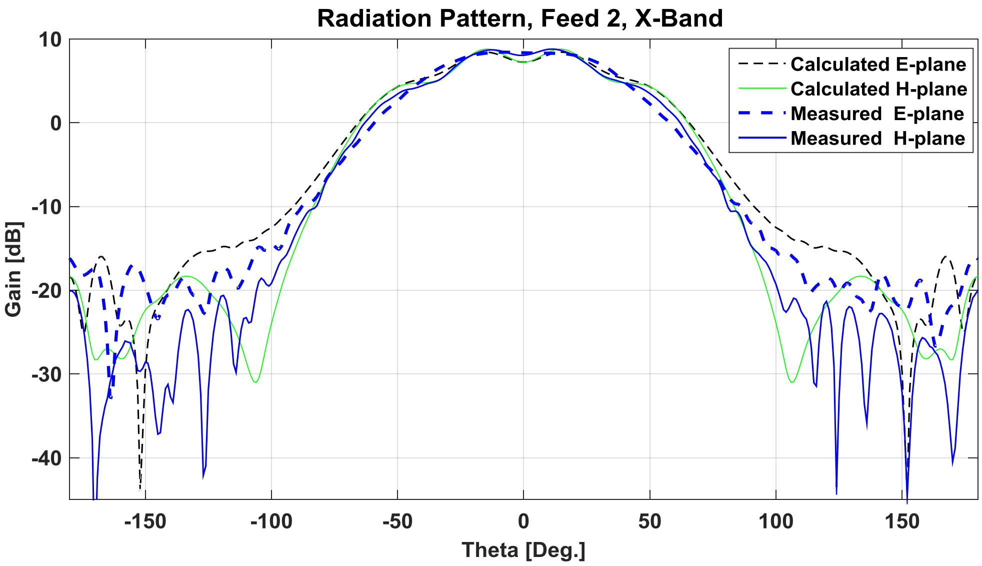

Fig. 13 - Feed 2, calculated and measured radiation patterns on X-band, linear polarization.

Calculated and measured impedance match prameters, *S11* are plotted in Fig. 14.

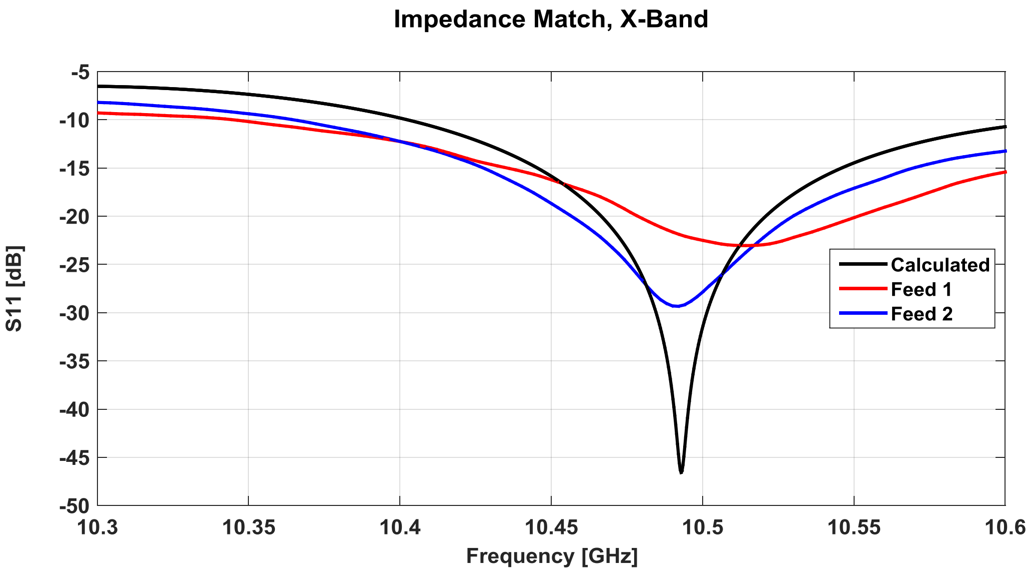

Fig. 14 - Calculated and measured *S11* parameters. The excitation probe of feed 1 is shorter, causing its minimum to be slightly above the working frequency.

5.2 S-Band Performance

Radiation patterns for Feed 1 and Feed 2 are displayed on Figs. 15 and 16.

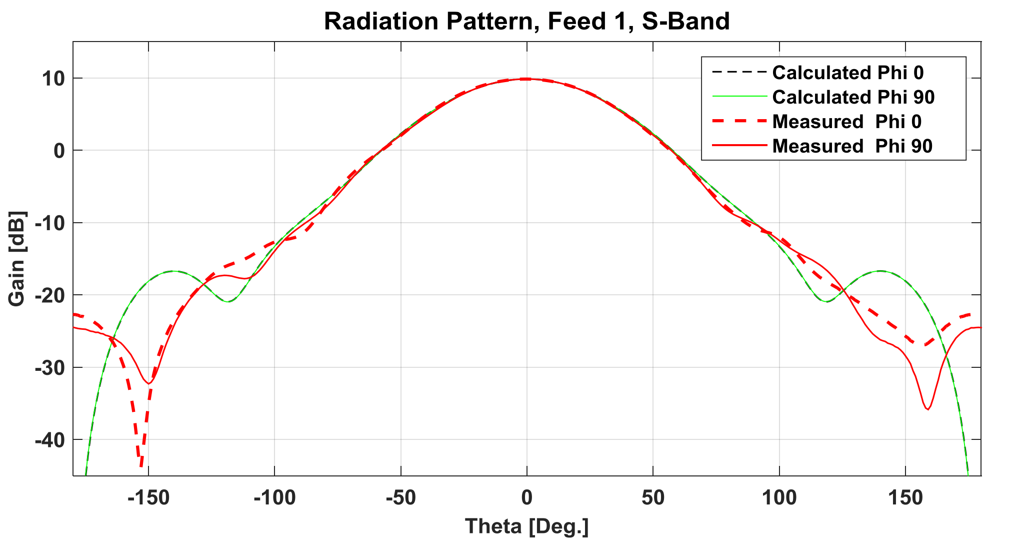

Fig. 15 - Feed 1, calculated and measured radiation pattern on S-band, circular polarization.

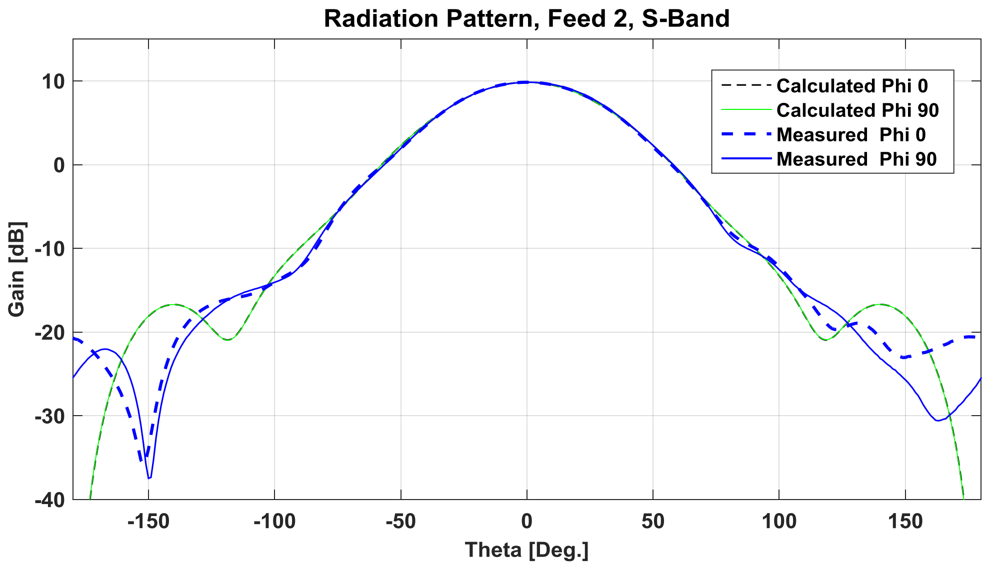

Fig. 16 - Feed 2, calculated and measured radiation pattern on S band, circular polarization.

Measurements of impedance match, *S22*, were performed at the input of the power splitter connector. Obviously, power splitter parameters influence the overall results. See Figs. 17 and 18. Another influence is the phasing cables. Two types of coaxial cables were tested, LMR195 and SM141FEP. All cables were fitted with 90 degree N-style male connectors on both ends. SM141FEP cables achieved an impedance match better than 26 dB and phase deviation of ±2 degrees. LMR195 cables had an impedance match below 20 dB and an average phase deviation of ±4 degrees.

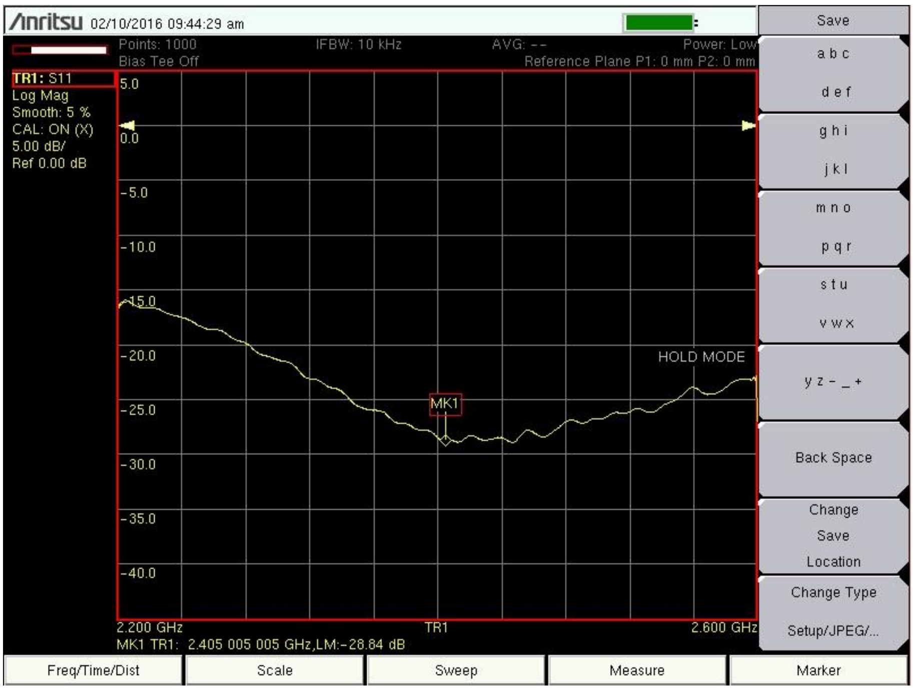

Fig. 17 - Impedance match of 4-way power splitter E-MECA 804-4-2.400.

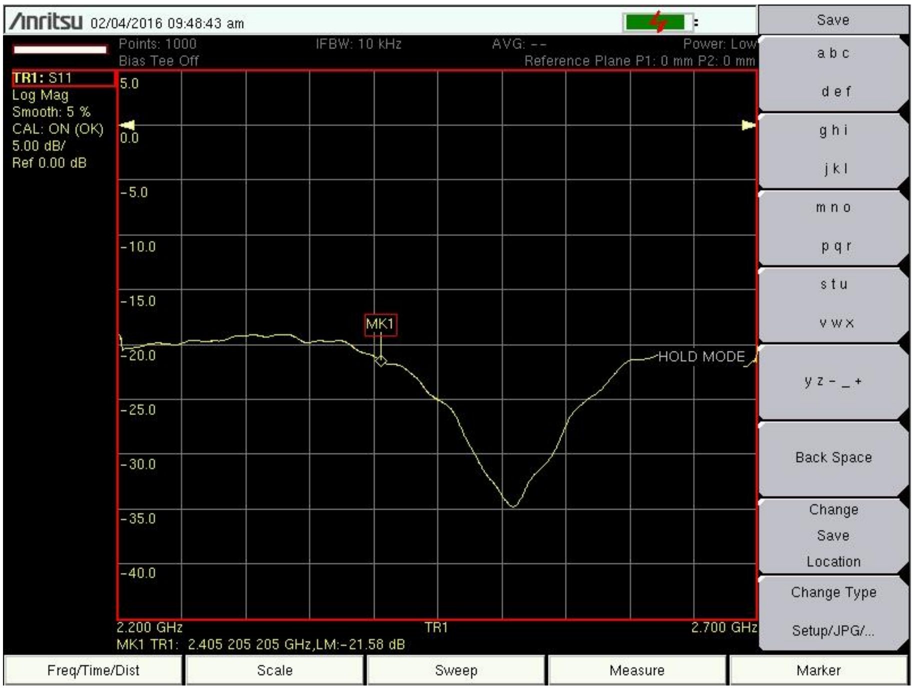

Fig. 18- Impedance match of 4-way power splitter MICROLAB/FXR.

Feed *S22* parameters are plotted in Fig.19

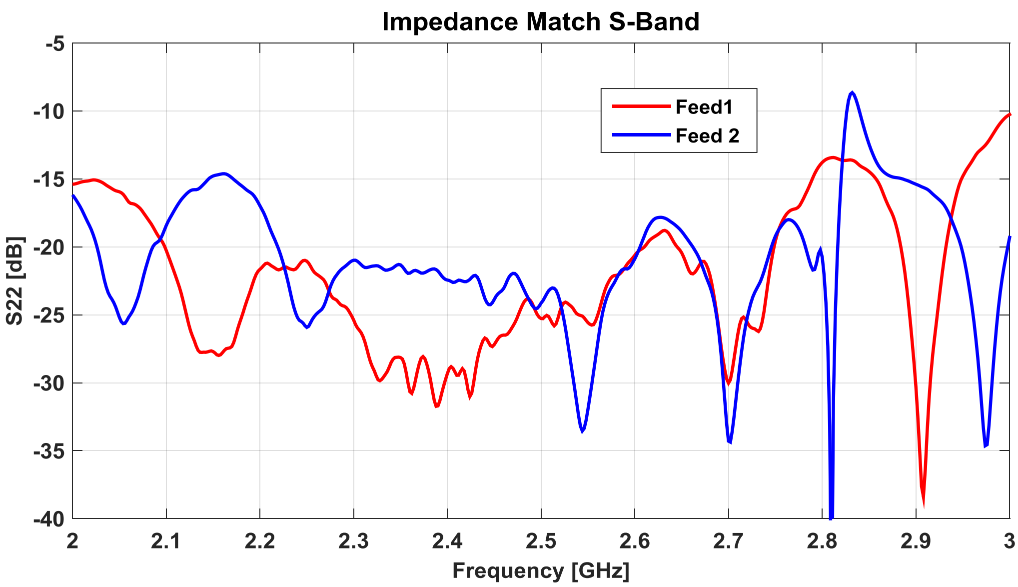

Fig. 19 – Measured impedance match *S22* on S-band.

5.2.1 Axial Ratio

The axial ratio mostly depends on phase shifts of the excitation signals. However, even with higher variation in phase shift, the axial ratio is still very good. See Figs.20 and 21.

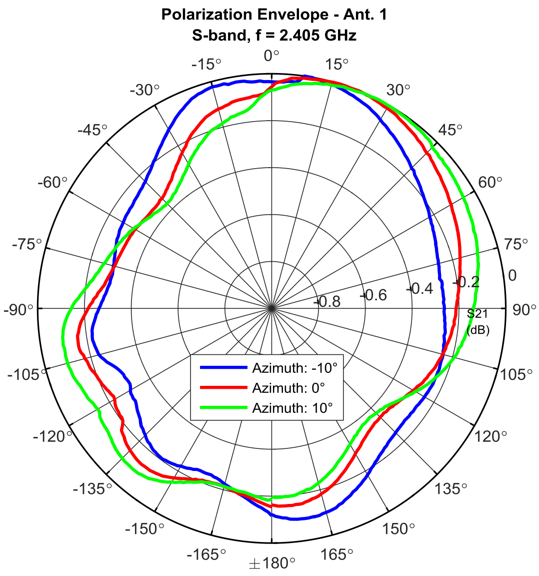

Fig. 20 - Polarization envelope of Feed 1 for three azimuths, -10, 0 and +10 degrees. The axial ratio at the feed boresight is better than 0.4 dB.

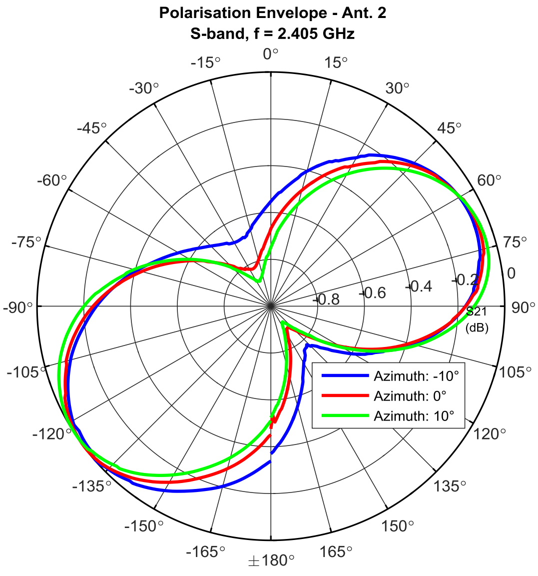

Fig. 21 - Polarization envelope of Feed 2 for three azimuths, -10, 0 and +10 degrees. The axial ratio at the feed boresight is better than 0.9 dB.

5.3 Port-to-Port Isolation *S21*

All measured signals at the S-band port were suppressed by more than 100 dB at the X-band port.

6. Feed Gain Factor

CST MW Studio software was used to calculate the efficiency of both bands with the feed optimally positioned for the X-band. The same numerical procedure described in our previous project [12], a combination of Time Domain and Integral Equation Solver (MLFMM), was applied. Calculated results are shown in Figs. 22 and 23.

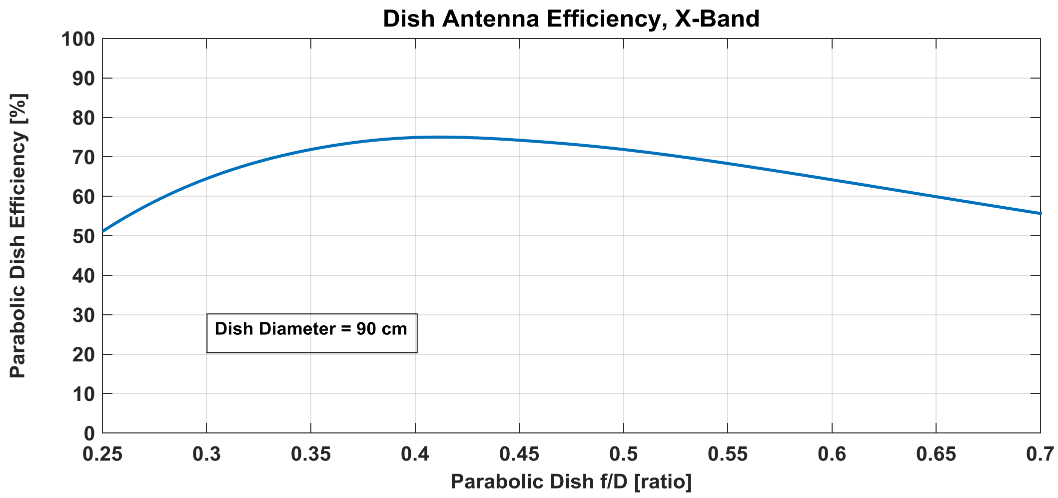

Fig. 22 - Calculated feed gain factor for X-band.

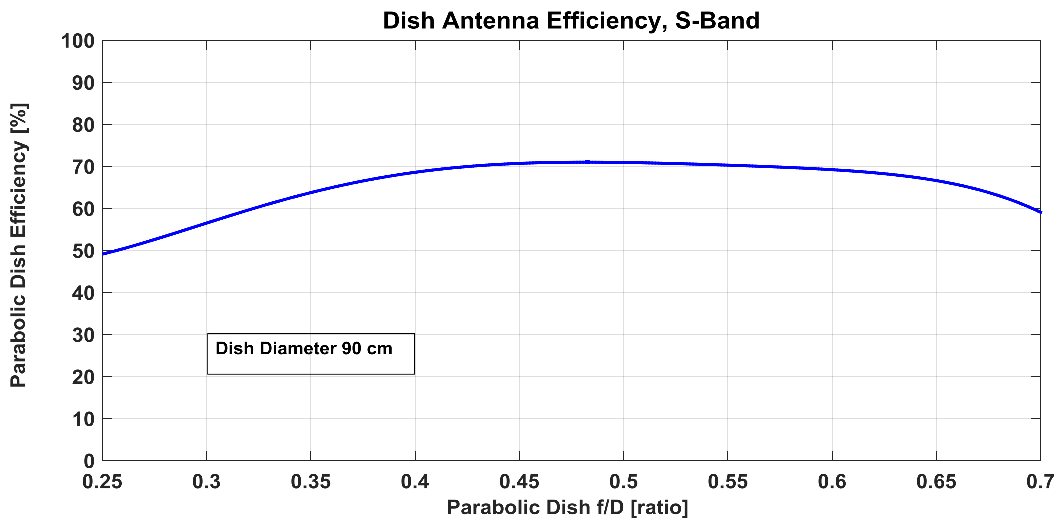

Fig. 23 - Calculated gain factor for S-band. Lower efficiency is due to the relatively small dish diameter (7.2λ). An additional negative factor is the short distance between the feed and dish. The feed works on the edge of nearfield and farfield.

7. Simple Equipment Setup

A simple earth station may be easily constructed using a 10 Watt, 144 or 432/2400 MHz transverter for transmission and a modified professional Ku band LNB satellite downconverter and associated SDR dongle unit, for reception. For serious work, an LNB downconverter with low noise PLL and thermally stable local oscillator should be used. Several of these units are available on Ebay at an affordable price. We procured and tested a SPC Electronics model SPCR5300F. See Fig. 24.

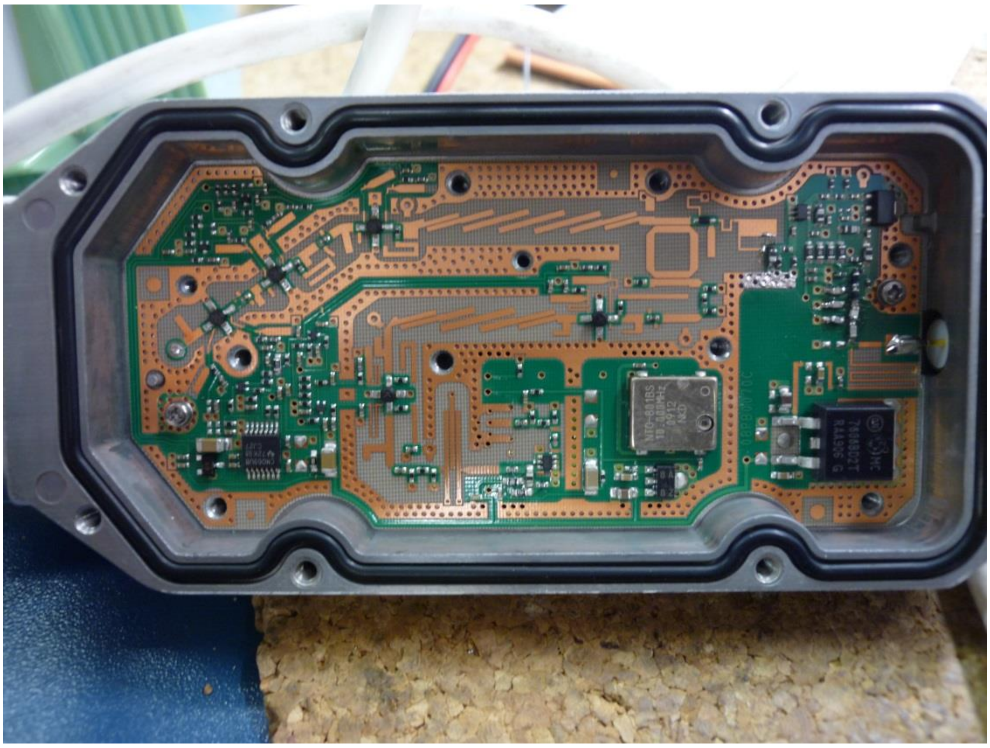

Fig. 24 – A modified SPCR5300F Low Noise Block.

This LNB is equipped with a UBR120 flange for a WR-75 waveguide port. A circular-to-WR-75 waveguide adapter is used as an interface between the antenna and LNB. Measurement of the LNB transmission characteristics has revealed that the original device was suitable for frequencies down to 10.7 GHz. Our frequency range required modification of the PCB microstrip and IF filters. Transmission characteristics are plotted in Fig. 25. Measured noise figures of the modified device are 1.1 dB@10.35 GHz and 1.05 dB @10.5 GHz respectively.

For the SDR receiver, any device with good frequency stability and coverage up to 500 MHz can be employed. Many of these devices have a relatively low dynamic range. To protect the SDR receiver front end from overload by emissions from the satellite`s high-power TV transponder at nearby frequencies, a low-cost SPAUN SLTE90 low-pass filter should be inserted between the LNB output and SDR front end. See Fig. 26.

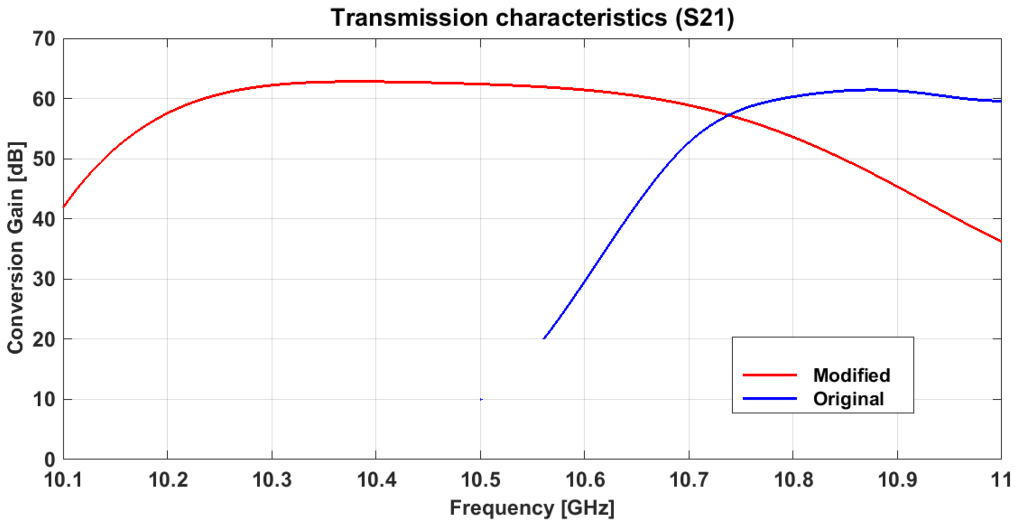

Fig. 25 - Transmission characteristics of SPCR5300F device.

Fig 26 – Transmission characteristic of SLTE90 low pass filter.

8. Summary and Conclusion

Deployment of a publically-accessible, geostationary satellite transponder covering almost one-third of the Earth's surface will mark the beginning of a new era of communication opportunities for amateur radio enthusiasts. Establishing contact requires only a small antenna and low-power transmitter employing conventional microwave technology. This simplicity thus enables utilization for not only common amateur radio applications, but also for education or emergency purposes.

Our antenna design goals have been achieved. The described prime-focus feed mounted on a parabolic dish reflector >75 cm diameter with *f/D* ratio ranging from 0.3 to 0.65 can be used with reasonable efficiency. Fabrication of several prototypes has allowed us to verify the reproducibility and ease of assembly as well as to confirm operational performance design parameters.

Assembled antennas, feeds and modified LNB's are available from the BTV Company [14].

Now, we must cautiously wait and anticipate a successful launch of Es'hail 2 into many orbits of trouble-free operation.

Acknowledgements

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Additionally, we thank RFspin s.r.o. [13], for the use of CST MW Studio software.

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2.		INNER CYLINDER	AlMg4,5Mn0,7	Ro100-222	AW5083	1		
3.		COVER	AlMg4,5Mn0,7	P3x30 - 30	AW5083	1		
4.		N CONNECTOR	Ag/Ni		J01021B0008	4		Telegärtner
5.		SMA 4 CONNECTOR	Au/Ni		STI 1206-142-PH	1		San-Tron
6.		CONE	AlMg4,5Mn0,7	Ro10- 22	AW5083	4		
7.		SCREW	Stainless steel	M4x12	DIN 912	8		
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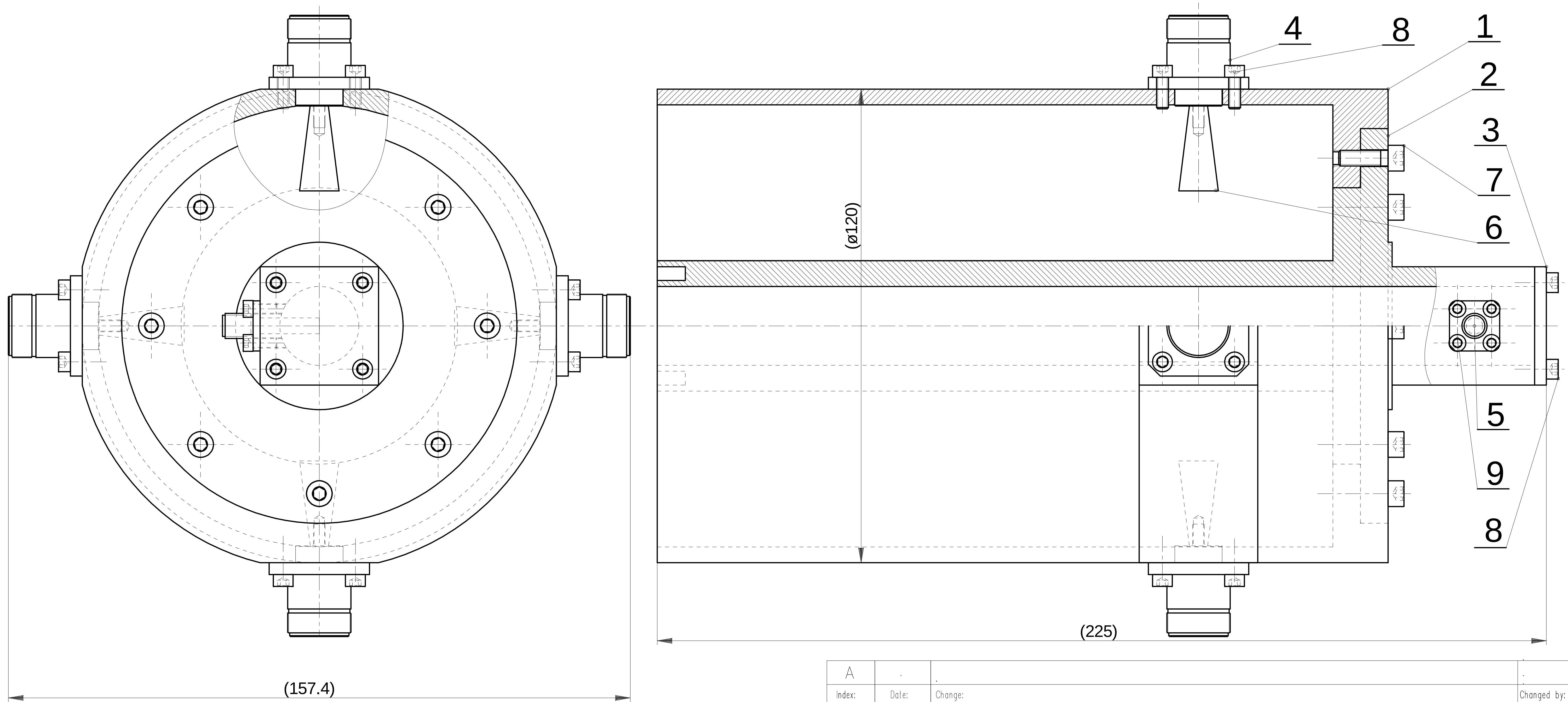

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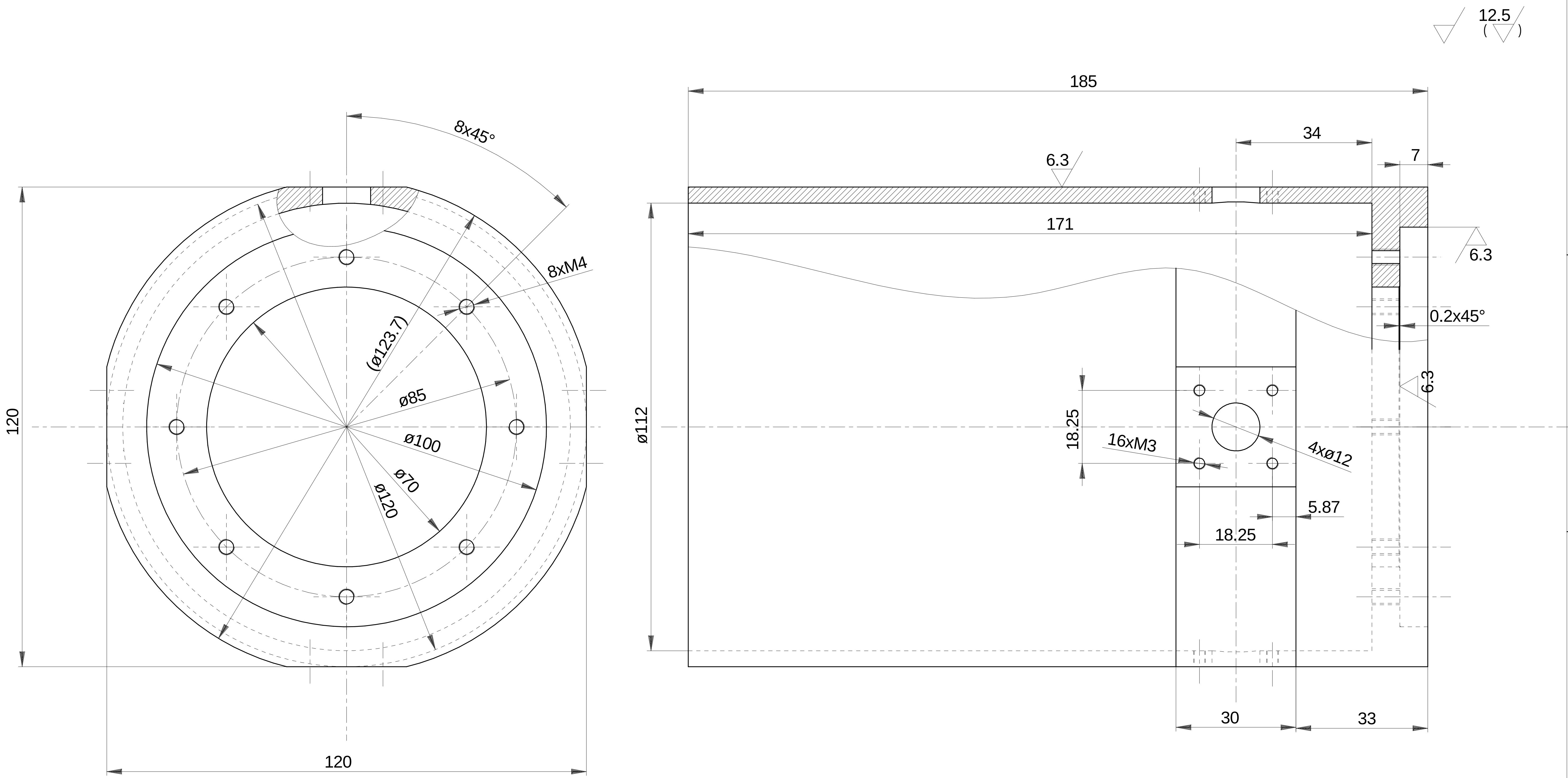
	Model		Weight:		

Sheet: 1 of 1



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Index:	Date:	Change:	Changed by:

Project: S/X DUAL BAND	Job number:	Tolerances: ISO 2768-mL		Semiproduct:	Ro123,7- 185
				Standard:	AW5083
DESIGN V PRIEMYSLE www.designprepriemysel.sk	Name:	Date:	Scale: 1:1	Material:	AlMg4,5Mn0,7
	Drawn: R.Galuscak	4/2016		Drawing Title:	OUTER CYLINDER
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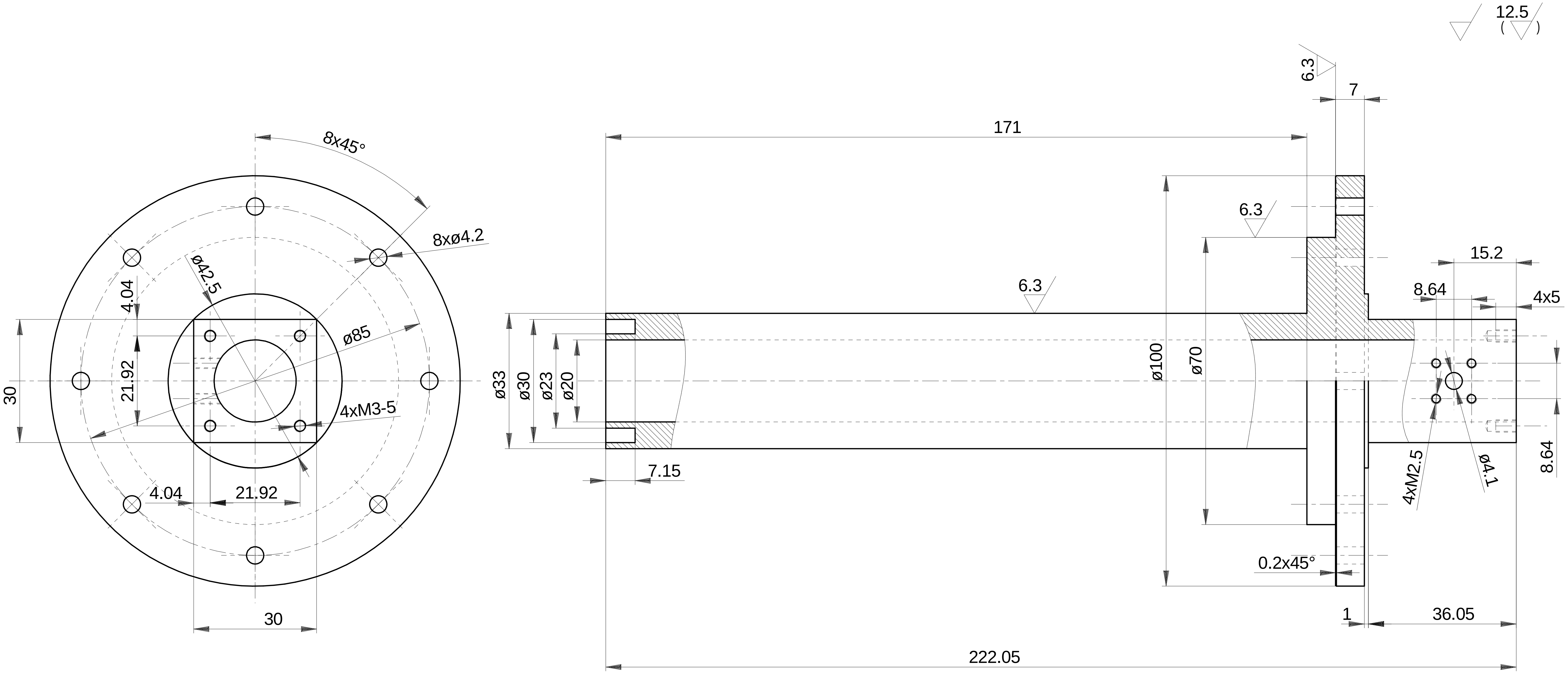
Sheet: 1 of 1



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				Standard:	AW5083
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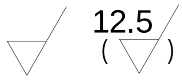
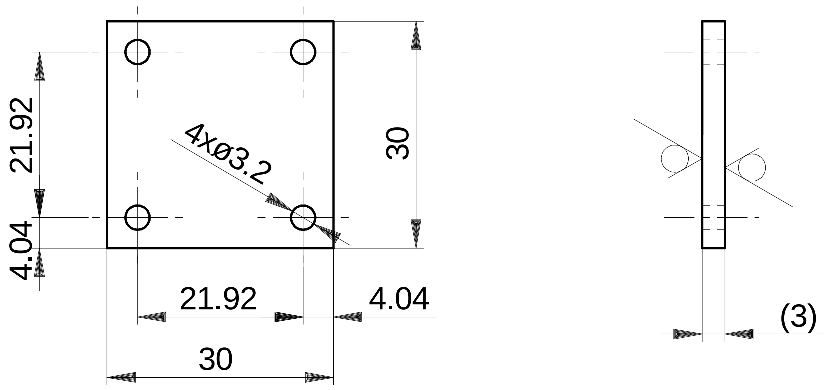
Sheet: 1 of 1





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Changed by:

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S/X DUAL BAND		ISO 2768-mL	Standard:	AW5083
	Name:	Date:	Scale: 1:1	Material: AlMg4,5Mn0,7
Drawn:	R.Galuscak	4/2016		Drawing Title: COVER
Checked:			Format: A4	
Technol.:				Drawing Number:
Model		Weight:		

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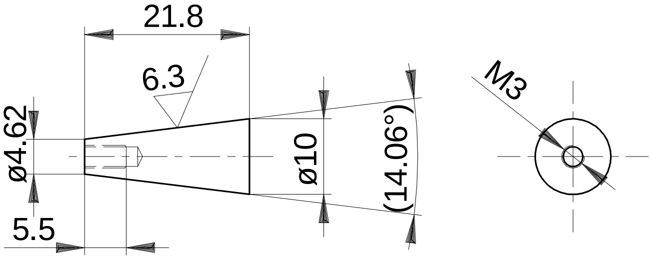
12.5



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				Standard: AW5083
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	Drawn:	R.Galuscak	4/2016		Drawing Title: CONE
	Checked:			Format: A3	
	Technol.:				Drawing Number:
	Model		Weight:		

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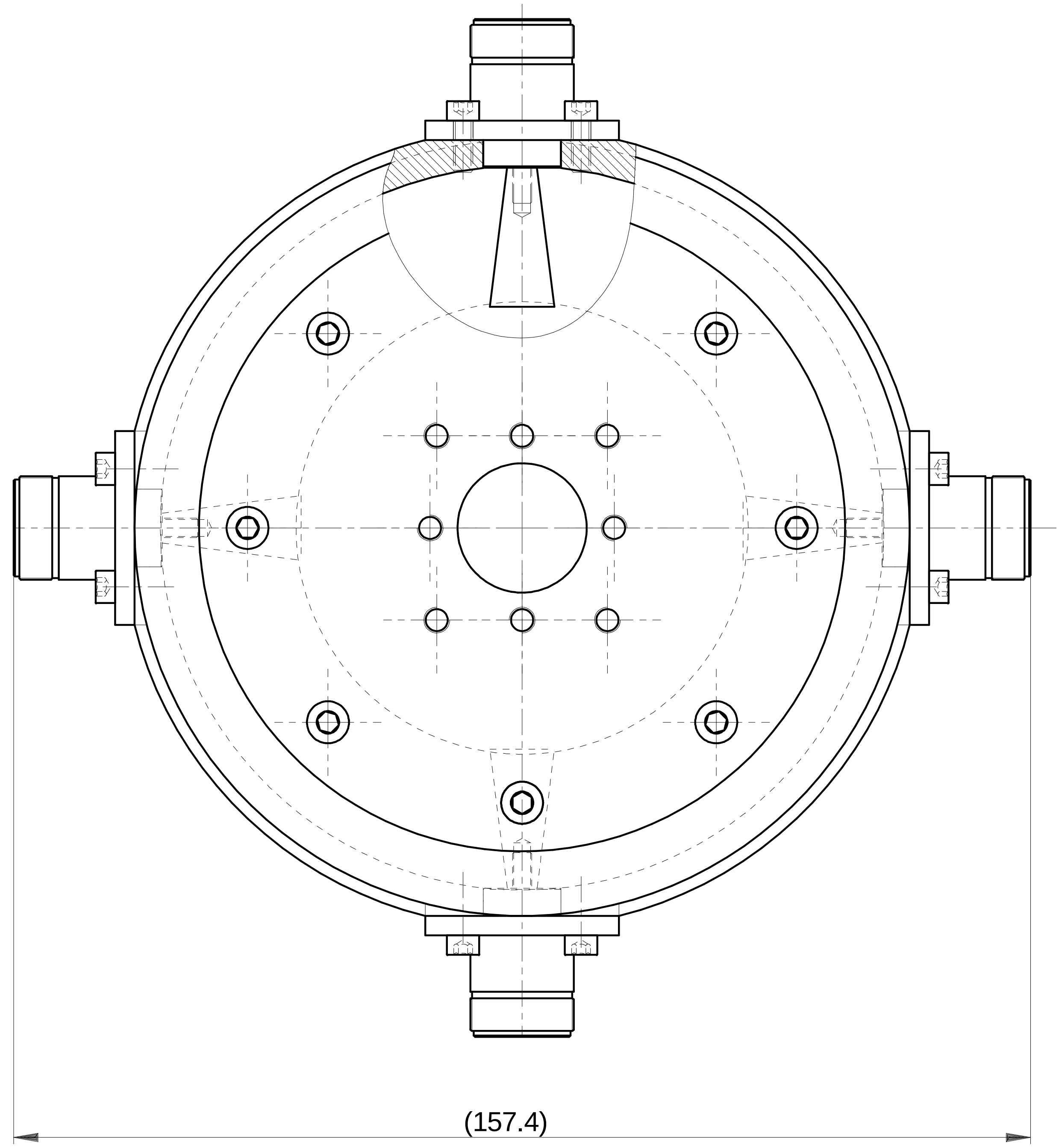
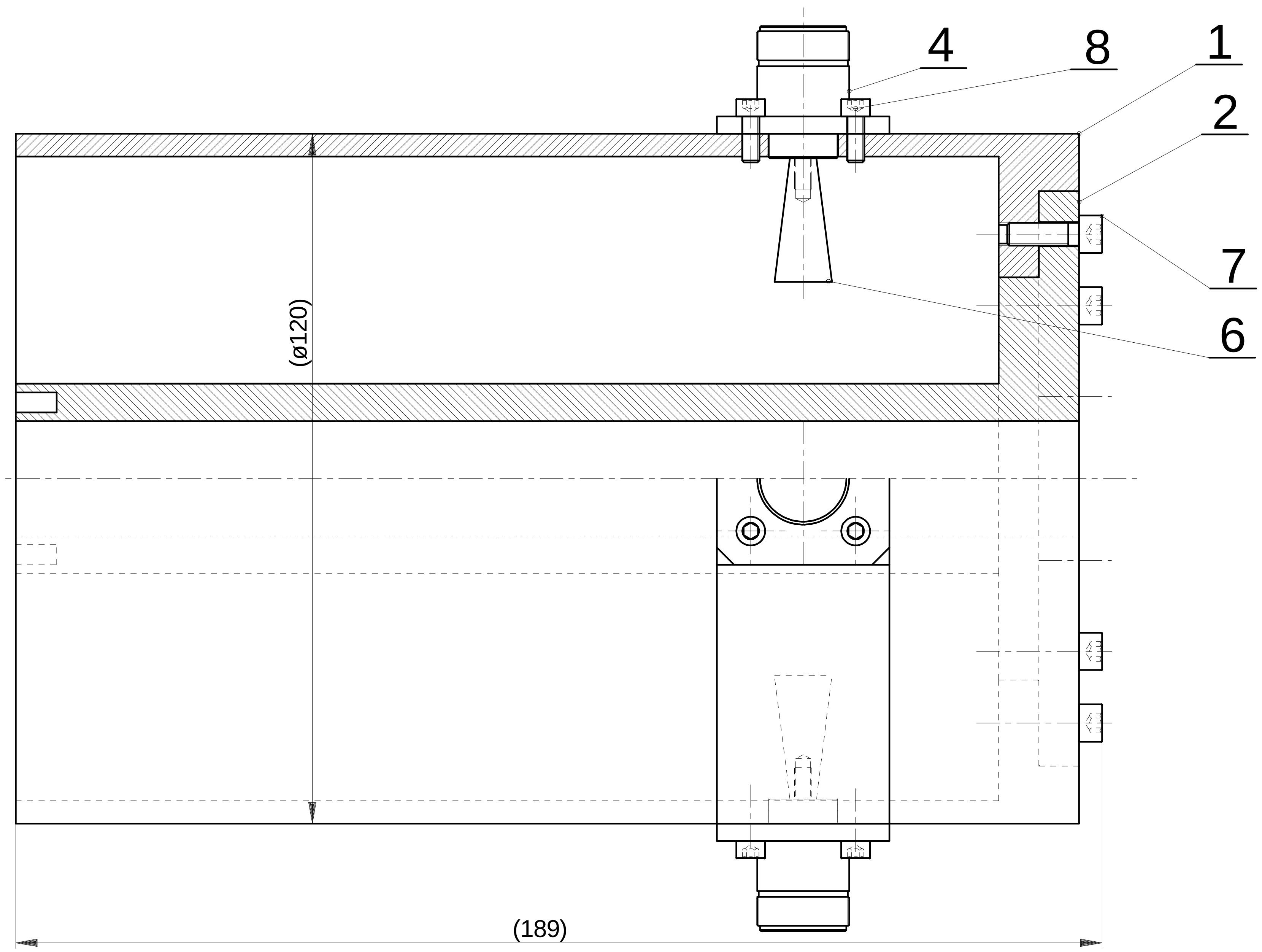
Sheet: 1 of 1

Pos.	Drawing Tittle:	Drawing Tittle:	Material:	Semiproduct:	Standard:	Qty:	Weight(kg)	Note:
1.		OUTE R CYLINDER	AlMg4,5Mn0,7	4H120- 185	AW5083	1		
2.		INNER CYLINDER	AlMg4,5Mn0,7	Ro100-222	AW5083	1		
3.		N/A						
4.		N CONNECTOR	Ag/Ni		J01021B0008	4		Telegärtner
5.		N/A						
6.		CONE	AlMg4,5Mn0,7		AW5083	4		
7.		SCREW	Stainless steel	M4x12	DIN 912	8		
8.		SCREW	Stainless steel	M3x8	DIN 912	16		
9.		N/A						





Index:	Date:	Change:	Changed by:
A	.	.	.

Project: DUAL BAND S/X

Job number:

Tolerances: ISO 2768-mL

Semiproduct:

Standard: .

Material: .

	Name:	Date:
Drawn:	R.Galuscak	4/2016
Checked:		
Technol.:		
Model		

Scale: 1:1

Format: A3

Weight:

Drawing Title: S/X DUAL - BAND COAXIAL FEED WG

Drawing Number:

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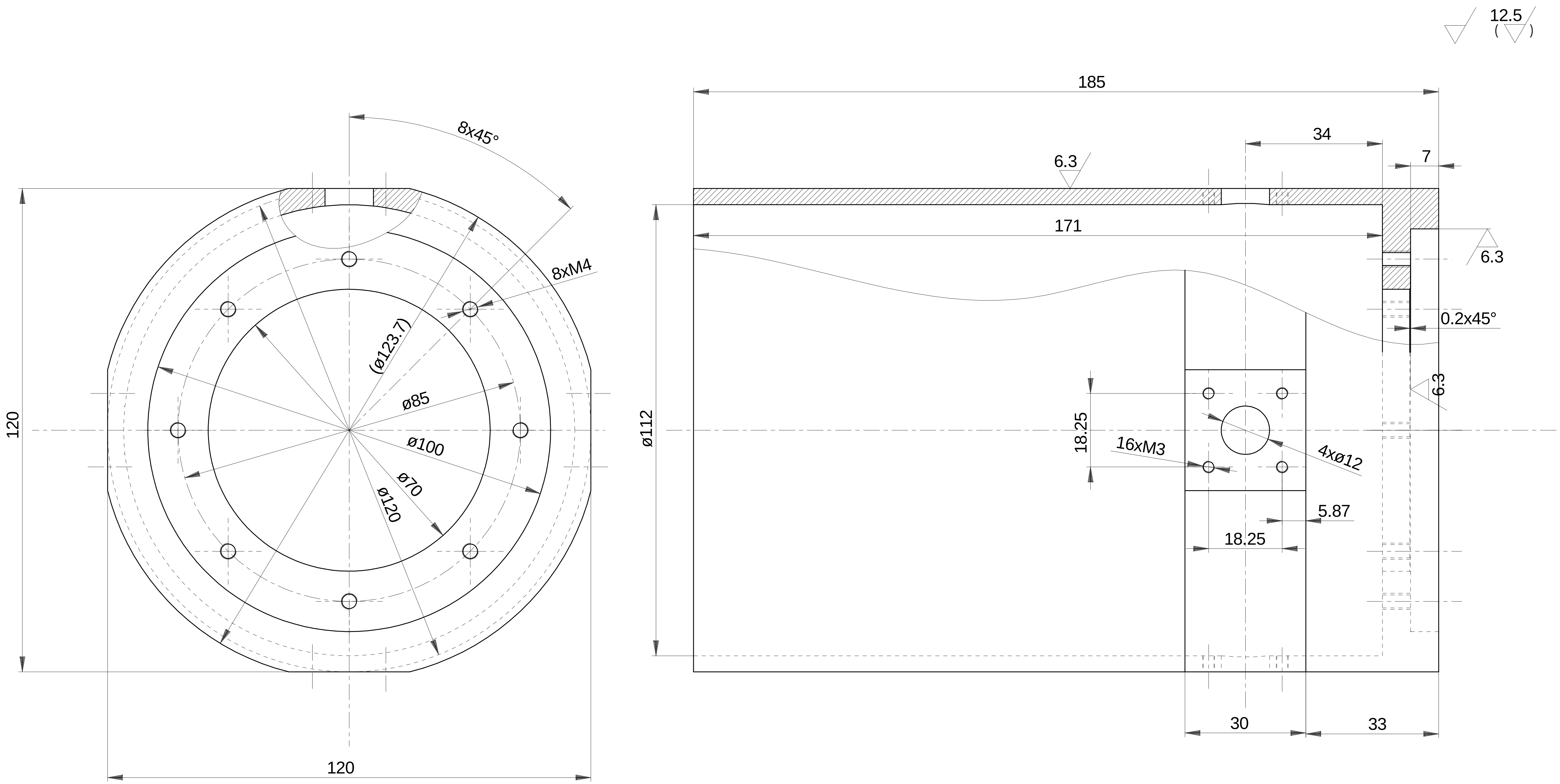
Sheet: 1 of 1



Index:	Date:	Change:	Changed by:
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Project:	Job number:	Tolerances:		Semiproduct:	Ro123,7- 185
S/X DUAL BAND		ISO 2768-mL		Standard:	AW5083
DESIGN V PRIEMYSLE www.designprepriemysel.sk	Name:	Date:	Scale: 1:1	Material:	AlMg4,5Mn0,7
	Drawn: R.Galuscak	4/2016		Drawing Title:	OUTER CYLINDER
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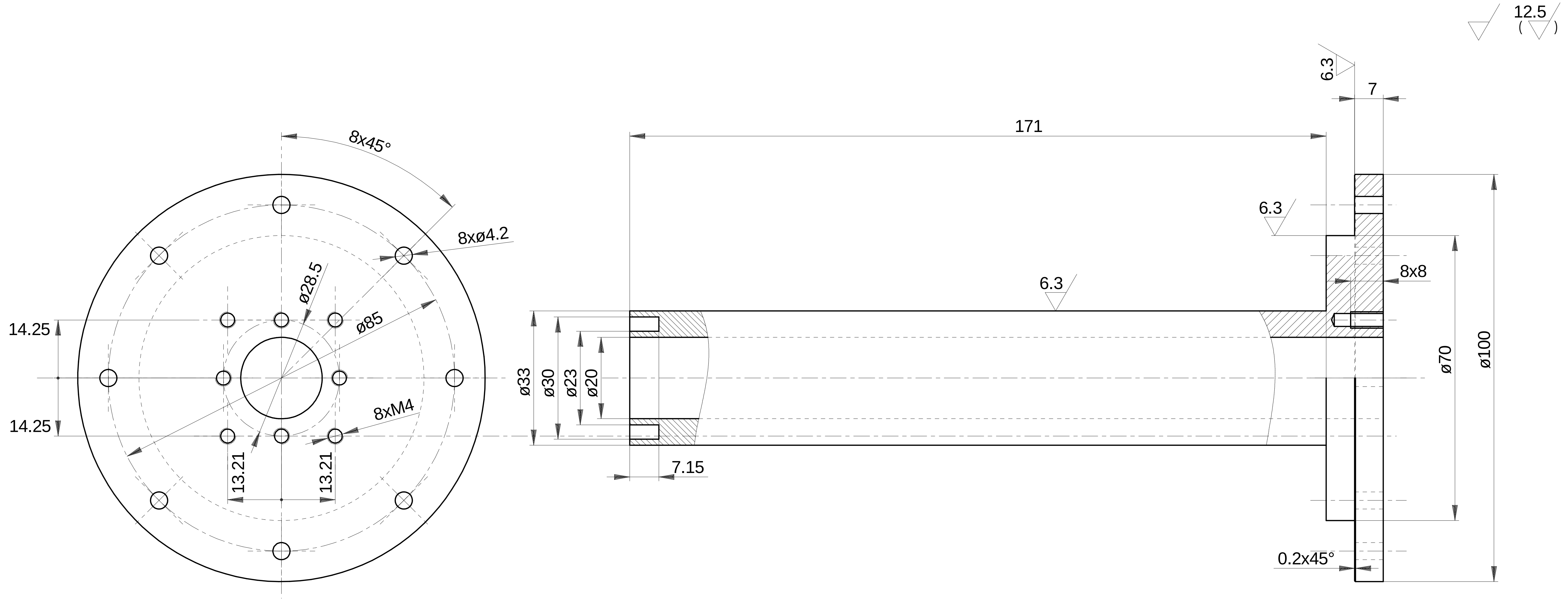
	Technol.:			Drawing Number:	
	Model	Weight:			

Sheet: 1 of 1



A	.	.	.
Index:	Date:	Change:	Changed by:

Project: S/X DUAL BAND	Job number:	Tolerances: ISO 2768-mL		Semiproduct:	Ro100-222
				Standard:	AW5083
DESIGN V PRIEMYSLE www.designprepriemysel.sk	Name:	Date:	Scale: 1:1	Material:	AlMg4,5Mn0,7
	Drawn: R.Galuscak	4/2016		Drawing Title:	INNER CYLINDER WG
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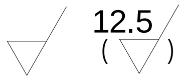
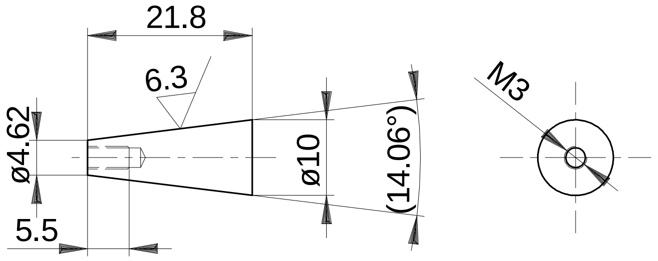
	Model		Weight:		

Sheet: 1 of 1





Index:	Date:	Change:	Changed by:
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Project:	Job number:	Tolerances:		Semiproduct:	Ro10- 22
S/X DUAL BAND		ISO 2768-mL		Standard:	AW5083
DESIGN V PRIEMYSLE www.designprepriemysel.sk		Name:	Date:	Scale: 1:1	Material: AlMg4,5Mn0,7
	Drawn:	R.Galuscak	4/2016		Drawing Title: CONE
	Checked:			Format: A3	
	Technol.:				Drawing Number:
	Model		Weight:		

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