A Low-Frequency and Wide-Band Reflector Antenna Feed for Future Earth Observation Radiometers

Executive summary report

Date	14/12/2022
Reference	ESR
Issue	1
Project code	**CRYO** ESA: ESA AO/1-10051/20/NL/AS
ESA Contract No	4000132342/20/NL/AS ESA AO/1-10051/20/NL/AS

DOCUMENT CONTROL

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ISSUE CONTROL

Date	Issue	Main changes
01/12/2022	0	Initial issue
14/12/2022	1	-

APPLICABLE DOCUMENTS

#	Ref.	Name	Issue
AD-01	ESA-TRP-TEC-SOW-017728	Statement of Work document named “AO1005”	1
AD-02	CRYO-EOS-ENG-RPT-001	TN1 State of the art review	0
AD-03	CRYO-EOS-ENG-RPT-002	TN2 Consolidated antenna requirements	1
AD-04	CRYO-EOS-ENG-RPT-004	TN3 Feed chain concepts trade-off	1
AD-05	CRYO-EOS-ENG-RPT-005	TN4 Feed chain preliminary design and analysis	1
AD-06	CRYO-EOS-ENG-RPT-007	TN5 Antenna detailed design	2
AD-07	CRYO-EOS-ENG-RPT-008	TN6 Breadboard antenna test plan and procedure	2
AD-08	CRYO-EOS-ENG-RPT-010	TN7 Test report	3
AD-09	CRYO-EOS-ENG-RPT-011	TN8 Development roadmap	0

REFERENCE DOCUMENTS

#	Ref.	Name	Issue
RD-01			
RD-02			
RD-03			

Content

1 Introduction

1.1 Objective

The objective of this document is to summarise the work done and the main achievements obtained under the CRYO project with reference REF: ESA AO/1-10051/20/NL/AS.

1.2 Scope

This document is a compilation of all the work done and the results obtained during the project. All this is presented in a form suitable for the correct reading and understanding by any reader (expert and non-expert in the field).

1.3 Document structure

The document is structured as follows:

- Chapter 1 – Introduction.
- Chapter 2 – Context and objectives.
- Chapter 3 – Solution overview and main achievements.
- Chapter 4 – Conclusions.

1.4 Acronyms

Table 1. Acronyms list.

Abbreviation	Definition
BB	Breadboard
CLSA	Conical Log Spiral Antenna
CP	Copolar
EE10	Earth Explorer 10
HF	High Frequency
HFWF	High Frequency Wideband Feed
LDR	Large Deployable Reflector
LF	Low Frequency
LFWF	Low Frequency Wideband Feed
TRL	Technology Readiness Level
UPM	Politechnical University of Madrid
UWB	Ultra Wide Band
XP	Cross Polar

2 Context and objectives

As described in the Statement of Work document named “AO10051-ws00pe.pdf” (ref: ESA-TRP-TEC-SOW-017728) [AD-01], the objective of this project was to **develop a novel compact circularly polarized low frequency and wide-band feed for Future Earth Observation Radiometers** which will serve to deeply study Earth's cold regions.

During the preparatory studies for the proposed future CRYORAD mission for the ESA EE10 missions, the difficulty of accommodating the necessary feeders to meet the mission requirements was detected. The final goal of this future mission will be able to carry out the study of ice sheets in cold areas of the earth with an accuracy and resolution that current instruments cannot achieve, for which it was deemed necessary to develop a set of new feeds with challenging requirements.

This project has covered this challenge, trying to develop the most optimal feed considering all the trade-offs in terms of RF performance and mechanical characteristics, as well as accommodation of the feeds on the mission and on the launcher and overall scientific requirements. All these trade-offs have made the work and finding an optimal solution a very complex task.

3 Solution overview and main achievements

The process carried out throughout the project has been as follows.

First, a detailed study of the state of the art of the technology and a search of different technologies was carried out to find the most promising one for this project.

Next, the array design process was carried out, in collaboration with Airbus so that the solution developed would illuminate the reflector optimally (second objective of the project).

Once the design phase was completed, a prototype representative of the developed feed was manufactured and tested.

Finally, the project has been closed with a study to continue the evolution and development of this feed and take it to the next step (TRL5 or TRL6).

3.1 State of Art and requirements

With the specifications and the main needs of the mission under consideration (CRYORAD) as a starting point, a detailed study of the state of the art has been carried out.

This study has focused on finding the best possible technology to complete the challenge of the project, to achieve a UWB feed at low frequencies and light and compact-enough to fit in the satellite. For this state-of-the-art study we have considered finding the best technology, looking for solutions as light as possible, with circular or linear polarization (ideally circular).

With these premises, a total of 10 technologies have been analysed. The different types of antennas analysed were.

- Conical log spiral antenna (CLSA)
- Spiral antenna (SA)
- Conical sinuous antenna (CSA)
- Quad ridge horn (QRH)
- Open boundary quad ridge horn (OBQRH)
- Eleven feed antennas (EFA)
- Four-arm log-periodic feed (FAPF)
- Dual polarized log periodic antenna (DPLPA)
- Vivaldi array antenna (VAA)

A summary of the main parameters of different reviewed UWB feed types and their advantages and limitations are summarized below.

Feed Type	BW %	Directivity (dB)	XPD	AR (dB)	IL (dB)	Size (λfmin)	Mass	Advantages	Limitations
DLPA	100-200	7.5-10		-	NA	0.6 0.6 1.5	NA	✓ Ultra-wideband performance ✓ Constant beamwidth and gain flatness within UWB ✓ High power handling capabilities ✓ Low VSWR ✓ Light solutions ✓Extremely rugged in physically demanding environments, robust mechanical design. ✓ Consolidated antennas widely used for different applications	× Limited maximum directivity (10 dB) × Large length × Phase centre position of classical LPDAs is not constant and varies with frequency
CLSA	150-164	7-10 for BW=150% 1-4 for BW=165%	< 11(single element) < 20 (4-element array)	< 5 (single element) < 2.5 (4-element config)	< 0.5	0.4 (single element) 0.4 1	0.5 (single element)	✓ Gain, polarization and input impedance UWB performance (up to 1:20) ✓ Single circular polarization generated by the structure without additional RF components ✓ Radiation pattern with low side lobe level (SLL) ✓ High aperture efficiency with reduced base dimension (at the expense of length increase) ✓ Mature technology successfully used in a similar application (not space but in an airplane in a cold environment)	× Limited achievable maximum directivity (14 dB with a very long ≈6 wavelengths [1] solution or 10 dB with reasonable lengths of 1-1.5 wavelengths following state of the art). × Challenging balun design required in terms of bandwidth and losses. However, a proper balun covering UWB up to 150% is available in the state of art. × Considerable space required between feeds in the cluster arrangement to avoid interaction between feeds
CSA	110-133	5-11 for BW=115-120% 1.3-6.4 for BW=133%		-	Low	0.33-0.47 0.33-0.47 0.6-0.26	< 4	✓ Beamwidth and gain UWB performance (10:1 bandwidth achievable) ✓Fixed phase centre in all the bandwidth ✓Low losses ✓ Low height in comparison with CLSA ✓ Lightweight (less than 4 kg/feed)	× Additional beamforming network is required to provide circular radiation × Possible input impedance variation with frequency if a ground plane is included × Larger aperture than CLSA × Considerable space required between feeds in the cluster arrangement to avoid interaction between feeds
VIA	100-120	5-7 (single element)	20	-	NA	0.6 (single element) 0.6 1.8	High	✓ Constant beamwidth and gain within all the band	×High SLL in comparison with other technologies × Considerable insertion losses (3 dB gain drop due to the loss of the Wilkinson network) × Considerable gain fluctuation within all the frequency × Only used in research environment

3.2 Feed chain design

The CryoRad mission performances, namely geometric resolution (i.e. footprint size), radiometric accuracy (related to beam efficiency) and revisit time (given by the combination of swath width and orbit selection) will be strongly defined by the selected antenna concept together with the selected mission altitude. The trade-off analysis demonstrated that a reflector size of between 12.5 to 15 m projected diameter would be suitable which together with a range of orbital altitudes between 550 km and 650 km would allow to achieve the required resolution, which is basically defined as a combination of the altitude and the size of the LDR.

One of the major drivers for the design of the feed and the reflector targeting the CryoRad mission is the compromise between the geometric resolution and the beam efficiency at secondary pattern level that guarantees the accuracy of the radiometric measurements. While the first is mainly driven by the size of the reflector, it is also influenced by the illumination factor in which the pattern of the feed illuminates the reflector, defined by the tapering level at the edges of the reflector. This second factor will basically set the level of sidelobes and spillover, translated into backlobe levels on the secondary pattern and hence the beam efficiency. Indeed, since the backlobes will point the cold sky, they will create an extra bias that depends on the cold sky TB, which can be further corrected with the use of the cold sky map.

After the studies carried out in the early stages of the project and considering the necessary constraints and trade-offs between performance and feasibility of the final design, the **conical log spiral antenna** was finally decided as the most promising technology.

Although initially it was considered to use a single feed to cover the entire 0.4 - 2 GHz band, due to the requirements of the mission it was realized that with a single feed it was not feasible to achieve the necessary performance and it was decided to carry out two complementary designs, one covering the 0.4GHz - 0.9GHz band and the other covering from 0.9GHz to 2-GHz. The whole array will work as a single unit composed of 29 elements (10 LF feeds and 19 HF feeds).

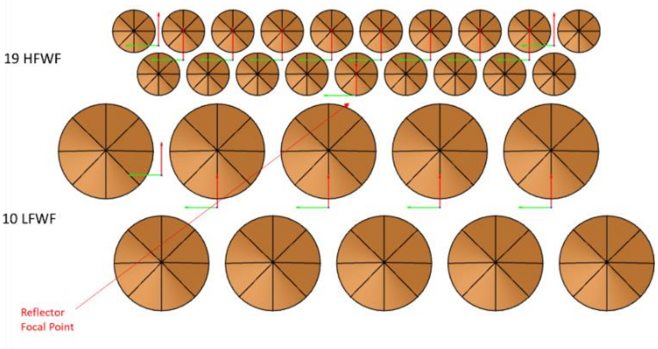

Figure 1. Detail of feeds in array configuration. On top 19 HF feeds elements and below 10 LF feeds elements.

During the design phase, a detailed electrical and mechanical design, including multiple analyses to ensure performance and integrity of the feeds under flight conditions, has been carried out.

First, the design of the feeds has been carried out in single configuration, thus optimizing all parameters at feed level such as radiation pattern, axial ratio, matching, pitch or return loss.

Next the detailed design at sub-array level has been done. Parameters at array level such as distance between elements, phase center, isolation between elements or radiation pattern has been optimized to achieve the best possible performance.

The result has been the detailed design of two different feeds, LF and HF, both sharing technology and requirements but scaled to operate in the frequency bands of interest. Each element (feed) is composed by the radiating element (conical log spiral antenna), the balun and the coaxial connector.

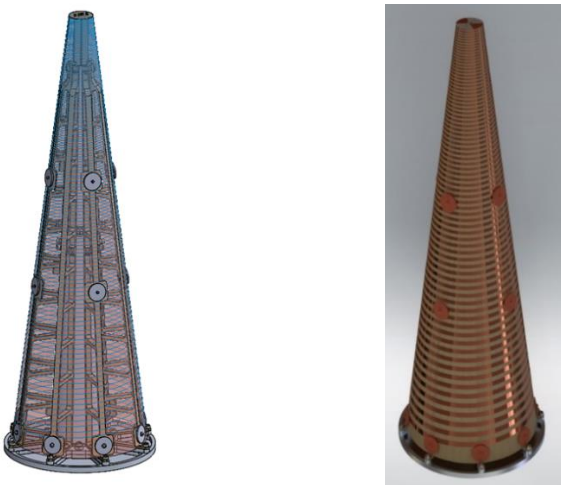

Figure 2. HFWF complete CLSA feed: (a) translucent model and (b) detailed render.

The High Frequency (HF) feed mechanical properties are shown in Table 2.

Table 2. HFWF CLSA feed mechanical properties.

Parameter	Unit	Value
Lower diameter (D)	mm	150
Height (h)	mm	455
Mass	kg	0.75
Mass center (x , y , z)	mm	(0 , 0 , 204)

The Low frequency (LF) feed properties are shown in Table 3.

Table 3. LFWF CLSA feed mechanical properties.

Parameter	Unit	Value
Lower diameter (D)	mm	320
Height (h)	mm	988
Mass	Kg	2.75
Mass center (x , y , z)	mm	(0 , 0 , 327)

3.3 Breadboard manufacturing and test

In the third phase of the project the manufacturing, assembly, and test of one HF feed breadboard (BB) has been accomplished.

For the manufacturing of breadboards different materials has been used. Pyralux AP for the radiant element (spiral), Rogers 5880 for the balun, PEEK 450GL30 for the inner structure, VESPEL and stainless steel for structural parts.

Assembly of the different parts has been carried out in the EOSOL aerospace laboratory by its qualified engineers and ready to be tested.

Figure 3. HFWF CLSA feed – Assembly of breadboards into laboratory.

The test campaign was carried out in the facilities of Universidad Politécnica of Madrid (UPM) in collaboration with EOSOL engineers.

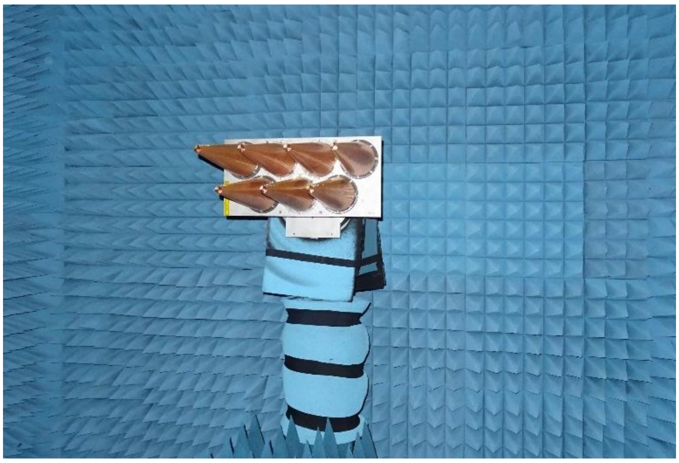

Figure 4. HFWF CLSA feed – Radiation pattern test into anechoic chamber.

A complete test campaign comprised of a total of 10 tests has been carried out in order to verify and validate the correct performance of the breadboard feed and the breadboard sub-array, both in standalone and embedded configuration (as it can be seen in the figure). The test campaign consisted of carrying out various tests measuring the most representative parameters: S-parameters, return loss, axial ration, radiation patterns and gain.

The following is a summary of the results obtained in test 9 (embedded HFWF sub-array).

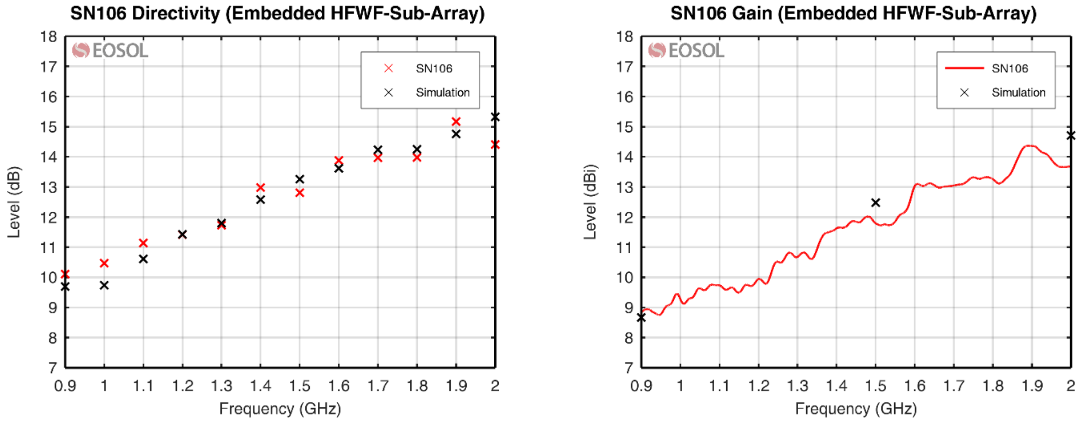

Figure 5. Comparison over frequency of the HFWF embedded sub-array SN00106 measured and simulated results of: (a) Directivity and (b) Gain.

In both the directivity and gain results there is a high correlation between the simulation and the results obtained during the test campaign held in the anechoic chamber.

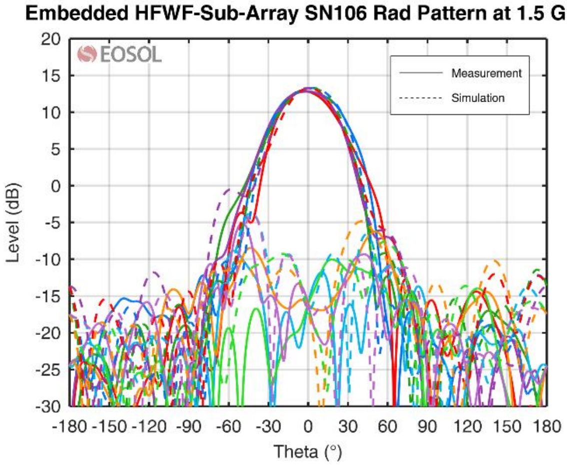

Figure 6. Magnitude radiation pattern measurement results of HFWF sub-array SN00106 in embedded configuration at 1.5 GHz.

Also, the copolar (CP) and crosspolar (XP) measurement magnitude radiation pattern results for different phi cuts of the HFWF sub-array manufactured in embedded configuration were compared with the simulated model. Again, there are no significative differences between them over the entire operating frequency range except for the maximum XP level, which increases around 3 dB in certain frequencies, and the axial ratio obtained at lower frequencies (from 0.9 to 1.2 GHz).

3.4 Development roadmap plan

In the final part of the project, the team has drawn the main conclusions of this development as well as identified the main limitations and areas of improvement. Furthermore, a development roadmap to reach TRL5 has been designed according to the future steps that shall be taken.

As a summary of the technical conclusions, it must be emphasized:

1. **The antenna is comprised of a large deployable reflector and a feed cluster.** The proposed CLSA feed cluster solution comprised of two types of arrays has the advantage of covering the required 120 km swath with a limited number of beams and receivers, 10 low frequency and 19 high frequency feeds. Each beam is generated by an aggregation of 3 feeds named sub-array.
2. **The achievable resolution is lower** than required even using an ideal gaussian feed. Moreover, the measured embedded sub-array has lower performance due to the phase center variation, the phase variation and the pattern shape. Resolution could be improved by employing a larger reflector.
3. **The beam efficiency improvement applying some techniques**. Despite of the initial results showing a low beam efficiency value for some beams, the results can be improved when considering the contribution of the sky to brightness temperature to the antenna temperature, which makes them suitable for a cryorad type mission, as they are fully compliant to the expected resolution and swath size. The contribution of the crosspolar component is considered in the computation of the efficiency.
   Beam efficiency can also be improved, especially for the high frequency channels by using digital beamforming techniques, which will provide additional scanning flexibility to the antenna.
4. **The embedded sub-array measured results match the simulated results:** They match with minor deviations that are considered normal and expected. The embedded simulation model can probably be improved adding more details to it and making the simulation more resource demandant and slower.
5. **The standalone feed has wideband high performance** and the design can be easily updated to cover more bandwidth maintaining the performance and constant radiation patterns over frequency. The complete frequency range of observation could be implemented with a single type of feeds. However, it has not been done in this antenna to move the phase centers of each radiating element closer.
6. **The insertion losses of the feed are higher than required.** However, they can be reduced by employing shorter feeds with less turns that will perform similarly.

Based on the main conclusions obtained from the project, the tasks that have been carried out and the needs of the potential CRYORAD mission, some technical and technological challenges have been identified for a feed and antenna evolution, which are:

1. Feed array arrangement and beamforming techniques
2. Larger offset mesh reflector analysis
3. Trade-off analysis of dual polarization measurements
4. Insertion loss and phase center variation reduction
5. LFWF manufacturing
6. Study of sunshield placement over the array cluster

7. Design under embedded environment of complete array cluster, HFWF and LFWF
8. Life test and S parameters and losses/gain characterization during thermal cycling

4 Conclusions

A technological development project has been carried out according to the needs presented by the European Space Agency. In this project, the performance and limitations of the feeds selected, after a thorough state-of-the art review, have been analysed and tested in detail, as well as their impact on the antenna level.

With the obtained results clear conclusions have been established, in addition to the technical ones presented in the previous section.

- Antenna and radiometry parameters, such as resolution and beam efficiency, obtained according to the CLSA feeds designs, show promising results and acceptable values which lead this project to be continued in new and future developments for CryoRad mission. With this work developed during two years it is clarified that feed technologies available nowadays could fit in this type of missions.
- New technical and technological challenges shall be then evaluated and analysed in detail to improve the feed array proposed to feed a 12.5m reflector, in order to improve the resolution and beam efficiencies really need for radiometry applications.

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