

A High-Performance Ka-band Cryo-Cooled Receiver for Deep Space Applications

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Abstract — This paper describes the design of a ground station antenna feed system, that includes feed horn, polarizer, rejection filter, mono-pulse tracking coupler and low noise amplifiers with polarisation switching. The entire feed system assembly is cooled to cryogenic temperature ($T < 10$ K) in order to maximise the G/T of the ground station antenna. The cryogenic cooling system described is fully redundant and this novel design allows one cryocooler to be removed and replaced, while the other cryocooler is still running. The design has been submitted for patent protection.

Keywords — ground stations, antenna feed, cryogenic electronics, space exploration, deep space antenna.

I. INTRODUCTION

ESA interplanetary missions are more and more demanding in terms of scientific data return and the 35-m ESA deep-space antennas will require significant G/T improvement in order to close the communication link with remote space probes.

Although current ESA deep-space antennas include cryo-cooled Low Noise Amplifiers (LNA) to improve sensitivity without increasing antenna gain, the overall noise performance of the complete receiver is mainly limited by the loss of the feed components which are operated at room temperature. As it is very difficult to lower insertion loss of passive components and develop LNAs with significantly lower noise temperature (T_N), the most efficient strategy is to cool down as many of the feeder components as possible to cryogenic temperature. An additional improvement is obtained by implementing a TE₂₁ mono-pulse tracking coupler in the RF chain to compensate any antenna pointing error which could significantly degrade the

antenna gain at Ka band. The overall objective of the work described in this paper was: (1) to design a cryogenic feeder including antenna horn, tracking coupler, polarizer, filters and cryogenic LNAs and (2) to manufacture and test a prototype. The prototype has now undergone acceptance tests. In the future the prototype will be upgraded to become an operational unit. ESA will deploy a Ka-band cryo-cooled feed in 2020 to support BepiColombo and JUICE missions with an expected downlink data rate improvement of 80%.

This new generation of receiver will replace the current room temperature feeder system and three cryogenic LNAs (two operational and one spare units). Several functionalities were required by ESA to meet operational constraints. Firstly, on the RF side, a proper redundancy concept based on an electro-mechanical cryogenic transfer switch has been implemented to redirect the received signal to the redundant channel in case of LNA failure. Secondly, the feed components are cooled down to around $T = 9$ K physical temperature using two cryogenic coolers (nominal mode). If one cooler is defective, an innovative technical solution has been developed to be able to disconnect and replace a faulty cryogenic cooler while the second one is still operated. In this case (degraded mode), the physical temperature on the cryo cooled RF chain is around $T = 11.5$ K. Doing this, the best trade-off has been achieved between maintaining high performance of the receiver operated at cryogenic temperature in the case of a failure of a key components, whilst avoiding outage time for the operation.

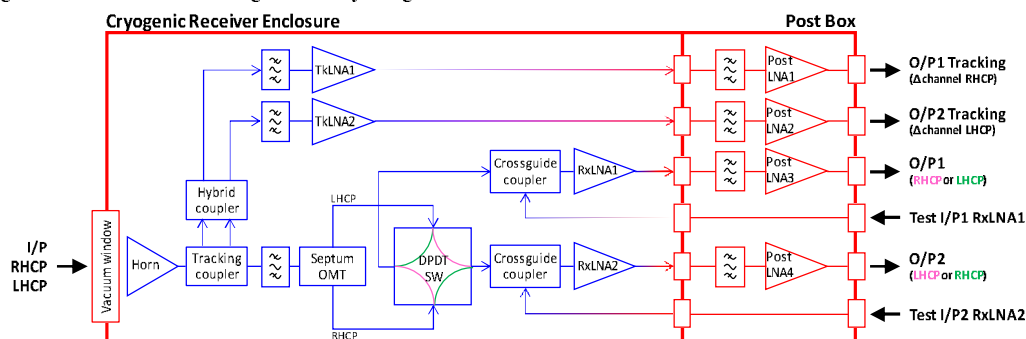


Fig. 1. Schematic diagram of the Ka-band cryogenic feed.

II. RECEIVER SYSTEM DESCRIPTION

The Ka-band functionality of the ESA deep space antennas is to receive circularly polarized signals in the 31.8 – 32.3 GHz frequency range while maintaining a high degree of rejection at 30, 34 and 40 GHz with an axial ratio better than 0.5 dB within 1 dB contour. Furthermore, the feed gain at the LNA inputs must be greater than 28 dB while the noise temperature at the horn aperture is being limited to $T_N = 25$ K.

For this purpose, all the critical components of the designed cryogenic system are enclosed in a dedicated Dewar. In Fig. 1, the red parts are room temperature components whereas blue parts are RF components operated at cryogenic temperature. The Dewar input interface is a window that shall isolate vacuum established inside the Dewar and be as transparent as possible at Ka-band frequencies. In addition, it shall avoid water condensation on the window layer and withstand the force due to the pressure difference. The design is based on pressure and vacuum windows made of Mylar with another expanded polystyrene foam layer [1] used to maintain and support mechanically the vacuum window which is put under severe stress. The RF chain includes a feed horn, the TE₂₁ tracking coupler, the low loss circular filter, the septum polarizer and the electro mechanical cryo switch. Several cryo-LNA are implemented to obtain a very sensitive receiver. Other standard elements such as rectangular waveguide sections, bends or injection couplers are less relevant in terms of noise addition. Room temperature post-amplifiers and filters are included to fulfil system requirements in terms of gain, out of band rejection and output compression point. Fig. 2 shows a cross-section sketch of the Dewar with all the front-end components assembled.

A. Feed Horn

This element represents a real challenge because at 32 GHz a conical corrugated horn having 29 dB of gain results in 500 mm long, and cannot be assembled in this kind of receiver. To overcome this drawback a dual shaped (sinusoidal + exponential) corrugated horn was designed to reduce the axial length by 30% while maintaining the specified gain and aperture diameter. The throat section was carefully designed to guarantee a TE₁₁ return loss better than 35 dB, a cross-polarization level better than 40 dB and sidelobes below 36 dB. Moreover, the horn return loss for the TE₂₁ modes is around 24 dB.

B. TE₂₁ Tracking Coupler

Conventional TE₂₁ travelling couplers represent an elegant and broadband solution that needs at least 200 mm in length at Ka-band [2]. To minimize again the axial length of the feed, a resonant four-slot TE₂₁ mode coupler in oversized circular waveguide was designed for this application where the final overall length is around 40 mm. By cascading a 90° hybrid coupler at the tracking ports, RHCP or LHCP error signals can be independently extracted and routed towards a conventional tracking receiver. This compact solution gives a return loss of

24 dB at the tracking ports while maintaining a port to port isolation better than 45 dB. This will assure a null depth of around 40 dB in the delta radiation pattern, which is largely enough for tracking purposes.

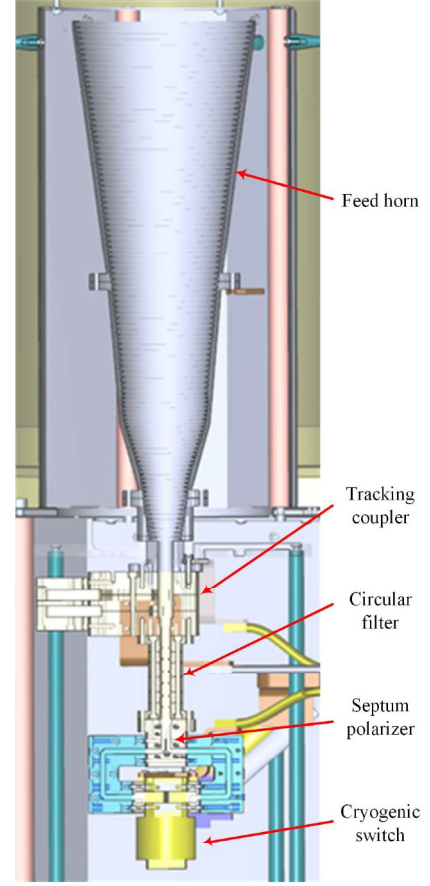


Fig. 2. Cross-section sketch of the developed receiver in the Dewar.

C. Circular Common Filter

In most of the existing cryo receivers the pre-LNA filtering operation is done in rectangular waveguide, that is, one filter per receiving channel. This means a large amount of mass to be cooled down. The proposed architecture uses a single circular iris coupled filter located in between the tracking coupler and the septum polarizer. As the filter was made of aluminium with a further silver plating, the design process took into account the silver thickness as well as the dimensional variation when cooled. The frequency shift from room temperature to $T = 15$ K cryogenic temperature was around 100 MHz upward and the insertion loss decreased down to 0.08 dB.

D. Septum Polarizer

This conventional circuit separates the two RHCP/LHCP incoming signals into two separate rectangular ports. As the key point is losses, the component was designed to be fabricated in two halves by using a special milling technique that seals the junction thus minimizing the mating losses. The input/output return loss is better than 30 dB while the measured insertion

loss remains in the 0.04 dB range. It should be pointed out here that this element was re-optimized along with the tracking coupler in order to ensure that the overall axial ratio remains below 0.5 dB.

E. Electromechanical Cryo Switch

The cryogenic switch is essential to provide the RF redundancy function. By actuating the switch at cryogenic temperature, it is possible to steer either RHCP or LHCP signals in one or the other channel. Thus, if one channel is defective, the other channel is still able to receive signals. To achieve this, a commercial waveguide switch has been specifically modified to be able to operate reliably at cryogenic temperature. Because measuring the insertion loss of the switch at cryogenic temperature is very difficult, a test bench has been designed to measure the noise temperature of a receiver with and without the cryo switch assembled in the chain. Between both configurations, the noise temperature was measured 0.1 - 0.2 K higher with the switch. Insertion loss of the switch has been found extremely low and estimated at around 0.01 - 0.02 dB at a physical temperature of $T = 25\text{K}$. Moreover, the switch has been actuated more than 10,000 times at cryogenic temperature and no defects were observed. The noise temperature was measured with a very good repeatability before and after the long-term test, which proved the high-performance and the reliability of the switch at cryogenic temperature.

F. Cryo LNAs

Two types of high-performance cryogenic LNAs have been evaluated during the project. A commercial cryogenic LNA (reference LNF-LNC23_43WA) has been purchased from Low Noise Factory (LNF, Gothenburg, Sweden). Two prototypes of cryogenic LNAs have been developed by Centro Astronomico de Yebes (CAY, Yebes, Spain) with new InAs-HEMT from ETHZ (Zurich, Switzerland). Table 1 summarizes the RF performance measured on both amplifiers.

Table 1. Cryogenic LNA RF performance summary.

Parameters at 15K	Specified value over 31.8-32.3GHz	
	LNC23_43WA	CAY YKa series
Frequency range	23 - 42GHz	25.5 - 32.3GHz
Noise temperature	7 K max	10 K max
Gain	27.5 dB mean	33.5 dB mean
Return losses	10 dB min input	12 dB min input
	14 dB min output	15 dB min output
Power consumption	10 mW	18 mW
Pout1dB	-10 dBm typical	-5 dBm typical

III. SYSTEM MEASUREMENT RESULTS

After completing the preliminary and detailed design phases, the RF chain has been manufactured and tested. Radiation patterns with antenna feed horn and tracking coupler have been also verified for the fundamental and the tracking modes. As it can be seen at Fig. 3, the TE₁₁ mode gain is 29.2 dB in boresight direction at 32.05 GHz, associated with a cross polarization of 37 dB within 1 dB contour. This leads to an axial ratio of 0.13 dB. For the TE₂₁ tracking mode, the null depth is around 39 dB

at 32.05 GHz and tracking slope is around 0.1 V/V/deg up to 4 deg theta angle as shown in Fig. 4.

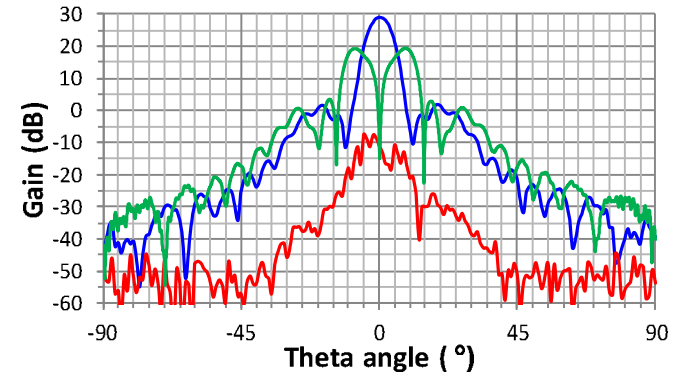


Fig. 3. TE₁₁ and TE₂₁ radiation patterns measured at 32.05 GHz and for 0 deg cut plane. Co-polar (blue line) and cross-polar (red line) of mode TE₁₁. TE₂₁ radiation pattern is plotted with a green line.

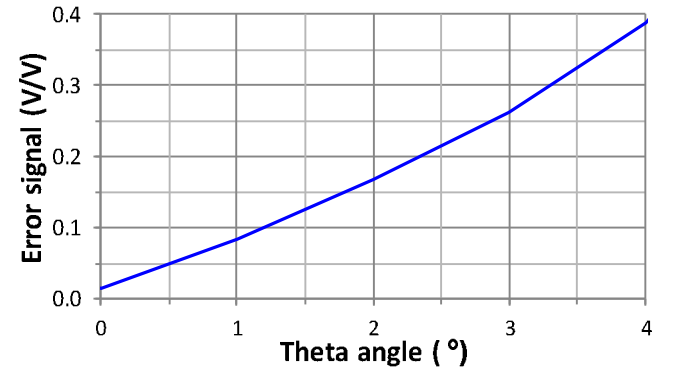


Fig. 4. TE₂₁ tracking error signal measured at 32.05 GHz and for 0 deg cut plane.

After RF chain validation, a Ka-band cryo cooled feed prototype Dewar has been successfully manufactured and assembled at Callisto laboratory. A picture of the whole system is presented in Fig. 5. The overall dimensions are around 610 x 1560 mm (including a cold head extraction tool) and its weight is in the order of 200 kg.

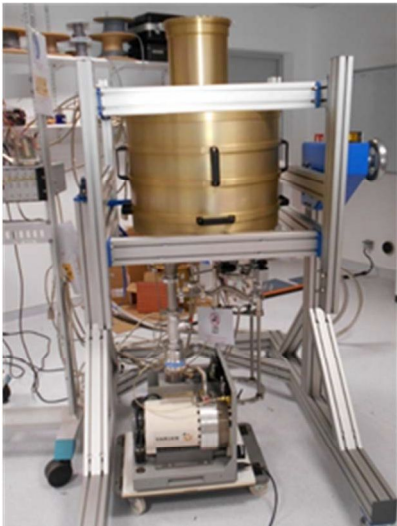


Fig. 5. Ka-band cryo cooled feed prototype Dewar overview.

As the complete RF chain with feed is cryogenically cooled inside a single enclosure, the cryocooler system becomes a single point of failure. It was then required to have redundant cryocoolers running on the receiver. However, when one of the two cryocoolers requires regular maintenance or even fails, the RF chains must remain at cryogenic temperatures allowing noise temperature to be low enough so as not to stop the ground station operations. To allow for replacement of the failed cooler while keeping the second cooler running, a custom sleeve system (called “double sleeve”) has been designed and successfully tested. It is basically a sealed inner sleeve with a second outer sleeve encapsulating the first one. The outer sleeve is attached to the cold head and connected via a set of clamps to the inner sleeve. By means of the clamps, the inner sleeve can be thermally uncoupled from the outer one and the cold head can be dismantled without any risk while the outer sleeve is still at cold temperature. The double sleeve is equipped with a hydraulic system to apply high linear force to extract the double sleeve at cryogenic temperature and under vacuum. The following Fig. 6 shows the temperature profile inside the receiver at various points whilst one double sleeve and cold head is extracted and the second cooler keeps running and maintaining the RF components at cryogenic temperature. After a successful reconnection of the extracted cooler and consecutive cooldown, the nominal cryogenic temperatures are recovered ($T = 9\text{K}$).

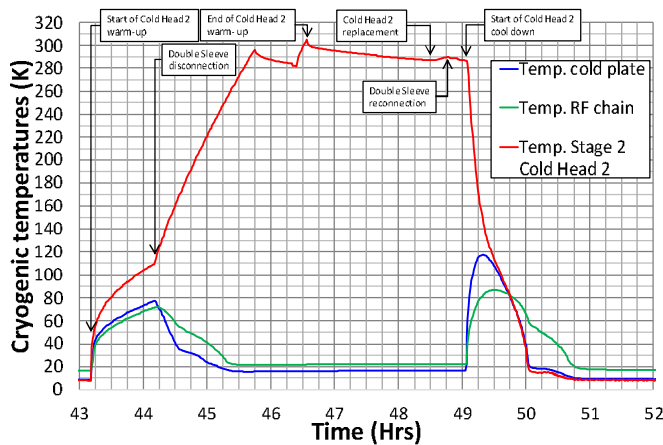


Fig. 6. Double sleeve extraction and temperature recovery under cryogenic operations.

Noise temperature has been tested using two RF matched loads with very well-known noise temperatures. The warm one is a room temperature absorbent foam set in front of the input aperture of the feed horn, the second is a cold load when antenna feed horn points towards clear sky. To calculate the cold sky noise, the sky brightness temperature is integrated within the antenna radiation patterns for TE_{11} and TE_{21} modes [3]. Noise temperature has been measured in both RHCP/LHCP channels and for both positions of the redundancy switch. The maximal noise temperature is around $T_N = 17\text{ K}$ over 31.8 - 32.3 GHz as presented in Fig. 7.

Gain and group delay have been measured by using cross guide cryogenic couplers ahead LNAs and test inputs with

around 31 dB of coupling factor. For the configuration with commercial cryogenic LNA, the gain is $58.9 \pm 0.5\text{ dB}$ and the group delay maximal variation is 0.5 ns over 31.8 - 32.3 GHz and 0.06 ns per 20 MHz. The rejection is within specification and is found around 140 dBc at 30 GHz, 120 dBc at 34 GHz and 125 dBc at 40GHz. Finally output compression point is measured at +12 dBm.

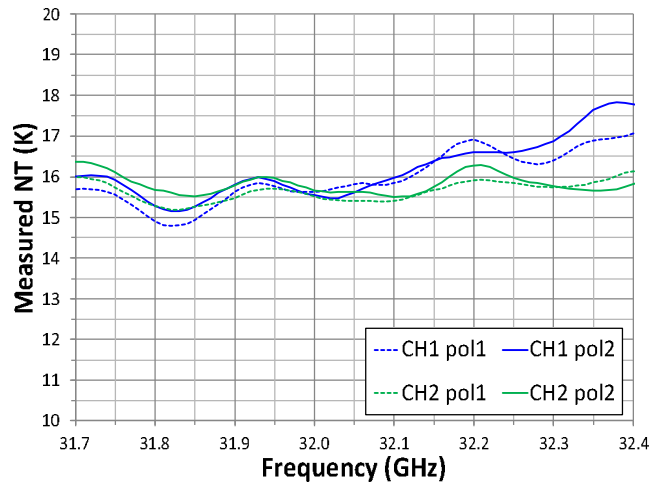


Fig. 7. Noise temperature measured on Ka-band cryo cooled feed prototype Dewar.

IV. CONCLUSION

A high performance cryo-cooled receiver operating in Ka-band has been developed for deep space applications. The proposed receiver will replace the existing systems in the ESA ground stations for deep space communications with improved RF and cryogenic performance for higher scientific data rates. Moreover, the maintainability has been increased by implementing an innovative redundancy solution for the cryogenic system. Doing this, the receiver can be operated at cryogenic temperature while maintenance is carried out, which reduces outage time during operation.

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