

# Compact Integration of Cryogenic LNA on Miniature Cryocooler

J. Delmas, R.J. Webber, I.V. Vernik,  
G. Prokopenko and D. Gupta

Hypres, Inc., Elmsford, NY, USA 10523

## ABSTRACT

Cryogenic low-noise amplifiers (LNAs) have been used in radio astronomy for some time, in particular as the first stage of receivers at microwave frequencies and more recently in IF sections following mixers at millimeter-wave and sub-millimeter-wave frequencies.

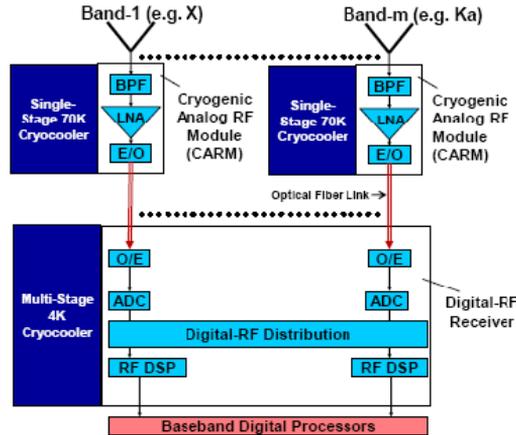
For some of these applications, the cryogenic LNA is mounted onto a cryocooler. However, compactness and energy efficiency of the whole system are seldom a major requirement. Two-stage coolers are thus widely used as they provide both low temperature and significant cooling power, necessary to cool down a low-loss input line in order to minimize the receiver noise temperature.

HYPRES is currently developing an approach for an all cryogenic receiver, comprising a split architecture. This configuration detaches the analog radio frequency (RF) components in front of the analog-to-digital converter and houses it in a much smaller module, cooled by a single-stage cryocooler that allows placement close to the antenna; the rest of the components are left in a larger module including a two-stage 4K cooler.

In this study we focus on the front-end module and examine the integration of a 20 GHz cryogenic LNA with a miniature single-stage Stirling cryocooler. The objective of this cryogenic packaging is to optimize the technical characteristics of the LNA such as gain, linearity and noise temperature, as well as the size, weight and power of the system. We discuss different solutions studied for the input and output RF lines, both in terms of electrical performance and heat load, and describe the different technological choices adopted to comply with strict size requirements. Finally, we present preliminary RF measurements of the final system.

## INTRODUCTION

HYPRES has been successfully integrating superconducting Integrated Circuits (ICs) into different 4 Kelvin cryocoolers for quite some time. This includes both digital receiver systems [2 to 6], and Voltage Standard chips [9,10]. More recently, some effort has been put into integrating systems, superconducting or not, with miniature cryocoolers. These small coolers are mainly targeted at the market of increasingly sophisticated portable cryocooled infrared imagers that are developed for a variety of applications, including surveillance, reconnaissance, and navigation. Most of the miniature compact cryocoolers are based on either rotary Stirling or Linear Split Stirling principles and are readily available. The performance of these systems, for which size, weight and power are critical, is extremely attractive for a variety of applications.



**Figure 1.** The “Split” receiver architecture detaches the analog RF front-end as a separate module.

### Motivation

The system described in this paper originally comes from the need for a “split architecture” for an all-digital receiver. The principle of a compact cryogenic amplifier can however be applied to many different applications at various frequencies, such as MRI or instrumentation.

Superconductor analog-to-digital converter (ADC) technology enables direct digitization of RF waveforms with high linearity and opens up new architectures for increasing spectrum efficiency. Direct digitization, followed by distribution and processing of RF signals in the digital domain, facilitates superior monitoring, control and utilization of the RF spectrum as well as enables advanced communication concepts involving multiple frequency bands and multiple polarizations. In addition to this primary benefit, a secondary benefit of using superconductor ADCs, which require cooling to very low (4 K) temperatures, is in lowering the receiver noise temperature. Applications, such as satellite communications, where the antenna noise temperature is low, are excellent candidates for such cryogenic receivers [1].

Typically, in addition to the 4-K stage, a cryocooled superconductor digital-RF receiver system includes one or more intermediate (e.g. 40 K) temperature stages, often with excess cooling capacity. This additional temperature stage has been used in these systems to host analog RF components, such as a high-temperature superconductor (HTS) filter, and optionally a low-noise amplifier (LNA). Using commercial 4-K cryocoolers, several such rack-mounted systems have been developed [2 to 5]. These are suitable for large satellite ground stations.

However, the space under the dish is quite limited for smaller terminals and calls for a different configuration. Ideally, signal digitization at RF should occur as close to the antenna as possible. However, depending on the space and power dissipation constraints, it may not be possible to place a complete receiver unit at or near the location of the antenna. A 77-K single-stage cryocooler system requires much less space and power than a 4-K multi-stage cryocooler. Therefore, the system is split in two parts and a small cryocooled analog RF unit, comprising a wideband filter and low noise amplifier (LNA), is placed near the antenna and the larger unit, linked via optical fiber, is placed at a distance where more space is available (Figure 1). In the case of satellite communication on a shipboard platform, this smaller cryogenic analog RF module (CARM) would be placed right behind the dish and the digitizer would be placed below deck. A similar configuration, splitting the system into two parts also works for commercial wireless base-stations, where the larger rack-mounted digital-RF receiver will remain on the ground while a CARM is attached to the tower-mounted antenna. Most of the advantage of reducing the receiver noise temperature through cooling is retained in this architecture through the use of the cooled LNA. However, the elevated gain requirement for this cooled LNA must be carefully balanced against power consumption and linearity.

In the first implementation of the CARM, two variants have been designed for the satellite communication ground sector in Ka and X bands. These match well with the multi-band digital-RF receivers with two superconductor analog-to-digital converters (ADCs) that digitize the X/Ka bands directly. The first variant, not discussed here includes three analog chains, two for Ka-band right-hand and left-hand polarizations and one for X-band. The second, smaller, variant includes a single Ka-band chain and is cooled by a commercial-off-the-shelf 77K cryocooler. The current versions of the CARM include high-temperature superconductor (HTS) analog filters and semi-conductor LNAs; they do not include an electrical-to-optical converter (E/O).

## DESIGN OF THE SYSTEM

The most important characteristics of the system are its compactness and the ability to provide amplification with a minimum noise temperature. Designing a compact and efficient cryopackage is challenging both in terms of cost, reliability and technical achievement. The different heat loads, whether they are conductive, radiative or direct through heating of the amplifier have to be carefully assessed and controlled in order to have any hope of success. At this kind of temperature, vacuum is also a critical parameter, as the remaining gas after the initial pump out, coming from outgassing or virtual leaks, is not adsorbed by any cold surface as it can be in lower temperature systems and contributes to heating the cold parts. The final design, and especially the choice of materials, is thus a careful compromise between electrical performance, thermal conductivity, and behavior under vacuum.

### General Description of the System

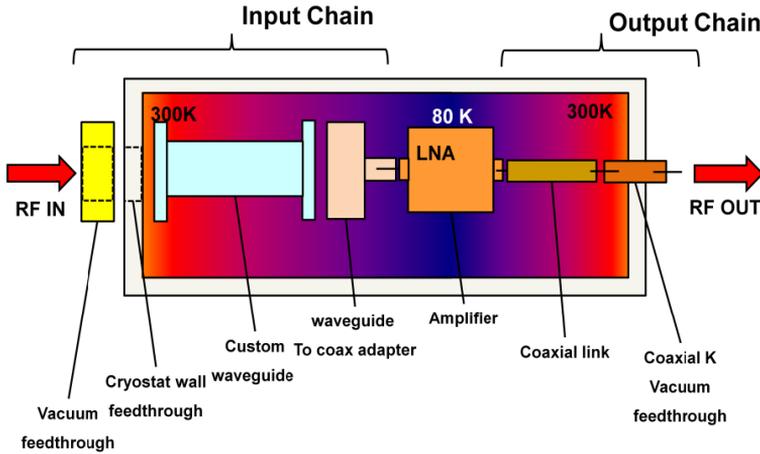
The heart of the system is the Low Noise Amplifier (LNA) that has to be cooled in order to get the best performance in terms of gain and noise. It is thus desirable to have a direct thermal link between the cooler and the amplifier, in order to get the best cooling. As it is not superconducting, there is no threshold temperature to reach to have the system working, and the amplifier works properly from room temperature down to its cryogenic operating temperature. However, its performance greatly increases when cooled down. The target operating temperature is below 80 K. Two diodes used as thermometers (one for temperature monitoring and one for the cooler temperature regulation feedback) are bolted onto the body of the LNA. The body of the LNA is connected to the cold head of the cooler via a flexible highly conductive thermal link in order to accommodate for thermal contraction of the different components while still providing an excellent cooling of the amplifier.

The output of the system is a K-type coaxial connector (also called SMA 2.92). A K-type feedthrough is soldered on the top flange of the cryostat, and a coaxial cable is connected between this feedthrough and the output of the LNA. As the cable is after the amplifier, RF losses are not critical as long as they remain of the order of a few dBs.

The input of the system is specified to be a square WR42 waveguide flange. Most of the amplifiers we considered have a coaxial input which means that a waveguide to coaxial adapter has to be part of the system. In terms of mechanical integration, the different choices are to do the conversion before the vacuum feedthrough or inside the vacuum enclosure. The advantage of the first solution is that the input vacuum feedthrough is then similar to the output, and coaxial vacuum feedthroughs are well known and readily available. The LNA is then connected to the waveguide to coaxial adapter via a coaxial cable. The second solution ensures the best electrical performance, as a waveguide induces fewer losses than a coaxial cable, but the vacuum feedthrough has to be a waveguide window that is less compact and most of the time custom made. Figure 2 shows the RF chain of the second solution.

### Heat Load and Electrical Loss Balance

The main challenge of the cryogenic integration of the system is to control both the heat load and the electrical losses. The electrical loss depends on the electrical conductivity and generally speaking, for metals, electrical and thermal conductivity are proportionally related. A high electrical conductivity thus induces a high heat load. The most compact commercially available coolers usually provide a cooling power between 500 mW and 1 W at 77 K. The overall heat load, including radiations, shall then be of this order of magnitude.



**Figure 2.** RF chain of the system using a waveguide vacuum feedthrough; the cooler is not shown.

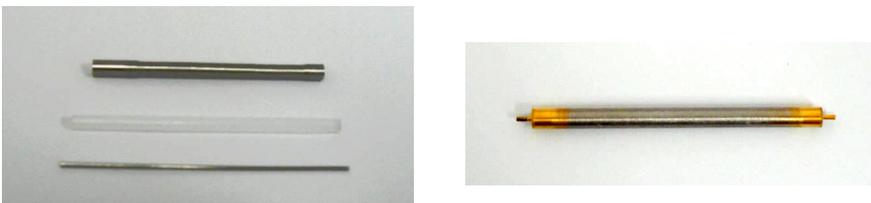
For the output coaxial line, as losses are not critical, a reasonable length of Be-Cu coaxes ensures a good enough RF performance and reasonable heat load. Thermometers and amplifiers are biased using thin phosphor-bronze twisted pairs. Although the bias current of the LNA is not negligible, it is still small enough not to induce a significant voltage drop across the twisted pair. As a result the total heat load conducted through the output line and biasing lines is kept below 100 mW.

The input signal line is the most critical in terms of RF losses. In order to keep the overall system noise low, the input line loss, which is in front of the amplifier, has to be minimized. We estimated that a loss above 0.25 dB in the input line would lead to a noise level higher than the one we targeted.

We initially considered the first option mentioned above, using a waveguide to coaxial adapter outside of the vacuum enclosure and then a coaxial feedthrough. To ensure both a good RF performance and a low thermal conductance, the link between the LNA and the feedthrough was made by a custom coaxial cable. As the system is operating at high frequency (20 GHz), only a few skin depths of metal are used in the signal transport, so it makes sense to remove any excess metal [8]. An off-the-shelf stainless steel coaxial cable was disassembled, plated with a few microns of gold and then the outer conductor was thinned out in order to reduce further the heat load (see Figure 3).

The resulting heat load created by the input coaxial line is then about 170 mW. In terms of RF loss however, the custom coaxial solution cable did not meet our requirements. The total loss (coaxial vacuum feedthrough connected to the custom cable) was a little lower than 0.5 dB, which is higher than needed.

The second option for a low RF loss input line is to have a waveguide vacuum feedthrough followed by a cryogenic waveguide up to the amplifier. The main challenges for this solution are to maintain a low heat leak through the waveguide, which is usually made of metal, and to provide a vacuum feedthrough that is both low loss and leak tight. Waveguide vacuum feedthroughs have been successfully built for high frequency [6,7], including by Hypres [9, 10]. The RF loss however



**Figure 3.** SS custom coaxial cable disassembled (left) and after machining of the outer conductor (right).

**Table 1.** RF loss of the different components of the input line.

<i>Component</i>	<i>Individual RF loss</i>
Input Waveguide	0.05 dB
Waveguide to Coaxial adapter	0.1 dB
Cryostat and vacuum window	0.1 dB
<b>TOTAL</b>	<b>0.25 dB</b>

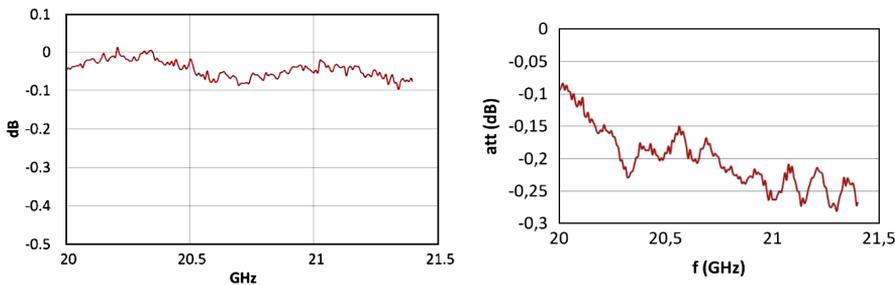
is often above 0.2 dB, which is higher than the targeted value of 0.1 dB for this component. After trying different solutions, an off-the-shelf WR-42 window met our requirement of leak tightness and 0.1 dB loss.

Concerning the cryogenic waveguide, the same approach as for the custom coaxial cable was used, that is to say minimize the RF loss by having an excellent electrical conductor of a few skin depths thickness, and minimize the heat load by removing as best as possible any extra heat conductive material. The length of the waveguide is 5 cm, and the conductive thickness is about 3 microns to ensure low loss signal transmission. Using copper, the heat load conducted through the conductive layer is about 130 mW. This heat load cannot be reduced without increasing the RF loss, and does not include the substrate. The choice of the substrate is then critical to maintain a low heat load.

A thin stainless steel waveguide (254 microns) can be found off-the-shelf and is easy to plate with a controlled thickness. The resulting heat load of such a 5cm waveguide plated with 3 microns of copper is about 560 mW of which 430 mW is created by the substrate that makes no contribution to the signal transport. In order to reduce these thermal losses we designed and made a custom low heat conductivity waveguide that can be mounted using off-the-shelf flanges. The waveguide is made of Torlon (polyamide-imide) that has the great advantages of having both excellent mechanical properties and low thermal conductivity [11,12]. It is then covered with a thin layer of gold or copper, in order to ensure a very low RF loss. The measured loss is below 0.1 dB, which is comparable to a regular solid copper waveguide of similar length.

If the input of the amplifier is a coaxial type, a waveguide to coaxial adapter is mounted at the end of the waveguide. Otherwise, the amplifier can be directly mounted onto the waveguide. The latter solution presents the advantage of eliminating the RF loss of the input coaxial connector. Table 1 shows the RF loss for each component of the input line, and Figure 4 shows the loss of the waveguide on the specified spectrum, as well as the loss of the whole input line. The overall input loss is lower than 0.27 dB which is relatively close to our initial 0.25 dB target.

Figure 5 shows photographs of the custom waveguide mounted with different amplifiers. The function of the Torlon material of the waveguide is only structural; it is a substrate for the plating layer and a mechanical support for the amplifier. The relevant properties for this application are thus its mechanical strength and its thermal conductivity. Compared to stainless steel, its ratio mechanical strength / thermal conductivity is more than 30 times better [11,12]. This allows a drastic reduction in terms of heat leak for a similarly strong waveguide. For ease of manufacturing, the thickness of the Torlon waveguide is kept well above the thickness of the original 254 microns



**Figure 4.** Individual loss of the Torlon waveguide (left) and RF loss of the whole input line over the used bandwidth (right).



**Figure 5.** Torlon waveguide connected to amplifier using waveguide to coaxial adapter (left) and Torlon waveguide directly connected to amplifier (right). The latter photograph shows the connectors for DC bias and instrumentation.

**Table 2.** Conductive heat load of the different components.

<i>Component</i>	<i>Heat load contribution</i>
Input Waveguide	210 mW
Output Coaxial cable	90 mW
DC bias lines and instrumentation	10 mW
<b>TOTAL</b>	<b>310 mW</b>

stainless steel waveguide and the resulting heat load comes to about 80 mW. The total heat load for the input line is then 210 mW, which is compatible with the type of cryocoolers we are using.

**Table 2** shows the conductive heat load brought by each component connected between the cold LNA and room temperature. The total heat load is 310 mW which is in the range of the off-the-shelf miniature 77 K cooler. Radiation contributes also to the global heat load by a significant amount that is difficult to estimate. The cryopackage is wrapped in multi-layer insulation (MLI), but significant openings in the insulation have to be made for the coaxial cable and the waveguide. The whole cross section of the waveguide in particular is fully exposed to 300 K radiation. In order to accommodate a significant margin on the heat load, the cooler chosen, a Ricor 543 rotary Stirling, provides 1 W of cooling at 77 K [13].

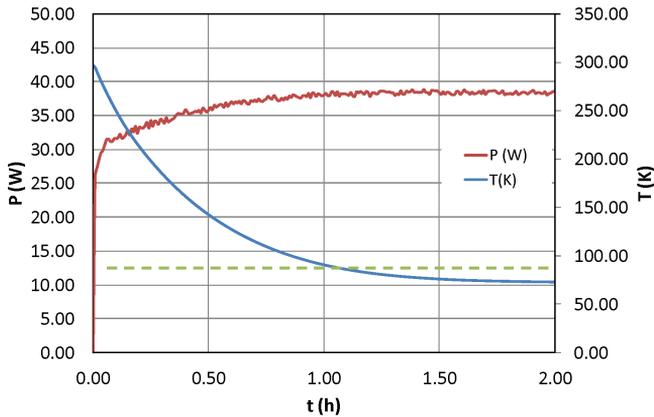
## RESULTS

### Test Set-Up

The system is assembled, pumped out and carefully leak checked and then connected to test equipment. In order to have a reasonable pump-down time, vent holes have been machine in the custom waveguide flange to allow pumping of the inner volume of the waveguide. Surprisingly, the machining of carefully placed vent holes does not induce any extra RF loss in the input line. As outgassing completely the MLI requires extensive pumping, we chose to pump continuously during testing in order to avoid any degradation of vacuum during this preliminary testing. Although this is not representative to the final system, which will be sealed, we considered that outgassing the MLI is only time consuming and can easily be performed during a further test campaign. Continuous pumping allows us to start the cooler after only 30 to 45 minutes of initial pump down.

The cryocooler is connected to a 28V power supply and the temperature sensor to a *Cryocon 24* temperature controller. The external temperature of the motor of the cooler, which is cooled by a standard computer fan, is also monitored. A dedicated program acquires temperature, pressure, and input power of the system.

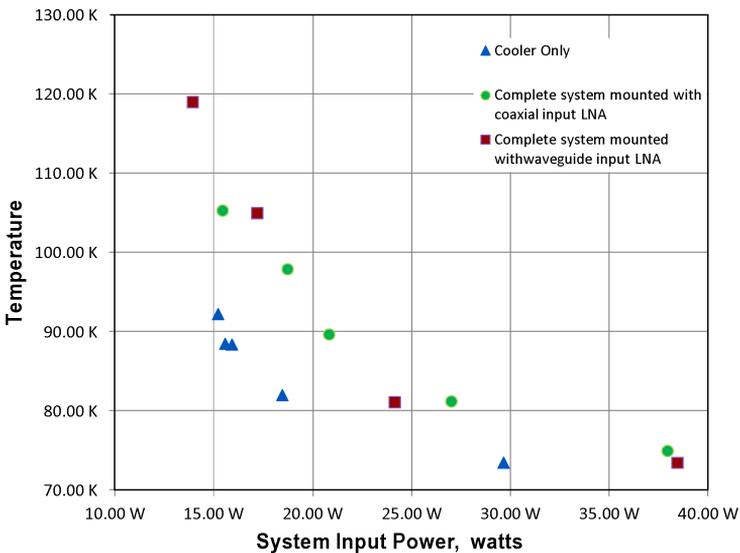
For noise measurements, the waveguide input of the system is connected to a noise source via a waveguide to coax adapter. The output is connected to a post amplifier and then to a spectrum analyzer or a Noise-meter.



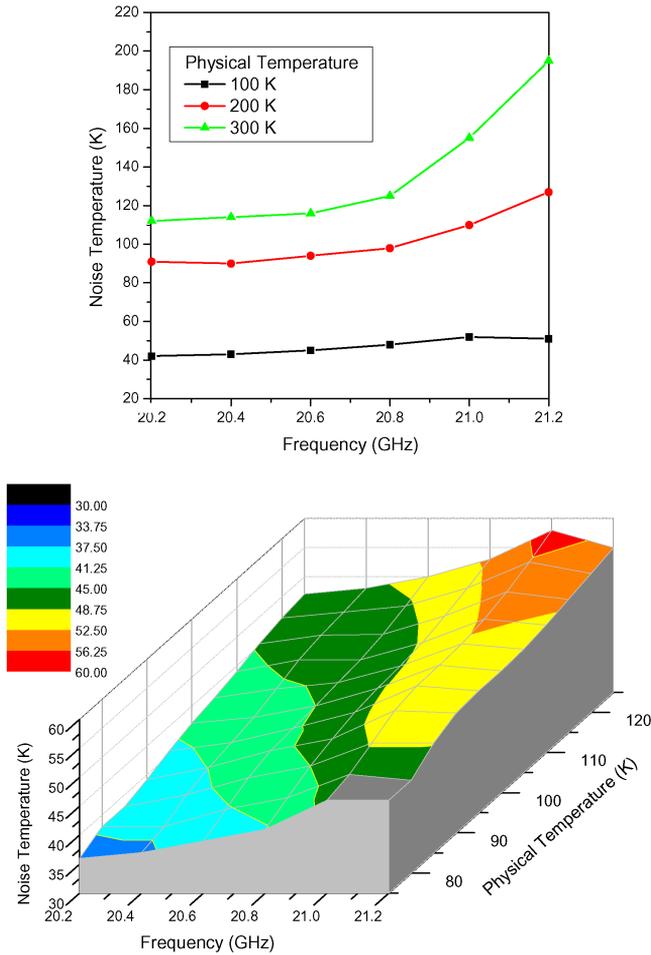
**Figure 6.** Temperature and input power of the system during cool down; the dotted line shows the operating temperature.

**Measurement Results**

As shown in Figure 6, the cool down to minimum temperature takes about 2 hours. After one hour however, the target operating temperature (80 K) is reached. As the temperature is not regulated (the set point on the cooler feedback loop is set lower than 70 K), the input power of the system increases up to a value of 38.5 watts. The set point can be adjusted while the cooler is running, allowing easy measurement of the input power vs. temperature characteristics for the same set-up. Figure 7 shows these data graphed for different system configurations: the complete system mounted with a waveguide type input LNA, the complete system mounted with a coaxial type input LNA (that requires a waveguide to coaxial adapter), and the cryocooler only. In the latter configuration there is no conductive heat load other than instrumentation biasing. The RF input and output of the cryopackage however are simply disconnected from the 300 K vacuum enclosure, so the heat load from radiation remains the same as for the complete system mounted with a coaxial type input LNA. In all cases, the input power is significantly larger than the specification provided by Ricor [13], even when the conductive heat load estimated earlier is taken into account. We thus attribute



**Figure 7.** Temperature vs Input power of the system for different configurations.

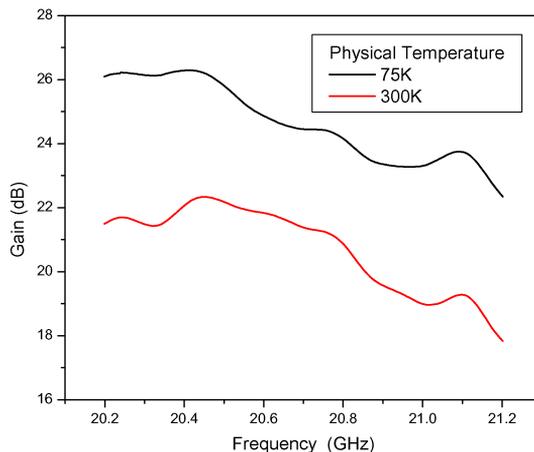


**Figure 8.** Noise temperature vs. frequency for different physical temperatures.

the difference to radiation on the package. Indeed, as mentioned earlier, the multi-layer insulation allows several direct windows to 300 K radiation, the biggest one being the waveguide inner volume. We can see that for the two configurations comprising a working LNA, the curves in Figure 7 are remarkably similar, which means that the waveguide-to-coaxial adapter does not reduce the conductive heat load of the input line by acting as a thermal break.

### RF Performance

RF performance such as noise and gain of the system can be measured at the same time as input power and temperature. Measurements are done over the whole bandwidth for different temperatures. As one can clearly see in Figure 8, there is a tremendous advantage in terms of noise in cooling the amplifier. The noise temperature decreases from above 120 K at room temperature to lower than 40 K at operating temperature. We can also observe a general rise in noise temperature at higher frequencies of the bandwidth, especially at high physical temperature. Although we do not fully understand this rise, we believe it is due to losses in the input RF line. Even if each component loss has been carefully measured before assembly the final assembly of the waveguide input line was not tested as a whole. A slight shift between two waveguide flanges allowed by machining tolerances can occur and create such a loss, not uniform on the whole bandwidth.



**Figure 9.** Gain of the system at room temperature and cryogenic operating temperature.

As we can see in Figure 9, the gain of the amplifier also benefits from the cool down and increases from 21 dB at room temperature to 25 dB at 75K.

## CONCLUSIONS AND FUTURE WORK

We successfully integrated different types of cryogenic LNAs onto a miniature rotary Stirling cryocooler. The final system meets the initial objectives in terms of robustness, efficiency and RF performance. The gain of the system is above 20 dB and its noise temperature is below 40K when cryogenically cooled. Furthermore, the small size of the overall system allows integration directly to the back of a satellite dish, which gives a key advantage in terms of final performance compare to bigger systems that have to be mounted remotely from the antenna. The system will be further tested after coupling to an antenna, and the improvement in G/T for the final receiver, compared to the existing non-cooled LNA, will be evaluated.

Several upgraded configurations are envisaged: the insertion of an HTS filter is for instance expected to improve further the signal quality; another major improvement will be to integrate several channels on a single system. The latter, however, doubles or triples the heat load, depending on how many channels are integrated. The need for a bigger cryocooler, say 2.5 W at 77 K arises and so far we have not been able to identify any off-the-shelf cryocooler compact enough to meet our needs.

## ACKNOWLEDGMENT

Funded in part by U.S. Navy, SPAWAR PMW 170 through the Small Business Innovation Research (SBIR) Phase 2.5 Program.

## REFERENCES

1. R.R. Romanofsky, et al., "A Cryogenic K-Band Ground Terminal for NASA'S Direct-Data-Distribution Space Experiment," *IEEE Trans. Microwave Theory & Tech.*, vol. 48, no. 7, pp. 1216-1220, July 2000.
2. D. Gupta, T.V. Filippov, A.F. Kirichenko, D.E. Kirichenko, I.V. Vernik, A.Sahu, S.Sarwana, P. Shevchenko, A. Talalaevskii, and O.A. Mukhanov, "Digital channelizing radio frequency receiver," *IEEE Trans. Appl. Supercond.*, vol. 17, pp. 430-437, Jun. 2007.
3. I.V. Vernik, D. E. Kirichenko, V. V. Dotsenko, R. Miller, R. J. Webber, P. Shevchenko, A. Talalaevskii, D. Gupta, and O.A. Mukhanov, "Cryocooled wideband digital channelizing RF receiver based on low-pass ADC," *Supercond. Sci. Technol.* vol. 20, pp. S323-S327, Nov. 2007.

4. O.A. Mukhanov, D. Kirichenko, I.V. Vernik, T.V. Filippov, A. Kirichenko, R. Webber, V. Dotsenko, A. Talalaevskii, J. C. Tang, A. Sahu, P. Shevchenko, R. Miller, S. B. Kaplan, S. Sarwana, and D. Gupta, "Superconductor Digital-RF receiver systems," *IEICE Trans. Electron.*, vol. E91-C, No. 3, pp. 306-317, Mar. 2008.
5. D. Gupta, D.E. Kirichenko, V.V. Dotsenko, R. Miller, S. Sarwana, A. Talalaevskii, J. Delmas, R. J. Webber, S. Govorkov, A. F. Kirichenko, I. V. Vernik, and J. Tang, "Modular, multi-function digital-RF receiver systems," *IEEE Trans. Appl. Supercond.* vol. 21, pp. 883-890, 2011.
6. G.A. Ediss, N. Horner, F. Johnson, D. Koller, A.R. Kerr, "WR-10 Waveguide Vacuum Feedthrough for the ALMA Band-6 Cartridge," *ALMA Memo 536*, National Radio Astronomy Observatory, 7 September 2005.
7. J.L. Hesler ., A.R. Kerr . and N. Horner, "A Broadband Waveguide Thermal Isolator," *ALMA Memo 469*, 30 May 2003
8. H. Kubota and H. Takeuchi, "Low Thermal Leakage Coaxial Cable for HTS Devices," *IEEE Trans. App. Supercond.*, Vol.9, No.2, June 1999.
9. Robert J. Webber, Charles J. Burroughs, and Masoud Radparvar, "Performance of a Cryocooled Nb DC Programmable Voltage Standard at 4 K," *IEEE Trans. on Applied Superconductivity*, vol. 17, no. 4, pp. 3857-3861, December 2007
10. Y.H. Tang, R.T. Hunt, R. Robertazzi, M. Fisher, J. Coughlin, R. Patt, E.K. Track, and E. Potenziani, "Cryocooled Primary Voltage Standard System," *IEEE Trans. On Instrumentation and Measurement*, Vol. 46, No. 2 (1997).
11. M. Barucci, E. Olivieri, E. Pasca, L. Risegari, G. Ventura, "Thermal conductivity of Torlon between 4.2 and 300 K", *Cryogenics*, Volume 45, Issue 4, April 2005, Pages 295-299.
12. Torlon® Resins Engineering Data, <http://www.hycompinc.com/PDFs/Torlon%20Design%20Manual.pdf>
13. Ricor's website, <http://www.ricor.com/Index.asp?ArticleID=178&CategoryID=59&Page=1>