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# Cryogenic Design of the Deep Space Network Large Array Low-Noise Amplifier System

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*This article describes the cryogenic design and performance of a prototype low-noise amplifier (LNA) system for the Deep Space Network (DSN) Large Array task. The system is used to cool a dual-frequency feed system equipped with high-electron mobility transistor (HEMT) low-noise amplifiers and the associated support electronics. The LNA/feed system operates at a temperature under 18 K. The system is designed to be manufactured at minimum cost. The design considerations, including the cryocooler to be used, vacuum system, microwave interconnects, mechanical components, and radiation shielding, are discussed.*

## I. Introduction

The Deep Space Network (DSN) Large Array task has a requirement for cryogenically cooled low-noise amplifiers (LNAs) with integrated feeds operating at 20 K or below. To be cost effective, the systems must be produced at low cost; also, the life-cycle cost of the systems, including operating cost and maintenance, must be minimized.

The operating temperature, input power, and reliability are largely controlled by the selection of the cryocooler. The selection process was based on a trade-off between the availability of existing coolers, the expected reliability, and the input power requirement.

In any cryogenic cooling application, the required cooling capacity or heat load determines the type and size of cryocooler needed. In general, the smaller the cryogenic heat load is, the smaller the input power requirement and physical size of the cooler are. Minimizing the cryogenic heat load was a major goal in the design of this system.

The goal of the mechanical design of the system was to minimize the manufacturing cost and to allow the system to be used as a test bed with different cryocoolers. Previous DSN LNA systems were designed around the cooler, using the cooler as a structural support for the LNA system. This cooler is designed to accept virtually all of the current cryocooler options with only minimal modification.

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In order to minimize maintenance costs, in the Large Array system the LNA/feed assembly must be light enough to be handled easily without special handling fixtures. The total weight of this system is one-tenth that of the DSN dual-frequency LNA system.

The microwave feed-through or “window” is a critical component in the design. The window must provide a low-loss signal path but maintain a degree of vacuum integrity. A significant amount of work was performed to design a novel high-performance window.

The Large Array also has special requirements for the vacuum system used to insulate the cryogenically cooled components. Normally, high-vacuum pumps are used to evacuate the vacuum space before the system is cooled. Because of the large number of coolers and their physical configuration, it is highly desirable to operate the systems without the use of dedicated high-vacuum pumps. This system has the potential to operate with a low-cost vacuum pump with only a moderate vacuum-pressure requirement.

## II. Cryocooler Selection

To identify suitable coolers for the task, an industry-wide request for quotation (RFQ) was released. The RFQ was sent to nine vendors. Two positive responses were received. Both were Gifford–McMahon (GM) two-stage coolers with first-stage operating temperatures near 50 K and second-stage temperatures near 15 K.

Cryomech Inc. responded with a quote for model GB-15 systems. The GB-15 is similar to the original Gifford–McMahon cooler evaluated by JPL in the 1960s. These are GM systems that produce 1.5 W of cooling at 15 K. The power consumption is 1.2 kW.

CTI Cryogenics responded with a quote for model 350 systems. The DSN has considerable operating experience with the CTI 350. It produces 3 W of cooling at 15 K. The input power requirement is 1.8 kW. The design has been used in hundreds of LNA systems over a 40-year span. The units typically operate for 18,000 hours before requiring maintenance.

## III. Cryogenic Heat Load

The heat load on the cryocooler is the sum of the load imposed by the LNA and supporting components from any residual gas in the vacuum space. The conduction load is added through solid supports, wires, signal cables, and the residual gas in the vacuum space. Radiation load is from the room temperature surroundings to the cryogenic components.

The first stage of the cooler intercepts the radiation load from room temperature to the cooled components with the radiation shield. The first stage also is used to minimize heat conducted to the second stage by intercepting heat from components that have a connection between room temperature and the second stage.

This system includes a cryogenically cooled feed and feed horn. The horn has a 12-cm aperture that is subject to radiation from the ambient. The 12-cm feed is the largest cooled aperture that has been used in the DSN in a closed-cycle cooling system. The system imposes a heat load of 10 W on the first stage and 1 W on the second stage of the cooler. Radiation loading from the cooled feed accounts for over 50 percent of the second-stage heat load. Graphs showing the contributions of individual heat loads are shown in Figs. 1 and 2.

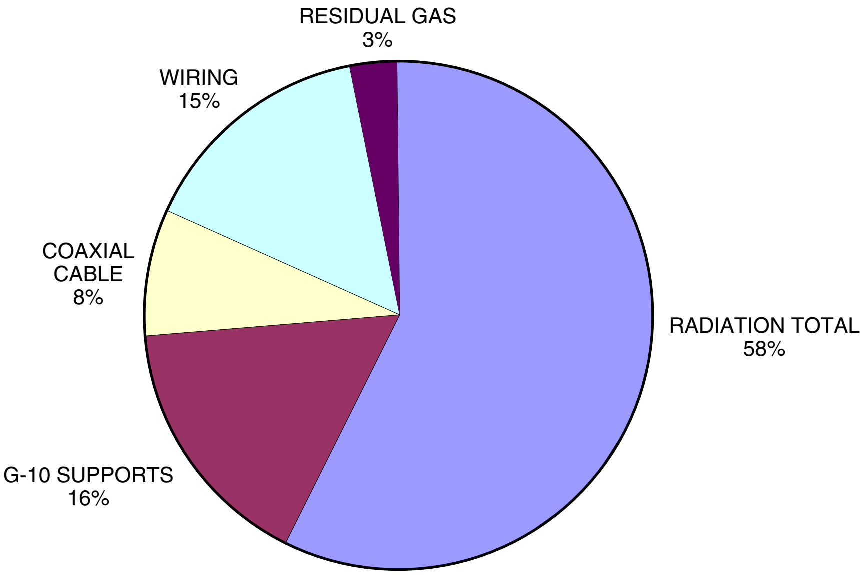

Fig. 1. First-stage heat load.

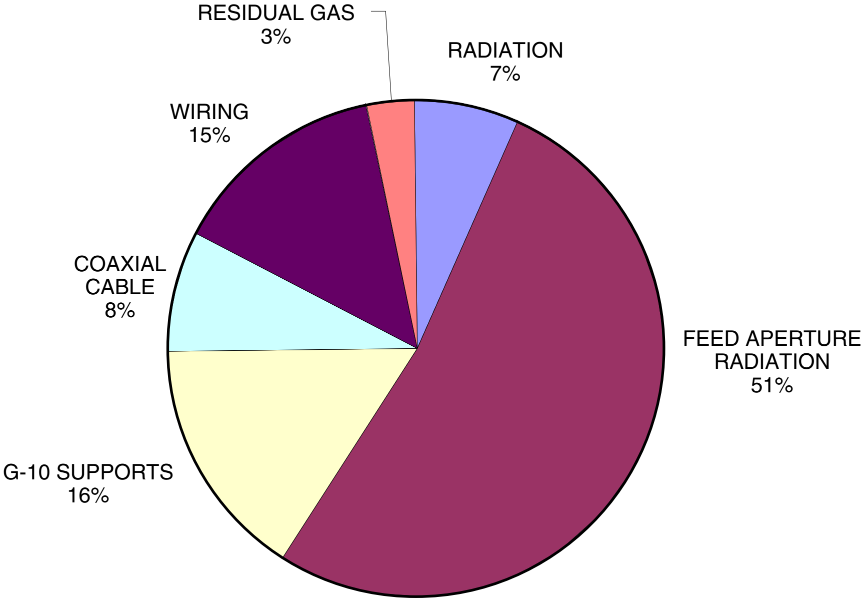

Fig. 2. Second-stage heat load.

## IV. Mechanical Design

To evaluate both coolers, the prototype cooler was designed to accept both the CTI 350 and the Cryomech GB-15. The package is in a 25-cm-diameter, 42-cm long, cylindrical vacuum housing. The feed and cooler are offset to provide the most usable space in the cold volume. The assembly is designed to use the Cryomech GB-15 and CTI model 350 coolers interchangeably with only bolt-in modification. The cryocoolers installed in the LNA assembly are shown in Figs. 3 and 4.

The vacuum housing chosen for the breadboard system is constructed using aluminum tubing. It eliminates welding and the problems associated with vacuum leaks and warping. In production runs, this technique can be cost effective. It provides the benefit of minimum weight and allows the vacuum housing to be sized optimally.

The end plate for the vacuum housing uses the standard DSN machined aluminum plate design. The plate is fitted with simple gland-seal O-ring connections. It uses commercial coaxial cable interface connectors. The feed is supported mechanically from the base plate with G-10 fiberglass supports. The installed feed is shown in Fig. 5. There is no mechanical connection from the opposite end of the assembly. This design has several advantages: It provides minimal heat conduction to cooled components, allows the package to be easily assembled, and minimizes mechanical stress due to thermal expansion.

In an effort to reduce manufacturing costs, the mechanical hardware was constructed using sheet-metal technology wherever possible. The radiation shield is a simple rolled cone. It is attached with screws to the flanges, which also are simple sheet-metal parts. It eliminates costly and time-consuming welding or silver brazing used in traditional DSN designs. Normally copper is used for shields. The radiation shields for the prototype are constructed of 1100F alloy aluminum. The aluminum provides acceptable thermal

**Fig. 3. GB-15 cryocooler installed.**

Fig. 4. CTI 350 cryocooler installed.

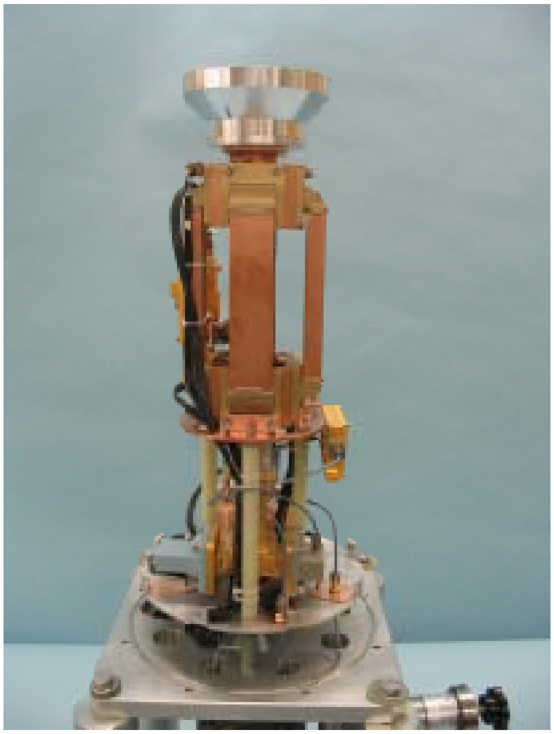

Fig. 5. Feed installed in the LNA assembly.

conductivity for the application, provides higher resistance to oxidization, and is lighter than copper. The radiation shield installed on the cooler is shown in Fig. 6.

The weight of the LNA assembly is an important factor in maintenance of the LNA system in a Large Array application. DSN LNA assemblies traditionally are heavy enough to require special handling fixtures during installation on antennas. The design goal is to provide an LNA assembly that is light enough to be installed by two people in a conventional basket lift. The total expected weight of the prototype LNA is 31 kg. A chart showing the weight of the major components is provided in Fig. 7.

## V. Feed Window Design

The vacuum window is a critical component in the package design. Three options were considered:

(1) Closed-cell structural foams
(2) Low-loss solids
(3) Foam-backed membranes (Kapton)

In order to select suitable window materials, accurate estimates of the noise temperature contribution of the individual materials were required. The noise temperature contributions of 11 thin films and solids and 10 foam samples were measured. The noise contributions were measured radio metrically at 8.4 and 32 GHz. The data are shown in Figs. 8 and 9.

The closed-cell structural foam window is constructed of a disk of high-strength foam that provides a vacuum-tight seal and the mechanical strength required to support the external pressure on the window. A thin membrane serves to protect the foam from contamination or damage. This design is attractive

Fig. 6. Aluminum radiation shield installed.

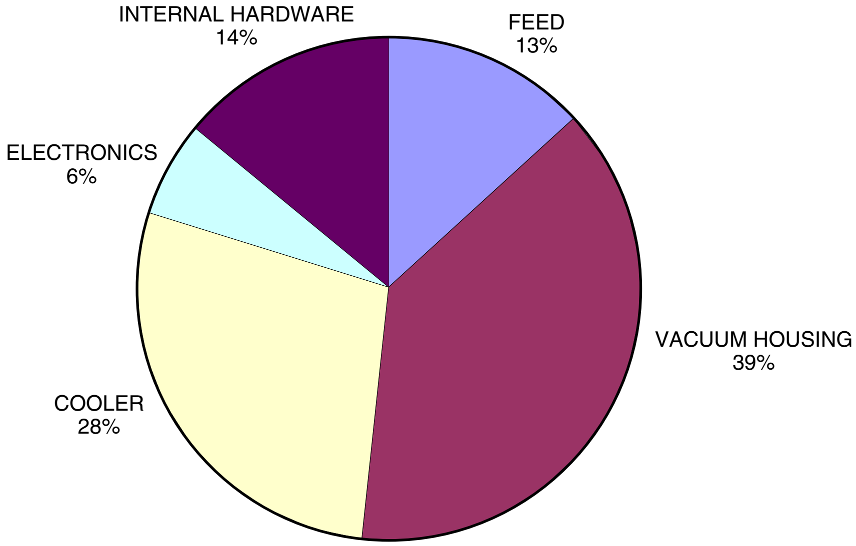

**Fig. 7. LNA assembly weight budget; total weight 31 kg.**

due to its simplicity and reliability. The thickness of foam required to provide sufficient strength would result in a noise temperature greater than 5 K and is considered unacceptably high.

Low-loss solid windows are simple and reliable. Teflon is a very low-loss material and has high ultraviolet (UV) resistance but does not have the required mechanical strength as a monolithic window. However, Teflon is very useful as a protective layer over other window materials. Teflon is also very hydrophobic and will minimize the effect of water on the feed cover.

Another option for a low-loss solid window is Rexolite, a very low-loss, high-strength, cross-linked polystyrene solid. It has low permeability to gasses, including nitrogen, water, and helium. It has a dielectric constant of 2.6. The broadband, dual-frequency requirement of the array feed makes designing a suitable Rexolite window challenging. A Rexolite dome lens was constructed to test its vacuum integrity. A window as thin as 1 mm is strong enough for the application. The design of a broadband Rexolite window is currently being investigated as an option.

The foam-backed membrane window was chosen for the prototype design. In this approach, the film strength of Kapton, a commercially available polymide film from Dupont, provides the vacuum seal and the mechanical strength. Low-loss, low-density foam acts as a thermal insulator and provides additional compressive strength.

To determine the required Kapton thickness, burst tests were performed on a typical clamped ring joint. The expected burst pressure for a 14-cm-diameter Kapton window was extrapolated from burst measurements of 2.2 cm and 9 cm. The data are shown in Fig. 10. To provide a burst pressure safety factor of 3, the window would require 0.07-mm to 0.13-mm Kapton film.

Kapton loses mechanical strength when exposed to the Sun. To solve this problem, a 0.25-mm film of Teflon radome material is sandwiched to the exposed Kapton with a clamp ring. The Teflon layer reflects and absorbs UV radiation, increasing the life of the Kapton. Teflon also is naturally hydrophobic and prevents water from collecting on the Teflon surface of the window, which is a major problem. The material demonstrated a 20-year life in radome service. A schematic of the window construction is shown in Fig. 11. Figure 12 shows the window installed on the LNA assembly.

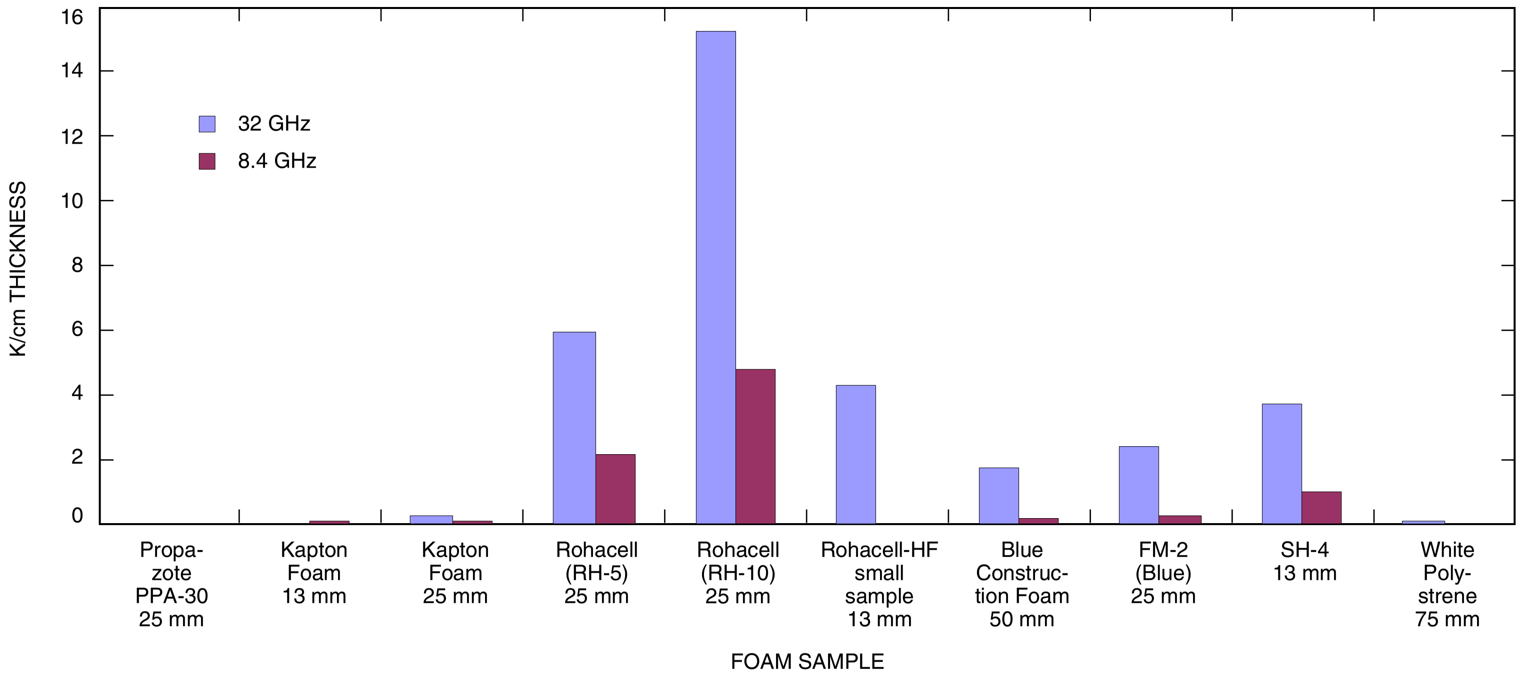

**Fig. 8. Noise temperature contribution of foams at 8.4 and 32 GHz.**

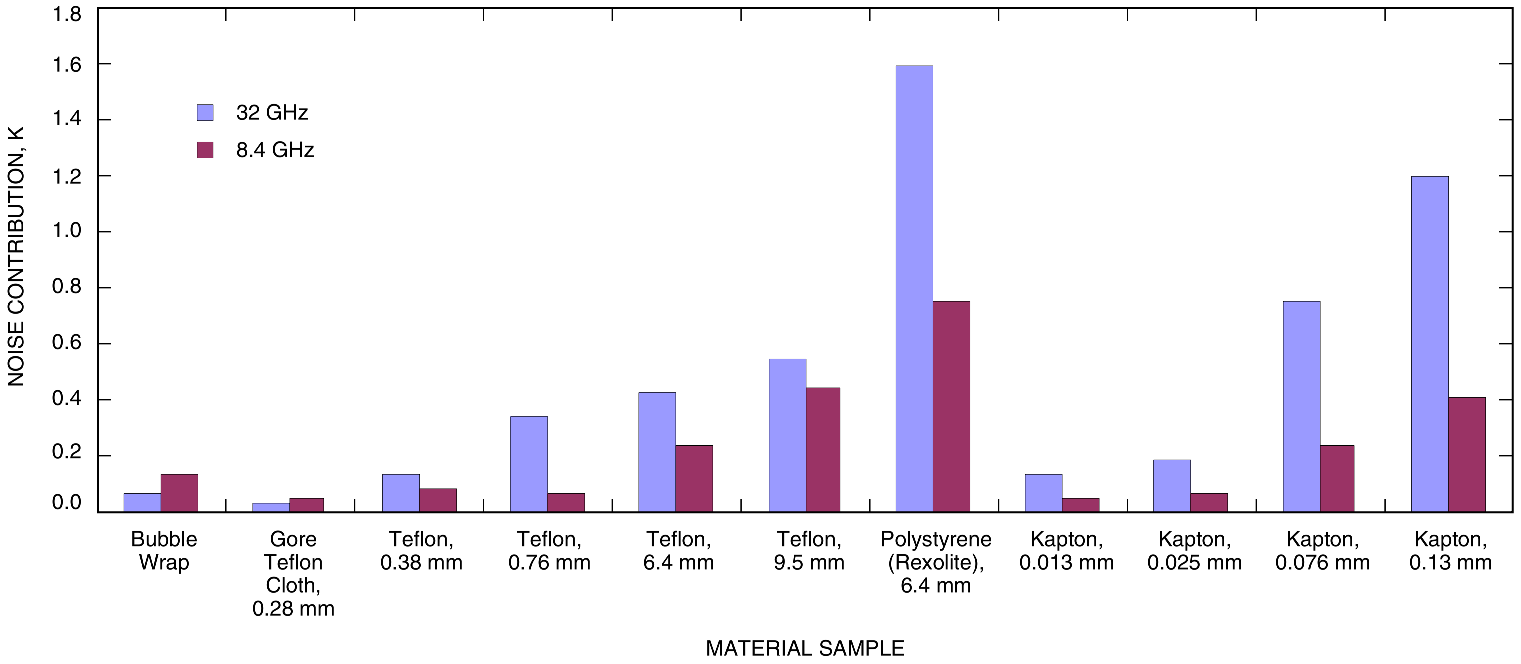

**Fig. 9. Noise temperature contribution of thin films and solids at 8.4 and 32 GHz.**

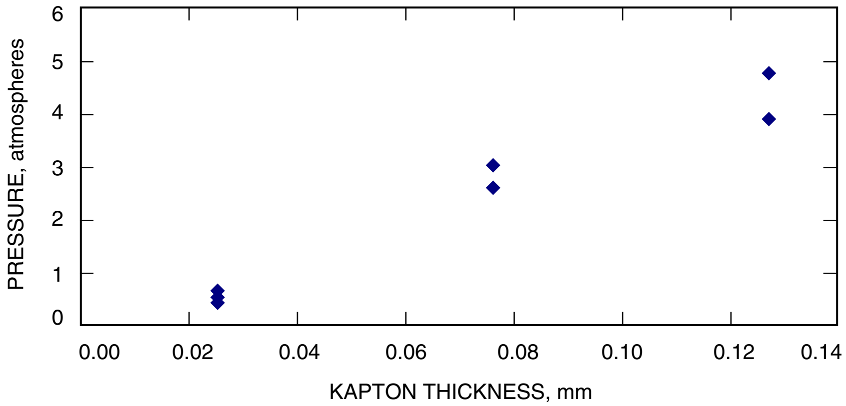

**Fig. 10. Measured Kapton burst pressure for a 14-cm-diameter window.**

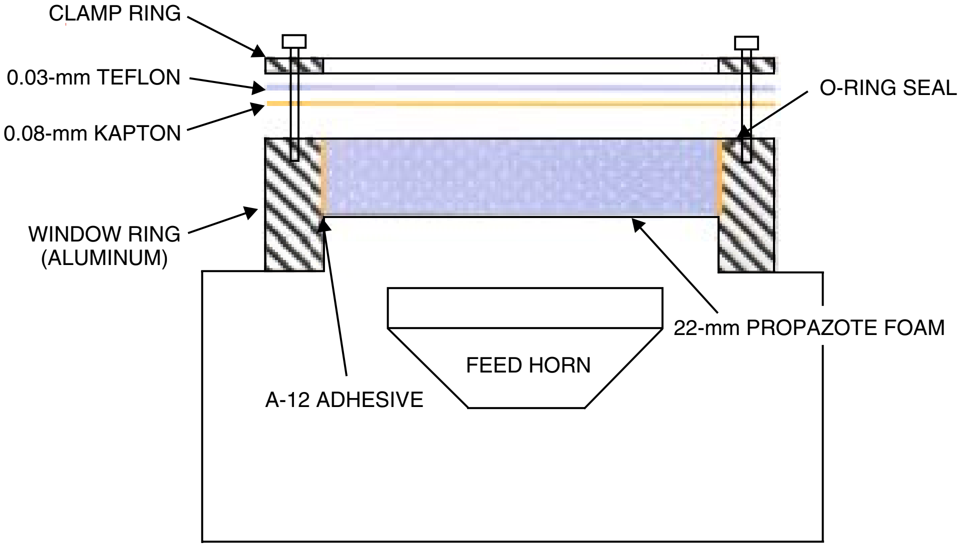

**Fig. 11. Schematic view of the vacuum window.**

A 20-mm thickness of Propazote PPA-30 foam is used behind the window. The foam acts as a thermal insulator to limit the radiation cooling from the cooled feed horn to the outer surface of the window. This insulation prevents moisture from condensing on the feed window, which dramatically increases the loss of the window. The Propazote foam has a high compressive strength. The foam is attached to an outer ring with Armstrong A-12 adhesive and supports the Kapton, reducing the strength required from the film itself.

The completed window has very low microwave loss of approximately 0.4 percent. The window contributes less than 1 K at 32 GHz and 0.2 K at 8.4 GHz. The window has been used for 1 year in laboratory service and has been pressure cycled from atmospheric pressure to $10^{-5}$ torr over 100 times without failure.

**Fig. 12. Vacuum window installed on the LNA assembly.**

## VI. Vacuum System

The vacuum system is a critical component of the array LNA. A vacuum pressure of $<10^{-5}$ torr is required in the vacuum space to minimize the heat leakage to the cooled components. The array LNA uses a "cryopump" to maintain the vacuum pressure. A schematic of the vacuum system is shown in Fig. 13.

The cryopump is an array of activated charcoal that traps gasses using the weak intermolecular forces between the gas and the cyropump material. The effect is similar to water vapor condensing on a cold drinking glass. The porous surface of the charcoal provides tremendous surface area for gases to collect.

Values for the absorption of air in charcoal [1] indicate that 1 g of activated charcoal cooled to 20 K can absorb 35 standard $\mathrm{cm}^3$ of air and maintain a pressure below $10^{-6}$ torr. This corresponds to an acceptable leak rate for the dewar of $10^{-6}$ standard cc/s per gram of charcoal. This is an easily achievable leak rate. Cryopumps containing 10 to 100 g of charcoal are practical. This theoretically would provide cryopump operation for 10 years.

In addition to the cryopump, a mechanical "roughing pump" is required to lower the pressure sufficiently to allow the cooler to overcome the heat load from the residual gas and cool the cryopump to the operating temperature. Traditionally, DSN systems have required a roughing pump that reduces the pressure from 760 torr (1 atmosphere) to $10^{-1}$ torr or less. Currently the DSN and many other LNA users use oil-lubricated mechanical rough pumps. Oil-lubricated pumps are inexpensive but have a number of disadvantages in the Large Array application. First, the lubricating oil absorbs moisture from the air and requires periodic service every 6 months to a year. Second, the pumps are gravity sensitive and would

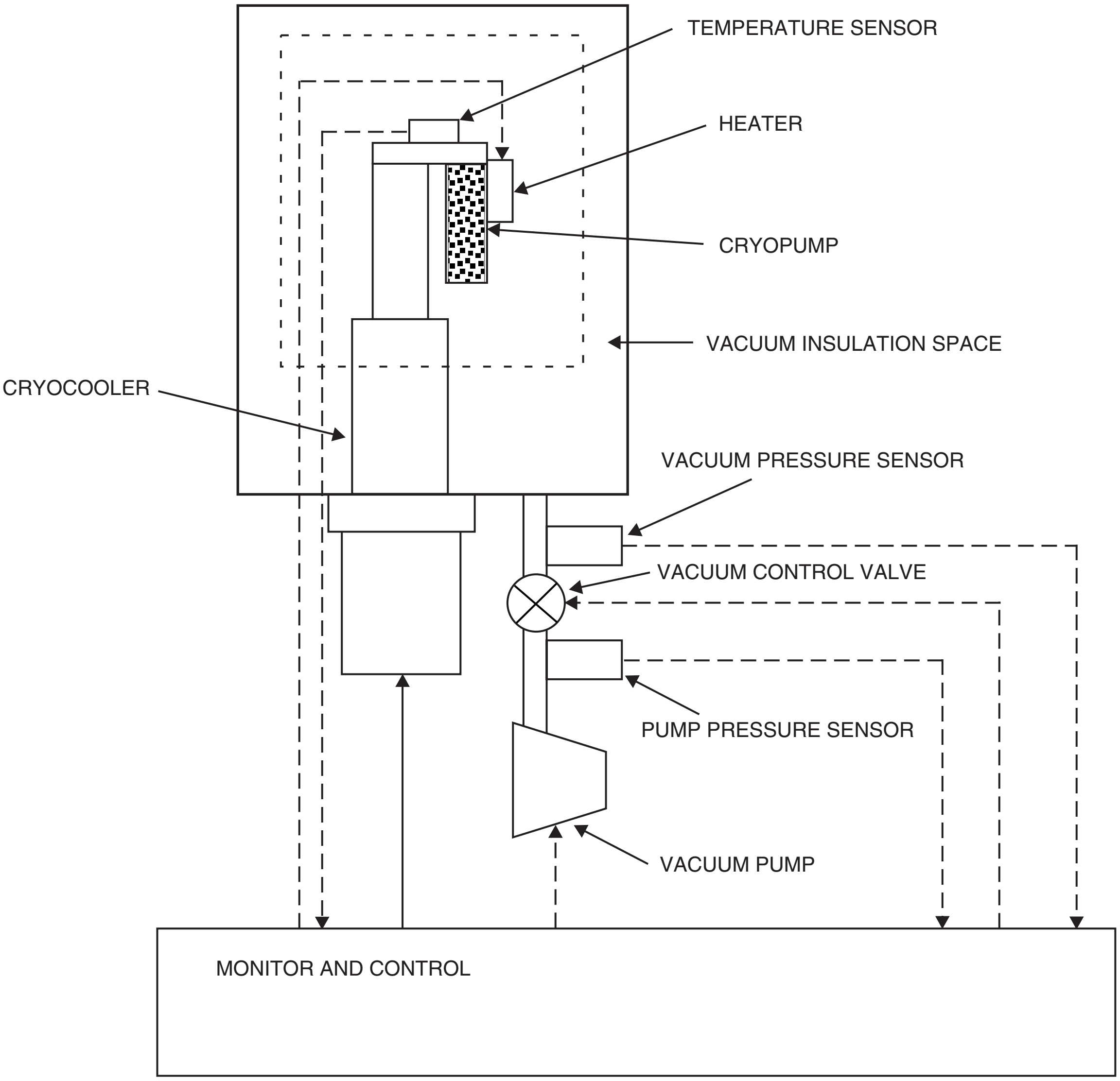

**Fig. 13. Vacuum and cryogenic system schematic.**

require gimbaled mounting, which adds cost and complexity to the system. Third, the lubricating oil also can back stream into the vacuum housing in some cases, contaminating the radiation shields and raising the cooler operating temperature.

To minimize the rough pump requirement, special attention was given to the vacuum design. The clearances between the cold and warm surfaces are substantially larger than existing designs. The radiation shield was sized to provide a 25-mm radial clearance between the concentric housing and shield. The result is a substantial reduction in the required rough pump ultimate pressure. The prototype cooler has been tested with a low-cost diaphragm pump. The pump achieves a pressure of 60 torr. The unit has been successfully cooled from a starting pressure of 100 torr.

## VII. Test Results

The prototype unit currently is being used to support noise temperature testing of the feed/LNA system with the CTI cryocooler. It has been thermally cycled over 50 times with no problems. The system cools from ambient to operating temperature in 10 hours.

In the current configuration, the entire feed LNA system is cooled to the second-stage temperature. The system operates with the LNA modules at 15 K. The measured temperature of the feed at the opposite end of the cooler is 18 K. The first stage operates at 60 to 65 K.

## VIII. Conclusion and Recommendations

The Large Array prototype LNA system described is a low-cost system that meets or exceeds the requirements for the initial breadboard phase of the Large Array Project. It was designed to be easy to manufacture at minimum cost. The heat load on the cryocooler is only 1 W at 15 K and 10 W at 60 K, including cooling the entire multi-frequency feed, LNA, and supporting hardware. A low-loss, high-performance vacuum feed window has been designed and tested. The window is a critical component, and its performance will not be fully understood until it has operated in field conditions for an extended period. Work on a solid Rexolite window should be continued.

# Acknowledgment

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# Reference

[1] R. B. Scott, *Cryogenic Engineering*, Boulder Colorado: Met-Chem Research Inc., pp. 164–1652, 1963, reprinted 1988.