

Feasibility Considerations for High Temperature Superconducting Transponders  
in Communication Satellites

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## ABSTRACT

This paper provides a comprehensive, background-rich framework around which a fully developed study of the use of superconducting transponders can be generated for a specific communication satellite. The approach divides results into two categories: signal benefits, and physical constraints. Each is realized in terms of metrics and methods warranted by the current state of superconductor technology.

The paper describes methods by which signal performance of superconducting transponder components may be approximated; also methods of evaluating heat generated by such a system; and finally, the selection of an appropriate cryogenic cooling system.

## 1. INTRODUCTION

With the proliferation of communication satellite applications, from digital television to global mobile connectivity, great demand has been placed on the strictly allocated bandwidth that satellite manufacturers may purchase from the FCC. In order for vendors to maximize bandwidth usage, various signal modification approaches have been implemented, such as data compression, or multi-phase transmission, but a method through which additional bandwidth can be gained remains the holy grail of the satellite communications industry.

This paper evaluates the methods by which the feasibility of the use of High Temperature Superconductor (HTS) Transponder for a particular communication satellite can be determined. These methods were applied to a Harvey Mudd College (Claremont, CA) Clinic project for Space Systems/Loral during the 1997/1998 school

year, and much of this paper is derived from that project.

## 2. APPROACH

By replacing the satellite's transponder with a HTS version, the low ohmic loss that superconductivity provides improved signal-to-noise ratio (SNR), and increases bandwidth. This improvement comes at the cost of the active cooling system required to bring the electronics down to superconducting temperature (70 K). The two distinct fields in which the integration of HTS components affects the satellite are thus in signal performance and physical characteristics.

## 3. PRINCIPLES

Superconductors are functionally defined as materials that conduct current with negligible resistance. These materials only act as superconductors at very low temperatures, traditionally no greater than 20K. However, in 1986, a class of ceramics was discovered that acts as superconductors at temperatures approaching 90K. This relatively high temperature makes these materials attractive since it is readily achieved using cryogenic techniques. Furthermore, HTS materials offer significant advantages over more standard materials in the field of electronics and signal processing; these potential advantages are briefly discussed below.

One potential use of superconducting materials is in filters. Filters are devices that attenuate all frequency components not contained in a particular range of frequencies called the passband. The frequency content of the passband is output to the next component in the system. However, to gain an idea of how

filters work, we must first understand what a resonator does.

A resonator is a component in which electromagnetic energy of a particular frequency is stored, that is, resonates. Resonators are typically described in terms of their quality factor, abbreviated Q. This dimensionless parameter is proportional to the amount of energy stored in a resonator divided by the amount of energy dissipated. The higher the Q factor, the more efficient the performance of the resonator. Typical microstrip circuits fabricated with normal metals have a Q factor in the low hundreds. Filter designs such as waveguides may have a Q factor of a few thousand. However because of their extremely low resistance, superconducting resonators can have Q factors in the tens of thousands.

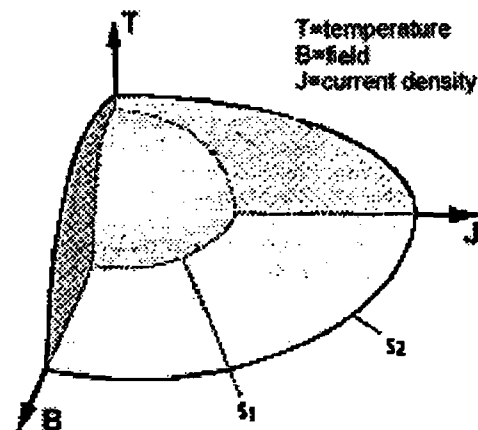
A microwave filter consists of a series of resonators, each tuned to a slightly different frequency in the filter's passband. The more resonators used in a filter with a given passband, the sharper the drop-off in signal strength at the edges of the filter, and the greater the offband rejection. However, simply adding more and more resonators to a filter to increase performance is problematic in that each additional resonator adds to the insertion loss, defined as the loss of signal strength in the passband due to the insertion of the filter into the system. The lower the Q factor of a resonator the greater the insertion loss. The insertion loss must be kept under a particular value for acceptable performance of the system. Furthermore, adding additional resonators to a filter increases the weight, size, and complexity of the filter.

Thus, the advantage of using superconducting materials in filters is their superior Q factors as compared to standard materials. For a given maximum insertion loss in a filter one can use a much greater number of superconducting resonators than normal metal resonators. This gives the filter far superior performance in terms of offband signal attenuation. Further advantages stem from the fact that superconducting filters give comparable performance to normal metal filters, but in a much smaller package. Using superconducting materials can thus save both size and weight, two very precious commodities on satellites.

HTS materials have two primary drawbacks. The first is that they must be operated at temperatures much below that of the

ambient environment, thus requiring some sort of cooling method. The second drawback is that HTS materials exhibit non-linear characteristics, as discussed below.

For all superconducting materials, there is a critical temperature below which they must be reduced in order to behave as superconductors. However, reducing the temperature of the materials below the critical temperature is not sufficient for superconducting behavior; the magnetic field around the material must be held below a critical value as well. Furthermore, since electric current produces a magnetic field this property limits the amount of current a superconductor can support. The result is that there is a limit on the power handling capabilities of a superconducting component. These properties are summarized in Figure 1 (Paul K., Chen M. IEEE Spectrum., May, 1998 p49)

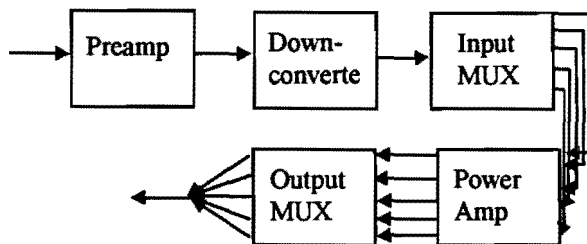


**Figure 1 States of a Superconductor. Zero-resistance (inside S1), transition state (between S1 and S2), normal conducting (beyond S2).**

These properties make HTS components fundamentally nonlinear, since doubling the input power may not result in a doubling of the output power. This problem must be resolved for each specific filter before it can be used in the transponder.

#### 4. COMMUNICATION SATELLITES

The most general description of the functionality of a communication satellite transponder is captured in Figure 2 .



**Figure 2 Transponder Block Diagram**

The incoming signal, weak due to propagation losses and atmospheric reflections, must be amplified before being processed by all subsequent blocks. The preamplifier must thus provide low noise amplification and exhibit good linearity over the entire uplink frequency range.

After amplification, the signal must be converted to the downlink frequency range by the frequency downconverter block. Since this block is dealing with the entire bandwidth of the signal, good linearity of the mixer is necessary; otherwise, the frequency converter would produce inter-channel modulation in the output signal.

At this point, the signal is divided into channels for individual processing. Each channel has its own input multiplexer block. This block is a band-pass filter with a center frequency tuned to that channel's frequency. Each filter must have very strong stop-band rejection, as well as a fairly flat pass-band and group delay response.

Each channel also has its own power amplifier block. Once the signal has been filtered, it is amplified at high power for retransmission. It is important to note that at this point the signal is at the downlink frequency, has a very narrow bandwidth, and is considered free from distortion. The power amplifier must provide a linear output with a high gain.

The final component of each channel is the output multiplexer block. It is at this point that the amplified signals are recombined for transmission. The output multiplexer is responsible for rejecting harmonics, noise generated by the power amplifiers, and interference from other channels. Like all other filters in the system, it must also have low insertion loss. This is necessary to minimize thermal dissipation as well as to maximize the output power to the transmitting antenna.

## 5. SIGNAL PERFORMANCE ANALYSIS

The primary reason for using HTS components in communication satellites is to improve the signal processing characteristics of the satellite. Thus a large part of any feasibility analysis is quantifying these improvements, and determining if they are worth the difficulties that result from the use of HTS materials in space.

### 5.1 Research

While high temperature superconductivity has been studied for many years, its application to microwave communications components is fairly new. A literature search was conducted to identify the state of the industry developments and academic research.

Attempts were made to find components that were exact matches for the components in a generic transponder. In some cases, parts were found in the correct frequency range and were space-qualified. In other cases, parts were from other frequency ranges or were one-of-a-kind items. Contact with industry and research representatives confirmed under what situations extrapolations could be made.

The commercial market for HTS microwave components is mainly limited to filters and amplifiers for the cellular base station industry. These components are for the 800 MHz and 1900 MHz frequency ranges. A number of companies were found that manufacture base station preselect filters.

The academic publications for HTS microwave components were much wider ranging and most of the research applies directly to the satellite communications field. Frequency ranges for components are between 1 and 11 GHz and many are space-qualified or have been used in prototype satellites.

The research effort revealed the difficulties in comparing the signal performance of a conventional system with a HTS version. It is impossible to find an exact match for every component. For example, some amplifiers have the correct gain, but are in the wrong frequency range.

Because of these difficulties, a two-part analysis is recommended. First, an investigation done at the system level. This simplified analysis attempts to identify any overall gains in the transponder performance. A more detailed

analysis is also necessary in order to understand the effect of replacing each type of component with an HTS version.

## 5.2 System Level Analysis

In system level analysis, each block in the system is considered as a collection of sub-blocks. The main blocks are the preamplifier, the downconverter, and the input multiplexer. This analysis is not concerned with details such as the number of amplifiers and filters used in the downconverter; only with the overall block performance.

In an analysis of this type it is important to identify the important system parameters. Satellite communications are typically described by link budget calculations. The primary statistic of comparison in a link budget is the signal-to-noise ratio. Therefore, we must keep track of the signal power and the noise power at each block in the system. By modeling each block with two parameters - insertion loss (or amplifier gain) and noise figure - it is possible to complete a link budget.

From the specification of a communication satellite that may be suited to including HTS components, information on the transponder input signal power may be derived. Additionally, obtaining insertion loss/gain and noise figure information for each block in the transponder makes it possible to combine all of the blocks and obtain an aggregate system gain and aggregate system noise figure. In order to calculate the signal-to-noise ratio at the input and output, one additional parameter is necessary: the noise power at the input of the system.

The uplink signal will be affected by a number of factors as it travels through the atmosphere. An atmospheric phenomenon such as rain fade or path loss can be modeled as either reductions in signal power or increases in signal noise. If these phenomena are modeled as power losses, the entire noise power at the input to the transponder can be lumped into the noise temperature of the antenna. This noise temperature will vary depending on the orientation of the satellite with respect to the sun, from 270K to 8000K. Since this variation is so great and it is unknown what orientation the final satellite will take, calculations should be done at both temperatures.

The noise power for the antenna is calculated based on coupling from a noise generator. This noise generator has a maximum thermal noise power of,  $N = k \cdot T_0 \cdot W$ , where  $k$  is Boltzmann's constant ( $1.38 \times 10^{-23}$  J/K).

It is now possible to combine the signal values through into an equivalent block as they are LTI (Linear Time Invariant) using the following formulas:

$$F_{\text{composite}} = F_1 + (F_2 - 1)/G_1 + (F_3 - 1)/G_1 G_2 + \dots + (F_n - 1 - 1)/G_1 G_2 \dots G_n$$

$$G_{\text{composite}} = G_1 G_2 \dots G_n$$

It is clear from these formulas that the largest reduction in noise figure occurs when the first block (the preamplifier) has a low noise figure (when  $F_1$  is small) and a high gain (when  $G_1$  is large). By using a superconducting preamplifier it is possible to substantially lower the composite noise figure.

Generally, channelized signals are allocated a fraction of the overall bandwidth. This fraction is then divided into usable bandwidth, surrounded by guard bands that form the inter-channel spacing see Figure 3. It is here, in the guard band, that the use of HTS components will have the most benefit. In order to assess this potential gain, we must examine the component level of each system.

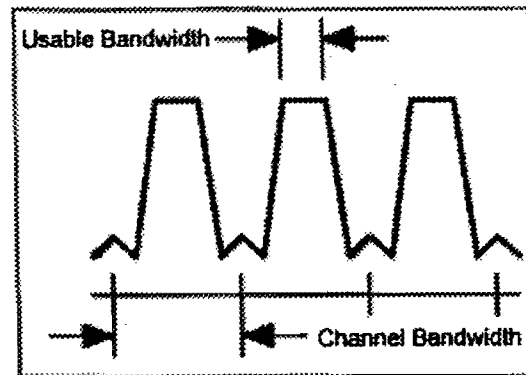


Figure 3 Channel bandwidth and channel spacing

## 5.3 Component Level Analysis

In component level analysis, each block in the system is considered independently. That is, if the downconverter calls for a series of three amplifiers, each of those amplifiers is

considered separately. The goal is to obtain a delta comparison for each specification.

### 5.3.1 Metrics and Methods of Analysis

Before HTS and non-HTS components can be compared it is necessary to determine a set of metrics and methods of comparison. The purpose of this section is to explain the methods that can be used to evaluate the improvements resulting from the use of HTS components.

#### 5.3.1.1 Analysis Using Q

The advantages of superconducting materials over their non-superconducting counterparts are often quantified in terms of a quality factor, abbreviated Q. Unfortunately, Q has two different definitions that, although related, are not in general equivalent. In order to understand how a component can be characterized by its quality factor, it is first necessary to understand the two definitions of the quality factor.

The two classifications of the term quality factor are unloaded Q ( $Q_u$ ) and loaded Q ( $Q_l$ ). Unloaded Q is also sometimes referred to as component Q, and gives the ratio of stored to dissipated energy in a component. An ideal reactive component such as a capacitor or inductor will have  $Q_u$  equal to infinity. However, all real components will dissipate as heat some fraction of the energy input to them. This fraction is quantified by stating the unloaded Q for a component. This lost energy manifests itself as insertion loss if the component is used as a filter. Insertion loss is thus inversely proportional to the average  $Q_u$  of the components in the device.

For bandpass filters, insertion loss also depends on the bandwidth of the filter, and knowing  $Q_u$  is not sufficient to characterize the filter's insertion loss. In addition, one must also know the loaded Q defined as follows:

$$Q_l = \text{center frequency/bandwidth}$$

The insertion loss of a bandpass filter is calculated according to the following formula:

$$I.L. = \frac{4.34Q_l}{Q_u} \sum_{n=1}^{n=N} g_n$$

Where g is a function of the filter type and number of poles.

In satellite communications where individual channels have relatively small fractional bandwidths, having a high  $Q_u$  becomes more important if one wants to keep insertion loss low.

Since unloaded Q is a material property, the characteristics of individual components are often quantified in terms of their  $Q_u$ . Using the above equations, this allows the insertion loss of a given component to be easily estimated. However, a full evaluation of relevant signal parameters such as group delay requires the use of a component's transfer function. This is discussed below.

#### 5.3.1.2 Analysis Using Transfer Functions

The analysis and comparison of superconducting and conventional components requires one to examine a number of parameters: insertion loss, insertion loss flatness, insertion loss slope, isolation, and group delay. All of these parameters are conveniently embodied in or can be derived from one metric; the transfer function. This transfer function is a linear mathematical model and does not take into account any non-idealities.

#### Validation

Let us consider superconducting filters, similar results can be derived for the other components. Superconducting filters closely represent an ideal situation. They have very low resistive loss and, once the transition temperature is reached, minimal variation in performance with temperature. These characteristics make it reasonable to model them with simple mathematical functions. This is not the case for semiconductor or wave-tube filters, which must take into account a variety of temperature and material properties.

#### Method

In order to use these filter transfer functions in the signal performance analysis, it is necessary to make a number of assumptions.

- If a journal or industry representative manufactures an Nth-order HTS filter, it

should be possible with enough time and patience, to tune that filter to closely match the ideal Nth-order mathematical model

- The filters are modeled as a linear, time invariant system (LTI). Any non-linearities in the filter pass- or stop-bands are ignored for this analysis.
- An equalizer can be built and attached to the system that will maximize the flatness of the group delay in the passband (by straightening the phase response). Since filters tradeoff performance in phase characteristics for performance in magnitude characteristics, it is important only to look at the types of filters that emphasize passband to stopband rolloff.

#### General Results

By comparing the results of the two analysis methods of HTS components with those of the conventional transponder components, it is possible to quantify the specific signal gains that may be obtained in HTS system.

Gains in SNR will primarily derive from the replacement of the amplifiers with HTS counterparts. The increased SNR can translate into lowered necessary transmission power, lower probability of error during transmission, or a potential increase in transmission rate.

The reduction in insertion loss resulting from the use of HTS filters enables higher order filters to be used. These filters exhibit a high quality factor, thus a sharper passband to stop-band transition, which implies a decrease in necessary guard band between channels, and thus an increase in useable bandwidth.

## 6. HEAT TRANSFER

### 6.1 Overview

The use of superconducting components in space requires that the components operate at temperatures around 70K. This is much lower than the ambient temperature of the satellite, which, although it fluctuates depending on the orientation of the satellite with respect to the sun, is approximately 290K. Passive cooling techniques, such as the use of radiators embedded in the outer wall of the satellite, can only reduce the temperature of a component down to about 100K. Thus the use of superconducting components requires an

active cooling source, that is, a cryocooler. Before a cryocooler can be chosen for this application, one must determine the heat load that will be presented to the cryocooler. This requires an understanding of the heat transfer environment in a satellite, which is described below.

### 6.2 Heat Transfer in a Satellite

In looking at heat transfer in a satellite, one must determine how heat enters the system and how heat exits the system. These are discussed in turn below.

#### 6.2.1 Sources of Heat

In general, there are three methods by which heat can be transferred from one location to another: conduction, convection, and radiation. In addition to these methods of heat transfer, heat is also generated through resistive heating in electronic components. In a satellite, due to the lack of an atmosphere, convection does not occur. Each of these sources of heat is described in the following paragraphs.

#### Radiation

Materials with ideal radiative properties are termed blackbodies, and for these materials heat transfer by means of radiation is governed by the equation

$$Q = \sigma A T^4$$

Where Q = heat transferred (Watts)

A = area of object receiving heat (square meters)

$\sigma$  = Stefan-Boltzmann constant =  $5.67 \times 10^{-8} \text{ W/m}^2/\text{K}^4$

T = absolute temperature of radiating surface (degrees Kelvin)

In order to account for the non-blackbody material properties of the absorbing surface, one must include the factor  $\alpha$ , or absorptivity, to the above equation, yielding:

$$Q = \alpha \sigma A T^4$$

Since the interior of a satellite is essentially a closed cavity, the thermal radiation inside the satellite can accurately be modeled as

radiation from a blackbody, the heat absorbed by an object can be determined from the above equation if the objects surface area and absorptivity are known.

#### Conduction

The conduction of heat into the HTS package occurs in two ways: through the connectors mounting the package to the wall of the satellite, and through the signal-carrying cables that connect the HTS components to the rest of the signal processing components.

For steady state, one-dimensional conditions, heat transfer through a material is governed by the equation:

$$Q = kA \frac{dT}{dx}$$

In this equation, Q is the rate of heat transfer, A is the cross-sectional area of the material through which heat is flowing, k is the conduction coefficient of the material, and dT/dx is the temperature gradient in the direction of interest. In a homogenous material at steady state, the temperature gradient has a constant value. Thus dT/dx will equal (T2-T1)/L, where T2 and T1 are the temperatures at the end of the material, and L is the length of the material.

#### Generation

The final source of heat is energy dissipated from electronic components. This heat generation is due to the flow of electrical current through resistive elements in the electronics. The heat generation is determined by looking at the difference in the signal's input and output power. Since signal strength is quoted in decibels (dB), it is necessary to first convert dB to Watts. This conversion is carried out as follows.

The strength of the signal reaching the satellite's receiving antenna is given in dBm. "dBm" is the signal's power in decibels, referenced to 1 milliwatt, as shown below.

$$dBm = 10 \times \log\left(\frac{\text{signal power}}{1mW}\right)$$

The signal strength in decibels at the multiplexer's input can be determined by adding the gains and subtracting the losses prior to the

multiplexer. Thus the signal power in dBm can be determined before and after the multiplexer if the insertion loss of the multiplexer is known. These decibel numbers are converted to power using the equation above, and the heat generated in the multiplexer is then determined.

#### 6.2.2 Removal of Heat

On current satellites, heat is removed passively. Physical structures called radiators are constructed that radiate heat out into space, thus cooling the satellite. Unfortunately, these radiators have relatively low heat removal capabilities, especially at low temperatures, since the amount radiated is a function of the temperature of a radiator raised to the 4th power.

The limitations of passive cooling devices imply the need for an active device: a cryocooler. A cryocooler works like a small air conditioner, removing heat from one location at a low temperature and exhausting this heat, plus the additional heat required by the laws of thermodynamics, at a higher temperature. The use of cryocoolers allows the removal of heat from HTS components at their low temperatures, and the radiation of this heat away from the satellite at a higher temperature where radiators are more effective.

### 7. CRYOCOOLER

As mentioned, some means of active cooling is required in order to reduce the temperature of the HTS components to operational levels. This active cooling comes in the form of a cryocooler. A cryocooler is a refrigeration device that is used to create the very cold temperatures necessary for superconductivity to occur. In order for a cryocooler to be suitable for applications in space, it must meet certain criteria. These are discussed in more detail below.

#### 7.1 Current Cryocooler Technology

The rapid increase in the number of applications for cryocoolers has been the impetus for the recent developments in cryocoolers. The main issues associated with cryocoolers are: reliability, efficiency, heat

capacity, size, weight, vibration, power, temperature stability, and cost.

There are currently five common types of cryocoolers under development. Each will be discussed in the following paragraphs.

### Stirling Cryocoolers

Stirling cryocoolers are inherently rugged and relatively easy to miniaturize. They also offer very high efficiencies, on the order of 85%. Dual opposed piston motion, or passive/active balancers can minimize vibrations. In addition, these cryocoolers are capable of operating over a wide temperature range, from ambient to below 35K. However, they tend to suffer from reliability limitations. A typical Stirling cycle cryocooler is shown below.

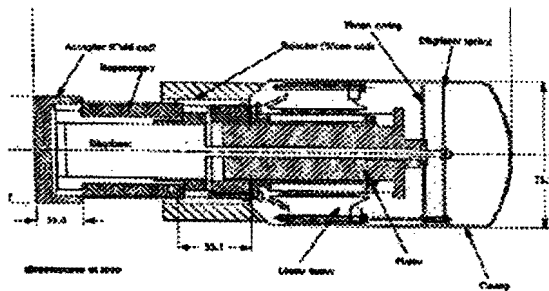


Figure 4 Stirling Cycle Cryocooler

The Stirling cryocooler works by establishing out-of-phase pressure and mass flow waves. First, the gas is compressed in the compression space by the piston. This compressed gas then travels through the regenerator, which is typically a stack of screen disks. As the compressed gas travels through the regenerator, the total volume is kept constant by movement of the displacer. The regenerator serves as a heat exchanger to remove the heat contained in the compressed gas to the outside as the gas travels to the cold end. Once the gas has reached the cold end, it is allowed to expand, which extracts heat from the cooled area. Finally, the gas is transferred back through the regenerator to the compression space, and a cooling cycle is complete. In practice, there is not a single volume of gas moving back and forth in the cryocooler; rather, out-of-phase pressure and mass flow waves created by the moving piston establish the cycle described above.

Most of the recent developments in Stirling cryocoolers have been aimed at

improving the reliability of the devices. Lifetimes of around 15,000 hours (due to wear at the linear compressor) are routinely reported in research.

### Pulse Tube Cryocoolers

In 1963, Gifford and Longworth discovered a new refrigeration technique that they called pulse tube refrigeration. There are three types of pulse tube refrigerators: basic, resonant (or thermoacoustic), and orifice. The orifice type is the only one that can achieve temperatures below 120K, and thus is the only one to be considered here. At a glance, it has the following advantages over the Stirling cooler: increased reliability, lower cost, lower vibration, less electro-magnetic interference, better launch survivability.

The pulse tube cryocooler is thermodynamically similar to the Stirling cooler; the refrigeration cycle is the same as that above. The difference is that in a pulse tube cooler, the displacer is replaced by a fixed geometry, the design of which results in the out-of-phase pressure and mass flow waves required for refrigeration. Figure 5 shows a schematic of a pulse tube cryocooler.

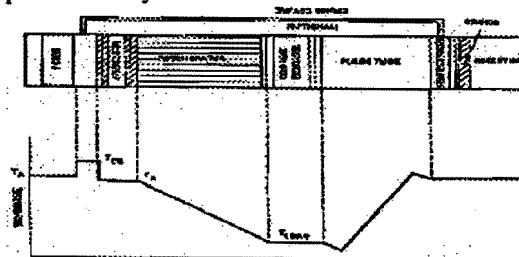


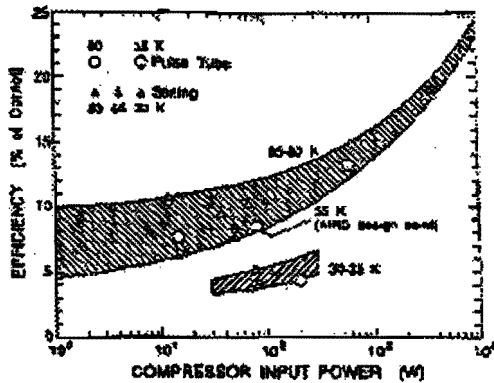
Figure 5 Pulse Tube Cooler Schematic and Temperature Distribution

The advantage of the pulse tube cryocooler is that there are no moving parts at the cold end of the cooler. Rather, the pulse tube section of the cooler is connected to a reservoir through a small orifice. This unit is tuned such that the desired performance of the cooler is achieved. It can achieve temperatures below 80K in a single stage.

The efficiency of the cooler suffers however as the expansion work is dissipated in the orifice instead of being recovered as in the Stirling cryocooler. Figure 6 compares the efficiency of pulse tube and Stirling coolers over a range of temperatures as a function of compressor input power. Here the shaded band denotes the typical efficiency of Stirling Coolers,



and the white circles denote recent pulse tube efficiencies. This demonstrates that pulse tube cooler technology is nearing Stirling levels of efficiency.



**Figure 6 Efficiency of Pulse Tube Refrigerators Compared With That of Stirling Refrigerators**

#### Joule-Thomson Cryocoolers

A two-phase cryocooler, the Joule-Thomson boasts good ease of integration, improved temperature stability, reduced weight, and reduced power consumption. The closed-cycle Joule-Thomson cryocooler has suffered from both low efficiency and poor compressor reliability. Although there is current research into the use of mixed refrigerants to improve expansion efficiency, and the use of sorption compressors to minimize moving parts, it seems they are not yet suitable for our application.

#### Brayton Cryocoolers

Brayton coolers do not suffer from the same expansion inefficiencies as Joule-Thomson cryocoolers. The use of a turbo-expander results in high reliability and very low vibration (from its high operating frequency). They are physically very small, and relatively light. They make very good candidates for space applications; however, there is insufficient development at this time to provide a suitable assessment.

#### Gifford-McMahon (GM) Cryocoolers

Gifford-McMahon (GM) cryocoolers use oil-lubricated compressors modified for use with helium gas. The coolers are relatively cheap, and are mostly used as two stage coolers to achieve temperatures around 4K. They are

not very efficient, unless coupled with a Joule-Thomson stage, which boosts its Carnot efficiency from 1.6% to 7.1%.

A further GM application is the construction of a Boreas cryocooler, which consists of a three-stage GM cryocooler. This is optimized for small, efficient operation at 4.2K. This report will not be considering the GM cooler, as the GM cooler is not suited to our particular application as we only require cooling down to 70K.

### 7.3 Selection Criteria

As when analyzing signal performance, the evaluation of cryocoolers requires metrics by which cryocoolers can be compared. These metrics are described below.

#### 7.3.1 Fixed Criteria

The following three criterion should be used to select the cryocooler: space qualification, operating temperature, heat load. All candidate coolers must meet these criteria.

#### Space Qualification

The cooler must be either space qualified, or space qualifiable. It must be able to withstand the vibration of launch, operate under conditions of no atmosphere and no gravity.

#### Operating Temperature

The cryocooler will be required to cool the HTS components from ambient temperature to their operating temperature after launch and deployment of the satellite. Thus the cryocooler must be capable of rejecting heat at the ambient temperature of the satellite and cool to the HTS temperature of 70K.

#### Heat Load

The cryocooler must be able to support the cooling load presented to it. The calculation of this cooling load was discussed in Section 6. Heat load is the steady-state cooling load that the cryocooler will face during its lifetime. This is a particularly critical area that results in high differentiation between available coolers during selection.

### 7.4 Secondary Criteria

Criteria which have trade-offs associated with them are: power consumption (efficiency), mass, size, and lifetime (reliability).

### Power Consumption

All of the power used to operate a satellite's systems comes from its solar cells. These solar cells are very expensive in terms of size, weight, and system complexity. Any additional power required to run the cryocooler would come at the high cost of additional solar cells. Thus, for a given cooling load, it is desirable to have as efficient a cryocooler as possible in order to decrease power consumption.

Input power is the leading driver of mass penalties. The greater the input power, the more massive the cryocooler. Power directly sizes the heat rejection, heat transport, cable systems, structure, and cold plumbing systems. A study performed on a large database produced the generic result of 0.375 kg/W as a system penalty. However, power efficient coolers (low power, high mass) have lower system penalties than mass efficient (low mass, high power) coolers.

### Mass

The additional mass of the cryocooler is somewhat offset by the reduction of mass that results from the replacement of the large waveguide filters with smaller HTS filters.

Mass of the cryocooler implies an additional cost of the support structure of the cooler, the cryogenic heat transport or cold plumbing between the cryocooler and the cooled instrument, the heat rejection system including transport and radiator, and the cryogenic thermal insulation or isolation.

### Size

The cryocoolers are generally physically large devices. A minimization in footprint would result in ease of adding redundant systems, and ease of design and placement.

### Lifetime (reliability)

The final consideration in evaluating cryocoolers for space applications is the lifetime of the units. Obviously, maintenance is impossible once a satellite has been put into orbit. Thus it is necessary that a cryocooler have a lifetime greater than or equal to the desired life of the satellite, which for most communications satellites is approximately 10 to 15 years. The fact that the latest cryocooler designs are only a few years old makes

accurately estimating their lifetimes difficult. Rates of failure are indeterminate as well. In order to obtain a usable estimate of cryocooler lifetime, one must look at the lifetime estimates provided by the manufacturers of the cryocooler and compare this to the expected lifetimes of the individual components contained in the device.

### Discussion

Through the metrics, a list of cryocooler criteria may be developed to aid in selection of a suitable cooler. Industry and research both point to the outstanding characteristics that Pulse Tube and Brayton coolers offer to satellite applications.

One of the major stumbling blocks with cryogenic coolers is the low expected lifetimes. The overwhelming mode of failure in pulse tube coolers is at the compressor. Advanced compressors, being researched by Mechanical Technology Inc. (MTI) under the U.S. Air Force (Phillips Laboratory), are expected to have lifetimes in excess of 100,000 hours. Some groundbreaking research has recently been performed at the Los Alamos National Lab in substituting the last moving part of the pulse tube cooler with a thermoacoustic engine. These engines produce pressure oscillation from heat in an acoustic standing wave resonating at the frequency of the desired pressure oscillation. This replacement would result in a dramatic increase in reliability.

## 8. Physical Properties

Having established the selection of HTS components to achieve maximum signal benefits, and selected a cryocooler that will cool the components to superconducting temperatures, it is now possible to evaluate the physical properties that a HTS system engenders.

### 8.1 Overview/Motivation

Critical to the feasibility of the proposed system are the physical restrictions of mass, DC power consumption, and physical size. An overrun in any of these three fields may prevent the launch of the satellite.

In order to provide readily accessible results, it is not necessary to examine any portion of the system that remains the same in HTS configuration. The approach is to take the

deltas or differences between the two systems, providing an 'at a glance' result as to what happens after the change for each criterion.

#### Mass

The mass of the system is one of the main determinants of launch cost, with the high cost of propellants being the cost driver.

#### Power

All DC power is derived solely from the solar panel array of the satellite. These solar panels provide power at the cost of their extra weight at launch time. The potential increase in power consumption may require additional solar panels, and is thus a critical feasibility issue.

#### Size

Finally, size is also an important issue, as it increases the complexity of layout of the electronics payload. It is possible to both evaluate the footprint and the volume of the additional components.

#### Discussion

Mass, size, and power consumption gains from using HTS components are likely to be overshadowed by the large size of the cryocooler system and its associated electronics. This point serves to underscore the importance of appropriate selection of a cryocooler, particularly if any form of redundancy in this system is being considered.

### 9. CONCLUSION

A methodology for quantifying the advantages and tradeoffs of a HTS transponder have been discussed in preceding sections. The final step is an analysis to determine if the advantages outweigh the tradeoffs. This analysis is based on the following factors:

- Communication system benefits
- Change in mass, power and size of the system
- Reliability

As discussed in Section 5, there is an important decision to be made with regard to which components benefit the most from cooling to superconducting temperature. There is no simple metric to quantify the gains and tradeoffs to formulate a recommendation. The decision must be based upon relative importance placed

upon each of the above factors, which of course will vary from satellite to satellite.

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