# Characterization of Cryogenic Flexible Transmission Lines Designed for the GUSTO IF Harness

Marko Neric, Hamdi Mani, Thomas Mozdzen, and Chris Groppi

***Abstract*—Cryogenic flexible printed circuit ribbons based on stripline transmission lines have been custom designed, fabricated, and characterized for an upcoming NASA Class-D balloon mission. The Galactic/Extragalactic Ultra-Long Duration Balloon (ULDB) Spectroscopic Terahertz Observatory (GUSTO) will make use of 8-channel flex ribbons to transmit Intermediate Frequency (IF) from 0.3-4 GHz while at cryogenic temperatures and in flight. In this configuration one individual flexible ribbon can replace up to 8 semi-rigid SS-SS coaxial cables that are 20 inches in length. The GUSTO focal plane array consists of 24 pixels that would otherwise require an equal number of coaxial cables. Similar performance can be achieved using only 3 sets of flex ribbons, each of which is comprised of two circuits in series. This will not only reduce the weight and form factor of the IF harness, but also provide improved thermal performance. The ground planes of the flex circuit have been reduced to minimize heat transfer into a cryogenic system which can extend mission lifetime by mitigating coolant boil off. Each channel of the flex circuit conducts a quarter of the heat that a coaxial cable would. To accommodate the unique design of the GUSTO cryostat three pairs of flex ribbons will be RF coupled to provide the necessary length and shape for routing between IF components. Flex circuits were designed with a staggered array of SMP type press on connectors instead of SMA which makes coupling 8 channels achievable in one easy maneuver. The circuits can be clamped together to prevent separation in flight or other high vibration conditions all in less time than it would take to install coax. All RF testing was done using a closed cycle vacuum cryogenic station with the test bed held at 20 K. Each pair of flex ribbons was thermally coupled to the 20 K stage. The flexible transmission lines showed an average insertion loss of 3.07 dB/ft at 5 GHz, while the industry standard SS-SS UT-85 coax loss is 2.80 dB/ft. The GUSTO IF system will use state of the art ASU cryogenic low noise amplifiers to more than make up for the higher insertion loss. Any future systems that can correct for, or accept the additional loss will benefit more from the other features of the flex circuit design. The custom made cryogenic flexible transmission lines are still the preferred method of signal transmission for applications that require complex routing, lightweight components with small form factor, easy assembly, lower heat transfer, and flexibility.**

***Index Terms*—RF, Cryogenics, Transmission Lines.**

## I. INTRODUCTION

THE intermediate frequency (IF) harness of the Galactic/Extragalactic Ultra-Long Duration Balloon Spectroscopic Terahertz Observatory (GUSTO)[1] has been designed, fabricated, and characterized. GUSTO is a NASA balloon mission that will observe THz signals from within the Milky Way and the Large Magellanic Cloud. GUSTO will have a 24 pixel focal plane made up of three separate 8 pixel arrays. Each array is housed inside the same vacuum cryogenic system. The IF harness must transmit the signals of 24 independent pixels from within the cryogenic station to an outside interface.

Two choices for a harness were considered. The first was 24 sets of stainless steel - stainless steel (SS-SS) semi rigid coaxial cables. The benefits of semi-rigid coax include their well characterized performance, and their repeated use in commercial and space applications which gives coax a long heritage. Stainless steel is often chosen for transmission in and out of vacuum cryogenic systems due to its low thermal conductivity despite more signal loss than alternatives. The drawbacks to using coax become more evident as the pixel count in an instrument increases. The resulting increase in pixels requires an increase in transmission lines. For a system using coax this means each cable must be individually installed to the same specifications. This increases the risk of individual failure while also increasing the overall form factor of the harness and installation time. The industry standard SS-SS semi rigid coax is UT-085 which has an outer diameter of 0.087". Smaller cables than this are available but tend to be more fragile and higher in loss. Semi-rigid cables can be more difficult to route through a cryogenic system since they cannot accommodate paths with sharp turns or some narrow spacing. It often becomes necessary to install hermetic vacuum feed-through adaptors at several points within a cryostat to complete the harness which further increases the number of coax lines and potential areas of failure.

The second option considered was to make the IF harness using ASU cryogenic flexible transmission line ribbons[2]. The ASU flex ribbons use a stripline design as a base and can incorporate several channels in a single ribbon. A prototype 8-channel ribbon was designed previously with the GUSTO mission in mind and to test key features that would give the flex ribbons an edge over coax. The prototypes were 8-channel circuits in either a straight ribbon or a curved ribbon to test the effects of in-plane turns on the individual channels. Each prototype had a width of 1.1", and a total length of 20". The ribbons were populated with press on connectors that allow fast an easy connections. They can be custom designed to meet the specific routing needs of the mission without significant signal loss. The prototypes achieved similar RF performance to coax, and transfer significantly less heat into the cryogenic system which has a limited supply of coolant. The drawbacks to this approach are that the best RF performance is achieved when the ribbon is at cryogenic temperatures, and that is still slightly higher in signal loss than SS-SS coax. Low noise amplifiers can be used to boost the IF signals to make up

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for the slightly higher loss of the flex ribbons. The custom ribbons can meet the unique routing needs of the GUSTO mission without requiring alterations to the cryostat itself. For the above reasons the decision moving forward was to build a harness out of flexible ribbons.

## II. DESIGN

The limiting size of the individual flexible ribbons is the size of the panel which the flexible printed circuit material is made from. These have a working area of about 18" x 20". To mitigate cost it is advantageous to fit as many flexible ribbons on the same panel as possible. The average length of GUSTO's IF bands is 3.30 feet and each band takes a different path inside the cryostat. Due to these constraints a single ribbon could not comprise the entire harness. Instead each of the three IF bands is made of two flex ribbons. One ribbon designated a "cold" circuit because it is held closest to the 20 K stage of the cryostat, and the other known as the "warm" circuit which would interface with the outside of the cryostat. The cryostat designed for the GUSTO mission had a particularly challenging path the IF harness needed to go through. The flexible transmission lines were custom designed with short in-plane turn radii (inside radius no less than 1"). This resulted in 6 uniquely shaped ribbons. Figure 1 shows the GUSTO cryostat and the installed IF bands. Figure 2 shows the reference design for one of the "cold" circuits.

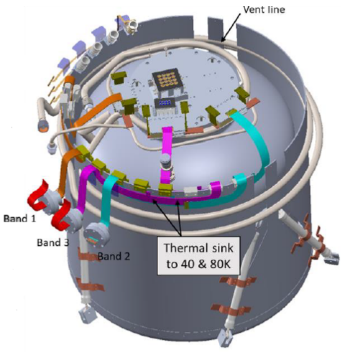

Fig. 1. This image of the GUSTO cryostat demonstrates how complex the routing of the IF harness will be. The custom designed flex circuits are shown as bands 1-3. Flexible transmission lines simplify the install process since the ribbons snap together to complete 8 signal paths whereas the same system would have needed a minimum of 24 discrete semi-rigid coaxial cables for the task.

For each band the ribbons required two points of contact with the cryostat. This is made possible by small 0.50" x 0.50" copper heat-sinking tabs that can be directly soldered to. The operating temperature for the GUSTO mission is a 20 K - 300 K gradient and using both heat-sinking tabs helps maintain this. Each ribbon is an eight-channel transmission line with the connections staggered so they can connect to one another. DELTA Electronics smooth-bore SMP press-on connectors were chosen because of their small form factor and low retaining forces. Limited or full detent versions may also be used, however their higher mate/de-mate force may reduce the lifetime of a ribbon after repeated use. The eight smooth-bore connections are sufficient to hold the flex circuits together, however a clamp may be used for added security. Fastener tabs like the one shown in figure 2 may be used for this purpose.

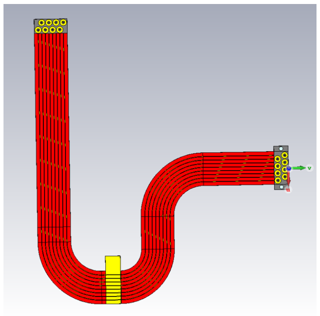

Fig. 2. Drawing of an individual custom flex circuit cable. There are two per band, and three bands total within the IF harness. Each circuit has a unique shape in order to facilitate the complex routing within the GUSTO cryostat. Visible in this drawing is a small heat-sinking tab that can be directly soldered to. Each band has two tabs that can be attached to separate stages of the cryostat for temperature control. Also visible are fastener holes used to secure the circuit on one end. Copper is shown in yellow, the kapton substrate is in red, and the top layer of soldermask is shown in grey. The yellow copper stripes that follow the path of the substrate are copper ground planes necesary for stripline transmision. These are not the signal traces themselves. The signal traces are burried under the substrate layer.

The copper grounding planes on top and bottom of the flex circuit are required by the stripline. The overall metal content on both sides of the ribbon has been reduced to narrow 0.015" strips. This pattern lets the individual channels behave as a stripline and reduces overall heat transfer in and out of the system. Copper has a high thermal conductivity of 401 $WK^{-1}m^{-1}$ compared to that of stainless-steel which is 16.3 $WK^{-1}m^{-1}$. Reducing the metal content of the flex ribbon drastically changes the cross sectional area of conducting metal. The result is that a single channel of the flex ribbon conducts 25% of the heat a UT-085 SS coax cable would.

The ribbons can be bonded to custom made vacuum flanges to break out of the cryostat. Prototype circuits were potted directly to modified Aluminum KF flanges using commercial scotch weld epoxy adhesive. The adhesive can be applied directly to to the circuit. As mentioned above and as shown in Figure 2, there is a reduced copper ground plane on top and bottom of the flex ribbon. This exposes the layer of kapton underneath. Bonding the ribbon to a vacuum flange over the substrate has been tested and shows no degraded performance. The aluminum flanges were helium leak checked to test their vacuum. No leaks were detected. The flanges were then thermally cycled, and leaked tested again with no leaks detected.

The flex ribbons designed for the GUSTO mission had a solid copper plane where the vacuum flange was to be potted. The vacuum flange was to be a modified stainless-steel CF flange commonly used in high vacuum instruments. The first set of "warm" circuits were bonded to the CF flanges and vacuum tested. No leaks were present at the time of the initial leak check. The circuits were than thermally cycled for a temperature range of -40 C to +60 C for a total of six cycles. The bonded circuits were then leak tested again to make sure the adhesive held together. This time unfortunately two out of the three circuits registered an air leak above tolerance. The leak occurred at the interface between flange and adhesive.

A second set of modified CF flanges were made and this time the surfaces were prepared differently before bonding. The flange was bead-blasted to give it an abrasive surface that the scotch weld might better adhere to. Industrial grade chemical solvents were used to clean the CF flange of any machine oils or other contaminants that would prevent complete adhesion. The CF flanges were also cleaned using mineral spirits and isopropyl alcohol in a sonic bath. Test circuits were bonded to the cleaned flanges. Initial leak testing found no leaks. The flanges were thermal cycled and tested again, just as before, two out of three flanges were observed to leak. The leak was again detected on the interface between flange and adhesive. The flex circuit itself is not believed to be the source of the leak.

It is unclear whether or not the leak is a result of the thermal cycling method (i.e. time dependence of thermal cycles) or if the chosen adhesive does not retain its bond with stainless-steel surfaces due to a mismatch in expansion coefficients. Aluminum flanges have not had any leaks. Due to costs of aluminum CF flanges to replace the stainless-steel ones for GUSTO, and the time constraints of the mission, an alternate break-out scheme was designed. A CF flange with 8 hermetic feed through adapters will be used as the outside interface. The flex ribbons will reach this flange and a series of short coax lines will serve as the interconnects between flange and ribbon.

The boards were designed at ASU and fabricated by Coast-To-Coast circuits. The SMP press-on connectors were assembled and DC tested at GMA Manufacturing. Cryogenic and RF testing was done at ASU.

## III. RESULTS

A closed cycle vacuum cryogenic 10 K test bed was used to characterize the IF harness. All RF measurements were done using a Rhode & Schwarz ZVA 24 Vector Network Analyzer (VNA) that was certified calibrated and following a pre-approved test plan. The VNA test port power was set to 0 dBm, with 10x averaging and an IF frequency of 100 Hz. The measurement bandwidth was 0.1 - 6 GHz which encompasses the 0.3 - 4 GHz operating frequencies the IF harness will see during its mission. Due to the limiting size of the test bed only one band could be tested at a time.

The cryostat interface was a custom made bulkhead plate with four hermetic SMA feed-through adapters. Short mini circuits SMA-SMP UT-47 coax cables were used to transition from the bulkhead to the flex ribbon. Earlier tests were done using small flex ribbon segmants specifically made to serve as adapters for the flex circuit interface. The change to coax was done to better reflect the in flight conditions. These coaxial adapters were not heat-sunk and therefor closer to the ambient temperature outside the cryostat. In order to de-embed their effects from the flex ribbon room temperature measurement of the mini-circuits cables were recorded. The room temperature data was then subtracted from the cryogenic result at all frequency points. Four total bulkhead adapters were used in each measurement so all eight channels of the IF harness could be reached in a single cool-down. Measuring all eight channels at once saves time by reducing the number of cryogenic cycles per band. This also means that the environmental conditions inside the test bed remained unchanged for each ribbon.

The two flex ribbons of each band were fastened together using a clamp and then installed on the 10 K stage of the cryogenic test bed. One heat-sinking tab was thermally coupled to the 10 K stage. There was insufficient space to couple the second tab of any band and still be able to connect the flex ribbon to the cryostat output. This resulted in a much higher temperature gradient through the flex ribbon than the likely temperature profile it will have in flight. Thus all results presented are worse than expected for the actual mission. When the ribbon is fully installed a temperature sensor is placed in contact with the circuit at the heatsinking tab. Two resistor heaters were attached to the 10 K stage.

The test bed can reach $\sim$ 10 K temperatures in just under three hours. The system was run until a stable 10 K temperature was achieved, and the heaters were slowly dialed up so the cold plate temperature would stay above 20 K as is expected during the GUSTO mission. RF measurements were taken to test the signal transmission, reflections, and isolation or cross-talk. After a band was measured the heaters, and cryogenic station were turned off. The system was brought back to ambient room temperatures overnight without the use of heaters. Figure 3 is a plot of the average s-parameters of all three bands with an average band length of 3.3 feet.

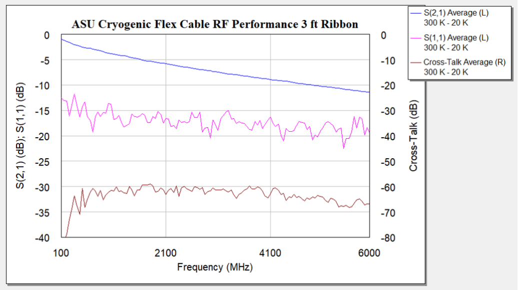

Fig. 3. Average s-parameters of all three IF bands are shown. The cryogenic testing was done with one end of the band held near 300 K and the other end held at 20 K. The average length of each band is 3.3 ft. At 5 GHz frequency the average loss per band is 3.07 dB/ft which exceeds design specifications. The cross-talk between adjacent channels is below -60 dB for nearly the whole bandwidth which also exceeds the specifications. There are no requirements for the reflection, however a value below -15 dB is usually desirable in RF applications.

The design specifications for the GUSTO IF harness were: IF bandwidth of 0.3 - 4 GHz, a signal loss no greater than 6.00 dB per 20 " length of harness at 5 GHz frequency, and 30 dB or more of isolation between channels. As shown in figure 3, the average loss of all three bands is 5.12 dB per 20" length. The measured cross-talk shows greater than 60 dB of isolation between channels for nearly the entire IF bandwidth. The circuits were measured from 0.1 - 6 GHz. Having met all specs the IF harness has been delivered for integration with remaining flight hardware.

## IV. CONCLUSION

The GUSTO mission will showcase several of the best features and abilities of the ASU cryogenic flex ribbons. Upcoming instruments that have a high pixel count, complicated or limited routing space, and have need of compact and lightweight solutions for their IF system will benefit from using the ASU flex ribbon. The lessons learned from the GUSTO mission will drive further innovation of the flex ribbon that already offers comparable performance to industry standard semi-rigid coax with other measurable benefits. The ASU flex ribbon exceeds all design specifications that were set for the GUSTO mission. They achieve a bandwidth that includes 0.3 - 4 GHz with an insertion loss at cryogenic temperatures that is 3.07 dB/ft and Isolation much greater than 30 dB over the entire bandwidth.

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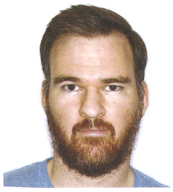

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