Development and Testing of an Innovative Two-Arm Focal-plane Thermal Strap (TAFTS)

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Abstract

Maintaining temperature stability in optical focal planes comes with the intrinsic challenge of creating a pathway that is both extremely flexible mechanically and highly conductive thermally. The task is further complicated because science-caliber optical focal planes are extremely delicate, yet their mechanical resiliency is rarely tested and documented. The mechanical engineer tasked with the thermo-mechanical design must then create a highly conductive thermal link that minimizes the tensile and shear stresses transmitted to the focal plane without design parameters on an acceptable stiffness.

This paper will describe the development and testing of the thermal link developed for the Portable Remote Imaging Spectrometer (PRISM) instrument. It will provide experimentally determined mechanical stiffness plots in the three axes of interest. Analytical and experimental thermal conductance results for the two-arm focal-plane thermal strap (TAFTS), from cryogenic to room temperatures, are also presented. The paper also briefly describes some elements of the fabrication process followed in developing a novel design solution, which provides high conductance and symmetrical mechanical loading, while providing enhanced flexibility in all three degrees of freedom.

Introduction

Air-borne and space infrared cameras require highly flexible direct cooling of mechanically-sensitive focal planes. A thermal electric cooler is often used together with a thermal strap as a means to transport the thermal energy removed from the infrared detector. In cooling focal planes, a cooling solution must be highly conductive, lightweight, and able to operate within a vacuum with no out-gassing. Furthermore, the device must also be highly flexible in all axes to accommodate adjustment of the focal plane while transmitting minimal force.

The aluminum foil-based thermal strap or link is a device that often meets the weight, conductivity, and flexibility requirements needed for thermal management of sensitive components. This type of thermal link consists of hundreds of aluminum foils carefully stacked and swaged into terminals [1]. While effective, traditional thermal straps are only highly flexible in one axis, moderately flexible in a second axis, and relatively stiff in the third axis. Stiffness and vibration transmission on a simpler thermal strap design was carried out by Kobayahsi and Folkman [2]. While the standard thermal strap is highly effective in cooling mechanical components, the flexibility requirements for the thermal strap are more stringent when it connects it to an adjustable focal plane, however.

Thermal Management of the PRISM Focal Plane

The Portable Remote Imaging Spectrometer (PRISM) is a pushbroom airborne instrument in development at the Jet Propulsion Laboratory (JPL), California Institute of Technology which will acquire data for the ocean science research community. The instrument will operate in the 350-1050nm range and a thermoelectric coolers and flexible thermal straps are used to maintain temperature stability and to keep dark current to manageable levels [3].

A two-armed thermal strap using three swaged terminals and a twisted section offers enhanced elastic movement, significantly beyond the motion permitted by existing thermal straps. This design innovation allows for large elastic displacements in two planes and moderate elasticity in the third plane. By contrast, a more conventional strap of the same conductance offers less flexibility and asymmetrical elasticity.

Key to achieving high conductance is the fabrication process which involves the cold welds that occur between swaged or crimped surfaces. Examination of this phenomena is available in the literature [4,5]. Mrokowski and Geckle, verify the transfer of conductor material at the swaged interface using Scanning Electron Microscopy (SEM) [4].

The two-arm configuration reduces the bending moment of inertia for a given conductance by creating the same cross-sectional area for thermal conduction, but with only half the thickness. This reduction in the thickness has a significant effect on the flexibility since there is a cubic relationship between the thickness and the rigidity or bending moment of inertia.

Mechanical Characterization

A CAD model of the two-arm focal-plane thermal strap (TAFTS) can be seen with the PRISM assembly model in Figure 1. The thermal strap must allow for translations in all three axes as depicted in Figure 2. Furthermore, a small amount of rotation in all axes must also be accommodated with minimal mechanical resistance, as the resulting stress is applied directly to the optics mount. In Figure 1, the optical detector mount can be seen with its adjustment screws. The thermal strap is mounted onto a TEC which is then mounted onto a conductive connector. This connector then mounts onto the straps terminal's positive XY plane (just opposite of the XY-face shown in Figure 2). Also in Figure 2, the Belleville washers-mounted screws can be seen. This mounting arrangement helps maintain contact forces between the thermal strap mount and the vacuum plate as the assembly is tested by cooling to cryogenic temperatures.

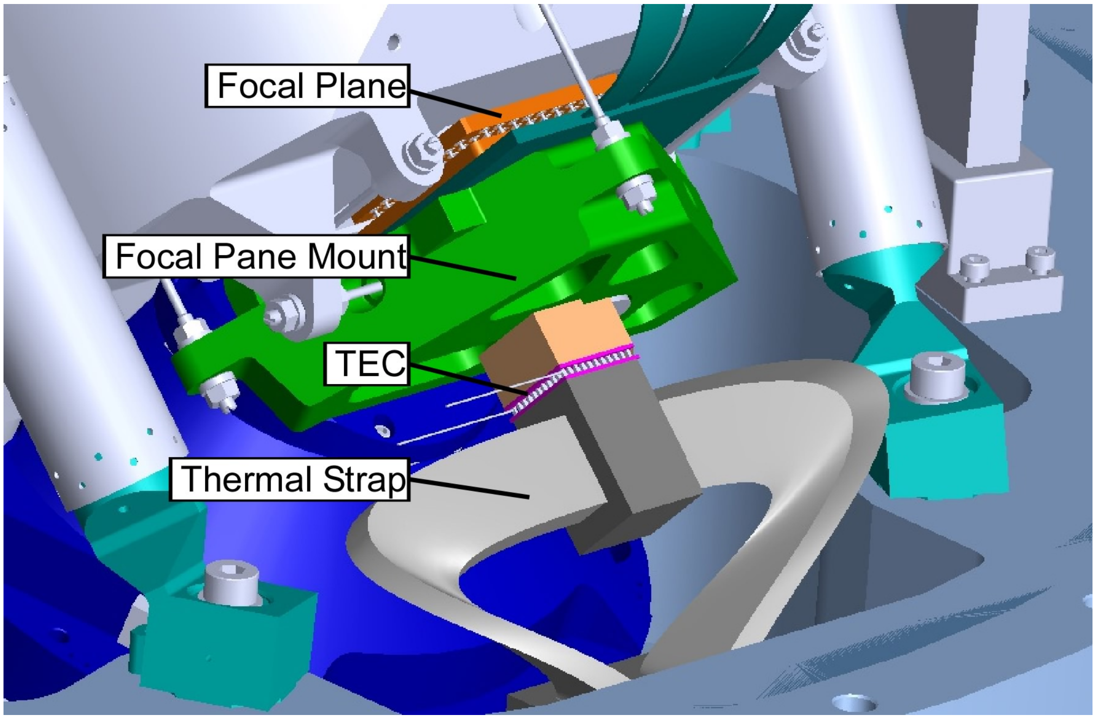

Figure 1: TAFTS and focal-plane mount assemble on a CAD molde of the PRISM instrument.

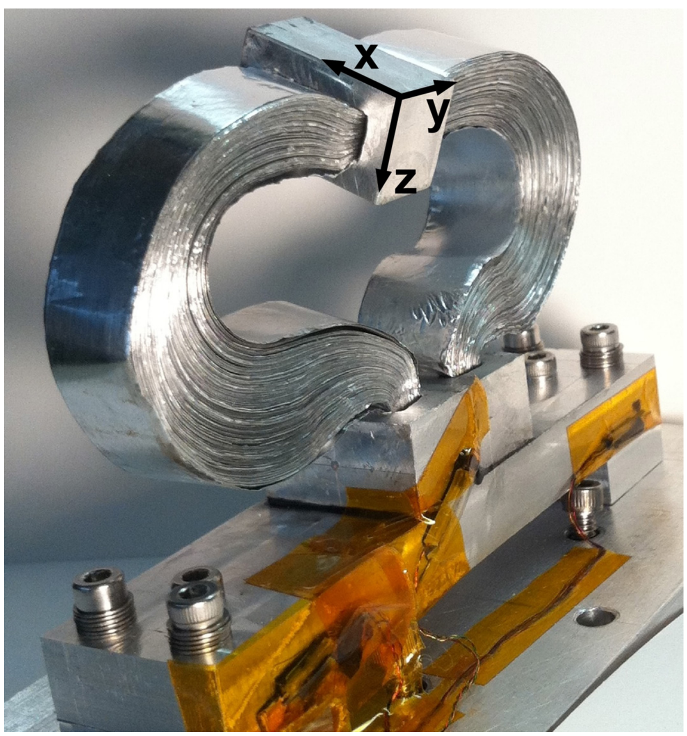

Figure 2: TAFTS co-ordinates on the center terminal showing the mounted silicon-diodes.

In order to resolve the amount of force imparted by the thermal strap onto the optical focal plane, the mechanical stiffness of the thermal strap must first be resolved to ensure that the adjustment mechanisms on the optical bench can resist the spring force in the strap. While qualitatively it appeared sufficiently flexible, obtaining elasticity data for the first time on the mechanical performance of a two-arm flexible thermal strap will be useful for future designs involving thermo-mechanically sensitive focal plane assemblies.

An experimental setup was devised to hold the thermal strap assembly such that a predetermined weight on a thread pulled on the strap in the coordinate axes shown in Figure 1. The displacement of the center terminal was then measured by hand using a caliper. To reduce the error associated with taking a measurement by hand, the measurement was taken three times independently an averaged. The thermal strap was then relieved of the weighted thread and allowed to return to its rest position bearing only its own weight. Finally the weight was reapplied a second and occasionally a third time; with application of the weight displacement was measured several times and averaged. The stiffness of the TAFTS was calculated and is plotted in Figure 2. The stiffness can be seen to be relatively constant (somewhat linear in the z-direction) through displacements typical for the application.

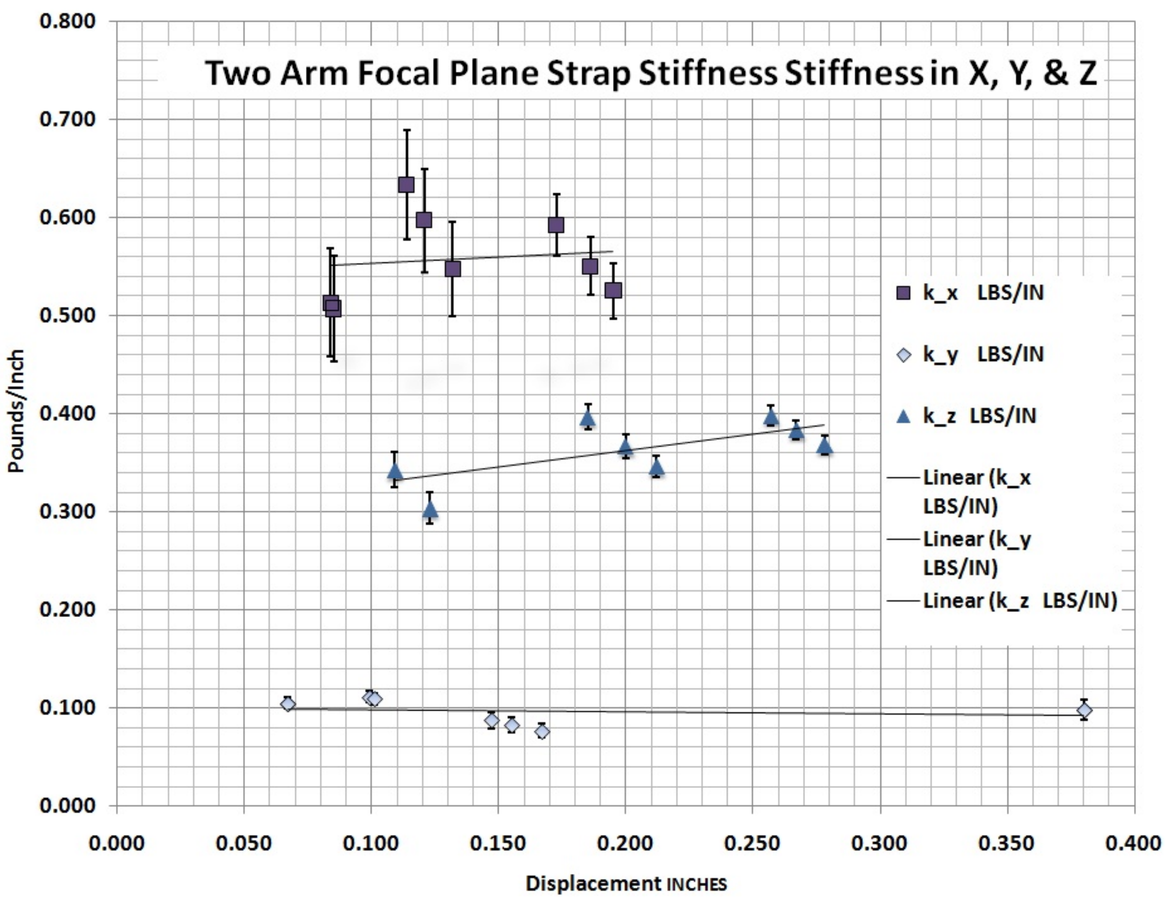

Figure 3: Experimentally determined elasticity data for the X, Y, and Z displacements for the two-arm flexible thermal strap design

The stiffness, and the relative error associated with its calculation from measured data, was calculated using both the accuracy of the scale (±0.01 grams) used to measure the test weight, and the accuracy of a hand caliper measurement, assumed to be within ± 0.020 inches. The error tolerance on the stiffness of the thermal strap is shown in the error bars in Figure 2. The relative error tolerance varied from ±2% in the most elastic direction, to ±11% in the stiffest direction. The more elastic direction measured had the largest displacement, which in turn reduced the relative error with the caliper hand measurement. While the precision could be better with a more elaborate setup, the goal here is to provide valuable engineering data to aid in future thermo-mechanical design of focal plane mounts and thermal control systems.

Thermal Characterization

The thermal strap terminals are made of Al 1100 while the foils are Al 1245; both alloys are greater than 99.0% aluminum. The alloys are extremely maleable and little springback is exhibited when compared to thermal straps made of Al 6061. The higher purity alloy makes this thermal strap more conductive, but also makes the foils more delicate and the fabrication somewhat more challenging as well. In fabricating the thermal strap assembly, the bottom-terminals were attached to each other as well as to the strap mount using Tra-bond 2151 epoxy mixed with 1-mil glass beads, which provide a constant bond-line thickness.

In thermally characterizing the thermal strap Lakeshore silicon diodes were placed at the center and bottom-left terminal. Silicon diodes were also placed on both edges of the strap mount, which is made of Al 6061. An aluminum cryocooler adapter plate was made to mate the thermal strap assembly to a Gifford-McMahon cryocooler at Jet Propulsion Laboratory, California Institute of Technology as shown in Figure 4.

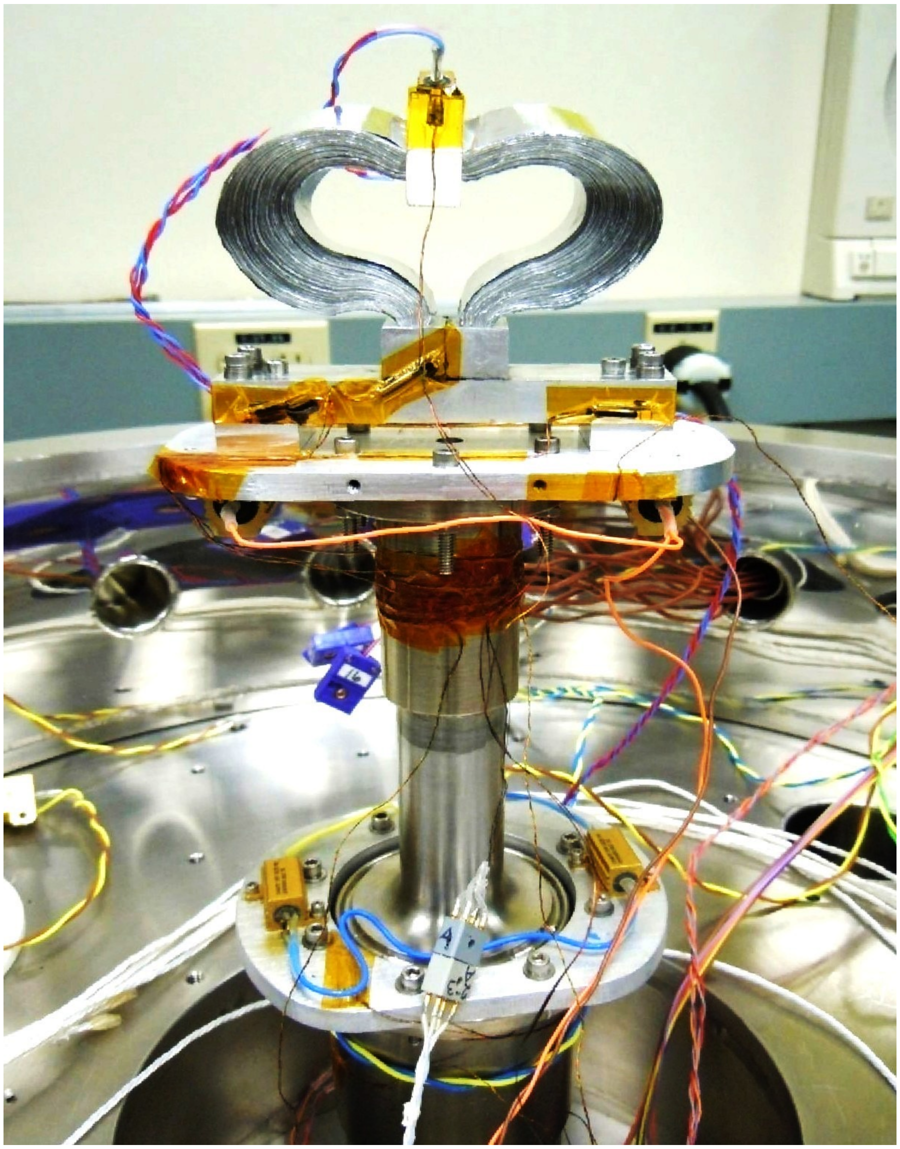

Figure 4: The TAFTS assembly mounted on a Gifford-McMahon cryocooler at Jet Propulsion Laboratory, California Institute of Technology

A resistor is the heat source and is epoxy mounted on the center TAFTS terminal. Manganin wires are used on the diodes to minimize thermal conduction and a four-wire technique is used on the resistor so to more precisely measure only the power disipated through the resistor and not the in the lead wires which extend beyond the vacuum chamber to the power supply.

Starting from at 23K, 4 Watts of heat were generated by the resistor. By controlling the temperature of the thermal strap mount and sequentially rising the temperature and waiting for steady state temperatures to be reached, the conductance of the mount was calculated. The average temperature of the strap rises until the final measurement is taken at room temperature. The thermal conductance of the TAFTS is measured and plotted in Figure 5, using diamond indicators and labeled “T. Strap Data”.

The thermal conductance of the TAFTS including the horizonal bar mount is also plotted using squares and labeled “T. Strap + Mount Data.”

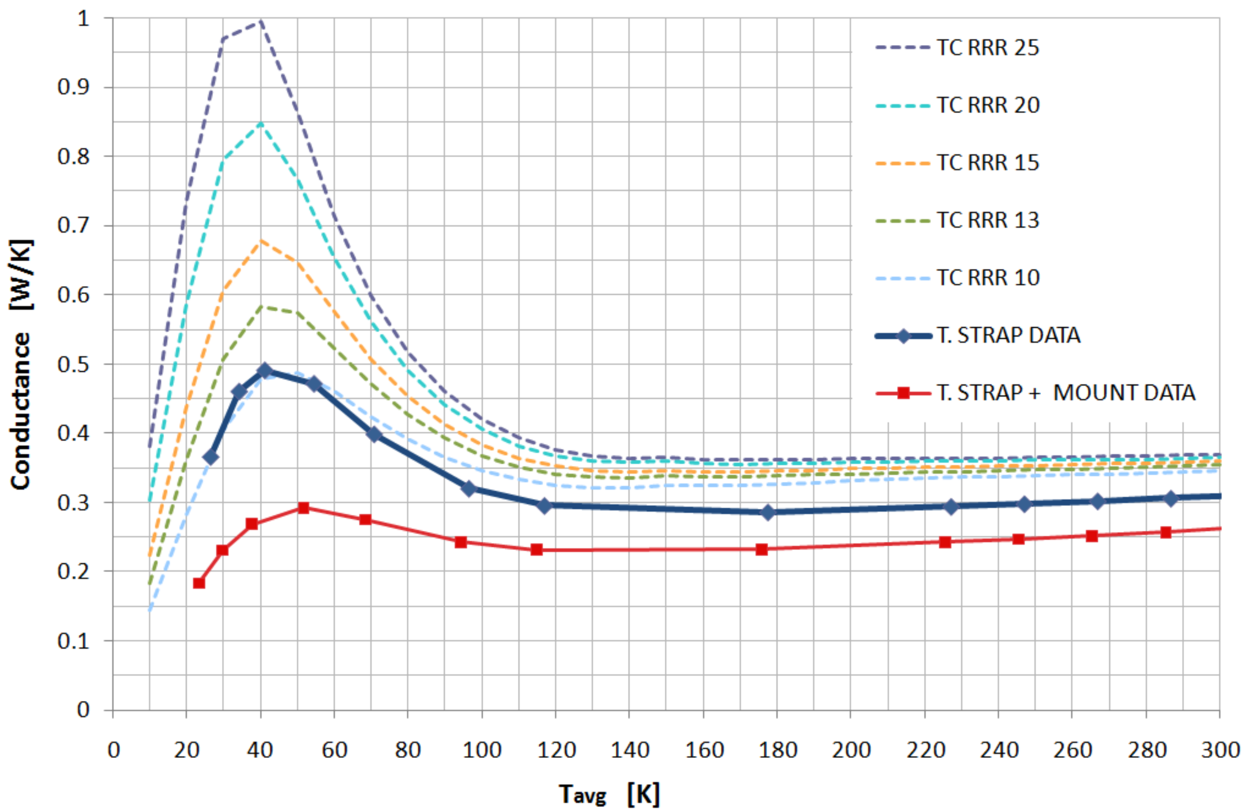

Figure 5: Experimentally determined elasticity data for the X, Y, and Z displacements for the two-arm flexible thermal strap design

The sensitivity of the thermal conductivity of aluminum is highly dependant on the purity. While the purity of the aluminum used here is not known, when the geometry is used to caluclate the conductance the theoretical conductance of the TAFTS can be calculated. Using data from CRYOCOMP [6] it seems like the effective relative resistance ratio (RRR) of the aluminum in the thermal strap assembly is somewhere in between 13 and 20, since the epoxy bonds and swaged connections all reduce the achievable conductance.

Conclusions

The novelty of the technology lies in the mechanical design and manufacturing of the thermal strap. The enhanced flexibility will facilitate cooling of mechanically sensitive components such as infrared focal plane mounts as discussed here. While the static elasticity is high, the dynamic response has not been studied and this too could be important when considering dynamic system loads. This development contributes to the field of thermal control and cooling of delicate optics. It is known to be especially important in the thermal control of optical focal planes due to their highly sensitive alignment requirements and mechanical sensitivity; however, many other applications may exist.

References

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Acknowledgments

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