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Development and testing of an innovative two-arm focal-plane thermal strap (TAFTS)

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A B S T R A C T

Temperature control of 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 time, cost, and their unique nature means that 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 and without data on the stiffness of previously implemented thermal links.

This paper describes 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 dimensions.

1. 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, flexibility, and reliability requirements needed for thermal management of sensitive components. This type of thermal link often 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 providing thermal control of mechanical components, the flexibility requirements are more stringent when the strap connects to an adjustable focal plane.

2. Thermal management of the PRISM focal plane

The Portable Remote Imaging Spectrometer (PRISM) is a push-broom 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 350–1050 nm spectral 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.

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Several thermal straps have been fabricated in-house prior to TAFTS, and stresses on the terminals have been controlled such that excellent consistency has been achieved in correlating analytical models to test data. Key to achieving high conductance is the fabrication process which involves the cold welding that occurs between swaged or crimped surfaces. Examination of this phenomena is available in literature [4,5]. Mroczkowski and Geckle, verify the cold welding phenomena by examining the transfer of conductor material at the swaged interface using Scanning Electron Microscopy (SEM) [4].

The two-arm configuration in TAFTS 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 of a conventional design. 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 in bending.

3. Mechanical characterization

A CAD model of the two-arm focal-plane thermal strap (TAFTS) can be seen within the PRISM assembly model in Fig. 1. The thermal strap must allow for translations in all three axes as depicted in Fig. 2. Furthermore, a small amount of rotation in all axes must also be accommodated with minimal mechanical resistance, as the resulting load is transmitted directly to the optics mount. In Fig. 1, the optical detector mount can be seen with its adjustment screws. The cold side of a TEC is epoxy bonded to the focal plane mount while the hot side is bonded to the center terminal of the TAFTS on the opposite *YZ* face as identified in Fig. 2. The Belleville washer mounted screws can be seen in Fig. 2. This mounting arrangement helps maintain contact forces between the thermal strap mount and the vacuum plate as the assembly is tested to cryogenic temperatures.

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 the TAFTS design 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 Fig. 2. 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 time and occasionally a third time. With each application of the weight a displacement was measured several times and averaged. All measurements were taken at room temperature which corresponds with the TAFTS application temperature.

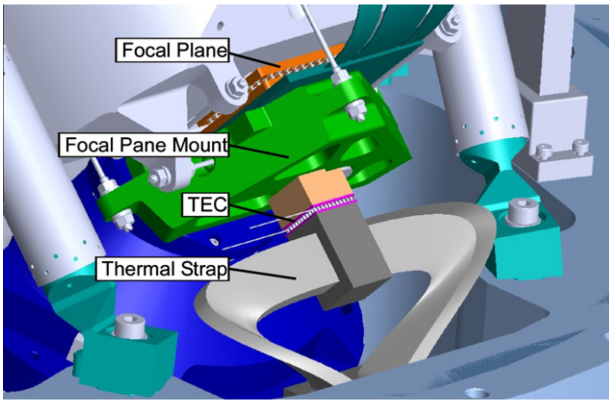

Fig. 1. TAFTS and focal-plane mount assembly on a CAD model of the PRISM instrument.

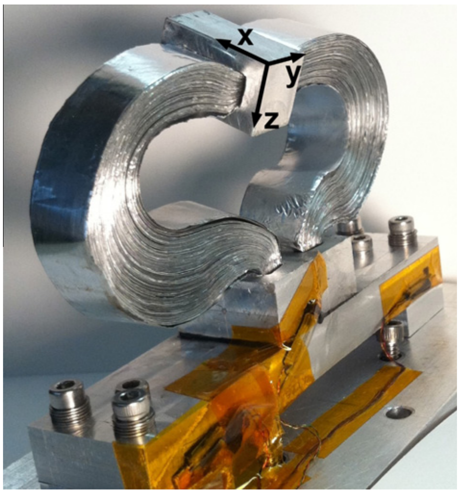

Fig. 2. TAFTS co-ordinates on the center terminal showing the base mounted silicon-diodes.

The stiffness of the TAFTS was calculated and is plotted in Fig. 3. A linear regression trendline (calculated in Microsoft Excel) shows the effect of displacement on the stiffness in each direction. The stiffness is fairly constant in the *x* and *y*-direction (somewhat linearly displacement-dependent in the *z*-direction) through displacements significantly exceeding those typical for the application.

The stiffness, and the relative error associated with its calculation from measured data, was calculated using both the accuracy of the scale used to measure the test weight (±0.01 g or $\pm 2.205 \times 10^{-5}$ LBS), and the accuracy of a hand caliper measurement, taken to be within ±0.020 in. The error tolerance on the stiffness of the thermal strap is shown in the error bars in Fig. 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 improved 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.

4. 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 malleable and much less 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 Stycast 2850 epoxy mixed with 3-mil glass beads (2–3% by weight), which provide a constant bond-line thickness to increase bond strength.

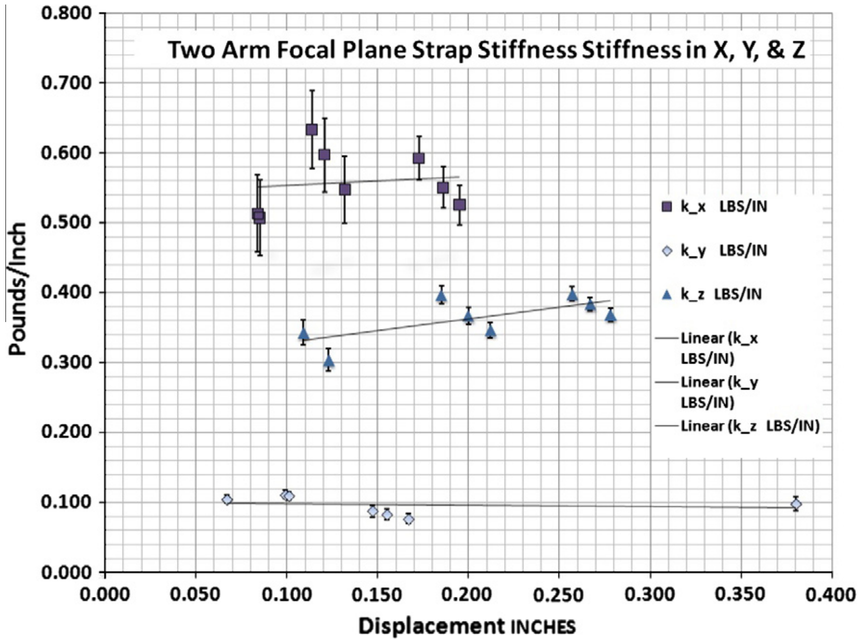

Fig. 3. Experimentally determined elasticity data for the *X*, *Y*, and *Z* displacements along with linear regression trendlines for TAFTS design.

The TAFTS is thermally characterized at cryogenic temperatures despite that in PRISM the TAFTS will only operate at room temperature. To monitor temperature Lakeshore silicon diodes were placed at the top-center terminal, bottom-left terminal, and 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 Fig. 4.

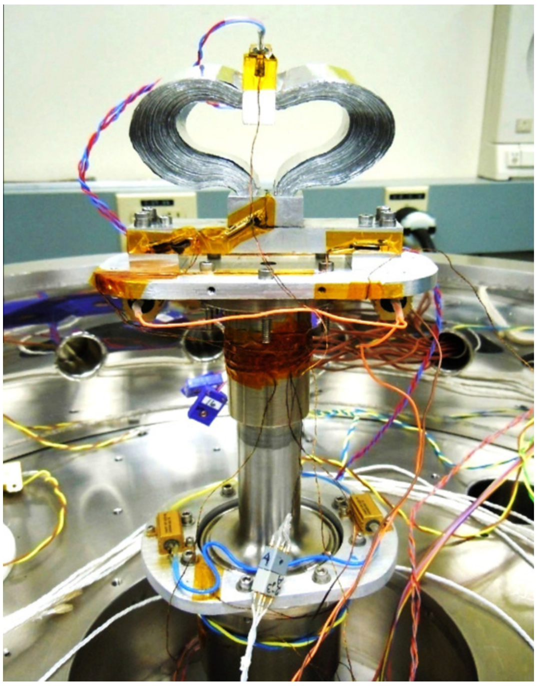

Fig. 4. The TAFTS assembly mounted on a Gifford–McMahon cryocooler at Jet Propulsion Laboratory, California Institute of Technology.

In the thermal test a resistor is used as the heat source and is epoxy mounted on the top 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 dissipated through the resistor and excluding the lead wires which extend beyond the vacuum chamber to the power supply.

Starting from a temperature of 23 K, 4 W of heat were introduced by the resistor. The conductance of the mount was calculated using the difference in temperatures between the top center terminal and the TAFTS bottom base terminals. The conductance was also calculated between the top center terminal and the strap mount after waiting for steady state temperatures to be reached. This process was repeated at increased temperatures and data was collected twelve times until reaching room temperature. The thermal conductance of the TAFTS is measured and plotted in Fig. 5, using diamond icons and labeled "T. Strap Data". The thermal conductance of the TAFTS including the horizonal bar mount which is also part of the PRISM assembly is also plotted using squares and labeled "T. Strap + Mount Data".

The purity of the aluminum used here is not known beyond the Al 1100 classification (>99% Al). The sensitivity of the thermal conductivity of aluminum is highly dependant on its purity, especially at cryogenic temperatures. A thermal resistance network model was created and analyzed for the TAFTS geometry. Aluminum thermal conductivity data was obtained from CRYOCOMP [6], which quantifies aluminum purity using the relative resistance ratio (RRR). The model along with temperature dependant thermal conductivity allows for the calculation of thermal conductance curves for the TAFTS geometry; these are plotted for various aluminum purities in Fig. 5. It should be noted that the conductance curves are idealized in that they only vary the purity of the aluminum. The curves do not include the resistance due to the epoxy bonds, interfaces, imperfections, and swaged connections, for this reason, the modeled curves overpredict the measured conductance for the TAFTS. Using data correlated from previous tests it is estimated that the RRR of the aluminum in the thermal strap assembly is actually between 13 and 20.

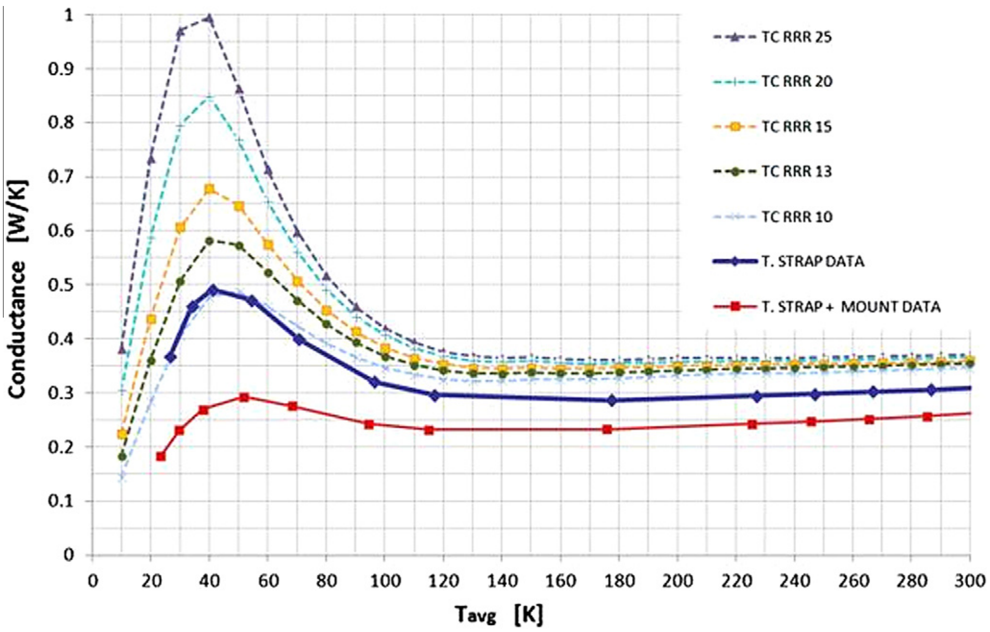

Fig. 5. Experimentally determined elasticity data for the *X*, *Y*, and *Z* displacements for the two-arm flexible thermal strap design.

5. 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 in some applications when dynamic system loads are significant. 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.

Acknowledgments

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