# Progress in broadband infrared nulling technology for TPF

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## ABSTRACT

TPF-I has set for itself a host of challenging technical milestones along its path to demonstrating the feasibility of infrared nulling for planet detection. Our activities are focused solely upon the experimental demonstration that deep nulling in the mid-IR over a wide bandpass can be accomplished. Specifically, we have the near-term goal of demonstrating a contrast of $10^{-6}$ at 10 μm with a 25% spectral bandwidth. To meet these goals, a host of supporting technical developments is required. These include: single-mode infrared fibers, bright infrared sources, laser path-length and tip/tilt metrology, and component testing under cryogenic temperatures. Progress in each of these areas of technical development will be reviewed as well as progress in meeting the overarching technical milestones.

**Keywords:** Single mode fibers, nulling interferometry, extra-solar planets, infrared sources, laser metrology.

## 1. INTRODUCTION

The number of known extra-solar planets discovered over the past decade has grown from zero to almost two hundred. To date, the vast majority of these have been discovered indirectly, primarily using the techniques of radial velocity and astrometry. The next step in this exciting exploration of our galactic neighborhood is the direct detection of planetary photons from these systems. The challenges here owe mainly to the large contrast ratio of the star and planet (~$10^9$ in the visible) as well as their small angular separation. NASA's Terrestrial Planet Finder Project (TPF) has set for itself the goal of meeting these challenges via two different techniques: coronagraphy in the visible part of the spectrum TPF-C, and nulling interferometry or TPF-I.

The challenges for an infrared nulling interferometry mission can be broken down into the ability to control systematic errors and the ability to deeply null over a broad spectral bandpass. This paper will describe the technology development that is a requirement for achieving deep and broadband nulls in the mid infrared independent of both the nulling architecture and the systematic errors.

## 2. Nulling Requirements

Our specific testbed requirements are driven entirely by a flow down of requirements that is driven by our core science objectives, namely number of target stars. This allocation of factors that contribute to the ultimate achievable null contrast is outside the scope of this paper. However, factors contributing to ultimate required contrast are shared between systematic errors and nulling error terms. Our testbed is then tasked with the experimental demonstration of deep nulls that is consistent with the objectives of the mission A discussion of the TPF-I testbed constructed to address the systemic effects of nulling interferometry will be covered in this series of talks.

Specifically, the achromatic nulling testbed must demonstrate non-cryogenic nulling to a level of $10^{-6}$ for a thermal source of bandwidth > 25% centered at 10 μm. This null is required to have a stability that is an order of magnitude greater. That is, in the frequency analysis of a nulling time series, all frequencies larger than 0 (DC in the time series) must be lower by a factor of 10.

Currently, we are pursuing several nulling architectures in the attempt to reach this milestone. These architectures are known as the phase plate, through focus and nulling periscope. The current status of each of these architectures is reviewed in another talk in this session by another engineer working on their development. More detailed information

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on the nature of those testbeds, their advantages and disadvantages, and their current results is reported there. For each of these architectures, the accessible nulls depths for each would similar and far from the requirement of a million to one where it not for the associated technology developments discussed below.

A review of the best broadband mid IR nulling result to date quickly conveys the need for the additional technology development.

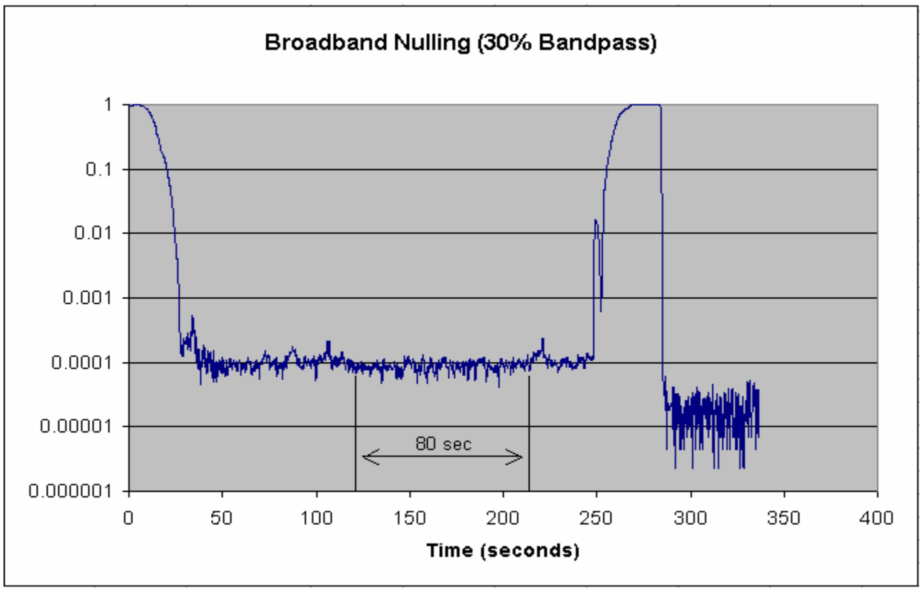

Figure 1. A demonstration of nulling at a contrast of 10K:1 using a broadband thermal source. The noise floor of the detection process is shown a the end of the data series. This data was taken with the single-glass phase plate architecture that has a limiting fringe contrast of ~30K:1 over this bandpass.

Figure 1 shows a scan of the null fringe from the constructive peak, to the destructive null and back again. In this measurements, it's possible to see the full contrast of the null measurement. If future nulling results are to improve upon what is shown above, it's apparent that increasing the dynamic range of the fringe measurement is the first order of business. In other words, if the nulling architecture were such that a much deeper null could be achieved, it would be challenging to measure a null greater than about 50K:1. Let's then consider ways that this contrast may be improved.

One method of increasing the contrast is to increase the amount of flux at the top of the fringe: put more light into the system. The thermal source used to take the data in Figure 1 is a standard IR source called glo-bar. It's a resistive element that has a blackbody temperature of about 1500 K. Unfortunately, as the temperature of a blackbody is increased, most of the gain in flux occurs at shorter wavelengths (near the visible part of the spectrum). The flux at a wavelength of 10 μm grows almost linearly with temperature. Thus, in order to increase the flux by a significant amout, say an order of magnitude, the effective temperature must increase by almost an order of magnitude: ~10,000K. This is hotter than the effective temperature of the sun. We will describe a source with these properties subsequently.

The noise floor of the detector is shown in end of the trrace in Figure 1. Clearly dynamic range is also improved by not only going higher with the source but by going lower with the noise floor of the detection process. The current detector is a single pixel HgCdTe cooled to liquid nitrogen temperatures. One of the most sensitive detectors currently available is a single pixel of a MidIR array. These arrays require a more complicated arrangement: liquid helium operating temperatures, low thermal background environments, and a set of read out electronics to allow slow, full-frame operation as well as rapid readout of a few pixels. Our design for such a system and its current status will be described below.

Wavefront errors of two varieties must also be addresses in order to reach deep nulls. The first is path length fluctuations that can be due to mechanical vibrations in the experiment, or differential index of refraction fluctuations of air in the two arms of the interferometer. These path length fluctuations can be monitored and stabilized with a laser metrology system that is independent of the nuller itself and that only acts to make rigid the path length differences at the point of recombination. Computing power has allowed the systems to mature to the point where closed loop operation of a few hundred hertz and dara recording at 10kHz is now feasible. We'll describe such a system.

Finally, the cumulative effect of surface figure errors throughout the beam train serves not only to degrade the imaging quality to also prevents complete interference at the point of recombination. This can be mitigated to some effect by securing optics of extremely good wave front quality, or by spatially filtering the wave front before detection. It's not as oversimplification to say that spatial filtering not only reduces the requirements on surface figure errors for the optics, but it actually makes nulling to deep levels possible. We would have no chance of reaching a deep and broadband null were it not for single mode optical filters (fibers). We will describe our current answer to this vexing fact.

## 3. Supporting Technologies

### 3.1 Argon Arc Source

As mentioned previously, for a blackbody radiator, going hot is the only way to get a sufficient quantity of 10μm photons. The source we chose to develop was based upon the work of very similar source at NIST. Typically, arcs are quite bright in the visible portion of the spectrum, however at 10 um, the source is not optically thick. However, a design whereby it's possible to look along the length of the arc increases the optical depth and emissivity.

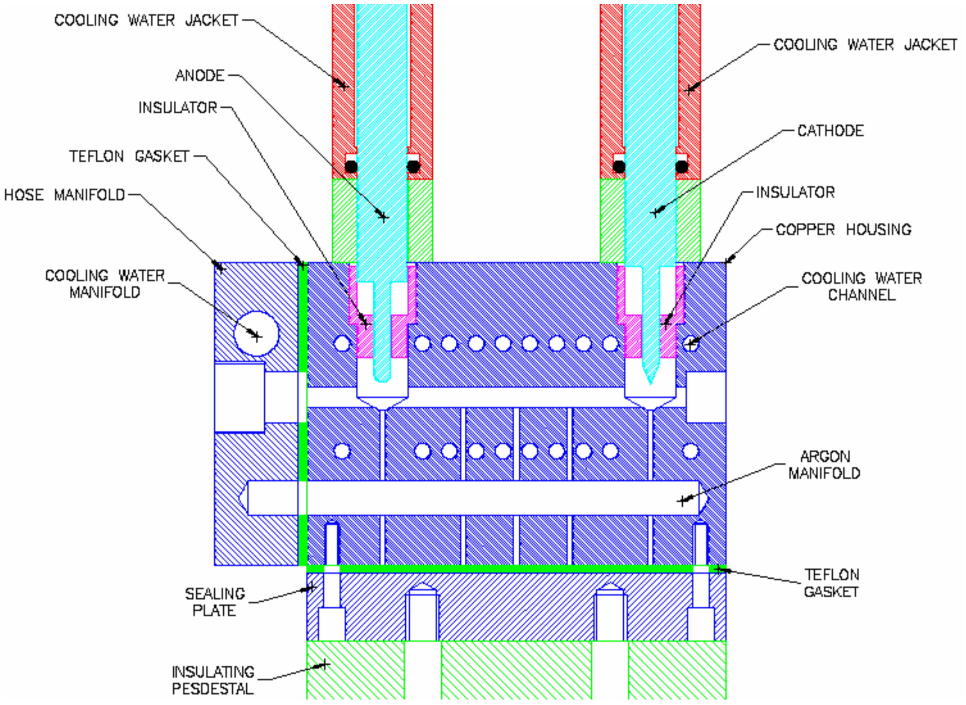

Figure 2. A illustration of the arc source used in our experiments. Light is emitted from the front and back of the source. The source enclosure and the spherical retro-reflector is not shown.

That is how our arc source was constructed. Our design made slight improvements of existing designs by improving the flow through the housing, active cooling of the electrodes and a better manifold for the argon gas. We also employ a few additional safety features such as a temperature sensor on the body of the source, a water flow meter for the supply coming from the chiller. Both of these are tied to the electrical interlock such that a failure of either will shut the current source down. The system is also enclosed with a housing that makes accidental shorting of the electrodes virtually impossible. The system readily strikes with a tungsten striking rod, similar to those used in welding applications. At peak operating conditions the systems consumes 8kW of electrical energy steady-state. A photograph of the source is shown in Figure 3 and a comparison between the arc source and the ceramic source is shown in Figure 4.

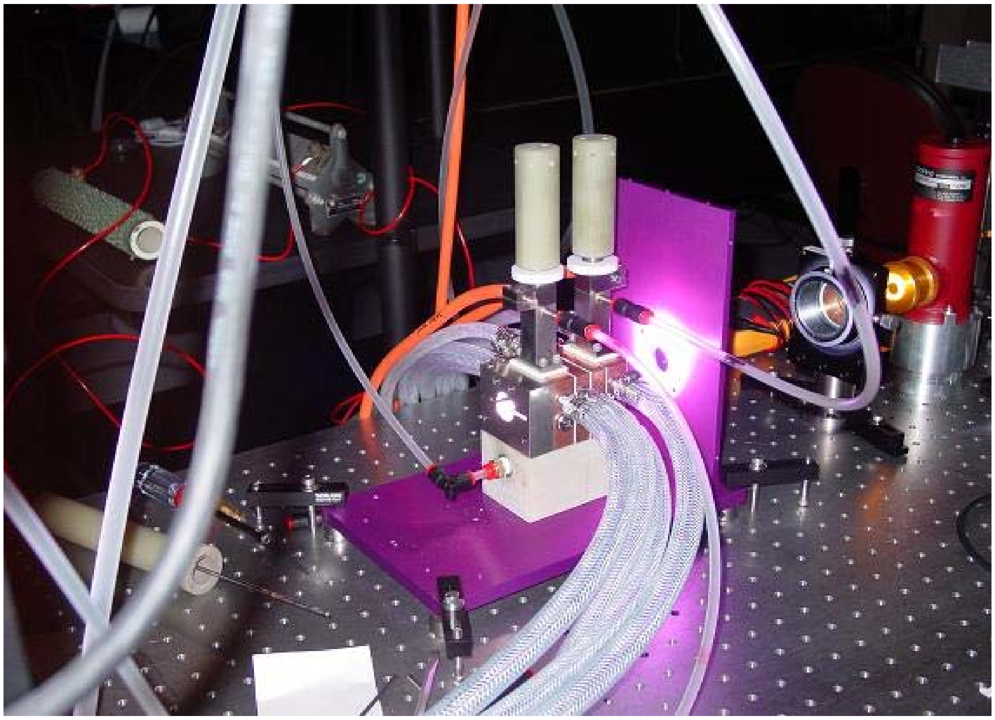

Figure 3. Photograph of the argon arc source in operation. The side panels of the enclosure have been removed to show the operation of the source. The nest of tubing on the sides of the arc source body have been replaced with a single manifold.

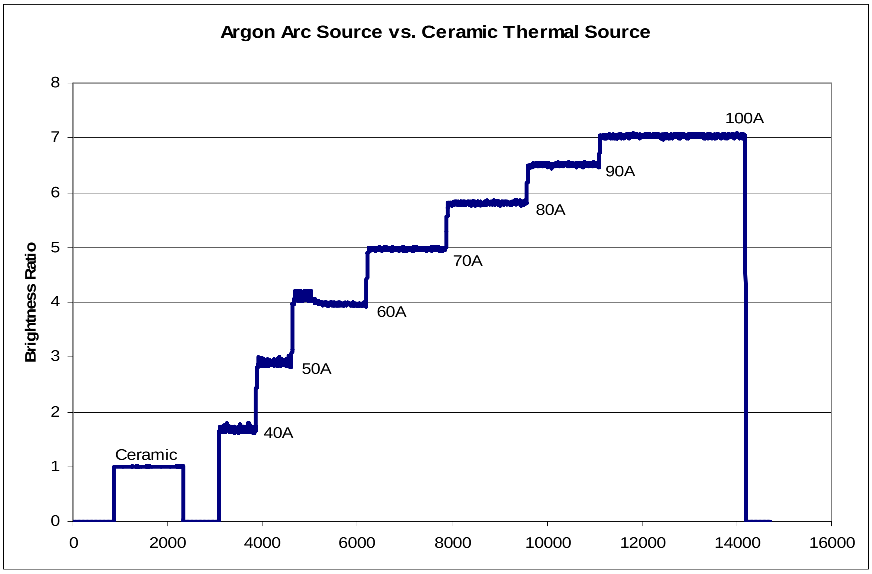

Figure 4. A side-by-side comparison of the ceramic source and the argon arc source illustrates the difference in their brightness. This comparison was done using the same detector, spatial filter, lock-in amplified and chopper wheel. At it's peak, the arc source is a factor of 7 brighter.

### 3.4 Mid IR Camera

The detector of choice for improving the sensitivity of our null measurements is the arsenic-doped silicon, block-impurity band high-flux array from DRS Technologies. This device is 128x128 in size with 75 um pixels. If operates at a temperature of 10K and needs extensive baffling of the thermal background to minimize signal corruption. What we gain in detector sensitivity we pay in system complexity. A cross section of the dewar is show below in Figure 5.

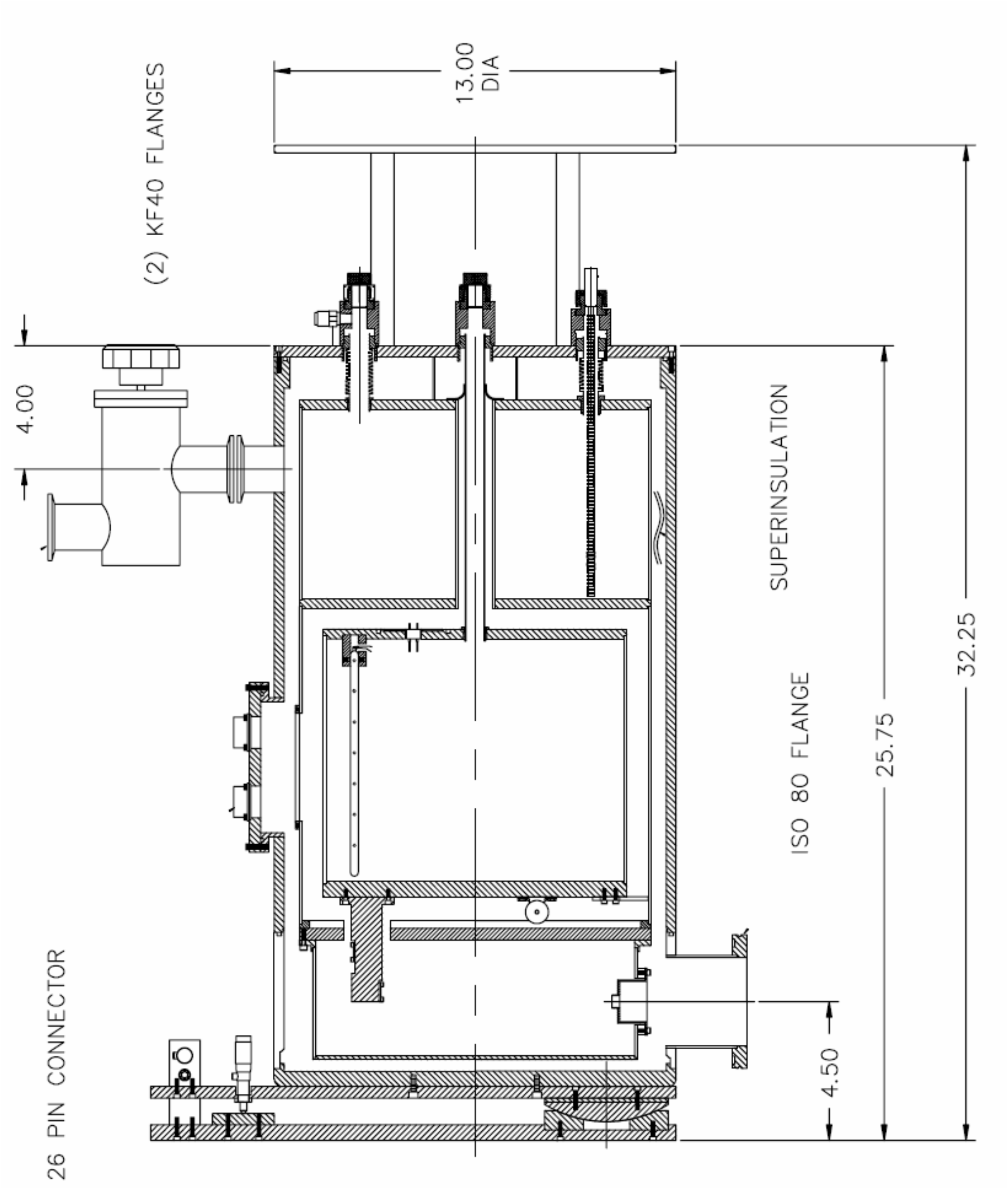

Figure 5. A cross section view of the Mid IR camera dewar. The optics are no shown. The prominent features are the LN2 and LHe liquid cryogen vessels. The hemisphere at the bottom of the dewar allows us to pivot the whole assembly about the pinhole that serves as the entrance aperture.

The dewar has a host of conveniences including an integral liquid cryogen level sensor for both the LN2 and the LHe. These will be used in conjunction with the autofill system for both the liquid cryogens. The system is also outfitted with adjustments external to the dewar that permit us to adjust the location of the light on the array by pivoting the whole dewar about a point that is also the center of the entrance pinhole. The LHe cold finger also provides a thermal contact to a cold baffle also at LHe temperatures. This provides a very cold solid angle to minimize thermal background. Quick and simple access to the cold surface is accomplished by first removing the bottom dewar housing and then the inner cold shield. Since the electrical feed throughs are located on the opposite side of this dewar split, there is no additional complication from disconnecting the fanout board. The optical beam train subsequent to the pinhole includes a re-collimating lens, a bandpass filter and low-order direct view prism followed by another lens that forms the image on the array. The array temperature is maintained by temperature sensor and heating element. A total of ten temperature sensors are placed at different locations along the beam train and on the cold plate. Two additional KF-40 flanges are also available in the event that more feed thrus may be necessary. We anticipate delivery of the dewar of the in early July. This will be followed by integration of the optics and camera electronics.

### 3.2 Single Mode Spatial Filters

Single mode fibers have long be praised for their ability to extract from a wave front that has been distorted by imperfections a remaining, perfect component. In this regard, we view these devices as absolutely essential in allowing us to complete our testbed goals. However, it should also be mentioned that a couple of nulling architectures rely upon a single mode input source in order to reach highest possible contrast. The through-focus and nulling periscopes both need a source that is a single mode. These architectures perform and geometric flip of the pupil such that at the point of recombination, opposite sides of the pupil are interfering with each other. The only way to insure that this occurs completely is to have an input pupil whose phase relationship with other parts of the pupil is constant.

The spatial filters created for our testbed are single mode fibers. These were procured via a subcontract with Naval Research Laboratories (NRL). Their double-crucible technique for creating near-IR fibers is well documented. With a slight change in the glasses that form the core and cladding, they were able to produce fibers which appear to be sufficiently single mode for our applications.

The single mode behavior is predicted based upon a direct measurement of the index of refraction of the core and cladding glasses as well as the geometric radius of the core. The fibers are conveniently connectorized and packaged in a protective jacketing. Integrating them into our through focus experiment provided an impressive validation of their operation: they immediately improved our nulls by a factor of 100!

The only downside to our current fibers is the Fressnel loss we experience at each air/glass interface. The glasses employed have a high index of refraction the result is that after passing through two fibers, the throughput is only 40% of what it would be without them.

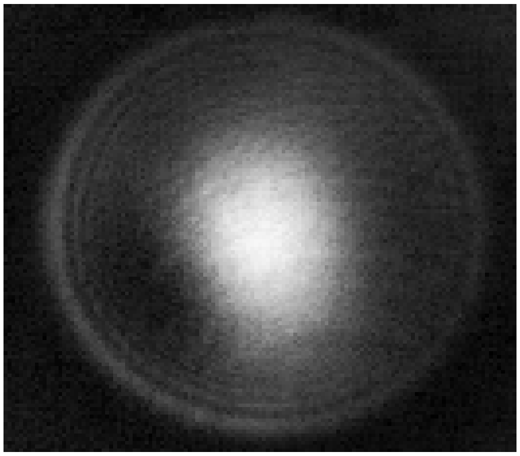

Figure 6. Irradiance distribution in the pupil plane illuminated with the output from an ostensibly 10 μm single-mode fiber.

### 3.3 Laser path-length metrology

One might be led to believe that nulling at a level of a million to one with a wavelength of 10 microns is easier than nulling to the same level in the visible portion of the spectrum. However, the visible portion of the spectrum affords one with many more photons for sensing and control. The path length stabilization schemes for the Mid IR therefore require a system proxy to the science band to stabilize the optical path internal to the interferometer. Fortunately for us, these laser metrology systems for path length stabilization have a long and fruitful history in interferometry.

Our initial attempts at path length stabilization have permitted us to demonstrate sub-nanometer control. This level of control is consistent with our ultimate nulling milestone of one million to one. This result allows us to declare success on this aspect.

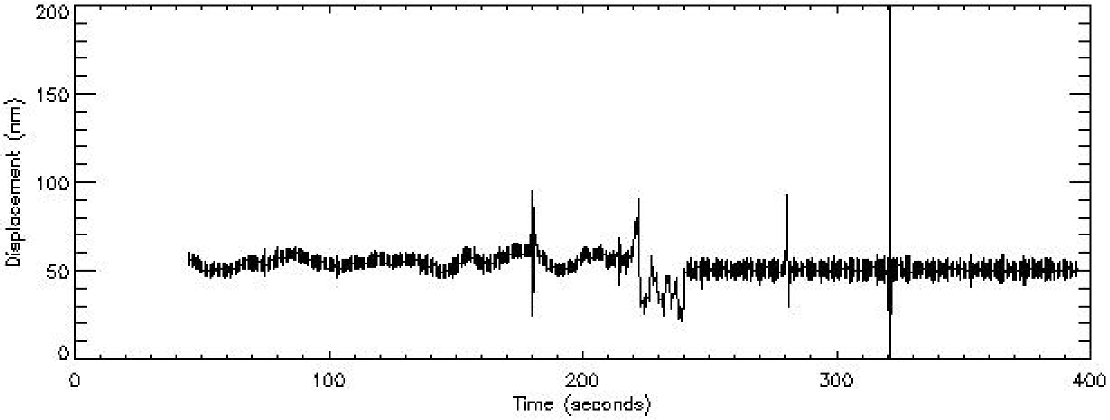

Figure 7. A demonstration of path length stabilization to sub-nanometer levels.

Unfortunately, piston stability is only part of our technical challenge. When coupling into a single mode spatial filter, point errors couple in as amplitude errors. Therefore tip/tilt metrology is required to maintain a constant angular alignment between the two arms of the interferometer. This angular metrology is accomplished by introducing another pair of linear metrology beams that are collinear with the original pencil beam for piston control. The signals from the three gauges then form a metric for piston, tip and tilt.

We have built up a test station where we can test and develop the full tip/tilt/piston metrology system. It is wrapped around a compact nulling interferometer working at 10 um. This will allows us to fully explore it’s behavior before integrating it with the rest of the nulling architectures.

## CONCLUSION

Several areas of technology development are required in order to experimentally demonstrate deep nulling of mid IR light over a broad optical bandpass. We have described: 1) an argon arc source, 2) a mid infrared camera, 3) single mode spatial filters and 4) laser metrology for path length stabilization. We have made great strides in bringing all of these into reality and are beginning the process of integration. With all of these elements working in concert, we expect to experimentally demonstrate the nulling consistent with requirements for NASA’s TPF-I.

## ACKNOWLEDGMENTS

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