Cryogenic Delay Line for Far-IR Interferometry in Space

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Abstract: We discuss the design, current status, and ongoing development of a cryogenic delay line for long-baseline direct-detection interferometry in the far-infrared.

1 Introduction

Direct-detection interferometry in space at far-IR/submillimeter wavelengths would enable unprecedented combinations of sensitivity and angular resolution. High angular resolution observations at wavelengths of 40–400 microns would allow the determination the star formation rate as a function of redshift and an investigation of fundamental questions relating to the history of star formation, galaxy formation, and the evolution of the universe (Swain 1998; Mather et al. 1998; Rieke et al. 1999). High angular resolution is required to avoid confusion due to the extragalactic background, with the highest resolution only being accessible through the use of long-baseline interferometry. At these wavelengths cryogenic optical systems are required, augmented with the active servo systems necessary for interferometry. One of the most challenging and crucial components of an interferometer is its delay line. We have designed and assembled a prototype cryogenic delay line to provide delays of up to 0.5 m that we are now in the process of testing. Its design, current status, and ongoing development are described.

2 Design Requirements for Far-IR Interferometry

Although two mission studies for far-IR space interferometry, SPIRIT and SPECS, are presently being developed at NASA's Jet Propulsion Laboratory and Goddard Space Flight Center (Shao et al. 2000; Leisawitz et al. 2000), no direct detection long-baseline interferometer has ever previously been designed, let alone built, to work at wavelengths longer than about 20 microns. The far-infrared and submillimeter require low temperature optics and extensive baffling for background limited observations. Our objective was to design a precision mechanism without the use of axles, capable of accepting 10 cm optical beams and providing 50 cm of optical delay while operating in hard vacuum at temperatures as low as 4 Kelvin.

The delay line must be designed so that its motion does not significantly degrade the measured fringe visibility; thus path-length vibrations, angular fluctuations, and the lateral shear of the optical beams must be minimized. We have adopted a movable cat's eye optical design, typical of ground-based interferometers, and have required the total visibility losses to

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be less than 1%. The cat's eye is similar to a retro-reflector in that the input and output beams are always parallel, but lateral motions of the cat's eye double the shear between the input and output beams. To maintain visibility losses due to shear to be less than 0.5% for a 10 cm beam implies a straightness of travel of 250 μm over the full stroke, and for a 0.5% loss due to piston jitter the motions must be less than 1.2 μm rms at a wavelength of 100 μm.

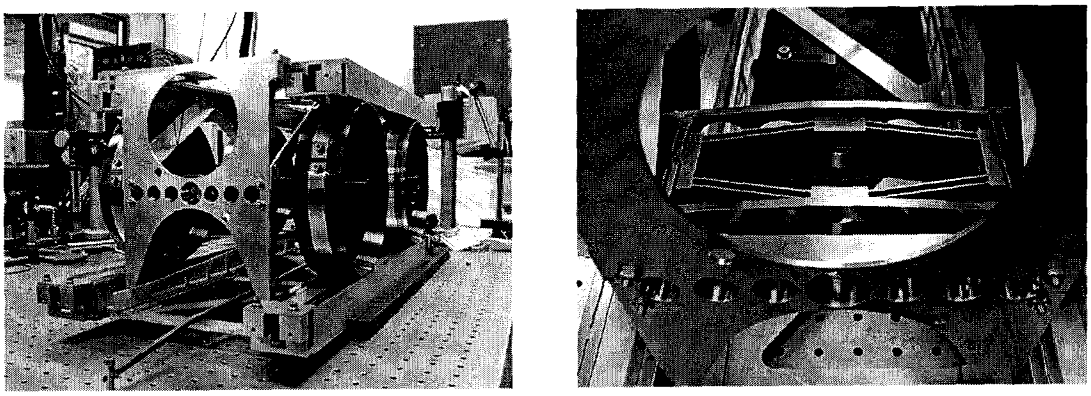
3 Strapped-Wheel Delay Line

Our initial studies focused on a "double porch swing" design, developed by Donald E. Jennings at the Goddard Space Flight Center. However, because of our concerns about the complexity and rigidity of the double porch swing we have developed an entirely new design as shown in the photographs of Fig. 1, and previously reported by Lawson et al. (2000). The principle of operation is simple: an upper carriage carrying the optics sits on four wheels that roll to translate the delay line. There are no axles in this system; the wheels are constrained only by straps and the carriage preload.

In our design each wheel has three straps, visible in Fig. 1 (a). Two outer straps are held with an adjustable preload at the end of the bottom stage, pass underneath the wheel, on the left and right rim, and terminate on the end of the upper stage above where they were launched. For each pair of wheels on the left and right-hand side of the carriage there is also a strap that binds the pair together as a unit, passing around the outside circumference of the pair and so setting the wheel separation. The alignment of the wheels is tuned by adjusting the preload tension for the outer straps. The carriage is aluminum with the exception of the the stainless-steel straps and the magnetic carriage preload. The carriage preload comprises 24 Neodymium Iron Boron magnets (0.5-inch in diameter), set in counterbores within the aluminum base, which clamp (across an air gap) to a pair of steel rails suspended from the upper platform. This provides remarkable rigidity. The carriage has been tuned for a run-out of 25 μm over its full travel—a factor of 10 better than our requirement.

With a cat's eye design, a collimated input beam arrives parallel but to one side of the optical axis of a parabolic mirror, is focused to a flat mirror, and then is re-collimated and output on the opposite side of the axis, parallel to the input beam. This design allows rapid path length corrections to be introduced by a small piezo-driven flat mirror at the focus of the parabola. Our design is sized to accommodate 10 cm diameter beams at a wavelength of 100 μm, yielding a Fresnel number of 10 at a distance of 2.5 m. The parabolic mirror is 123 × 254 mm with a 381 mm focal length, manufactured by Axsys Technologies as a lightweighted diamond-turned 6061-T6 aluminum mirror with a surface expected to be 0.25–0.50 waves peak-to-peak (HeNe) over the 10 cm subapertures. This will provide a $\lambda/30$ surface at a wavelength of 10 μm, where preliminary tests will be conducted.

The metrology and servo control system for the delay line is being implemented using Pentium PCs running real-time Linux (RTAI). A pathlength-control servo loop with a sample rate of 2 kHz will be adequate to control the jitter and should be easily obtainable using PC-based hardware and hard real time software. The delay will be monitored with a Zygo ZMI-2000 metrology system with a compact single-beam interferometer and PC measurement board, providing a resolution of 0.6 nm, position range of ±21.2 m, a maximum velocity of 4.2 m/s, and a readout rate of 60 kHz. A two-stage servo will be implemented comprising the piezo transducer (PZT) on the cat's eye assembly, and a cryogenic stepper motor. The stepper motor (Phytron VSS 42 model) is configured to provide 0.47 μm/step in microstep mode and 9.4 μm/step in full-step mode, allowing the full range of travel to be scanned in 26 seconds. The piezo actuator is a custom Physics Instrumente HVPZ-239 model, with sub-nm resolution



(a) (b)

Figure 1: Strapped-wheel delay line: (a) Overview, (b) Close-up of piezo amplifier prior to the installation of the secondary mirror and transverse piezo stack.

and mounted to provide a full-wavelength stroke at λ=100 μm. To compensate for the loss of travel at cryogenic temperatures, the PZT is mounted in a novel mechanical amplifier that holds the cat's eye secondary. This device, shown in Fig. 1 (b) was designed by one of the authors (JDM) based on an original concept by Rob Calvet of JPL dating from 1993. It is compact and momentum compensated with only a single piezo stack, making it ideally suited for phase-measurement in a cryogenic environment.

4 Conclusions

The strapped-wheel delay line prototype is largely complete, and initial mechanical tests at temperatures as low as 120 Kelvin, have shown it able to meet or exceed our requirements. The optics and PZT have been installed, and the fully assembled system will undergo warm duration tests in the near future. Work is also underway to implement the necessary servo controls and to test the piezo amplifier.

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