Progress Toward Astronomical Nulling

INTRODUCTION

Perhaps the most difficult and unusual challenge of finding planets around nearby stars is that of rejecting the light of the parent star. The traditional approach on a filled aperture telescope is to use a coronagraph to enable faint objects to be found beyond a few diffraction widths of a bright object. As demonstrated on the Hubble Space Telescope (HST), coronagraphic rejection 0.5″ from a bright star can be as great as 10^4 (Schneider *et al*. 1998). A number of techniques have been suggested to combine a coronagraph with active optics that might work orders of magnitude better than a simple coronagraph (Malbet, Yu, and Shao 1995; Angel and Woolf 1997; Trauger *et al*. 1998). However, the level of rejection needed to detect an Earth-like planet 10 pc away at visible wavelengths, a factor of $1\text{-}10 \times 10^9$, implies wavefront and amplitude control of ~0.1 nm over an entire 8 m aperture and lies many years in the future. As described in Chapter 6, the approach that appears technologically most feasible within the next decade is an interferometric one using destructive interference, or nulling, to remove the on-axis light from a parent star. This chapter describes techniques for nulling, highlights the present state of the art in experiments in the laboratory and at the telescope, and presents a road map for continued progress.

Two experiments made in the last six months lead to the important conclusion that nulling is not just a theoretical construct:

1. Images of the dust cloud around Betelgeuse (α Ori) have been made by nulling the central star (Hinz *et al*. 1998a,b,c) to a modest factor of 24:1.
2. A laboratory nulling experiment has demonstrated at visible wavelengths a null depth of 25,000:1 (Serabyn *et al*. 1999).

These experiments have demonstrated the basic technique of nulling in the laboratory and at the telescope more than six years in advance of the start of the TPF project. A NASA-funded program of technology development using laboratory experiments and astronomical tests (Keck Interferometer, the Large Binocular Telescope, and the Space

Interferometry Mission) will ensure that nulling is a mature technology in time for TPF.

INTRODUCTION TO NULLING

Conceptually, nulling is no more complex than standard Michelson interferometry, but with a phase shift of π radians introduced into one beam, so that the crests of light in one arm of the interferometer coincide with the troughs of the waves in the other arm, resulting in destructive rather than constructive interference at zero path difference for a source located on the optical axis. The challenge of nulling for TPF involves making the null sufficiently deep and achromatic that a broad range of wavelengths can be passed to enable detection of any weak off-axis sources such as a planet.

The null depth, N, is defined as the ratio of the intensity of leakage through the null, I_{null}, divided by the un-nulled intensity, I_0:

$$N = I_{\mathrm{null}}/I_0 = (1\text{-}V\cos(\varphi))/2 \sim (\varphi/2)^2$$

where V (taken to be 1) is the fringe visibility, $\varphi=2\pi\sigma_{\mathrm{OPD}}/\lambda$ is the phase error between the two interfering beams, and σ_{OPD} is the optical path difference error between the two beams. The null depth is then given by $N = (\pi\ \sigma_{\mathrm{OPD}}/\lambda)^2$.

The depth and breadth of the null required for an observation depends on the distance and radius of the star (i.e. its subtended angle), the wavelength, and the relative importance of other noise sources, e.g. the local zodiacal emission. Table 10.1 shows the nulling needed for a solar-type star at the indicated distance and at the wavelength of various spectral features. The values are set by demanding that the leakage signal produce less than 25% increase in noise. The nulling demands are modest for the longer wavelength CO_2 and H_2O observations. The nulling demands are more severe at shorter wavelengths where the zodiacal emission is declining and the star is becoming brighter.

Table 10.1. Required Nulling Performance

	7 µm ($CH_4 + H_2O$)	9.7 µm (O_3)	15.6 µm (CO_2)	19 µm (H_2O)
4×3.5 m G star @ 8pc	1,000,000	250,000	32,000	22,000
4×3.5 m G star @ 15pc	284,000	71,000	9,100	6,300
4×2 m G star @ 8pc	350,000	83,000	11,000	7,200
4×2 m G star @ 15pc	100,000	24,000	3,100	2,100

Table 10.2. Requirements for Achieving a Deep Null

Error Source	Constraint	Requirements for Null $<10^{-6}$@ 7 µm; $<5\text{x}10^{-5}$@ 20 µm)
Optical Path Errors	$\sigma_{OPD} < \lambda N^{1/2}/(\pi(1 + 2^{1/2})^{1/2})$	3.5 nm 70 nm
Transmission Asymmetries between Beams	$\sigma_{Inten}/I < 2N^{1/2}$	<0.2% <1.4%
Pointing Jitter	$\alpha < 0.8 (\lambda/D)^4 N^{1/2}$	10 milli-arcsec 75 milli-arcsec
Differential Polarization Rotation	$\varphi < 2N^{1/2}$	0.1 deg 0.7 deg
Differential Polarization (s-p Waves) Delay	$\Delta < 4N^{1/2}$	0.2 deg 1.4 deg

N = Null depth; D = Telescope diameter, 3.5 m; See Table 6.6.

Table 10.2 describes some of the factors that must be controlled to achieve a particular null depth. The most stringent wavefront control required for TPF operation is at 7 µm, corresponding to an optical path stability of $\sigma_{OPD} \sim 3.5$ nm. At 20 µm, the nulling requirement is less stringent due to the more favorable planet-star ratio and easier to achieve because of the longer wavelength, $\sigma_{OPD} \sim 70$ nm. Thus, substantial progress could be made on characterizing terrestrial planets at long wavelengths with even a relatively poor null. By way of comparison with laboratory experiments, it is interesting to note that the few nanometer control needed for a 10^{-6} null at 7 µm is easier to achieve than the recently achieved null depth of 10^{-4} at visible wavelengths.

In addition to stringent phase control, intensities in the two interfering beams must be balanced to 0.2%, and linear polarization and birefringence controlled, so as not to make different polarization components try to interfere. Then to make the interferometer produce an achromatic null, these requirements must be extended over a broad spectral band. Yet at the same time, because extrasolar planet signals are faint, the interferometer needs to have a high optical efficiency.

ROADMAP TOWARD TPF NULLING PERFORMANCE

TPF's ultimate goal of nulling starlight to 10^{-5}-10^{-6} across the 7-20 µm region (in a series of spectral resolution $R = \lambda/\Delta\lambda \sim 20$ bands) requires significant technological progress that will be demonstrated through a series of laboratory testbeds coupled with a series of astronomical experiments on ground-based and space-based telescopes (Table 10.3). Groups in industry, universities, and NASA centers are involved in the NASA program with similar activities underway in Europe in support of ESA's Infrared Space Interferometer mission

Table 10.3. Nulling Development for TPF

Activity	Date	Mid-IR	Visible Light
Telescope Demonstration	3/98	25:1 (UofA)	
Passive, Open-Air, Laboratory Nuller (laser)	2/99		25,000:1 (JPL) 6,000:1 (UofA)
Passive, Open-Air, Laboratory Nuller (white light)	6/99		300:1 (JPL)
Keck Mid-IR Nuller (active, cryogenic)	2001	10,000:1 (JPL)	
Active, Vacuum, Laboratory Nuller (white light), SIM Prototype	2001		10,000:1 (UofA, JPL/Lockheed Martin)
Large Binocular Telescope/ MMT Mid-IR Nuller	2003	10,000:1 (UofA)	
TPF Laboratory Prototype (cryogenic, vacuum)	2005	100,000:1 (requirement) 1,000,000:1 (goal)	
SIM Nulling Experiment (vacuum, white light, in space)	2005		10,000:1

(IRSI). While there are no insurmountable technical obstacles, extremely careful attention to experimental detail will be required, including increased refinement in areas such as optical coatings and pathlength control, infrared polarization devices, infrared spatial filters, beamsplitters, etc.

The first step toward deep nulling involves experiments aimed at mid-infrared interferometry on large ground-based pairs of telescopes, such as the twin Keck telescopes and the Large Binocular Telescope (LBT). An initial demonstration of the concepts involved has recently been obtained using a pair of segments on the former Multiple Mirror Telescope (MMT; see Recent Laboratory and Telescope Demonstrations of Nulling section at the end of this chapter). From the ground, residual atmospheric wavefront distortions will likely limit the null depths attainable in these experiments to 10^{-3}-10^{-4}. However, these experiments will provide initial guidance in several key areas, including intensity, polarization, and pathlength control, and a host of subsidiary issues such as beamsplitter reflection/transmission ratios and spatial filter (pinhole and fiber) efficiencies.

Equally important, a cross-comparison of the different nulling schemes will soon be possible. These schemes, which should all work in principle, are based on the need to introduce an achromatic π radian phase shift between two incoming beams. There are several possible ways to do this, including:

- Reflecting the two beams using orthogonal rooftop reflectors in a Twyman-Green interferometric combiner (at JPL).
- Reflecting the two beams using a pair of cat's eye reflectors in an interferometric combiner. One cat's eye has a flat secondary at its focus, while the other has a curved secondary before its focus.
- Introducing a dispersive element in one arm to compensate for the fact that the other arm has a fixed 5 µm delay that corresponds to π radians at only one wavelength, 10 µm (University of Arizona).

The ground-based, cryogenic mid-infrared experiments will be followed by a nulling experiment on Space Interferometry Mission (SIM) at optical wavelengths, the goal of which will be to demonstrate in space the requisite level of pathlength control that TPF will eventually need. This corresponds to a null depth of 10^{-4} at a wavelength of 1 µm, and so will necessitate correspondingly tighter constraints on polarization and intensity control as well. Finally, to enable cancellation to the 10^{-6} level, TPF will again require a step forward in intensity and polarization control. To reach this series of goals, steady improvements in both the optical and control arenas will be needed, focused on the needs of mid-infrared nulling. Coatings (beamsplitter, anti-reflection, and protective layer) will require increasingly stringent optimizations. Interferometric (as opposed to single pass) beam combiners relax the constraints on the beamsplitter coatings, so the results of initial testbed cross-comparisons will be eagerly anticipated.

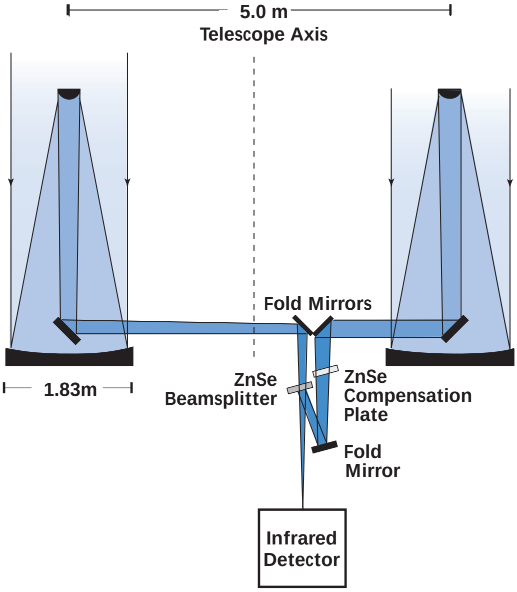

Figure 10.1. The experimental configuration used at the MMT in a first test of nulling for astronomical observations. Results are shown in Figure 10.2

Another important area of research is the spatial filter (Simon *et al.* 1990; Shao and Colavita 1992; Mennesson 1998). A single mode spatial filter significantly reduces the number of degrees of freedom that an active control system must control. Using a spatial filter, in the form of an optical fiber, waveguide, or pinhole, can greatly relax the requirements on the quality of the telescope and other optical components upstream of the nulling beam-combiner and even on telescope pointing (Ollivier and Mariotti 1997). But the best mid-infrared spatial filters at present are pinholes. Thus, the maturation of single-mode mid-infrared fiber technology or waveguide technology would be a boon to TPF.

Intensity matching in the interferometer beams, an area that is outside the normal scope of optical design, will need to be developed, and the various schemes tested for broadband properties. Further, in the individual schemes proposed, optical elements need refinement–in particular, the quality of rooftop mirrors, and the design of phase matching waveplates. At the low residual light levels desired, the elimination of unwanted stray radiation will likely need to receive extremely careful attention. Finally, broadening the band over which given solutions apply, or finding ways of separating the bands without introducing phase or amplitude problems will be the final technical hurdle.

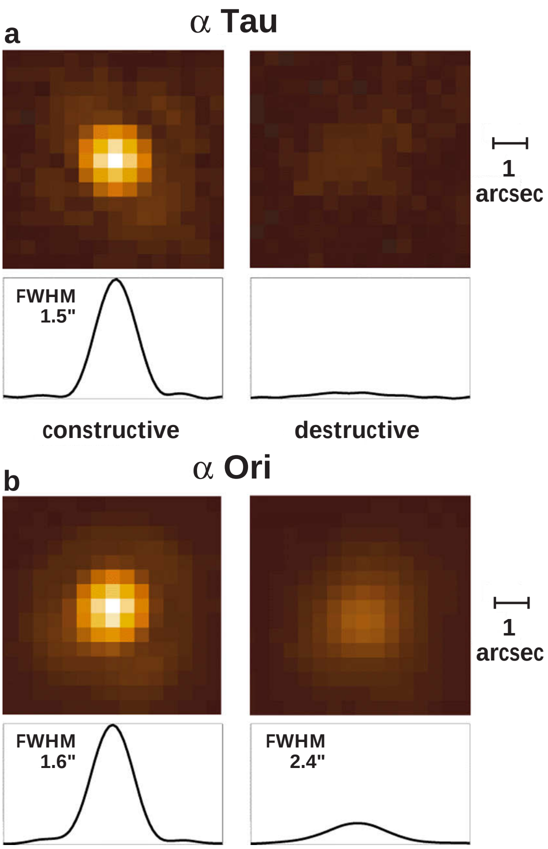

Figure 10.2. Nulling observations at the MMT. Two images (top) of the unresolved star α Tau without and with nulling. The nulling ratio is about 24:1 . Two images (bottom) of the star α Ori (Betelgeuse) are shown without and with nulling; the nulled image reveals the presence of an extended dust cloud around the star.

RECENT LABORATORY AND TELESCOPE DEMONSTRATIONS OF NULLING

As a part of the TPF program, nulling was first used astronomically at the Multiple Mirror Telescope to observe circumstellar envelopes around red giant and supergiant stars by Hinz *et al*. (1998). Figure 10.1 shows the instrumental configuration, while Figure 10.2 shows images from these observations. In this first astronomical test, phase was not controlled and the atmospheric seeing was used to scan phase. The nulling factor achieved was about 24:1 in a R~10 spectral bandwidth, a modest but important milestone on the route to TPF.

An interferometer at JPL recently achieved a null depth of a part in 25,000 on a visible-light diode laser with a 0.5% (R=200) bandwidth as shown in Figure 10.3. A modification of this experiment produced a 900:1 null on a broadband light source (R=20) in a single polarization. Improvements in this apparatus in the next two years, including vibration-isolation, operation in a vacuum, implementation of a control loop are expected to allow nulls of comparable depth to be obtained in broad-band visible light.

CONCLUSION

Nulling is a crucial and challenging technology needed for TPF. While there are at present no known insurmountable barriers to high precision, high efficiency, or broadband nulling, it is very difficult to forecast the paths needed to improve a technique by a number of orders of magnitude. The present laboratory performance does not satisfy the

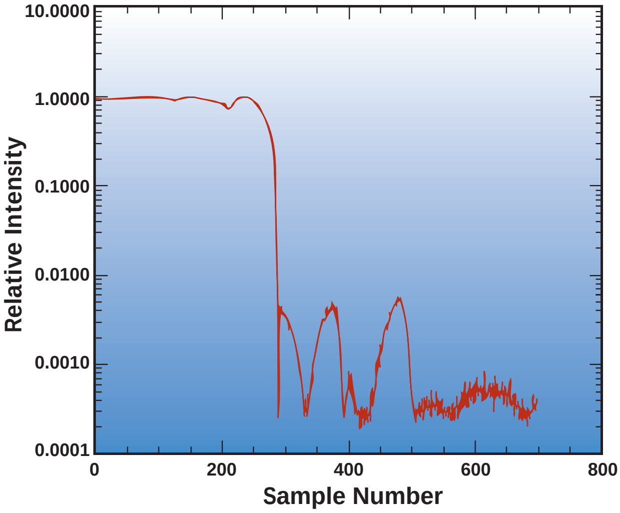

Figure 10.3. A nulling interferometer at JPL (using rooftop prisms illustrated in Figure 11.4) recently demonstrated a null depth of one part in 25,000 on a laser diode source. The intensity of light coming out of the nulling apparatus is shown first when the optical path length is set away from, and subsequently onto, the nulling position.

final TPF requirements since existing systems for making deep nulls are monochromatic, transient—lasting only a few seconds in open loop operation—and function in only one polarization. However, the basic technique has been demonstrated in the laboratory and at the telescope more than six years in advance of the start of the TPF project. By following the technology development program outlined in Table 10.3 with laboratory testbeds as well as instruments on Keck, LBT, and SIM, the nulling capability needed for the full range of TPF requirements will be in place to support a start for TPF sometime in the next decade.

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