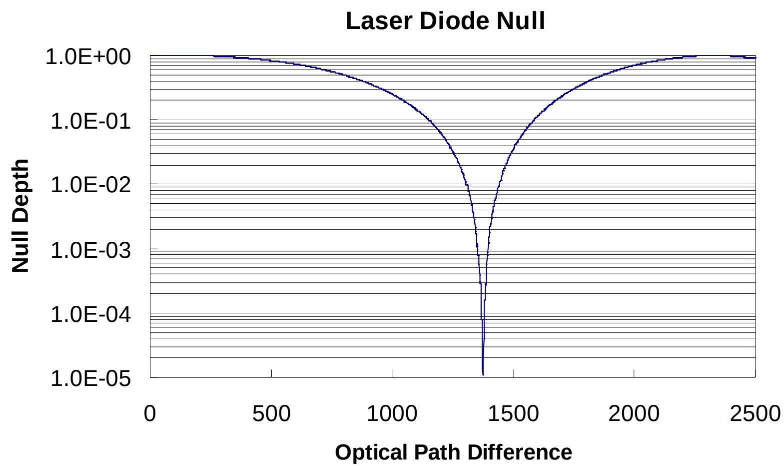

Figure 16.21: Experimental results from JPL's fiber-coupled RSI. An OPD scan through the expected central null fringe shows a null of 1×10^{-5}. The laser diode bandwidth is 0.5%.

with both the cat's eye and phase retardation approaches. The level of stellar rejection achieved in both cases is consistent with limitations imposed by optical surface quality and atmospheric issues.

16.7 Multi-Baseline Nulling

The preceding sections have focused largely on the optical physics of the nulling process. However, there is one further aspect to consider, that being whether a two-telescope, i.e., single-baseline, interference pattern is sufficient to successfully detect planetary companions to nearby stars. In particular, two goals are in opposition: to null a star out to its rim, a deep and wide central fringe is desirable, suggesting short baselines. On the other hand, short baselines do not provide sufficient angular resolution to resolve near-in planets from possibly bright exozodiacal emission. Thus, to generate both a deep and wide central null fringe for stellar nulling, and to retain high angular resolution off the central null, multi-baseline nulling configurations have been considered (e.g. Angel, 1990; Angel and Woolf, 1997a,b; Beichman *et al.*, 1999; Leger *et al.*, 1996; Mennesson and Mariotti, 1997; Velusamy *et al.*, 1999; Woolf and Angel, 1997). The basic idea is to combine the outputs of single baseline nulls to generate cancellation near the optical axis to higher powers of the off-axis field angle, θ, than the θ^2 nulls that a single baseline can supply.

Several specific cases have been developed which are capable of modifying the basic single baseline null to broader and more effective θ^4, θ^6, etc. nulls (Angel, 1990; Woolf and Angel, 1997; Mennesson and Mariotti, 1997). One particularly promising configuration is the combination of short nulling baselines with longer post-nulling imaging baselines (Velusamy *et al.*, 1999). Another promising variant is the reflection-asymmetric fringe patterns provided by the modulation scheme of Angel and Woolf (1997a). A recent tally of configuration concepts is provided by Lawson *et al.* (1999). However, the general question of the optimal nulling configuration remains without a clear answer, as the field is still quite young, with novel configurations no doubt awaiting discovery. Indeed, envisaged space missions based on nulling interferometry, such as NASA's proposed Terrestrial Planet Finder (Beichman *et al.*, 1999), and ESA's proposed Infrared Space Interferometer (Darwin) mission (Leger *et al.*, 1996) are still in very early developmental phases, with no clear favorite for the configuration as yet. Thus, given recent progress in the experimental demonstration of deep nulling, such configuration level questions can now be considered to be one of the most pressing unresolved issues in the development of nulling into a tool for exozodiacal light and extrasolar planet detection.

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References

J.R.P. Angel, A.Y.S. Cheng, and N.J. Woolf, "A space telescope for infrared spectroscopy of earthlike planets," Nature **322**, 341–343 (1986).

J.R.P. Angel, "Use of a 16 m telescope to detect earthlike planets," in *The Next Generation Space Telescope*, P.Y. Bely, C.J. Burrows, and G.D. Illingworth, eds., Proc. NASA/STSI Workshop, 81–95 (Baltimore: Space Telescope Institute, 1990).

J.R.P. Angel and N.J. Woolf, "An imaging nulling interferometer to study extrasolar planets," Astrophys. J. **475**, 373–379 (1997a).

J.R.P. Angel and N.J. Woolf, "The Large Binocular Telescope: a unique scientific and technology precursor to Planet Finder," in *Planets Beyond the Solar System and the Next Generation of Space Missions*, D.R. Soderblom, ed., ASP Conf. Ser. **119**, 207–222 (Provo, Utah: Brigham Young University, 1997b).

R. Angel, "Sensitivity of nulling interferometers to extra-solar zodiacal emission (EZE)," in *Exozodiacal Dust Workshop*, D.E. Backman, L.J. Caroff, S.A. Sanford, and D.H. Wooden, eds. NASA/CP, **1998-10155**, 209–218 (1998).

D.E. Backman and F. Paresce, "Main-sequence stars with circumstellar solid material: the Vega phenomenon," in *Protostars and Planets III*, F.H. Levy and J.I. Lunine, eds., 1253–1304 (Tucson, AZ: Univ. of Arizona Press, 1993).

P. Baudoz, J. Gay, and Y. Rabbia, "Interfero-coronography: a tool for detection of faint companions," in *Brown Dwarfs and Extrasolar Planets*, R. Rebolo, E.L. Martin, and M. Osorio, eds., ASP Conf. Ser. **134**, 254–261 (Provo, Utah: Brigham Young University, 1998a).

P. Baudoz, Y. Rabbia, J. Gay, E. Rossi, L. Petro, S. Casey, P. Bely, R. Burg, J. MacKenty, B. Fleury, and P.-Y. Madec, "First results with the achromatic interfero coronograph," in *Adaptive Optical System Technologies*, D. Bonnaccini and R.K. Tyson, eds., Proc. SPIE **3353**, 455–462 (1998b).

C.A. Beichman, N.J. Woolf, and C.A. Lindensmith, eds., *Terrestrial Planet Finder* (Pasadena, California: Jet Propulsion Laboratory, 1999).

A.J. Booth, M.M. Colavita, M. Shao, P.N. Swanson, G.T. van Belle, S.L. Crawford, D.L. Palmer, L.J. Reder, E. Serabyn, M.R. Swain, G. Vasisht, and J.K. Wallace, "The Keck Interferometer: Instrument overview and proposed science," in *Working on the Fringe: Optical and IR Interferometry from Ground and Space*, S. Unwin and R. Stachnik, eds., ASP Conf. Ser. **194**, 256–263 (Provo, Utah: Brigham Young University, 1999).

M. Born and E. Wolf, *Principles of Optics*, Section 8.8.4, 6th edn. (Oxford, UK: Pergamon Press, 1980).

R.N. Bracewell, "Detecting nonsolar planets by spinning infrared interferometer," Nature **274**, 780–781 (1978).

R.N. Bracewell and R.H. MacPhie, "Searching for nonsolar planets," Icarus **38**, 136–147 (1979).

M.M. Colavita, A.F. Boden, S.L. Crawford, A.B. Meinel, M. Shao, P.N. Swanson, G.T. van Belle, G. Vasisht, J.M. Walker, J.K. Wallace, and P.L. Wizinowich, "The Keck Interferometer," in *Astronomical Interferometry*, R.D. Reasenberg, ed., Proc. SPIE **3350**, 776–784 (1998).

D.J. Diner, "IBIS: an interferometer-based imaging system for detecting extrasolar planets with a next generation space telescope," in *The Next Generation Space Telescope*, P.Y. Bely, C.J. Burrows, and G.D. Illingworth, eds., Proc. NASA/STSI Workshop, 133–141 (Baltimore: Space Telescope Science Institute, 1990).

D.J. Diner, E.F. Tubbs, S.L. Gaiser, and R.P. Korechoff, "Infrared imaging of extrasolar planets," J. British Interplanetary Soc. **44**, 505–512 (1991).

P.M. Hinz, J.R.P. Angel, W.F. Hoffmann, D.W. McCarthy Jr., P.C. MacGuire, M. Cheselka, J.L. Hora, and N.J. Woolf, "Imaging circumstellar environments with a nulling interferometer," Nature **395**, 251–253 (1998).

P.M. Hinz, J.R.P. Angel, N.J. Woolf, W.F. Hoffman, and D.W. McCarthy Jr., "Imaging extra-solar systems from the ground: the MMT and LBT nulling interferometers," in *Working on the Fringe: Optical and IR Interferometry from Ground and Space*, S. Unwin and R. Stachnik, eds., ASP Conf. Ser. **194**, 401–407 (Provo, Utah: Brigham Young University, 1999).

P.R. Lawson, P.J. Dumont, and M.M. Colavita, "Interferometer designs for the Terrestrial Planet Finder," in *Working on the Fringe: Optical and IR Interferometry from Ground and Space*, S. Unwin and R. Stachnik, eds., ASP Conf. Ser. **194**, 423–429 (Provo, Utah: Brigham Young University, 1999).

A. Leger, J.-M. Mariotti, B. Mennesson, M. Ollivier, J.L. Puget, D. Rouan, and J. Schneider, "Could we search for primitive life on extrasolar planets in the near future?: The DARWIN project," Icarus **123**, 249–255 (1996).

B. Mennesson and J.-M. Mariotti, "Array configurations for a space infrared nulling interferometer dedicated to the search for earthlike extrasolar planets," Icarus **128**, 202–212 (1997).

R.M. Morgan and J.H. Burge, "Initial results of a white light nulled fringe," in *Working on the Fringe: Optical and IR Interferometry from Ground and Space*, S. Unwin and R. Stachnik, eds., ASP Conf. Ser. **194**, 396–400 (Provo, Utah: Brigham Young University, 1999).

M. Ollivier and J.-M. Mariotti, "Improvement in the rejection rate of a nulling interferometer by spatial filtering," Appl. Opt. **36**, 5340–5346 (1997).

W.T. Reach, B.A. Franz, J.L. Weiland, M.G. Hauser, T.N. Kelsall, E.L. Wright, G. Rawley, S.W. Stemwedel, and W.J. Spiesman, "Observational confirmation of a circumsolar dust ring by the COBE satellite," Nature **374**, 521–523 (1995).

E. Serabyn, "Nanometer-level path-length control scheme for nulling interferometry," Appl. Opt. **38**, 4213–4216 (1999).

E. Serabyn, J.K. Wallace, G.J. Hardy, E.G.H. Schmidtlin, and H.T. Nguyen, "Deep nulling of visible laser light," Appl. Opt. **38**, 7128–7132 (1999a).

E. Serabyn, J.K. Wallace, H.T. Nguyen, E.G.H. Schmidtlin, and G.J. Hardy, "Nulling interferometry: working on the dark fringe," in *Working on the Fringe: Optical and IR Interferometry from Ground and Space*, S. Unwin and R. Stachnik, eds., ASP Conf. Ser. **194**, 437–442 (Provo, Utah: Brigham Young University, 1999b).

E. Serabyn, "Nulling interferometry: symmetry requirements and experimental results," in *Interferometry in Optical Astronomy*, P.J. Léna and A. Quirrenbach, eds., Proc. SPIE **4006**, 328–339 (2000).

E. Serabyn, M.M. Colavita, and C.A. Beichman, "Exozodiacal disk detection potential with the Keck Interferometer," in *Thermal Emission Spectroscopy of Dust, Disks, and Regoliths*, M.L. Sitko, A.L. Sprague, and D.K. Lynch, eds., ASP Conf. Ser. **196**, in press (Provo, Utah: Brigham Young University, 2000).

M. Shao, "Direct IR interferometric detection of extra solar planets," in *The Next Generation Space Telescope*, P.Y. Bely, C.J. Burrows, and G.D. Illingworth, eds., Proc. NASA/STSI Workshop, 160–168 (Baltimore: Space Telescope Institute, 1990).

M. Shao, "Hubble extra solar planet interferometer," in *Space Astronomical Telescopes and Instrumentation*, P.Y. Bely and J.B. Breckinridge, eds., Proc. SPIE **1494**, 347–356 (1991).

M. Shao and M.M. Colavita, "Long-baseline optical and infrared stellar interferometry," Ann. Rev. Astron. Astrophys. **30**, 457–498 (1992).

W.A. Traub, N.P. Carleton, and J.R.P. Angel, "On the detection of exo-zodiacal light by nulling interferometry with the Magellan telescopes," in *Science with the VLT Interferometer*, F. Paresce, ed., 80–85 (Berlin: Springer-Verlag, 1996).

T. Velusamy, C.A. Beichman, and M. Shao, "A dual 3-element nulling interferometer for TPF," in *Working on the Fringe: Optical and IR Interferometry from Ground and Space*, S. Unwin and R. Stachnik, eds., ASP Conf. Ser. **194**, 430–436 (Provo, Utah: Brigham Young University, 1999).

N. Woolf and J.R. Angel, "Astronomical searches for earth-like planets and signs of life," Ann. Rev. Astron. Astrophys. **36**, 507–537 (1998).

N.J. Woolf and J.R.P. Angel, "Planet Finder options I: new linear nulling array configurations," in *Planets Beyond the Solar System and the Next Generation of Space Missions*, D.R. Soderblom, ed., ASP Conf. Ser. **119**, 285–292 (Provo, Utah: Brigham Young University, 1997).