Terrestrial Planet Finder: Coda to 10 years of Technology Development

Peter R. Lawson

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

ABSTRACT

The Terrestrial Planet Finder (TPF) was proposed as a mission concept to the 2000 Decadal Survey, and received a very high ranking amongst the major initiatives that were then reviewed. As proposed, it was a formation-flying array of four 3-m class mid-infrared telescopes, linked together as an interferometer. Its science goal was to survey 150 nearby stars for the presence of Earth-like planets, to detect signs of life or habitability, and to enable revolutionary advances in high angular resolution astrophysics. The Decadal Survey Committee recommended that \$200M be invested to advance TPF technology development in the Decade of 2000–2010. This paper presents the results of NASA's investment.

Keywords: Astronomy, interferometry, coronagraphy, extrasolar planets, nulling, formation flying

1. INTRODUCTION AND OVERVIEW

The idea of a Terrestrial Planet Finder mission originated in the early 1990s both in Europe and the United States, although the name wasn't coined in the US until 1998.

At that time it seemed unlikely that a coronagraph would ever be able to detect Earth-like planets, because of the limited resolution that would be available, and the required surface figure exceeded the state of the art.[1]

Ronald Bracewell had suggested in 1978 that an infrared interferometer would be a promising approach.[2] At infrared and mid-infrared wavelengths the surface figure of any mirror is relaxed by a factor of 10 or 20 compared to optical wavelengths. Moreover, the blackbody spectrum of an Earth-like planet peaks between 10 and 20 μm, longward of the peak of the Sun's spectrum.[1] The planet-to-star contrast is between 1:10^6 and 1:10^7, whereas at wavelengths shorter than 4 μ the contrast is dominated by reflected light and is approximately 1:10^{10}.

By using an interferometer, the available resolution is limited not by a single aperture diameter, but by the largest separation of telescopes in an array. In 1995 NASA convened a group of experts to recommend *A Roadmap for the Exploration of Neighboring Planetary Systems (ExNPS)*,[3] which then used Bracewell's concept for its baseline design: a 75-m long cryogenic space observatory with four 1.5-m telescopes. This concept paralleled a proposal to the European Space Agency for a mission dubbed Darwin,[4] championed by Alain Leger and Jean-Marie Mariotti. Both ESA's and NASA's technology roadmaps for planet-finding were centered exclusively on interferometer technology.

The rationale for a formation flying interferometer gained currency at this time. The results of an ESA study in 1995–1996 suggested that space interferometer based on free-flying elements would be a better approach than building an interferometer based on the moon.[5] NASA sponsored industry studies with TRW, Lockheed-Martin, and Ball Aerospace in 1996–1997 which suggested that although a 75-m structure would be feasible, a formation flying array would have on operational flexibility making it more attractive to a wider astronomical community.

Further author information: Send correspondence to Peter Lawson, Jet Propulsion Laboratory, MS 301-451, 4800 Oak Grove Drive, Pasadena CA 91109-8099, USA. E-mail: Peter.R.Lawson@jpl.nasa.gov, Telephone: +1 (818) 354-0747.

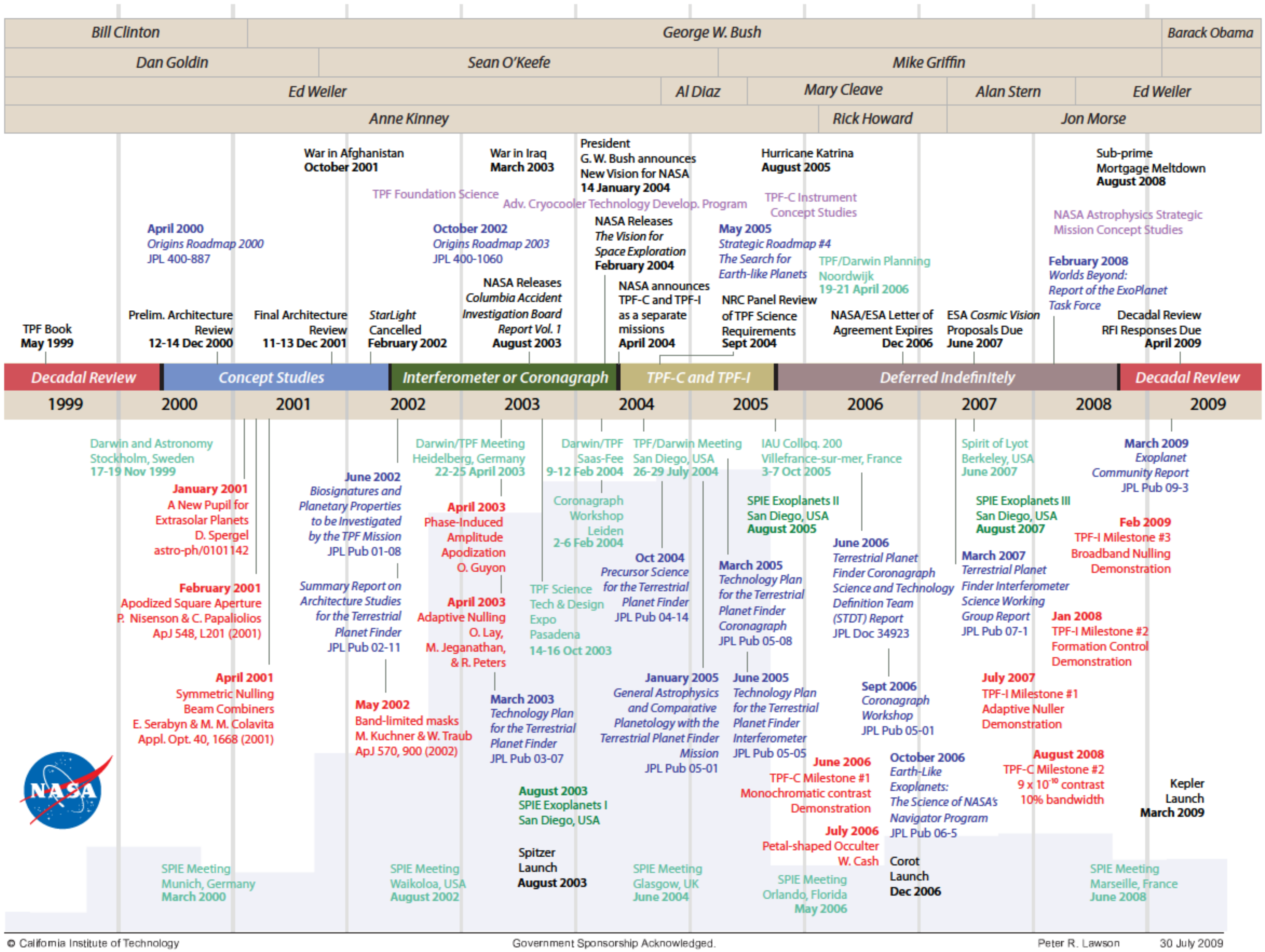

Figure 1. State of the Art in Nulling Interferometry: Laser experiments have shown that achromatic effects (predominantly pathlength variations) can be controlled in the lab at a level that allows nulls better than 1×10^{-6} to be achieved repeatedly. The best broadband mid-infrared nulls ach ieved to date have been 1.1×10^{-5}, with the Adaptive Nuller. The laser results therefore exceed the TPF-I requirements, and the broadband results are just shy of the TPF-I goal of 1.0×10^{-5}.

2. DECADAL REVIEW: 1999–2000

In preparation for the 2000 Decadal Survey, the name *Terrestrial Planet Finder* was coined and the case was made for a planet finding mission whose baseline design was a four-element mid-infrared interferometer. The *TPF Book* was published in preparation for the Decadal Review.[6] The goal of the mission was to search approximately 150 nearby stars and measure the spectra of any Earth-like planets it could detect. Half the mission would be devoted to planet finding and the other half to general astrophysics. The architecture of the interferometer greatly resembled the design described by Angel and Woolf,[7] who proposed an array of 1-m telescopes operated in a Jupiter-like orbit to overcome noise from local zodiacal dust. The new book-concept used 3.5-m telescopes in an Earth-trailing orbit. The first results of nulling interferometry had recently demonstrated nulls of 1 part in 24 on the sky[8] and experiments in the lab using laser diodes had yielded nulls of 25,000:1.

TPF was ranked by the Panel on Ultraviolet, Optical and Infrared Astronomy from Space as the second-priority major mission for the 2000-2010 decade after JWST.

> Designed to observe directly Earth-sized planets near other stars, it is potentially the most scientifically exciting of all the major missions, depending on the breadth of its mission goals. It is the second logical path to improved image resolution and sensitivity in space: distributed aperture interferometry. Because TPF will depend on the successful technology development for both SIM and NGST, the panel saw it as being less technologically ready for the coming decade and therefore gave it a lower priority.

In the overall ranking of Major Initiatives it appeared 6^{th} with a recommendation that $200M be spent on technology development before the end of the decade.

3. CONCEPT STUDIES: 2000–2002

In late 2000, the TPF Project initiated a set of coordinated industry studies with TRW, Ball Aerospace, Boeing (SVS), and Lockheed-Martin to evaluate architecture trades. These major contractors were required to team with academic researchers to provide as broad a set of trades as possible. They were specifically told by the Project that there was nothing sacred about the interferometer architecture contained in the TPF Book, and that they were to come back with their best ideas for TPF. In the first year (2000–2001) they were to examine as wide a set of trades as possible, and in the second year (2001–2002) they were to narrow the trades to a few candidates from which they would base their recommendations. In parallel a new TPF Science Working Group (SWG) was convened, which replaced the SWG that had participated in the TPF Book.

During this period a concept for a visible-wavelength Apodized Square Aperture[9] was advanced by the Boeing (SVS) team and a shaped pupil[10] by the team with Ball Aerospace. TRW proposed a large segmented IR coronagraph, similar to JWST, and Lockheed-Martin proposed a four-element interferometer. In brief, three out of four contractors favored a coronagraph approach over an interferometer design.

Other significant advances took place during this period. A solution to the design of nulling interferometers was proposed that balanced the transmissions and reflections.[11] A band-limited mask,[12] and by extension a notch-filter mask,[13] was described that would suppress sidelobes in a coronagraph.

The science working group was tasked with providing a case for visible-wavelength biomarkers, which appeared initially as a JPL publication,[14] and eventually a paper in Astrobiology Journal.[15]

4. INTERFEROMETER *OR* CORONAGRAPH: 2002–2004

The TPF Project responded by recommending that three architectures be pursued for further study: a visible wavelength coronagraph, and a mid-infrared interferometer with either a fixed structure or formation flying.[16] There would be only one TPF, and so a plan was put in place to advance the technology and mission studies, such that by September 2006 a downselect would take place between the competing designs. A unified technology plan, spanning both interferometers and coronagraphs, was published.[17]

A formal Letter of Agreement was signed between NASA and ESA to collaborate on the design of the interferometer. This agreement was to expire in December 2006, after the final design had been agreed upon.

In February 2002 the Starlight mission had been cancelled, and most of the managers and engineers that took part in Starlight were transfered to TPF to plan the new interferometer testbeds and coordinate the mission studies.

New ideas continued to appear. In 2003 the Phase-Induced Amplitude Apodization appeared,[18] with a design similar to radio telescope approaches four decades previous.[19] The Adaptive Nuller was also described for the first time.[20]

In February 2004, both the coronagraph and interferometer teams were in Europe. The interferometer team took part in an ESA interferometer design workshop at Saas Fee, Switzerland,[21] and the coronagraph team took part in a coronagraph workshop at the University of Leiden, the Netherlands.[22]

The approach to the mission studies became more sophisticated. The TPF SWG was asked to develop a Design Reference Mission, and efforts for the coronagraph now included the notion of obscurational completeness in the observations of planetary systems. Because a starlight suppression would obscure the center of its field of view, it would not be able to detect some planets throughout much of their orbits. Approaches to optimize the number of detected planets were pioneered in studies of the coronagraph[23] and later also applied to the interferometer.[24]

The TPF Project also broadened its support for supporting science. In 2003 a NASA Research Announcement on the subject of TPF Foundation Science was issued and would continue to be offered for the next three years. In conjunction with this, in 2003–2004 a strategy of precursor science[25] was developed for TPF, which would later be revised and adopted by the Navigator Program.[26]

It was felt that the field was so rapidly developing that a dedicated SPIE conference was needed in odd-numbered years* to span the gap between SPIE's conference on Astronomical Telescopes and Instrumentation.

5. TPF-C *AND* TPF-I: 2004–2005

In January 2004, in response to the Report by the Columbia Accident Investigation Board, President George Bush announced a *Renewed Spirit of Discovery*, his new vision for NASA. The vision was specifically directed at a renewal of NASA's manned space program, retiring the space shuttle and providing a staged approach to putting astronauts on Mars. There was also a recommendation in the vision to build telescopes to search for extrasolar planets. On the strength of this recommendation, the TPF Project obtained support from NASA Headquarters to pursue two separate and complementary missions: TPF-C and TPF-I.

The TPF Coronagraph was then put on a fast-track to enter Phase A in September 2006. A Science and Technology Definition Team (STDT) was established for TPF-C, and a new TPF-C Technology Plan was written.[27] The relative merits of eighth-order masks[28] were debated, given the likely relaxation in telescope tolerances.[29] A NASA Research Announcement was issued for TPF-C instrument concepts.

A TPF-I SWG was also established with the notion that the interferometer would progress with a development schedule that lagged 5 years behind the coronagraph. A TPF-I Technology Plan was also written.[30]

This new direction was not well received by the National Academy of Sciences in the United States nor by the European Space Agency. In January 2004, the NRA Committee on Astronomy and Astrophysics, was charged by NASA HQ with re-evaluating the science case for TPF, and this request was ammended in April to take into account TPF's split into two missions. Their report reconfirmed the importance of TPF science, but protested the appearance of TPF-C without peer review by the National Academy.[31] Representatives of ESA, meanwhile, were extremely displeased that they had not been consulted in this process and that spirit of the Letter of Agreement had been violated.

In December 2004, the interferometer team undertook an architecture downselect interferometer concepts, the result of which was the adoption of the X-Array as the baseline design.[32]

---

*The SPIE Conference on *Techniques and Instrumentation for Detection of Exoplanets* was started in 2003 by TPF Project Manager, Daniel Coulter. The volume you are holding is the fourth volume in this series.

In July 2005, the coronagraph team completed its design study for the TPF-C Flight Baseline Design, which described a coronagraph with an elliptical 3×8-m mirror.[33]

6. DEFERRED INDEFINITELY: 2005–2008

In summer 2005 NASA's available budget for TPF collapsed. The planned reports were completed. The Project staff was reduced, with those remaining now focused on the existing technology testbeds. Efforts were made to redesign the missions so that they were smaller and less costly.

6.1. Completing the Flagship Mission Studies

The TPF-C Instrument studies were completed, and their recommendations included in the TPF-C STDT Report.[34] However, plans for the mission to enter Phase A were deferred indefinately.

The TPF-I SWG Report was likewise published.[35] The TPF-I and Darwin teams met in April 2006 at ESA ESTEC in Noordwijk, the Nethelands, to reaffirm the collaboration and also to review issues that were then still unresolved. The required null depth for observations and the implications of instability noise[36,37] were debated. The US and European performance estimates for Darwin and TPF-I still differed, and the required resolution of the array to resolve multi-planet systems was discussed.[38]

In early 2007 the TPF-C STDT, TPF-I SWG, and TPF Technology Advisory Committee were disbanded.

6.2. ESA's Cosmic Vision

The Letter of Agreement with ESA expired in December 2006. The final collaborative meeting occurred earlier that month when the ESA Terrestrial Exoplanet Science Advisory Team (TE-SAT) met in Granada, Spain.

At that time, ESA was soliciting proposals to the first round of Cosmic Vision, with proposals due at the end of June 2007. So as not to give an unfair advantage to the Darwin proposal, all NASA/ESA discussions concerning TPF-I and Darwin were suspended until after the proposals were evaluated.

By this time, the concepts for TPF-I and Darwin had already merged to a common design.[39,40] Moreover, the performance estimates for the two missions, which had previously differed, were now fully reconciled.[41] Darwin, however, was not selected for Phase A study, and that also brought to an end technology support that ESA had been providing to Darwin for more than a decade.

6.3. The Search for a New NASA Strategy

NASA was looking to rebuild a strategy for exoplanet missions that still led toward TPF, but yet placed it in the distant future. In December 2006, the National Science Foundation, NASA, and the Department of Energy established the Exoplanet Task Force as a subcommittee and chartered it to to recommend a new 15-year strategy. The intent was to provide guidance to those agencies and also to lay the groundwork for the 2010–2020 Astronomy Decadal Survey.

Their report recommended that an astrometric mission be launched within 6–10 years, followed by a microlensing mission, then a coronagraph or interferometer in 11–15 years. The course of technology development, emphasizing coronagraph or interferometers, would hinge on the frequency of Earth-like planets as estimated by Kepler.[42]

By 2007, TPF had already ceased to exist as a mission concept in NASA's planning. There was no longer a single named mission behind which the community could unite. If flagship missions were pushed to the indefinate future, it was still evident that much technology still needed to be developed even to enable smaller missions. What replaced TPF was a line of technology development that would serve the needs of the coronagraphs or interferometers might follow.

7. MILESTONES IN TPF TECHNOLOGY: 2006–2009

By 2006 both the coronagraph and the interferometer had separately undertaken mission studies, had well developed error budgets, performance models, and target lists for planet detection and characterization. Programs for general astrophysics had also been researched and documented. The mission concept for the coronagraph more advanced compared to the interferometer, because of the effort in the run-up to entering Phase A. But in 2005–2006 there were no longer the resources to sustain this effort, and work then focused on the technology testbeds.

Despite the reduction in project scope, the investments in TPF technology in previous years had now built up the testbeds and enabled a very productive period of technology progress. Highlights of this work are described in the following subsections.

7.1. Coronagraph

Laser[43, 44] and broadband[45] experiments demonstrated, to within a factor of two, that a coronagraph equipped with a band-limited mask could meet the flight requirements, and only incremental progress would be needed to attain contrasts of 10^{-10}.

A variety of competing approaches to starlight suppression were also maturing. In narrowband and broadband tests both in air and in vacuum the shaped-pupil masks achieved almost 10^{-9} contrast and mirror pairs for Phase-Induced Amplitude Apodization reached better than 10^{-6}. An optical vortex, a concept descended from the Four Quadrant Phase Mask, proved promising.

Wavefront control algorithms had progressed from theoretical concepts of implementing a dark hole with a deformable mirror[46] to practical implementations using only the science camera,[47] to more sophisticated broadband algorithms.[48]

The designs of band-limited masks were extended to include both amplitude *and* phase compensation in an attempt to correct for phase shifts inherent in the designs. A dielectric layer was added to selectively delay the phase front through the mask to balance delays introduced by the apodization.

7.2. Interferometer

Mid-infrared broadband experiments demonstrated the phase and amplitude control[49] and starlight suppression of 10^{-5} required for flight.[50] Measurements were taken for a total of 18 hours, using a bandwidth of 34% centered a 10 microns.

New single-mode mid-infrared filters were demonstrated using chalcogenide[51] and silver halide[52] materials to provide the mode-suppression required for nulling.

Formation flying algorithms for guidance, navigation and control were demonstrated in the lab using flight-like hardware.

8. DECADAL REVIEW: 2009–2010

The Decadal Review committees now face a very different task in 2010 than they did in 2000. In 2000 there was a single concept for TPF, which served to unite the astronomical community. There were no competing concepts. Ten years later, the TPF technology effort has been so successful that it has given rise to numerous competing approaches: the mid-infrared interferometer has matured, but there are now also numerous possible visible-wavelengths coronagraphs and occulters. There is no longer a single vision for TPF. This very diversity is a healthy sign of the vitality of the field, but the lack of consensus makes the task of setting priorities more challenging for the Decadal Review. The key issue is no longer feasibility, but cost.

ACKNOWLEDGMENTS

This work was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. Reference in this paper to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

REFERENCES

1. J. R. P. Angel, A. Y. S. Cheng, and N. J. Woolf, "A space telescope for infrared spectroscopy of earth-like planets," *Nature* **322**, pp. 341–343, July 1986.
2. R. N. Bracewell, "Detecting nonsolar planets by spinning infrared interferometer," *Nature* **274**, pp. 780–+, Aug. 1978.
3. C. A. Beichman ed., *A Road Map for the Exploration of Neighboring Planetary Systems (ExNPS)*, Jet Propulsion Laboratory, Pasadena, California, JPL Pub. 96-22, August 1996.
4. 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?," *Icarus* **123**, pp. 249–255, Oct. 1996.
5. P. Bely, R. Laurance, and S. Volonte eds., *Kilometric Baseline Space Interferometry: Comparison of free-flyer and moon-based versions*, European Space Agency, 8-10 rue Mario Nikis, 75738 Paris Cedex 15, France, ESA SCI(96)7, June 1996.
6. C. A. Beichman, N. J. Woolf, and C. A. Lindensmith eds., *The Terrestrial Planet Finder (TPF)*, Jet Propulsion Laboratory Publications, Pasadena, California, JPL Pub. 99-3, May 1999.
7. J. R. P. Angel and N. J. Woolf, "An Imaging Nulling Interferometer to Study Extrasolar Planets," *Astrophys. J.* **475**, pp. 373–+, Jan. 1997.
8. P. M. Hinz, J. R. P. Angel, W. F. Hoffmann, D. W. McCarthy, P. C. McGuire, M. Cheselka, J. L. Hora, and N. J. Woolf, "Imaging circumstellar environments with a nulling interferometer," *Nature* **395**, pp. 251–253, Sept. 1998.
9. P. Nisenson and C. Papaliolios, "Detection of Earth-like planets using apodized telescopes," *Astrophys. J.* **548**, pp. L201–L205, 2001.
10. D. N. Spergel, *A New Pupil for Detecting Extrasolar Planets*, astro-ph, ArXiv Astrophysics e-prints, 2001. arXiv:astro-ph/0101142.
11. E. Serabyn and M. M. Colavita, "Fully symmetric nulling beam combiners," *Appl. Opt.* **40**, pp. 1668–1671, 2001.
12. M. J. Kuchner and W. A. Traub, "A coronagraph with a band-limited mask for finding terrestrial planets," *Astrophys. J.* **570**, pp. 900–908, 2002.
13. M. J. Kuchner and D. N. Spergel, "Notch-Filter Masks: Practical Image Masks for Planet-finding Coronagraphs," *Astrophys. J.* **594**, pp. 617–626, Sept. 2003.
14. D. J. Des Marais, M. Harwit, K. Jucks, J. F. Kasting, J. I. Lunine, D. Lin, S. Seager, J. Schneider, W. Traub, and N. Woolf, *Biosignatures and Planetary Properties to be Investigated by the TPF Mission*, Jet Propulsion Laboratory Publications, Pasadena, California, JPL Pub. 02-11, June 2002.
15. D. J. Des Marais, M. O. Harwit, K. W. Jucks, J. F. Kasting, D. N. C. Lin, J. I. Lunine, J. Schneider, S. Seager, W. A. Traub, and N. J. Woolf, "Remote Sensing of Planetary Properties and Biosignatures on Extrasolar Terrestrial Planets," *Astrobiology* **2**, pp. 153–181, June 2002.
16. C. A. Beichman, D. R. Coulter, C. A. Lindensmith, and P. R. Lawson eds., *Summary Report on Architecture Studies for the Terrestrial Planet Finder*, Jet Propulsion Laboratory Publications, Pasadena, California, JPL Pub. 02-11, June 2002.
17. C. A. Lindensmith ed., *Technology Plan for the Terrestrial Planet Finder*, Jet Propulsion Laboratory Publications, Pasadena, California, JPL Pub. 03-007, March 2003.
18. O. Guyon, "Phase-induced amplitude apodization of telescope pupils for extrasolar terrestrial planet imaging," *Astron. Astrophys.* **404**, pp. 379–387, June 2003.
19. V. Galindo, "Design of dual reflector antennas with arbitrary phase and amplitude distributions," *IEEE Trans. Antennas Propagat.* **AP-12**, pp. 403–408, 1964.
20. O. Lay, M. Jeganathan, and R. Peters, "Adaptive nulling: a new tool for interferometric exo-planet detection," in *Towards Other Earths: DARWIN/TPF and the Search for Extrasolar Terrestrial Planets*, M. Fridlund and T. Henning eds., eds., *ESA SP* **539**, pp. 503–506, 2003.
21. C. A. Henry ed., *Proceedings of the Darwin / Terrestrial Planet Finder Interferometer Design Workshop*, Jet Propulsion Laboratory Publications, Pasadena, California, JPL Pub. 04-3, February 2004.
22. A. Quirrenbach, *Coronographic Methods for the Detection of Terrestrial Planets*, astro-ph, Leiden Observatory, The Netherlands, 2005. http://arXiv.org/abs/astro-ph/0502254.

23. R. A. Brown, "Single-visit photometric and obscurational completeness," *Astrophys. J.* **624**, pp. 1010–1024, 2005.
24. O. P. Lay, S. R. Martin, and S. L. Hunyadi, "Planet-finding performance of the TPF-I Emma architecture," in *Techniques and Instrumentation for Detection of Exoplanets III*, D. R. Coulter, ed., *Proc. SPIE* **6693**, p. 66930A, 2007.
25. P. R. Lawson, S. C. Unwin, and C. A. Beichman eds., *Precursor Science for the Terrestrial Planet Finder*, Jet Propulsion Laboratory Publications, Pasadena, California, JPL Pub. 04-14, October 2004.
26. P. R. Lawson and W. A. Traub eds., *Earth-like Exoplanets: The Science of NASA's Navigator Program*, Jet Propulsion Laboratory, Pasadena, California, JPL Pub. 06-5, October 2006.
27. J. A. Dooley and P. R. Lawson eds., *Technology Plan for the Terrestrial Planet Finder Coronagraph*, Jet Propulsion Laboratory Publications, Pasadena, California, JPL Pub. 05-8, March 2005.
28. M. J. Kuchner, J. Crepp, and J. Ge, "Eighth-Order Image Masks for Terrestrial Planet Finding," *Astrophys. J.* **628**, pp. 466–473, July 2005.
29. S. B. Shaklan and J. J. Green, "Low-Order Aberration Sensitivity of Eighth-Order Coronagraph Masks," *Astrophys. J.* **628**, pp. 474–477, July 2005.
30. P. R. Lawson and J. A. Dooley eds., *Technology Plan for the Terrestrial Planet Finder Interferometer*, Jet Propulsion Laboratory Publications, Pasadena, California, JPL Pub. 05-5, June 2005.
31. Committee on Astronomy and Astrophysics, *Review of Science Requirements for the Terrestrial Planet Finder: Letter Report*, National Academies Press, Washington, DC, 2004. http://books.nap.edu/catalog.php?record_id=11105.
32. O. P. Lay, S. M. Gunter, L. A. Hamlin, C. A. Henry, Y. Li, S. R. Martin, G. H. Purcell, B. Ware, J. A. Wertz, and M. C. Noecker, "Architecture trade study for the Terrestrial Planet Finder Interferometer," in *Techniques and Instrumentation for Detection of Exoplanets II*, D. R. Coulter, ed., *Proc. SPIE* **5905**, pp. 8–20, 2005.
33. V. Ford ed., *TPF Coronagraph Flight Baseline 1 Design Interim Status Report*, Jet Propulsion Laboratory, Pasadena, California, 2005. http://planetquest.jpl.nasa.gov/documents/TPFC-FB1_Report.pdf.
34. M. Levine, S. Shaklan, and J. Kasting eds., *Terrestrial Planet Finder Coronagraph Science and Technology Definition Team (STDT) Report*, Jet Propulsion Laboratory Publications, Pasadena, California, JPL Document 34923, June 2005.
35. P. R. Lawson, O. P. Lay, K. J. Johnston, and C. A. Beichman eds., *The Terrestrial Planet Finder Science Working Group Report*, Jet Propulsion Laboratory, Pasadena, California, JPL Pub. 07-1, March 2007.
36. O. P. Lay, "Systematic errors in nulling interferometers," *Appl. Opt.* **43**, pp. 6100–6123, 2004.
37. O. P. Lay, "Removing instability noise in nulling interferometers," in *Advances in Stellar Interferometry*, J. D. Monnier, M. Schöller, and W. C. Danchi, eds., *Proc. SPIE* **6268**, p. 62681A, 2006.
38. O. P. Lay, "Imaging properties of rotating nulling interferometers," *Appl. Opt.* **44**, pp. 5859–5871, 2005.
39. P. R. Lawson, O. P. Lay, S. R. Martin, C. A. Beichman, K. J. Johnston, W. C. Danchi, R. O. Gappinger, S. L. Hunyadi, A. Ksendzov, B. Mennesson, R. D. Peters, D. P. Scharf, E. Serabyn, and S. C. Unwin, "Terrestrial Planet Finder Interferometer: 2006-2007 progress and plans," in *Techniques and Instrumentation for Detection of Exoplanets III*, D. R. Coulter, ed., *Proc. SPIE* **6693**, p. 669308, 2007.
40. C. S. Cockell, A. Leger, M. Fridlund, T. Herbst, L. Kaltenegger, O. Absil, C. Beichman, W. Benz, M. Blanc, A. Brack, A. Chelli, L. Colangeli, H. Cottin, V. Coude du Foresto, W. Danchi, D. Defrere, J.-W. den Herder, C. Eiroa, J. Greaves, T. Henning, K. Johnston, H. Jones, L. Labadie, H. Lammer, R. Launhardt, P. Lawson, O. P. Lay, J.-M. LeDuigou, R. Liseau, F. Malbet, S. R. Martin, D. Mawet, D. Mourard, C. Moutou, L. Mugnier, F. Paresce, A. Quirrenbach, Y. Rabbia, J. A. Raven, H. J. A. Rottgering, D. Rouan, N. Santos, F. Selsis, E. Serabyn, H. Shibai, M. Tamura, E. Thiebaut, F. Westall, and J. G. White, "Darwin - a mission to detect, and search for life on, extrasolar planets," *Astrobiology* **8**, p. accepted, 2008.
41. D. Defrere, O. Lay, R. den Hartog, and O. Absil, "Earth-like planets: science performance predictions for future nulling interferometry missions," *Optical and Infrared Interferometry* **7013**(1), p. 701321, SPIE, 2008.
42. Exoplanet Task Force, *Worlds Beyond: Report of the Exoplanet Task Force*, National Academy of Sciences, Washington, DC, May 2008.

43. J. Trauger, B. Kern, and A. Kuhnert eds., *TPF-C Technology Milestone #1 Report*, Jet Propulsion Laboratory Publications, Pasadena, California, JPL Document 35484, 10 July 2006.
44. J. T. Trauger and W. A. Traub, "A laboratory demonstration of the capability to image an Earth-like extrasolar planet," *Nature* **446**, pp. 771–773, 2007.
45. B. Kern, A. Kuhnert, and J. Trauger eds., *Exoplanet Exploration Technology Milestone #2 Report*, Jet Propulsion Laboratory Publications, Pasadena, California, JPL Document 60951, 8 August 2008.
46. F. Malbet, J. W. Yu, and M. Shao, "High-Dynamic-Range Imaging Using a Deformable Mirror for Space Coronography," *Pub. Astron. Soc. Pac.* **107**, pp. 386–+, Apr. 1995.
47. P. J. Bordé and W. A. Traub, "High-contrast imaging from space: speckle nulling in a low-aberration regime," *Astrophys. J.* **638**, pp. 488–498, 2006.
48. A. Give'on, B. Kern, S. Shaklan, D. C. Moody, and L. Pueyo, "Broadband wavefront correction algorithm for high-contrast imaging systems," *Astronomical Adaptive Optics Systems and Applications III* **6691**(1), p. 66910A, SPIE, 2007.
49. R. D. Peters, O. P. Lay, and M. Jeganathan, "Broadband phase and intensity compensation with a deformable mirror for an interferometric nuller," *Appl. Opt.* **47**, pp. 3920–3926, 2008.
50. R. D. Peters, O. P. Lay, and P. R. Lawson, "Mid-infrared adaptive nulling for the detection of Earth-like exoplanets," *Pub. Astron. Soc. Pac.* **121**, p. submitted, 2009.
51. A. Ksendzov, O. Lay, S. Martin, J. S. Sanghera, L. E. Busse, W. H. Kim, P. C. Pureza, and V. Q. Nguyen, "Characterization of mid-infrared single mode fibers as modal filters," *Appl. Opt.* **46**, pp. 7957–7962, 2007.
52. A. Ksendzov, T. Lewi, O. Lay, S. Martin, R. Gappinger, P. Lawson, R. Peters, S. Shalem, A. Tsun, and A. Katzir, "Modal filtering in mid-infrared using single mode silver halide fibers," *Appl. Opt.* **47**, p. submitted, 2008.