

COMPARISON OF SEVERAL CORONAGRAPHIC APPROACHES TO THE TERRESTRIAL PLANET FINDER*

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1. HIGH DYNAMIC RANGE IMAGING AND GENERALIZED CORONOGRAPHY

Planetological and technical issues have led to a renewed interest in visible coronagraphic concepts for a Terrestrial Planet Finder mission. This has stimulated rapid development of new, generalized coronagraphic techniques, including exotic apodizations and nulling schemes. Hitherto, it has been difficult to compare different concepts, owing to the complex interaction between details of the concepts and instrument and mission parameters and optimization.

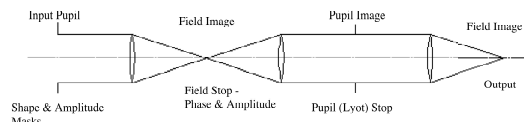


Fig. 1: The term Generalized Coronagraphy is adopted to describe a coronagraphic system incorporating advanced beam and field tailoring options such as: apodization selectable by aperture shape and aperture transmission profile, or by pupil redistribution, amplitude and phase focal plane masks, selectable Lyot stops, and multiple stage implementation.

2. THE STUDY

Our team has carried out a detailed comparison of three concepts: an apodized square aperture, a Gaussian Spergel/Kasdin aperture, and a classical Lyot coronagraph with graded field mask. The techniques used are physical optics modeling including Fraunhofer and Fresnel propagations, signal-to-noise analysis, structural and thermal modeling, ray tracing, error-budget and figure of merit models.

3. THE RESULTS

Each concept was optimized with respect to such parameters as the apodization description and the stop size. Among the most useful results are the resulting PSF as a function of optical surface quality.

Additional details of the study and of the results will be found in Lyon et al (Ref. [3]). Further discussion of recent developments in coronagraphy will be found in Ref. [4].

*Work under contract to JPL, contract No. 1242231

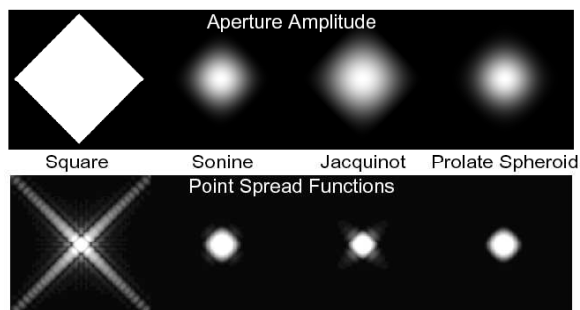


Fig. 2: Apodized Square Apertures and point spread functions (Fourier modeling)

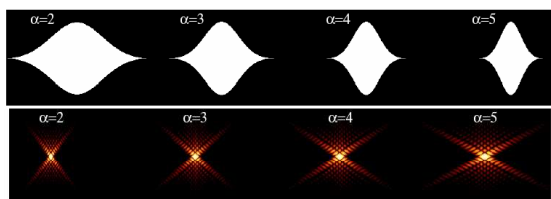


Fig. 3: Gaussian Apertures and point spread functions (Fourier modeling)

4. THE CONCLUSIONS

For the three concepts compared, with a fixed maximum aperture dimension of 4m, the Soft-edged Lyot coronagraph offers distinctly higher performance than either the apodized square aperture or the Spergel/Kasdin aperture concepts. The reason is, basically, that the apodized concepts considered here (but see below) incur a loss in angular resolution and in throughput and have greater sensitivity to both low- and mid-spatial frequency wavefront error. Angular resolution and throughput losses can only be mitigated against with an increased aperture diameter to carry out a given program. The classical Lyot, with its higher angular resolution, and for some source geometries higher throughput, can achieve sufficient PSF suppression and wavefront suppression to provide higher net performance.

As an illustration, our calculated estimate for the number of stars that could be searched for terrestrial planets with the three techniques in a 2.5 year mission, employing $\lambda/10000$ optics, is shown in Table 1.

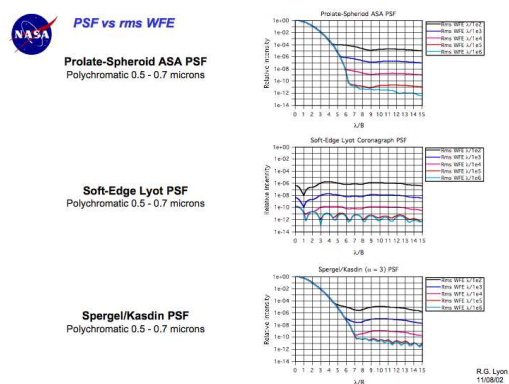


Fig. 4: Examples of point spread functions for systems with varying degrees of wavefront error.

This shows the relative superiority of the Lyot concepts in this comparison, as well as the significant potential for a modest aperture telescope in pursuing the TPF mission.

Table 1. The number of stars which could be searched for terrestrial planets during a 2.5 year mission

Lyot	57
ASA	9
Gaussian	7

In addition, the Lyot and apodized techniques differ in their sensitivity to low order aberrations, including pointing errors, so there are concept-dependent system issues to be considered in the detailed design of telescope-spacecraft performance.

5. CONTINUING AND FUTURE DEVELOPMENTS

Already since this study was carried out, new exciting concepts and results are available which require further analysis. A new concept for apodization (Guyon et al, poster at this conference) will provide the suppression of the PSF wings with no resolution or throughput loss. Multiple stage coronagraphic correction (Labeyrie et al, Ref. [2]) promises a robust approach to suppression of residual PSF speckle. New analytical techniques are clarifying the optimization of hybrid concepts such as apodized nulling and Lyot systems (Aime et al, Ref. [1] and Soummer et al, Ref. [5]). Considerable work remains in fully exploring and optimizing coronagraphic telescopes with these new tools.

6. THE TEAM

SVS (later Boeing-SVS) formed a team to carry out a study of concepts for the Terrestrial Planet Finder. This study came to the conclusion that a visible filled aperture concept could offer the first and most plausible opportunity for a major TPF mission. During the study, team members developed several new concepts for High Contrast Imaging. Subsequently, a second Boeing-SVS team formed to carry out a comparative study of the leading contenders in this area. Phase I of this study has been completed.

7. REFERENCES

1. Aime,C.,Soummer,R., and Ferrari,A., 2002, Total coronagraphic extinction of rectangular apertures using linear prolate apodizations, *Astronomy and Astrophysics*, Vol. 389, 334-344.
2. Labeyrie, A., H. Le Coroller, J. Dejonghe, F. Martinache, V. Borkowski, O. Lardi re, L. Koechlin, 2003, Hypertelescope Imaging: from exo-planets to neutron stars, *Interferometry in Space*, Michael Shao, editor, Proceedings of SPIE Vol. 4952, 206.
3. Lyon, R.G., Hollis, J.M., and Dorband, J.E., 2003, Comparative Optical Analysis of Extra-Solar Planetary Imaging Techniques, in *High-Contrast Imaging for Exo-Planet Detection*, Alfred B. Schultz, Richard G. Lyon, Editors, Proceedings of SPIE Vol. 4860, 251.
4. Ridgway, S.T., 2003, Filled Aperture Concepts for the Terrestrial Planet Finder, in *Interferometry in Space*, Michael Shao, Editor, Proceedings of SPIE Vol. 4852, 210.
5. Soummer,R., Aime,C., and Falloon,P.E., 2003, Stellar coronagraphy with prolate apodized circular apertures, *Astronomy and Astrophysics*, Vol. 397, 1161.