

Direct Detection of Extra-Solar Planetary Systems From Balloon Borne Telescopes

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Abstract

Analysis of a 1.5 meter diameter High Altitude Balloon Circumstellar Imaging Telescope (HABCIIT) indicates that it offers a fast and low cost path to direct detection of extra-solar planets. Above an altitude of about 30 kilometers, scatter in the visible due to the atmosphere is more than 1000 times smaller than the diffraction sidelobes for a 1.5 meter telescope at 1 arcsecond in the visible. This permits a thousandfold reduction in the total background against which the planet must be detected. By flying a scatter compensated 1.5 meter telescope and high efficiency coronagraph on a balloon platform, a very near term and low cost opportunity exists to achieve exciting scientific results and technology demonstrations. For a thousandfold reduction in the background, Jupiter could be detected around more than 70 stars with an average integration time of 16 hours. For the very nearest stars complete planetary systems can be characterized down to nearly Earth sized planets.

Balloon flights up to three weeks long at altitudes of 38-40 km are possible from both Inuvik, Canada or Antarctica with a total permitted payload of 3000 pounds. Borrowing the detailed studies of the AIT telescope it appears that the weight budget of a high altitude platform could be met with modest weight saving measures. Several important technologies can also be demonstrated including, high efficiency coronagraphs for the reduction of diffracted light and

either scatter compensated figuring or adaptive mirrors for the control of scattered light.

The CIT Concept.

The Circumstellar Imaging Telescope (CIT) [1,2] has been specifically designed for the planet search problem in that it minimizes the stellar scattered and diffracted light (while maximizing the planet encircled energy). Because of this optimization it is a robust planet detection instrument with only a 1.5 meter aperture. The telescope has been under development for the past eight years [cf. 3] and studies have included systems engineering reviews and technology demonstrations [4]. Its single imaging instrument is a high efficiency coronagraph [5] designed to reduce stellar diffracted light by a factor of 10,000.

The optical system is keyed to the coronagraph so that within its 5-7 arcsecond field of view the total residual light in the focal plane which consists of scattered and residual diffracted light is 1000 times less than it was without the coronagraph. Optical performance at the required level has already been demonstrated in the breadboard coronagraph at the IDOS [6] and is illustrated in Figure 1. The CIT goal requires a reduction in scatter by a factor just over 1000 or a mid-frequency figure error that is about 15 times smoother than that of the Hubble Space Telescope.

It is important to note that the thousandth wave figure requirement applies solely to mid-frequency errors in the telescope. More than eight years of study and experiments has shown that in every other way the telescope requirements are no different than those of a basic diffraction limited telescope of the same aperture. In particular, telescope alignment requirements do not enter into the

residual scattered light budget. This is due in part to the fact that the coronagraph continues to work and in fact compensates for the scatter consequences of low order aberrations like those associated with focus, secondary alignment, or conic mismatch. This was conclusively shown with both models and experiments [7].

Scatter Compensated Optics.

The key to achieving the low scatter required for the CIT is to realize that it is required only over a limited field of view. In terms of figure errors leading to scatter, this means only over a limited range of spatial frequency (5-50 cycles per aperture). Because these are essentially long period errors they can be viewed as resulting from coherent addition of primary and secondary mirror errors and can be corrected by using one optic to negate the errors of the other. Figure 2 shows the geometry for phase compensated optical manufacture. Each scatter compensating optic is figured to $\lambda/100$ and the individual elements are then brought together and tested as a system. This test is autocollimating and requires no null corrector. The only auxiliary optics (a flat (f-) and a sphere (S)) can be calibrated absolutely (for the AXAF program a flat was calibrated at the Angstrom level). The test is double pass so that the error signal is doubled with respect to the auxiliary optics, doubling the sensitivity. Furthermore no separate error budget entries are needed for primary and secondary mirrors and no rssi'ng of the two is required, Phase error cancellation on one optic by the other at the 90% level results in a thousandth wave optical system and puts a scattered light "hole" within 5 arcseconds of an on-axis source. Over larger field angles the scattered light halo degrades smoothly from the coherent sum of the two optics to their incoherent sum (i.e. from a thousandth wave halo to a hundredth wave halo).

In order for phase compensation to occur it is necessary that the secondary mirror be held in a particular position with respect to the secondary. This has been calculated to be in excess of 100 microns which exceeds the normal alignment tolerance for just maintaining diffraction limited performance. The idea of phase cancellation is not new (the secondary mirror of a R-C telescope corrects the spherical aberration generated by the hyperbolic primary) but this application extends it to a larger range of spatial frequencies. CIT metrology in general has been studied as part of a PDDP grant (1 IDOS Project Report B11-0348) and this idea in particular has been analyzed optically, with error budgets developed for the interferometer, auxiliary optics and secondary mirror alignment requirements (1 IDOS Tech Memo -AIT Metrology, 1992). The latter analysis showed that the requirements on knowledge of the auxiliary optics and the interferometer were within the levels either already achieved at 1 IDOS or reported in the literature elsewhere.

Should high spatial bandwidth adaptive mirrors become readily available, an alternative path for CIT development is to use slow adaptive correction of the wavefront. This offers potential weight and cost savings with a likely penalty in field of view. Five arcseconds of quality FOV in CIT corresponds to a Nyquist frequency of 60 cycles per aperture requiring about 3000 actuators assuming modest optical bandwidth requirements. This requires small high density, high finesse actuators with placement in an adaptive secondary the like choice since even for 0.5mm actuator spacing the adaptive mirror would need to be 0.3m in diameter.

Planet Detection With CIT

The performance of a 1.5 meter CIT has been studied as part of the Astrometric Imaging Telescope project (AIT). The CIT has superior

performance than the All" since its unobscured optics allow far more throughput (nearly a factor of ?) anti greater encircled energy for the candidate planet (about a factor of ?). A 1.5 meter CIT allows the direct detection of Jupiter-sized planets around more than 70 stars with an average integration time of 16 hours and would also permit detection of Neptune sized objects around 14 stars. All detections are broad band and the entire field of view is searched simultaneously. More importantly from the point of view of the study of planetary systems is that in 200 hours of integration around the nearest stars a region the size of our own solar system (out to 30 AU for example) could be searched for planets smaller than Neptune in diameter. For the closest stars this limit can be reduced to objects very near the Earth in diameter. Thus the telescope can made significant statements not only about the abundance of Jupiter's but also about the entire spectrum of planets down the nearly Earth size objects, Rotation of the telescope would smooth the background further permitting of order 100 Jupiter detections with an average integration-I time of ?0 hours. Increasing the aperture would also produce a dramatic increase in performance.

Balloon Program:

The essential assumption of the CIT is that the incoming wavefront has negligible phase errors compared to the CIT requirement. This permits reducing the telescope scatter to the point where planet detection becomes possible and argues for a space borne platform. The smooth incident phase condition, however, can also be met at high attitudes. Analysis of balloon data by R. Hufnagel (private communication) has shown that at altitudes in excess of 30km the atmospheric scatter produced at one arcsecond is less than one thousandth of diffraction. Since the atmospheric power spectrum is steeper than that typical of optics it follows that over the CIT field of view telescope

phase errors will be the dominate source of scatter. Note that baseline CIT pointing calls for jitter correction using the secondary mirror (already calculated to be within the budget for scatter compensated fabrication) and the rejected stellar image from the reflecting occulting mask. Ibis would automatically take out platform jitter and any residual atmospheric tilt components. The CIT balloon concept is an early, relatively low cost experiment with enormous scientific returns:

1. It would search for Jupiter sized planets around seventy stars and examine the circumstellar regions for disks, Zodiacal components etc.
2. It would (with only a 2 hour integration) image the Alpha Centauri system with enough sensitivity to find earthlike planets.
3. It would complete its survey in a 3-4 year program from today.
4. It would provide direct planetary detection for only a fraction of the cost of a space mission.
5. It would validate technologies and reduce the risk of any future mission using this technology.
6. It would provide early exciting results which would help gain scientific public support.

The telescope itself would be available for use on other platforms and could be eventually flown as an attached Shuttle payload. No detailed cost numbers have been run for the balloon experiment but a rough order of magnitude estimate is 20 M\$.

NASA and NSF currently support the National Scientific Balloon Facility. There are currently five sites where flights are conducted with the following characteristics (balloon information from Herb Pickett, JPL and Danny Ball, NASA National Scientific Balloon Facility):

Location	Payload (lb)	Altitude	Duration
Palestine, Texas:	6000	38-40	12 hours
Fort Sumner, New Mexico	8000	34-35	24 hours
Alice Springs, Australia	6000	38-40	24 hours
Antarctica	3000	38-40	1-3 weeks
Inuvik, Canada	3000	38-40	1-3 weeks

Mass numbers for circumpolar flights (Antarctica and Canada) are science payload numbers, all others are total mass of science plus gondola.

Recovery technology has improved over the years so that currently 98% of payloads are recovered for reflight undamaged. The largest balloons available are about 40 million cubic feet and will lift 2-3 tons to 38-40 km. The Canadian launch site is new and particularly attractive in that payloads are recovered downrange in Greenland with no delay. Particularly exciting and relevant to the CIT program is the development of long duration balloon flights [8]. NASA is working to develop tougher balloon materials that could permit circumpolar flights with hundred day duration. This would render balloons as the premier diffraction limited science platform and make balloon borne planet detection extremely attractive.

As part of the ongoing AIT definition study a weight budget was generated for the spacecraft by a JPL team of experts in each field of spacecraft design.

The balloon relevant components are repeated below:

<u>Component</u>	<u>Mass (Kg) (from AIT Final Report 1993 JPL)</u>
Science Instrument	41
Optical telescope Assembly Optics, metering truss, baffles, main ring	1068
Power Batteries, limiters, charge control monitors, pyro driver etc.	58
Telecomm Transponder, low gain antenna etc.	10
Structure: Door	15
Light shield	?1
Thermal: MI 1, louvers and radiators, heaters, TE coolers etc.	174
TOTAL	1387 kg 3058 lb

Many of the components are probably over-designed for balloon altitudes and some may need strengthening but this careful study has shown that a telescope meeting balloon requirements is possible without heroic weight saving measures. The payload was not developed with a strict weight constraint in mind and could be reduced further. A similar study to that which defined the spacecraft parameters is required to better define the payload weight,

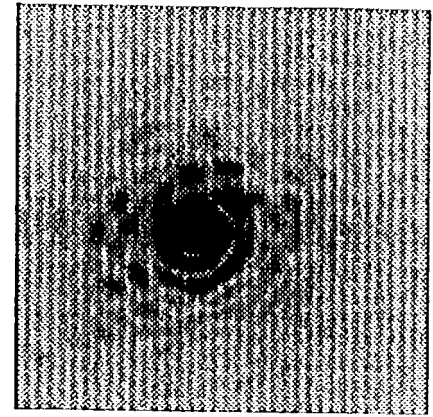
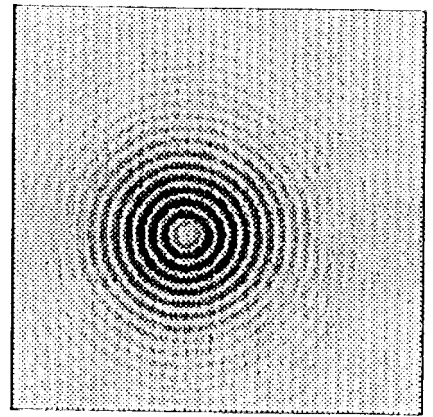
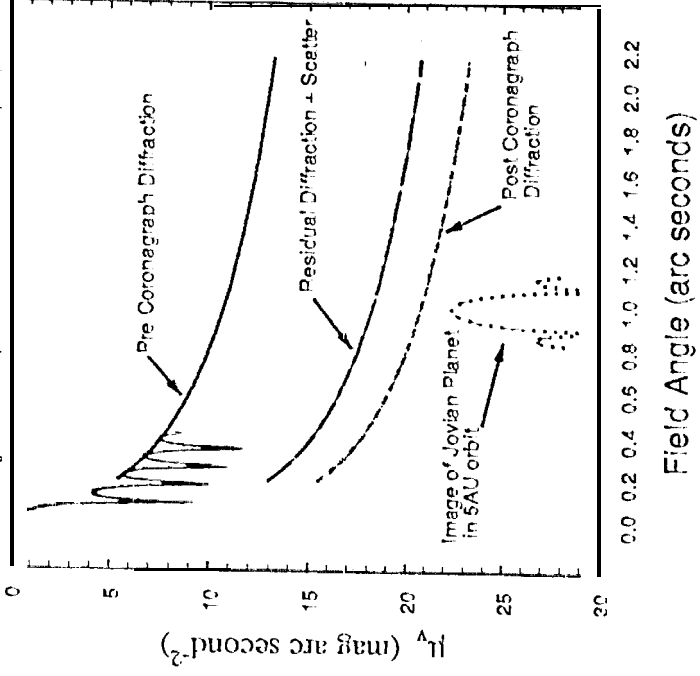
Conclusion.

CIT is a quick way to significant breakthroughs in planet detection. It is relatively compact with fast detections because it was designed specifically for this task. Study of its unique optical system have concluded that it is within the scope of current technology with many aspects already demonstrated. A very fast path to pictures of planetary systems is offered by the possibility of

putting the CIT telescope on a high altitude balloon platform. Borrowing the detailed studies of the All telescope it appears that the weight budget of a high altitude platform could be met with modest weight saving measures.

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Detection of Jovian Planet by Direct Imaging
 Star is $m_V=5$ at 5pc, 1.5m Telescope, $\lambda=0.6\mu m$



The image on the left has been occulted by a tapered transmission occulting mask whose 50% transmission point is at $4\lambda/D$. There is no Lyot stop. Note that imaging is possible through the mask. In the figure on the right both an occulting mask and Lyot mask are in place completing the coronagraph. The difference in the exposure parameters of the two images is such that if the exposure on the left was 1 second, the one on the right would be 25 minutes. This demonstrates the required total diffraction reduction of 10^3 . (Images taken in the HDOS coronagraph laboratory.)

Phase Compensated Optical Manufacture

Makes maximum utility of the small angle nature of the problem

Bring $\frac{\lambda}{100}$ primary and secondary to $\frac{\lambda}{1000}$ system.

- Double pass test.
- No null corrector
- Only one high accuracy test
- Single error budget entry

Results in scattered light "hole" around each point in field.

"Hole" degrades gracefully from coherent sum to incoherent sum of optics with field angle.

