Flat mirror optics to study extra-solar terrestrial planets from space

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Abstract. NASA is planning the Terrestrial Planet Finder (TPF) mission to find and study Earth-like planets of other stars. Its goal is to detect directly their thermal radiation, and it will have the spectroscopic sensitivity to find strong atmospheric features, such as atmospheric water vapor (indicating oceans) and chemical signs of life, like Earth's biogenically-generated ozone. The TPF configuration currently under study is similar to ground based interferometers, with an array of afocal telescopes relaying beams to a central interferometric station where destructive interference of the starlight allows detection of the much fainter planetary signal. In this paper we consider a different implementation strategy which fully exploits the space environment. The primary optical elements are simply free flying flat mirrors made from thin stretched membrane of gossamer weight. The constellation of flats would be viewed by a single wide-field telescope with aperture no bigger than one flat, separately orbiting some distance away. Starlight directed from all the flat elements into the viewing telescope would be combined at the focal plane by small-scale interferometer optics. At the size envisaged for TPF, four 4-m flats in a 100-m constellation would be viewed by a 4-m telescope several km distant. A more powerful interferometric successor, well suited for detailed atmospheric studies of the most promising planets found by TPF, would have a dozens of 8 m flats reflecting into a single, NGST-sized combining telescope. The use of flat primary elements to study extra-solar planets is not limited to interferometry. True imaging telescopes with very large, nearly-filled aperture can be made with a primary collector synthesized from many flat segments, and the wavefront corrected at a scalloped tertiary mirror.

1. Introduction

During the last several years, more than 25 planets with masses like Jupiter's or somewhat heavier have been discovered around other stars, mainly from Doppler measurements (Marcy and Butler, 1999). Terrestrial mass planets are not heavy enough to be detectable by these methods. They should however be detectable through their thermal emission, and NASA is planning the Terrestrial Planet Finder mission for launch in 2011 to make a search in this way. The hope is to find planets which are like the Earth, not only in their mass, their orbit about a star like the sun and their temperature, but in showing the presence of oceans through water absorption in their thermal atmospheric spectra. One might even be found showing the same strong absorption feature of ozone that on our Earth is produced by life (Angel, Cheng and Woolf, 1986). TPF will have the sensitivity to start such atmospheric analysis through spectroscopy. Obviously if planets with spectroscopic indications of abundant life are found, there will be a strong desire to make further, more detailed observations with larger instruments.

Direct detection and spectroscopy of extra-solar planets is a daunting proposition, largely because they must be seen in the presence of a far brighter star very close by. For Earth-like planets whose water is in the liquid phase, detection of thermal emission is preferred over reflected starlight, because the contrast ratio is 1000 times more favorable. Carbon dioxide, water and ozone also have strong distinctive absorption features near the thermal peak. But even with a good coronagraph, a filled aperture telescope would have to be ≥ 50 m in diameter to distinguish a planet in a system at a distance of 10 pc, given the expected contrast ratio of around ten million. With such a telescope there would be strong enough flux of planetary light to obtain high resolution atmospheric spectra. But for the initial goal of finding Earth-like planets and obtaining crude spectra, the large aperture is overkill. TPF has thus adopted the method of interferometric nulling, which requires far smaller total aperture. Proposed by Bracewell (1978), this method was recently proven when it was used to obtain images of the thermal emission from the dust nebula around Betelgeuse (Hinz et al, 1998). Starlight arriving at two separate apertures is combined with inverted phase so as to interfere destructively, while at the same time light from the planet, which comes from a slightly different angle, interferes constructively. In this way strong star rejection of thermal emission from a star only 1/10 arcsec from a planet can be realized with small apertures separated by only 10 m. For TPF, multiple small apertures over a bigger total baseline will be used to obtain more effective nulling and true imaging, (Angel and Woolf, 1997), but the principle is the same. The price paid for the reduced collecting area is long integration times of weeks to obtain a spectrum with enough sensitivity to find even a strong feature like ozone at the level seen in Earth's spectrum. Larger interferometers or filled aperture telescopes will ultimately be needed to obtain better quality planetary spectra.

A summary of the requirements for detecting signatures of life on extra-solar planets may be found in the recently published NASA book, Terrestrial Planet Finder (Beichman, Woolf and Lindensmith, 1999). The concept described in this paper was first presented at the Ultra Lightweight Space Optics Challenge Workshop in Napa, CA., whose proceedings are available only on a web site (Angel, Burge and Woolf, 1999).

2. Large space optical systems made with flat mirrors

Space telescopes have not yet evolved to take advantage of the space environment. The Hubble Space Telescope is basically the 100-year-old Mt Wilson telescope placed in space. No interferometer has yet been operated in space. But free from the wind and distortion of our atmosphere, and set free from ever changing gravity force of the turning Earth, telescopes could be built to great size as multiple free-flying elements of gossamer structure. In this way the huge dimensions needed for the sharpest diffraction limited images and highest sensitivity should be achievable.

Our new concept to realize such telescopes is to use flat mirrors as the primary optical elements. It is applicable both to interferometers and to filled aperture telescopes of large diameter. In the past, figured concave mirrors have always been used for the primary elements, and indeed they are still required to form images. But flats can be of much simpler and lighter construction, and will allow us to greatly augment the collecting power and resolution of a conventional telescope, by directing more light into it from the target object. Multiple flat mirrors would be used in the same way they are to concentrate flux on a solar power tower, except the individual flats would be of high quality. The overlapping beams arriving at the quasi-focus would then be collected and sorted out with the aid of a wide field telescope. With an aperture no bigger than one flat segment, this single telescope brings the light from all the flats to individual focal points across its wide field. Small, auxiliary optics then combine the light from the different images interferometrically or even to form a single, high quality, diffraction-limited image.

The point of such optical systems is to avoid the need for large figured surfaces, so that large telescope collecting area in space can potentially be made much lighter and cheaper. The simplification arises because a flat is the natural, stable shape of gossamer thin reflecting material when placed under tension from a plane perimeter. There would be little gain if the supporting structure, which has to maintain the perimeter to optical flatness, were itself heavy. But by defining the perimeter by a set of discrete actuated points we can make the support from ultra-lightweight members, and use servo controlled actuators to maintain flatness. Active control is thus an integral part of the concept, both to sense wavefront aberrations across each element, and to correct tilt and phase errors when combining the different wavefronts. Correction signals will be relayed back to the individual elements as necessary.

2.1. Interferometers made from flats

Bracewell's original concept for a nulling interferometer used two elements, rotated about the line of sight to modulate the planet signal. Nulling with 4 or more elements is preferred for planet detection because of improved star cancellation. In general, the more elements the more perfect the nulling, and the greater our ability to reject systematic errors by phase modulation rather than rotation. Terrestrial Planet Finder is planned to have 4 elements. In the present concept the elements consists of conventional afocal telescopes with curved primary and secondary mirrors. Their output beams of reduced diameter are directed to a beam combiner at the center of the interferometer array. Here small, flat mirrors are used to bring all the beams in phase and parallel at the entrance to a beam-combining telescope, whose area must thus be equal to that of all the incoming beams combined.

In the new concept, the individual interferometer elements will be free-flying flats, in formation so as to be tangent to a paraboloidal surface with long focal ratio. The reflected starlight beams are directed to a separate spacecraft at the quasi-focus where they arrive in phase, with no additional path correcting reflections needed. The wide field telescope at the focus with aperture the same size as the single flat elements, forms multiple separated star images at its focal plane, one from each flat. It also forms behind these images a small scale image of the constellation of flat mirrors. Small scale interferometer optics are used here to collimate and combine the beams with the desired phase relationships. These optics are essentially a small scale version of what has been devised already for full scale interferometers.

2.2. Filled aperture telescopes

The idea can be extended to make a large filled aperture telescope as follows. Suppose the flats are densely packed to approximate a continuous paraboloidal surface, like the Keck telescope except that each segment is flat instead of an off-axis paraboloid. The tiled surface actually may approximate a long focal ratio paraboloid quite well. As an example, the surface of a 100 m mirror of 10 km focal length synthesized from 6 m flat segments will deviate from the ideal shape by +/- 0.1 mm, the error being in the form of dips at the segment edges. The wavefront reflected from the mosaic will be distorted in a quilted pattern of bumps, small enough that the images would be diffraction limited at 3 mm wavelength, rivaling the performance of the 100 m GBT! To make diffraction limited images at shorter wavelengths, we must use auxiliary optics to correct the wavefront error. As in the interferometer configuration discussed above, a wide field telescope will form an image of the segmented primary, but in this case a specially shaped tertiary mirror located at this image will be used to introduce an equal but opposite wavefront error. The mirror will take the form of scalloped segments, each scallop coincident with the image of an individual flat segment of the primary. The scallop edges (which are high) register with the objective segment edges, which are low. The amplitudes are made equal and opposite, so that the wavefront reflected by the tertiary is smooth. This is exactly the same principle by which the manufacturing error of the HST primary has been corrected. In addition, the tertiary will be given an overall concave shape, so the corrected wavefront is brought to a focus as a single star image.

3. Some basic design considerations

3.1. Orbits

Since weeks or even months may be required to obtain high sensitivity observations of a single planetary system, the constellation of flats and the collector must maintain a given inertial orientation despite orbital motion. The most favorable orbits are heliocentric, like the orbit one planned for SIRTF, with minimal corrective forces. Thus the gravitational acceleration of the Earth toward the sun is $5.10^{-3} m/sec^2$, and the added acceleration to hold the same period orbit when 5 km closer or further from the sun is about $2.10^{-10} m/sec^2$. Forces of less than a micro-newton per ton of spacecraft are all that is required.

A more challenging constraint is the need to maintain the optics at cryogenic temperature, requiring a shield against solar radiation. The type of thermal shield baselined for the NGST has a surface density referred back upon the primary of $\sim 3kg/m^2$. Much lighter shielding is needed if the benefits of large ultra-lightweight flat optics are to be realized. Ultra lightweight reflecting material being explored for solar sails may be appropriate. One possibility is to orbit shields far from the optics, at a distance of perhaps 50 times their diameter. A 100 m constellation could be shielded by a separate structure some 150 km across and orbited 5 km distant. From such a distance, warming by re-radiated heat would be negligible. The shielding structure could include solar collectors to relay power to the cold, shadowed constellation by microwaves. Another way to reduce shielding requirements might be to restrict observations to be approximately normal to the solar direction, so the optical surfaces are nearly edge-on to the sun and project to smaller area.

3.2. Optical design

In order to achieve images at the diffraction limit of the full aperture, light from all the different segments must arrive in phase. The basic design with flat segments tangent to a paraboloid accomplishes this, but alignment must be maintained by servo control. Figure errors across each segment must be well under a wavelength, depending on the Strehl ratio required. Phase and wavefront sensors will be built into the focal plane instrumentation, in the manner of the NGST, and actuators will be used to make closed loop corrections. To correct for deviations from flatness in the segments of the objective mirror, each scalloped segment of the tertiary mirror which is conjugate to a flat may need a deformable surface, with a two-dimensional field of actuators behind.

A key parameter for the design is the distance between the constellation and the collector telescope. The smaller the angle subtended by the constellation, the smaller the field of view needed by the collector, and the easier it will be to control field aberrations. On the other hand, if the flats are very distant, the view from the collector will be blurred by diffraction, and small scale measurements and correction of wavefront errors will be impossible. A specific example makes this easier to appreciate. Consider a design with 4 m elements, 100 m baseline and operation at $\lambda = 20$ microns. Let us suppose the collector telescope is 10 km distant, with the full array constellation imaged in a field of view of slightly more than half a degree. Each flat subtends 400 μrad at the collector, and its image is blurred by 5 μrad by diffraction. We can resolve no more than 80 resolution elements linearly across the aperture at 20 μm wavelength, though a 2 μm this number could be increased to 800.

Another important factor influencing system length comes into play when flats are used to synthesize a filled aperture telescope. The field of view of the system will be limited by violations of the sine condition at the pupil formed at the tertiary mirror. These will be minimized by using the largest system length, corresponding to the weakest scalloping of the tertiary. A detailed study of these and other design issues is ongoing.

4. Stretched membrane flats

In an ideal system, the requirements for the membrane to assume a flat surface are simply uniform thickness and positive tension applied from a plane perimeter. It will take up a position with its surfaces equidistant above and below this plane. Stretching a thin membrane flat is far easier than giving it a precise curve. As in a soap bubble, tension can be balanced against pressure to obtain a spherically curved surface, but for a solid membrane both the elastic properties and externally applied tension (as opposed to surface tension) must be highly uniform in two dimensions. (To obtain a flat surface, when there is no balance against pressure, the elasticity need not be uniform, and tension must be simply positive.) Pressure to produce curvature cannot be maintained for long in space because of micrometeorite holes, so membranes must be rigidized. The phase change from an elastic to rigid solid may result in change of shape, and there is no natural correcting force once the tension/pressure balance is gone. By contrast, tension on the flat can be maintained throughout its operation, so as to maintain flatness even when holes cause local distortion.

The allowable variations in the thickness of the membrane material are only a small fraction of the wavelength of the light it is to reflect. The membrane should also be free of creases or any permanent deformations not removed by the imposed tension. In an initial investigation, we find the best commercial thin plastic films have typically thickness variations of about 1 micron on a scale of centimeters, and would thus be suitable for wavelengths beyond 10 microns. Creases in plastic tend to heal by viscous creep, thus plastic reflectors might be folded for launch, and subsequently deployed. Metal films in space would be have much better stability against degradation under ultraviolet light in the space environment, but we find that because of the much higher elastic modulus and lack of viscous flow that creases in metal membranes of 10 microns thickness are not pulled flat, and do not heal over time. This suggests to us that if metal films are to be used, they should be pre-stretched in segment sized flat frames immediately after manufacture to prevent damage, and launched at full size. In space, they would be attached to a lightweight spaceframe for stiffening and adjustment. We have made optical tests with 1 m membranes of hexagonal and duodecahedral shape. As they would be in space, they are supported simply by in-plane tension applied to 6 or 12 tabs at the polygon corners. Position actuators at each corner act perpendicular to the surface, so the shape to be adjusted flat.

Acknowledgments. This work is supported by NASA under the NAIC grants program, under grant USR 07600-015. We are grateful to Richard Carreras of the USAF Research Lab, Jim Moore of SBS Inc, Huntsville Alabama and Arnoldo Valenzuela of Media Lario, Italy for providing test membranes.

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