Extremely large yet very low weight and low cost space based telescopes for detection of 140 meter diameter asteroids at 5.7 AU, and obtaining 6 year warning times for 1 km diameter comets

Ivan Bekey
Bekey Designs, Inc.
Annandale, VA. ibekey@cox.net

This White Paper addresses the detection of not only small asteroids, which has now been mandated by Congress, but also the detection at very long distances of long period comets which have been mostly ignored in NEO endeavors so far.

Asteroids smaller than ≈ 250 m size are difficult to detect and are very numerous, and can cause extensive and severe regional damage if not mitigated. The very large numbers of such asteroids demand fast search routines with large aperture telescopes, and much observing time will be needed. Larger ground telescope apertures have the advantage of increased search and detection distance, but the resultant narrower fields of view mean that many ground telescopes will be needed, preferably spread around the Earth and in both North and South hemispheres. These are large and expensive undertakings, and as astronomical instruments their observing time will have to be shared by NEO observers. As fundamentally, ground telescopes are generally limited to about 40-80 hours/month observation time due to daylight, seasons, clouds, moonlight, and night sky brightness, depending on location, exacerbating the pressure on observing time.

Space telescopes, in contrast, can observe the sky for small asteroids full time, gaining a factor of 720/80 = 9 to 720/40 =18. Thus 9-18 fewer space telescopes of the same aperture will be needed--ideally only one. This space telescope can be placed in solar orbit at 1 AU or at the Sun-Earth L2 point where it will be permanently shadowed by the Earth. There it can conjtinuously scan the sky up to about ± 150 degrees solid angle away from the Sun.

Long-period comets ≈ 1 km size or larger are much less probable than asteroids to impact the Earth. However NEOs 10 km or greater are much more likely to be comets, and thus comets can be extremely destructive and must be taken seriously. They can have very low albedo and usually have no coma beyond the orbit of Jupiter. They generally arrive from the Oort cloud, and many are new apparitions for which there is no data. Their extremely eccentric trajectories make their velocities very large when they cross the earth's orbit. Because of these factors they are very difficult to detect far away, and thus current discovery and warning times using ground telescopes are usually less than a year and frequently 1/2 year or less. Furthermore their outgassing and coma development as they approach the Sun makes precision epehemeris prediction prroblematical. Because of these difficulties long-period comets are usually placed into the "too hard" category and unfortunately ignored at this time.

How large must the aperture be?

Figure 1 shows the visual magnitudes expected for 1 km comets, 140 meter diameter asteroids and 70 meter diameter asteroids, all with 0.1 albedo, as a function of their distance (from the Sun as well from the telescope, presumed at 1 AU from the Sun).

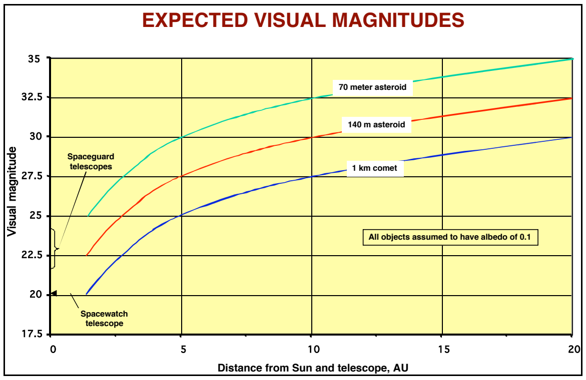


Figure 1: Visual magnitudes of the NEOs

All these visual magnitudes mean dauntingly weak signal objects compared to those the Space Guard survey has tackled so far. The aperture that would be required to detect such bodies is shown in Figure 2 as a function of distance in AU.

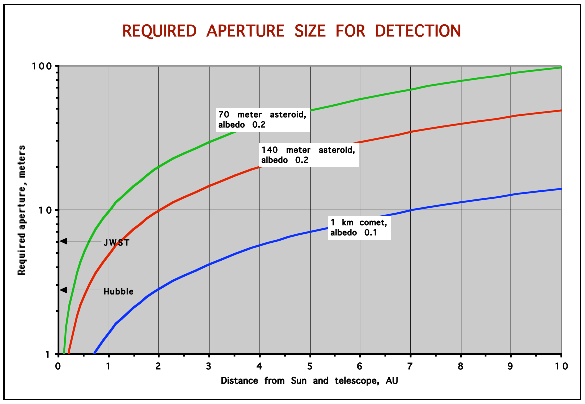


Figure 2: Aperture size required for NEOs

It is clear that the detection of 140 meter asteroids will be an undertaking limited to large ground telescopes, especially since their observing time will have to be shared with other observations. In addition the warning time provided by such telescopes against 1 km new apparition long period comets is shown in Figure 3, indicating that very large apertures will be required to attain warning times even a fraction as large as has been obtained against many same sized asteroids (in this graph the effects of outgassing are neglected).

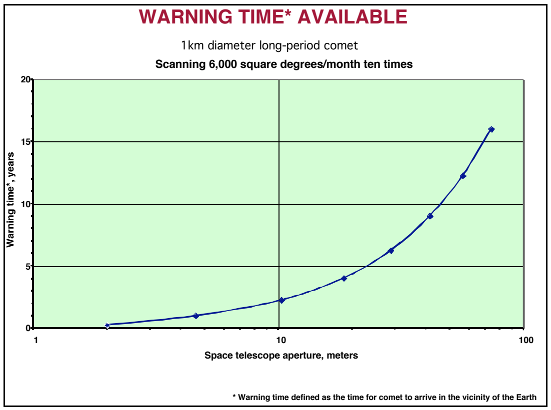


Figure 3: Warning time provided for comets

Current space telescopes are powerful scientific tools free of atmospheric and diurnal limitations, that have produced a wealth of scientific information and unforgettable images. But space telescopes are hideously expensive, a principal reason being that their optics and structures are high precision, heavy, and manpower-intensive to develop. This is principally because they are built using ground telescopes as models—that is constructing and launching a monolithic device with final required precision which must resist launch stresses. As a result the large apertures required for long-period comet and small asteroid detection are seen as daunting, far term, and risky space programs which are not imaginable, less affordable. But this does not have to be so. We have to completely change the design and development paradigms, so as to make use of the space environment instead of fighting it as do conventional designs. This white paper addresses a means of accomplishing that.

Concept description

A new principle is used in the propose space telescope: Replace precision apertures and structures with information. This capitalizes on the fundamental attributes of space in which mass is expensive while information and its processing are lightweight and cheap . The following concept description follows funded feasibility studies performed by the author initially for NASA/NIAC and then in much greater detail and with 5 subcontractors for the NRO.

To implement the principle we will use a membrane primary that is active over its entire surface, and is initially shapeless. This membrane will be limp and “Saran Wrap-like”, and untensioned. It will be folded like a blanket and launched . Once in final orbit it will unfold into an initially shapeless, though very roughly planar (± 1 meter) surface, and only then will it be actively shaped so as to attain the desired figure. The figure of this primary reflector will be set and maintained by closed loop control using software, and will form the first stage of a two-stage correction system, thus figure accuracies required can be nearly a millimeter.

With respect to the usual major telescope truss, not even advanced conventional designs have yet thought it through all the way, since there is no need for any truss in space--telescope trusses are a carryover of earth-bound thinking. Since g forces do not have to be resisted in orbit there is no need to have a truss to hold the elements at precise separations, and precision stationkeeping can be used just as well instead, forming a virtual truss. Both the formation flying and the primary figure adjustment can be made responsive to outside disturbances, and closed loop correction control introduced. Thus the telescope’s separated parts and flimsy membrane primary (together with a second stage of correction) can be maintained in a configuration whose performance can be indistinguishable from that of a conventional telescope with a solid or segmented aperture and fixed precision truss.

The functioning of the adaptive membrane is illustrated in Figure 4. The telescope consists of an unsupported and unstretched (not inflatable) adaptive piezoelectric bimorph film membrane, whose figure and surface accuracy are continuously corrected using an electron beam scanning its entire back surface. The beam causes charge to be deposited selectively which induces local bending of the piezo bimorph. The signals for the beam-induced charge density required at any location on the membrane are generated in response to a precision figure sensor which detects both gross and fine scale characteristics of the membrane surface, which are then turned into beam commands by a computer.

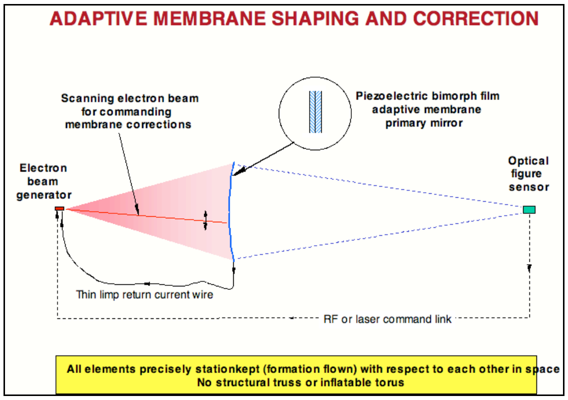


Figure 4: Adaptive membrane principle

This Adaptive Membrane technique is the heart of the new space telescope concept, which is described in principle, though not to scale, in Figure 5. There will be residual errors in the primary, caused by finite electron beam size, power limits, and metrology limits, not exceeding a fraction of a millimeter. These will be corrected by a second stage of correction, which is composed of a liquid crystal plate located in a separate focal assembly at a point in the optical train where a real image of the primary exists. This liquid crystal is driven by a voltage obtained from the figure sensor, which generates a 2-dimensional spatial distribution of the residual errors of the membrane surface after the adaptive piezoelectric correction loop has done all it can. This voltage causes a 2D distribution of the index of refraction across the liquid crystal, which in turn affects the speed of light though it, responsive to the residual errors of the primary. The aberrated light from the primary is thus corrected as it transits this liquid crystal, resulting in a phase-corrected coherent image. The net effect of the two stages of correction is to generate a near-diffraction limited image with a lightweight primary membrane that started initially only roughly flat and wrinkly.

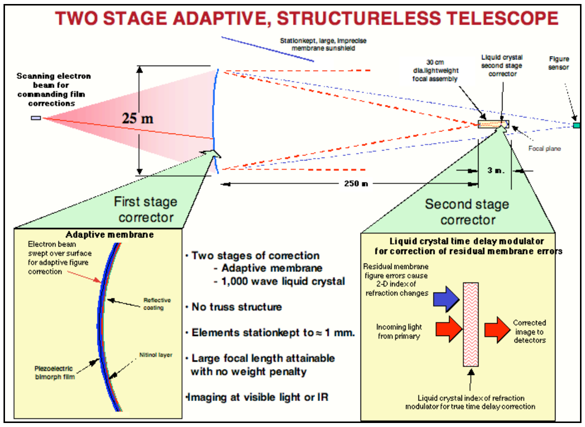


Figure 5: Two-stage structureless telescope

The complete space telescope concept using two stages of correction, with all elements formation-flown rather than connected by trusses, is illustrated in figure 6, this time to scale, and using an f/10 primary as an example. The focal assembly is stationkept at the focal point of the primary, 250 m on its axis. The figure sensor is stationkept at the center of curvature of the primary, at 500 m. on axis. The focal plane is located at one end of the focal assembly, which accomplishes reimaging via small secondary and tertiary mirrors, and also contains the liquid crystal. The large f number of the spherical primary used in the example, together with aspheric design of the secondary and tertiary mirrors, results in vanishingly small spherical aberrations, astigmatism, and coma, and makes for a relatively flat primary which is easier to shape by the piezoelectric forces than if the f number were smaller, though smaller number primaries are also possible. This design does not look anything like a traditional space telescope but it functions exactly the same.

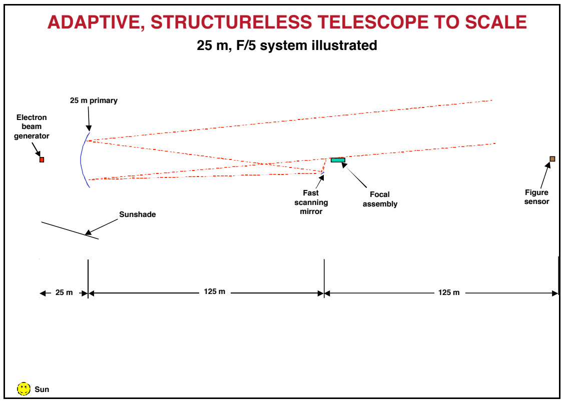


Figure 6: 25-m f/10 telescope, to scale

Since the piezoelectric primary membrane must be perpetually shaded from sunlight to prevent temperature damage to the piezoelectric characteristics of the film, a plain opaque membrane sunshade of crude figure is interposed between the Sun and the primary and kept there if the system is in solar orbit.

In operation all the telescope elements would be rotated and translated as an ensemble , maintaining the axial configuration of Figure 6, to point to the desired target sky region. Actually the best plan would be to limit most maneuvers of the primary membrane to only rotation, avoiding translational stresses and propellant, with all other elements of the telescope translating as well as rotating. Once the ensemble pointed in the right direction fine pointing control would be imposed, slaved to the image on the focal plane. After all dynamic perturbations damped down, observations could begin. Viewing objects within several degrees of the telescope axis would then be accomplished by moving only the small fast steering mirrors, without rotating or translating any other telescope components. Repointing to a different target area would be accomplished by rotating the entire ensemble of elements more slowly, and repeating the procedure.

There is research ongoing in some laboratories to employ inflatable reflective membranes supported by gas pressure against a clear front membrane for the primary of large telescopes. Inflatable membranes are deliberately avoided in this concept because inflation always results in a figure which is neither a sphere nor a parabola which is very difficult to compensate with another optical surface; creating variable thickness films so as to avoid this mis-figure is difficult and imprecise; the inflatable torus required at the membrane periphery in order to impart the required stretching forces on which a smooth surface depends adds substantial weight to the aperture.

The unsupported film used here has a second major advantage over a stretched film surface, which is its absence of surface tension which makes for very weak surface wave propagation along its surface, thus avoiding the typical “drum-head” membrane dynamics resulting from any disturbance to stretched membrane reflectors. In fact calculations indicate that a disturbance wave will take many hours to travel the diameter of the membrane, and feed forward control can effectively remove the effect of most disturbances.

The primary is illustrated in Figure 7. The film consists of a bimorph sandwich of two oppositely polarized piezoelectric films bonded together, with a Nitinol or other shape memory alloy layer which will allow the membrane to be folded for launch, and which will automatically deploy the film to its original roughly flat shape when heated by the Sun in space. The presence of any creases in the membrane resulting from these folds will be mostly removed by the adaptive piezoelectric figure control, and their residuals will be corrected by the liquid crystal stage. This technique will make it possible to fold the primary membrane into a very small and compact package, which can then be launched on a small booster.

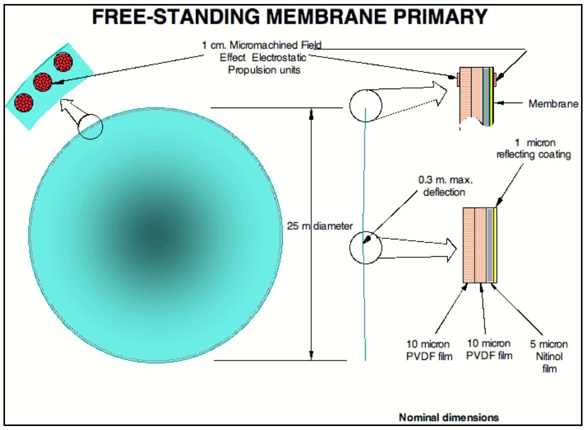


Figure 7: Adaptive Membrane primary

The attainable fine scale figure errors that can be removed are limited the ability to sharply focus the electron beam and by the resolution limits of the liquid crystal second stage corrector to a fraction of a millimeter. The primary membrane is envisioned to employ a large number of solid state micromachined FEEP propulsion units of the type now being developed by DARPA attached at its periphery to allow rotational and translational control. These are 3,000-5,000 Isp liquid Gallium or Indium low voltage thrusters with millions of micron-sized thrust orifices micromachined into a small block of silicon, and integral propellant tank. The presence of the piezoelectrically induced “artificial stiffness” in the membrane once figured allows the thrusters to move the otherwise limp membrane as a unit, as the thrust level is small enough so as to not distort the membrane shape.

The liquid crystal second stage corrector is similar in principle to correctors operating in the laboratory at the Air Force Research Laboratories in Albuquerque, which have a range of correction limited to a few wavelengths being designed for high frequency response as they are principally aimed at correcting atmospheric fluctuations. In contrast the liquid crystal for the space telescope concept is designed so as to have a correction capability of 0.1-0.5 mm or 200-1000 waves with low scatter, though with substantially slower response time. Such liquid crystals have been demonstrated in the laboratory.

The focal assembly is relatively conventional and uses conventional mirrors since they are so small as to make their weight inconsequential. The assembly can be housed in a tube nominally 40 cm diameter and 3 m long. Micromachined FEEP thrusters would be used on its periphery for attitude and translation control.

The focal plane is expected to be a conventional array, which could be a CCD device. The state of the art should allow the 10 cm focal plane to be populated with an array of 10,000 x 10,000 detectors, each 10 microns across. This will allow a good field of view, while also permitting use of focal plane processing both for time delay integration and for tracking to accomplish cross-axis stationkeeping.

The field of view can be rapidly and easily rotated by several degrees without moving any major element of the telescope using image plane scanning with two small fast steering mirrors, conceived by Glenn Zeiders of Sirius Associates. One mirror is stationkept in the close vicinity of the entrance end of the focal assembly. It directs light from the primary toward the second mirror, which is gimbaled to the assembly axis. By translating the stationkept mirror along the surface of a virtual ellipsoid of revolution it is possible to receive light far from the primary telescope axis yet continue to direct that light exactly into the assembly axis without moving either the primary or the focal assembly.

The electron beam assembly generates a scanning electron beam which is focused on the piezoelectric membrane material. The beam deposits a charge wherever it hits, and the presence of a thin conductive coating (a “back plane”) conducts the electrons back to the source, and is used for applying corrective potentials to the bimorph. The means of this conductance could be a very fine and compliant wire from the membrane, or a separate non-scanning electron beam could furnish this return path. The charge deposited in any particular point on the film will eventually diffuse laterally, as well as leak through the film due to its finite resistance. Based on laboratory data, after several minutes the charge will have to be replenished to maintain constant local curvature, and thus the primary is re-figured once a minute to correct accumulated errors as well as to accommodate any new shape commands.

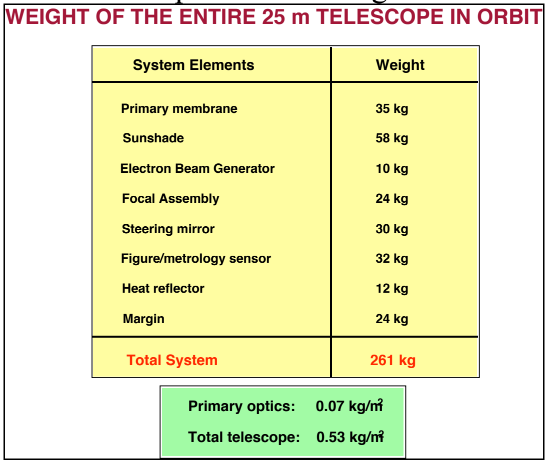
The figure sensor is located at the center of curvature of the primary membrane mirror. This allows sensing of the entire surface without any special patches or surface treatment. It has two principal functions: it senses the gross and fine scale figure of the primary mirror membrane for controlling the electron beam that corrects these errors, and it furnishes an external reference that enables correction in the liquid crystal. The assembly is also stationkept, responsive to the same master metrology and control system as controls the entire system. The assembly would also be translated and rotated via micromachined FEEP propulsion units mounted on its periphery.

A stationkept sunshade will be formation flown and will have micromachined FEEP propulsion units mounted on its surface to maintain relative position. It will be somewhat larger than the primary to assure shading. The sunshade will play a second and critical role, that is converting some solar energy to microwaves that it will beam toward the primary and the other elements, as they will all be shaded from sunlight, which will be rectified and used there for prime power.

A dedicated metrology system will be used to determine relative distances and orientations in the ensemble. This system will consist of microwave links for coarse information and optical links for fine information, between the elements. The required accuracy components have already been demonstrated.

The resultant space telescope

All elements of the telescope will be designed using microminiaturized components, and can be astonishingly lightweight, as shown in Figure 8 for a 25 meter clear diameter primary aperture. The weight is that of the complete telescope, not just the primary mirror. All weights are the result of conceptual-level designs.



WEIGHT OF THE ENTIRE 25 m TELESCOPE IN ORBIT

System Elements	Weight
Primary membrane	35 kg
Sunshade	58 kg
Electron Beam Generator	10 kg
Focal Assembly	24 kg
Steering mirror	30 kg
Figure/metrology sensor	32 kg
Heat reflector	12 kg
Margin	24 kg
Total System	261 kg

Primary optics: 0.07 kg/m²
Total telescope: 0.53 kg/m²

Figure 8: Total weight estimate of a 25-m. diameter filled aperture telescope

The areal densities attained are 0.07 kg/m^2 for the primary mirror assembly and 0.53 kg/m^2 for the entire telescope. These are phenomenally lower than attainable by any other known technique.

The weight of telescopes designed with this technique, as well as those of Hubble and JWST-based designs, were scaled with aperture diameter and the curves appear in Figure 9. It is seen that the weight advantages of the present space telescope concept are compelling, being 4 orders of magnitude lighter than Hubble-type designs and 2 orders of magnitude lighter than JWST designs.

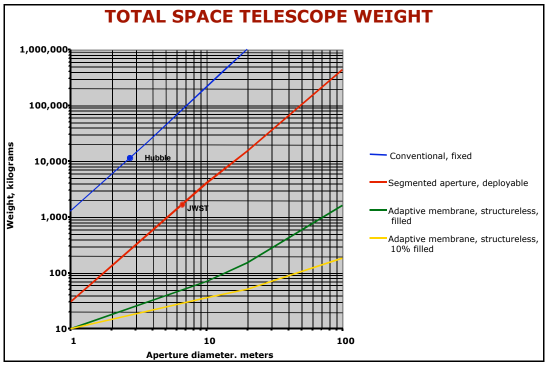


Figure 9:Parametric space telescope weight

In order to visualize the dramatic advantages offered by this new design paradigm it is compared to three other conceptual level space telescopes, each of them 25 meters aperture diameter. Two of them are the Hubble and JWST technologies extrapolated to 25 meter apertures, and one is a new technology telescope using an advanced all-inflatable non-adaptive one-stage corrected telescope design concept. These are illustrated in Figure 10.

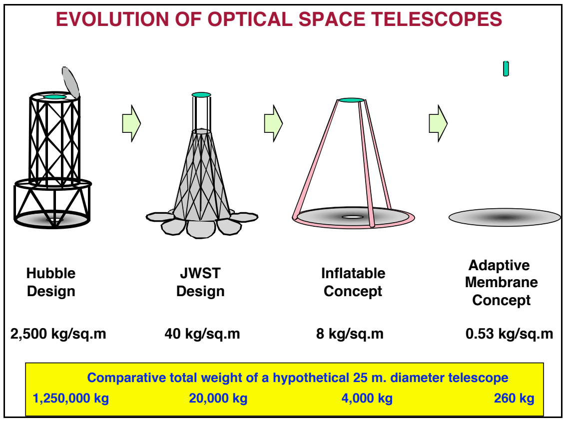
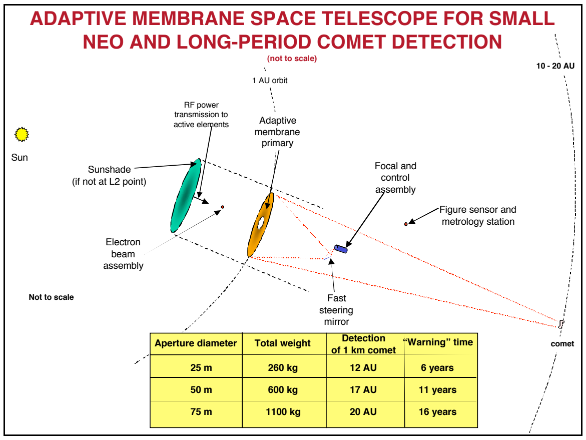


Figure 10: Weight of 25 meter telescopes

It is seen that the Adaptive Membrane structureless design is 4 orders of magnitude lighter than the one scaled using Hubble-type technologies, which would weigh millions of kg. It is also 2 orders of magnitude lighter than one scaled using JWST technologies, which would weigh some 20,000 kg. It is 20 times lighter than the best inflatable membrane design concept, which would still weigh some 4,000 kg. In contrast a 25 meter diameter telescope using the Adaptive Membrane structureless concept will weigh less than 300 kg!

While it is always hazardous to estimate costs for new technology telescopes, if cost continues to scale as weight, as it has done for essentially all past and current technology space systems, the cost of a telescope using the techniques described herein could well approach the same 2-4 orders of magnitude reduction as the weight. If that were the case then a 25 meter diameter space telescope would have a cost in the tens of millions rather the tens of billions it would cost if built using JWST technology and techniques.

An example of a NEO/astronomical near-diffraction-limited telescope in solar orbit is shown on Figure 11. If the telescope had a 100% filled apertures of 25 meters diameter its total weight would be 260 kg; for a 100% filled aperture of 50 meters diameter its weight would be 600 kg; and for a 100% filled aperture of 75 meters diameter the total weight would be 1,100 kg. In addition a 250 meter diameter 10% sparse aperture telescope was sized, and would only weigh 1,600 kg.



Aperture diameter	Total weight	Detection of 1 km comet	"Warning" time
25 m	260 kg	12 AU	6 years
50 m	600 kg	17 AU	11 years
75 m	1100 kg	20 AU	16 years

Figure 11: NEO detection and astronomical space telescope system

Technologies that need to be developed and demonstrated

The basic concept applied to a 25 meter telescope was defined and shown to be feasible in funded team studies led by the proposer, performed initially for NIAC and then in much greater depth and with 5 subcontractors for the NRO. The principal technologies that need to be matured are the primary reflector, the liquid crystal second stage corrector, and the metrology and propulsion techniques necessary for precision formation flying.

The primary membrane reflector requires development of piezoelectric film materials resistant to the space environment and having smooth surface; demonstration of membrane folding and deployment via shape memory material coating; and demonstration of closed loop shaping using a remote electron gun. Of these the latter is underway in the laboratory by The Aerospace Corporation. The estimated TRL is 3. The liquid crystal corrector must de developed and demonstrated to have at least 500 waves of correction capability simultaneously with low scatter and reasonable time constant. Early laboratory experiments have pointed the way, though its estimated TRL level is 2. Precision formation flying requires development of microgyros and sunsensors, which are underway; RF and optical metrology sensors which are being developed for related space applications; development and demonstration of micromachined FEEP thrusters, which is underway by DARPA at an estimated TRL level of 2-3. Simulation of a complete system including metrology and micropropulsion is also needed, and its estimated TRL level is 3. Thus the overall estimated TRL level of the space telescope system is more than 2 but less than 3.

These are not extremely difficult developments. Some of the required technologies are already being pursued in the laboratory, and a roadmap exists for their demonstration in space. Since the technologies are simpler and inherently require many fewer man-hours for development than conventional space telescopes, it should not take more than about 5 years to demonstrate them, first in the lab working separately and then in space with a small scale experiment with all technologies working together. It is because of this that it is likely that a complete 25 meter diameter aperture space telescope could probably be fielded in about 10 years. Phase A industry studies must be performed with the author's feasibility studies as a starting point. Phase B and C would then follow. A single space telescope would suffice. The likely cost of such a development would be astonishingly small compared to costs of conventional space telescopes. Thus an affordable and powerful means of detecting, tracking, and cataloguing asteroids smaller than 140 meters at great distances could be implemented relatively rapidly. This same telescope could also provide long distance detection of new apparition long-period comets, providing warning times of 6 years or more on typical 1 km diameter comets.