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Large Space Telescopes using Fresnel Lens for Power Beaming, Astronomy and Sail Missions

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Large Space Telescopes Using Fresnel Lens For Power Beaming, Astronomy and Sail Missions

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Abstract. The concept of using Fresnel optics as part of power beaming, astronomy or sail systems has been suggested by several authors. The primary issues for large Fresnel optics are the difficulties in fabricating these structures and deploying them in space and for astronomy missions the extremely narrow frequency range of these optics. In proposals where the telescope is used to transmit narrow frequency laser power, the narrow bandwidth has not been an issue. In applications where the optic is to be used as part of a telescope, only around 10^{-5} to 10^{-6} of the optical energy in a narrow frequency band can be focused into an image. The limited frequency response of a Fresnel optic is addressed by the use of a corrective optic that will broaden the frequency response of the telescope by three or four orders of magnitude. This broadening will dramatically increase the optical power capabilities of the system and will allow some spectroscopy studies over a limited range. Both the fabrication of Fresnel optics as large as five meters and the use of corrector optics for telescopes have been demonstrated at LLNL. For solar and laser sail missions the use of Fresnel amplitude zone plates made of very thin sail material is also discussed.

Introduction

The concept of using Fresnel optics as part of power beaming, astronomy or sail systems has been suggested by several authors[1,2]. The primary issues for large Fresnel optics are the difficulties in fabricating these structures and deploying them in space and for astronomy missions the extremely narrow frequency range of these optics. In proposals where the telescope is used to transmit narrow frequency laser power[1], the narrow bandwidth has not been an issue. In applications where the optic is to be used as part of a telescope, only around 10^{-5} to 10^{-6} of the optical energy in a narrow frequency band can be focused into an image.

This article addresses the fabrication of very large space optical systems with Fresnel lenses. The limited frequency response of a Fresnel optic is addressed by the use of a corrective optic that will broaden the frequency response of the telescope by three or four orders of magnitude. This broadening will dramatically increase the optical power capabilities of the system and will allow some spectroscopy studies over a limited range. Both the fabrication of Fresnel optics as large as five meters and the use of corrector optics for telescopes have been demonstrated at LLNL[3,4]. For solar and laser sail missions the use of Fresnel amplitude zone plates made of very thin sail material is also discussed.

Transmissive Fresnel Optics

A key feature of this concept will be the use of a thin transmissive primary optic in the telescope design. The problem with membrane mirrors, of course, is that it is hard to control their shape to the $\lambda/20$ scale precision needed to attain $\lambda/10$ optical tolerances. The source of this difficultly is that mirrors reflect light, thereby doubling the effect of surface errors. In contrast, path-length errors caused by surface distortion of a thin, uniform thickness transmissive film are canceled (not reinforced) as light arrives at and then departs from the surface. In actual lenses, this path-length cancellation is not perfect because the incoming and outgoing rays are not traveling in quite the same directions. If the light is bent through angle θ, then the path-length error in a mirror is amplified by a factor $(1 + \cos\theta)$, whereas that in a thin lens is reduced by $(1-\cos\theta)$. Thus lenses have a $(1+\cos\theta)/(1-\cos\theta)$ advantage over mirrors. By making the lens weak, i.e., by keeping θ small, this tolerance gain becomes huge. In a very slow lens (f/100) visible-light tolerances increase up to nearly a centimeter, a tremendous practical advantage when trying to field a thin optical-quality membrane optic in space.

LLNL has also addressed the issue of fabrication of large meter scale optics utilizing techniques that can be scaled to much larger sizes. At LLNL we have facilities that were built for fabrication of meter scale diffractive optics that are needed for the new laser fusion laboratory currently under construction. We now have facilities, techniques and experience personnel needed to produce very large (up to one meter in a single piece) diffractive optics in large numbers for use as diffraction gratings, Fresnel phase plate lenses or optical control elements. We have also addressed issues of joining meter sized optics together to fabricate much large optical structures. This basic capability can now be used to address the issues of design and fabrication of Fresnel phase plate optics in glass or plastic and amplitude zone plates in sail materials.

Diffractive Optics Theory

The classic circular Fresnel pattern for an amplitude zone plate is illustrated in Fig. 1. For a phase plate the glass surface local slope results in a 2π phase shift in each zone with a 2π step at the zone edge. Just as with standard optics a point focus can also be formed with orthogonal cylindrical lenses (Figures 2).

Figure 1 – Circular Zone Plate

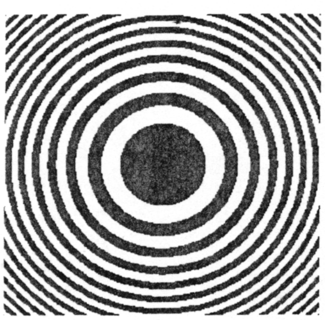
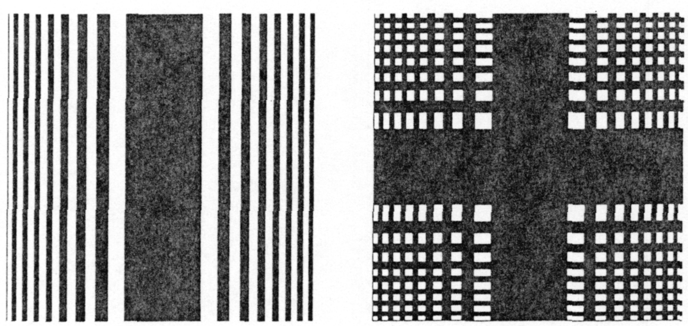


Figure 2 – Linear zone plates:
a) line focus b) point focus with orthogonal lines



The total number of zones, N, are given by:

$$N = D^2/8\lambda F = D/8\lambda f_{number} \qquad (1)$$

where λ, D and F are the wavelength, optic diameter and optic focal length respectively. The width of the outer zone (the smallest zone) is $2\lambda f_{number}$. When the f_{number} is very large, then these features become easy to fabricate using optical lithography technology.

Even with a normal lens the light distribution in the focal plane depends on the wavelength. For example the diameter of the central Airey spot, d, is proportional to the

$$d = (2.4F/D)\lambda \qquad (2)$$

wavelength. In a broadband image the short wavelength light has a higher resolution. However all the wavelengths have the same focal plane for zero dispersion optics.

For a given Fresnel optic the focal length will also depend on the wavelength and

$$F = (D^2/8N)(1/\lambda) \qquad (3)$$

will severely limit the useful bandwidth of a telescope. For good images:

$$\Delta\lambda/\lambda < 1/8N = f_{number}\,\lambda/D \qquad (4)$$

If the f_{number} of the telescope is 100 and the diameter is 100m, then for 1μm light $\Delta\lambda/\lambda = 10^{-6}$. Unless the telescope features extraordinarily large f-numbers, the zone plate primary optics will be inherently micro-bandwidth optical elements. The bandwidth may be acceptable for laser communications or power beaming, but it is a major limitation for an imaging system. For an imaging system we must achieve higher optical bandwidth by the use of chromatic correction optics.

In the next section we discuss how to correct for this chromatic aberration associated with Fresnel optics. The intensity distribution in the focal plane will also be different for different types of Fresnel lens, i.e. phase plates, circular zone plates and orthogonal zone plates. We will not attempt to change these amplitude distributions in the focal plane nor the wavelength pattern variation found in standard optics. It is essential to note that the chromatic corrections will address only the variation in focal length for the Fresnel lens.

Corrector Plate for Wavelength Aberrations

To achieve high-precision chromatic correction for the zone plate, we try to cancel its chromatic aberrations with correcting optics in the optical train of the telescope. A technique was invented 100 years ago by Schupmann[5] who showed that any chromatic dispersion introduced at one optical element could be canceled by placing a second, inverse-power element with the same dispersion at an image site of the original element. The corrector optic's effectiveness will depend on its size, but increasing the bandwidth of the telescope by four orders of magnitude should be possible.

Physically, the reason Schupmann correction works for a diffractive telescope is clear (figure 3); light leaves each point of the Magnifying Glass's diffractive lens in an angular spray, each color being sent into a different direction. As the light from this site travels towards the Eyepiece it spreads apart, diverging both spectrally and physically; both effects must be corrected. The physical reassembly is achieved first, by making the light pass through a reimaging telescope as it enters the Eyepiece. This internal telescope focuses the surface of the Magnifying Glass onto that of the Fresnel Corrector, thereby physically recombining rays which left each site on the first diffractive lens to a matching site on the second one. Now each site on the Fresnel Corrector sees an incoming angular/color spray corresponding to that from the departure site on the Magnifying Glass; by employing an inverse (defocusing) diffractive profile, it can remove this angular/color spray. As a result, each ray bundle is now both physically and spectrally recombined; the set of bundles can then be brought to a common achromatic focus.

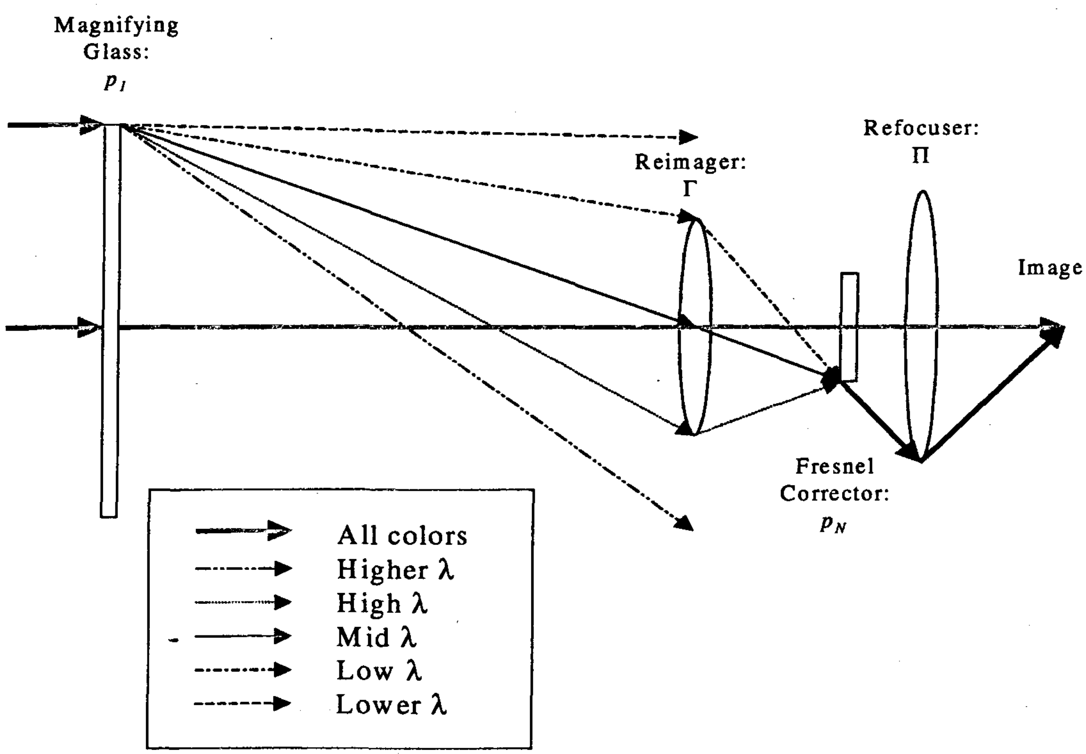


Figure 3 – Optical paths of different colors through Fresnel telescope

Demonstrations At LLNL

At LLNL we have fabricated Fresnel phase plates at diameters of 20 and 50cm. Using a corrector plate fabricated by JPL, we have demonstrated that the chromatic aberrations can be corrected in telescope configurations and that diffraction limited images can be formed with broadband ($\Delta\lambda/\lambda \sim 0.1$) light (figure 4). Both phase plates and amplitude plates have the same wavelength dependence in their chromatic aberrations, and broadband performance has been demonstrated with both types of optics.

To scale this technology to very large optics meter sized optical sections are made with current techniques joined to form a large optic. The joints must be designed to function in the space environment and to maintain the required optical position tolerances. Figure 5 shows a 5m Fresnel lens recently fabricated at LLNL. Most of the structure seen in this figure is bracing required to protect the lens from wind loads in this open air demonstration.

Space Deployment

For a f_{number} 100 optic the outer (thinnest) ring is around 100μm for a visible optic. Fabricating the rings to a fraction of this dimension with standard optical lithography has been demonstrated with the LLNL equipment. Holding this in-plane precision in a deployed optic will depend on the material properties and the thermal control of the optic. If the optic is held at uniform temperature, then the only impact of a change in temperature is an easily corrected change in focus[4].

The optic can be held flat by spinning (the preferred method) or by applying radial tension at the circumference with external structures. For transmissive optics the out of plane optical tolerances are large and easily achieved. The stresses must however be distributed without causing local in-plane distortions in the optic. In the case of amplitude zone plates for sails, if the solar sail consists of metal deposits on plastic, then the difference in thermal expansion coefficients cannot be allowed to distort the lens. If the zone plate consists of holes in a uniform reflective or absorptive material, then the issue is the stress patterns created by the openings.

Thin glass optics are flexible enough to be rolled into configurations that can fit into the payload volumes of current launchers. Circular primary optics of 9m can fit in the Delta III fairing and of 20m can fit in the Delta IV. For a larger primary the optics must be folded in origami patterns (figure 5) or fan folded and rolled.

Power Beaming Applications

Large low-mass Fresnel optics can enable power beaming over very long distances. Power beaming to and from geostationary orbits would be possible. Once long distance beaming is possible, then it no longer makes sense to locate the required power supplies and lasers in orbit. Placing these assets on the surface of the Earth will allow much simpler technology, practical maintenance and much lower costs. The laser power can be beamed up to a geostationary station using an Earth-based telescope with a large conventional primary optic and smaller adaptive optics in the optical train.

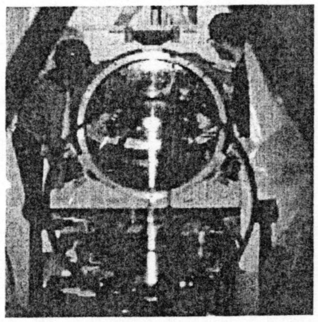
A satellite in geostationary orbit can capture the laser beam and redirect it to targets of interest using low-mass Fresnel phase plates. The Fresnel lenses will have transmissive efficiencies over 98%. Table 1 gives the typical ranges for several missions and the required lens size. The transmitting lens and the delivered spot size

Figure 4- Broad-band Diffractive Telescopes

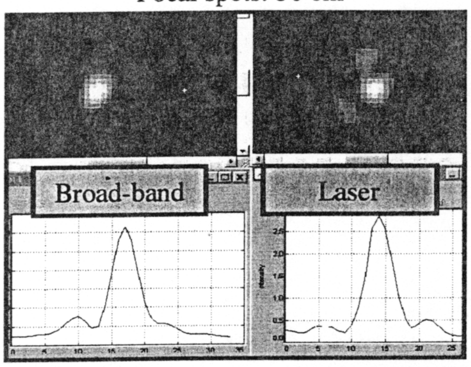
- Two telescopes
  - 20 cm wide, 20 m long
  - 50 cm wide, 50 m long

- Each performed properly
  - Diffraction-limited focus
  - For broad-band (470 - 700 nm) light

Optics: 50 cm



Focal spots: 50 cm



Lunar image: 20 cm

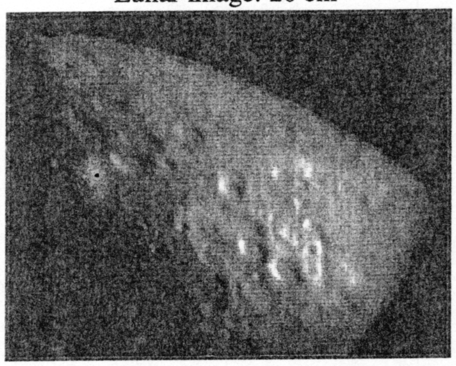
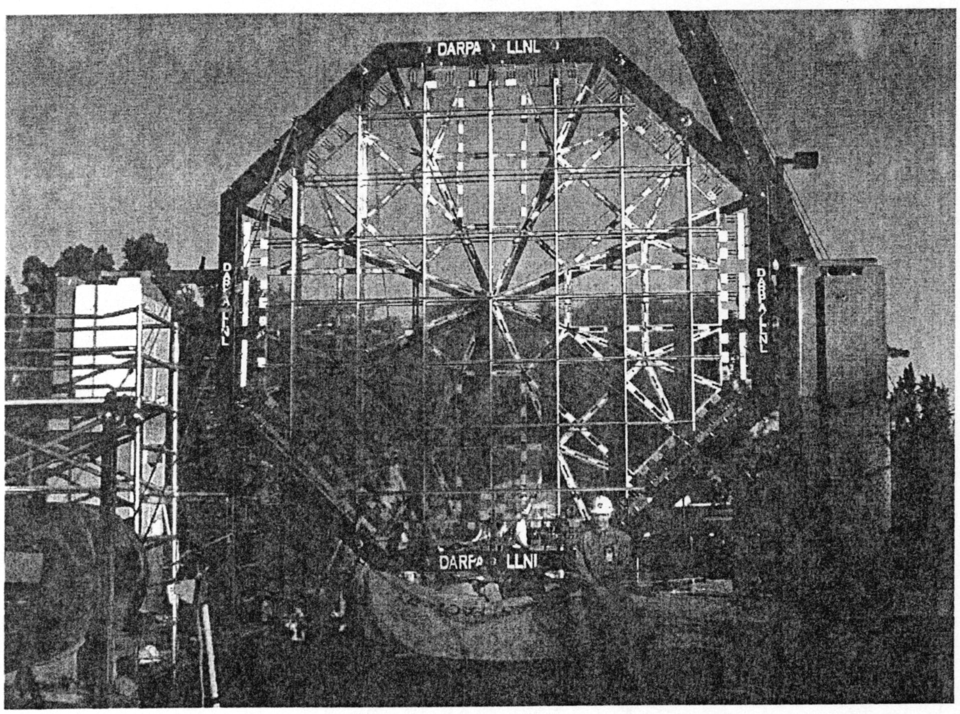


Fig. 5 - 5 m Fresnel lens made with 700μm glass



are assumed to be the same, but one can trade one against the other with their product being conserved.

Table 1 – Power beaming missions and required optic sizes

Mission	Range (10^3km)	Visible light spot / optic diameter (m)
geo to leo	40	6
geo to geo	80	9
geo to moon	400	20
geo to L1 / L2	1500	40

Nearer Term Applications

Before large Fresnel optics can be used for power beaming, the technology probably needs to be developed and demonstrated on other nearer term applications such as astronomy or spacecraft optical communications. A 20m telescope based on Fresnel optics could be packaged in a Delta IV and deployed in geostationary or higher orbits. Such a telescope would provide eight times the resolution and sixty-four times the light gathering capacity of the Hubble telescope. This telescope could observe weather details on Mars with 10km resolution and on Saturn with 100km resolution. It could provide 1AU resolution of planetary accretion disks or planetary nebula out to 600 light years. If the light scattering properties are acceptable, then this telescope design could also be used for extra-solar planet finding missions.

For spacecraft communications the low mass and easy tolerances of thin membrane Fresnel optics makes optical communication with large transmitting apertures possible. For spacecraft communications:

$$\text{Data rate / spacecraft transmitter power} \sim d^2_{transmitter} D^2_{receiver} / \lambda$$

Table 2 compares potential laser and radio communication systems and show that 1μm lasers may have four or five orders of magnitude advantage in terms of higher data rates or lower power requirements.

Table 2 - Comparison of laser and radio communication systems

	λ(m)	$d_{trans.}$ (m)	$D_{rec.}$(m)	d^2D^2/λ
radio	0.01	1	10	10^4
laser	10^{-6}	10	3	10^9

Solar Sail Mission Impact: Enabling for Fly-by Missions

The low payload capacity of solar sail spacecraft makes the inclusion of very large aperture imaging impossible unless the optics are extremely light. If the solar sail itself forms the primary optic, then very large aperture imaging systems may be possible. The solar sail must be reflective (or absorbing for carbon sails) and very thin. If the sail is used as a reflective optic, then the $\lambda/10$ optical precision requirement in a membrane structure will be extraordinarily difficult or impossible. The use of the sail as a transmissive optic greatly relieves the optical precision requirements, but one cannot make a transmissive Fresnel phase plate from this opaque material. The use of an amplitude zone plate optical design allows the use of reflective or absorbing sail material while still gaining the advantages of a transmissive membrane design.

For solar sails to be used in actual near and/or medium term missions, they must address requirements that are not easily satisfied with conventional rocket propulsion systems. This constrains potential sail mission opportunities to high Δv missions where conventional rocket systems are very expensive and have small payloads. For inner solar system missions a solar sail can be used for rendezvous or orbiting missions, but there are relatively few inner system mission opportunities. For outer solar system missions the solar sail becomes less effective at rendezvous or orbiting because of the low solar flux at the target.

There are numerous targets for high velocity fly-by missions in the outer solar system that potentially could be served with solar sail propulsion. The basic problem is that fly-by missions in the outer solar system have low scientific data returns due to the conditions at encounter. Any imaging systems will have very little time to take data, and the data is of low resolution. First the encounter relative velocity must be high. To reach outer system targets in reasonable times the outbound leg of the trajectory is highly elliptical. The velocity of the spacecraft is typically over 10-20km/sec (2-4 AU/y) relative to any target in a circular orbit[6]. Secondly with the exception of missions to Neptune or Uranus, the targets are typically small. Pluto and some satellites of the outer planets and potentially a few deep objects are of the order of 1000km in diameter. Most asteroids, comets, Kuiper belt objects and Oort cloud objects will be under 100km. To get any meaningful understanding of these objects we will want resolutions better than 1km. For deep space missions the problem is further exacerbated by the very low light levels that will push imaging systems to longer exposure times.

With the light payload capacities of deep space missions the typical imaging system will have an aperture of 10cm or less[6]. Table 1 gives the resolution of such a system for visible light as a function of range to target. Also listed is the time the target resolution exceeds a given value assuming the closing velocity is only 10km/sec. It can be seen that there is only a few hours of moderate resolution data and very little data with resolutions better than one kilometer. In this table it is assumed that the spacecraft has maneuvered close to the target and that the separation distance is primarily along the flight path. If the camera exposure times must be long due to low illumination levels, then the high resolution data could be quite limited.

If a large fraction of the solar sail is converted into a primary optic, then the imaging system capabilities can be dramatically different. If a 100m optic is part of a 200m diameter solar sail, then the imaging times and resolutions are given in Table 3. The long observation times and high resolution would enable significant imaging science. High resolution imagery of both hemispheres would be possible for even targets with low rotation rates. Dynamic events such as orbiting satellites could also be observed.

Table 3 - Imaging system performance assuming close fly-by at 10 km/sec

	10 cm optics			**100 m optics**			
Resolution	10.km	1.0km	100m	1.0km	100m	10m	1m
Distance to target (10^6km)	.7	.07	.007	70.	7.	.7	.07
Time to target	1 day	2 hr.	11 min.	3 mon.	1 wk.	1 day	2 hr.

For missions to the asteroid belt, Kuiper belt or Oort cloud the large solar sail optic would enable fly-by missions without the spacecraft being required to maneuver to the target. For these fields of small distributed targets the spacecraft would simply fly on a straight trajectory and targets would be imaged as they passed into range. The factor of 1000 increase in optic diameter would give a factor of 1000 increase in the range at which targets could be resolved. For example if a 100m optic was flown on a straight path through the Kuiper belt at 20 km/sec, in ten years based on current estimates of the belt population[6], it would be able to resolve hundreds of objects including approximately 100 objects with a 1000 line resolution across the image of the object.

One objective of the Gossamer Spacecraft Initiative for solar sails is to act as a precursor mission for laser driven lightsail for interstellar missions. While there are some speculative investigations on how to slow down a lightsail at the target star system, the basic concept of the lightsail is for a fly-by mission at speeds of 0.1c. The fundamental flaw in this mission concept is the high fly-by velocity's impact on data collection. While the target planets may be 10,000 km in diameter, Table 4 shows the limited observation times available at 0.1c. Laser lightsail sizes are quite large[7], so a one kilometer zone plate optic is assumed. The launch telescope for an interstellar lightsail must be around 100km. The use of this telescope for direct observation from the Solar System would provide resolutions near 1000km in the target system which are as good as the small optic fly-by. Very large optics are required to make the fly-by mission useful. If the optics investigated by this study are shown to be feasible, then the argument of using solar sails as precursors for interstellar or outer Solar System missions will be valid.

Table 4 - Imaging system performance assuming fly-by at 0.1c

	10 cm optics		**1 km optics**				
Resolution (km)	1000	100	1000	100	10	1	0.1
Distance to target(10^8km)	.7	.07	7000	700	70	7	0.7
Time to target	30 min.	3 min.	7 mon.	3 wk.	2day	5 hr	30 min

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