Fresnel Lens Condenser for a Solar Sail

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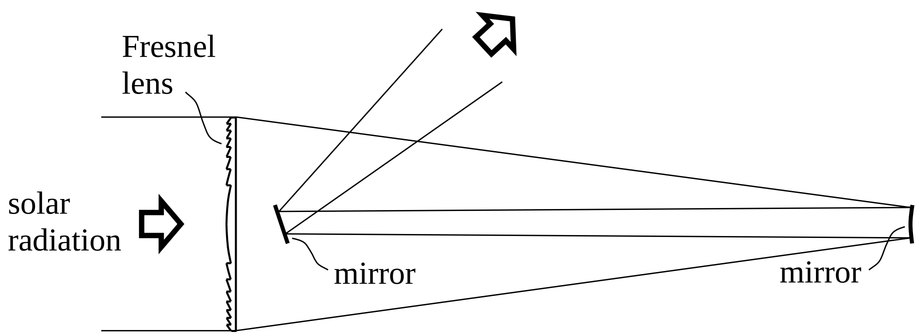
A solar sail typically uses a large reflective surface to accelerate a spacecraft via radiation pressure. By angling the sail to the radiation direction, the direction of momentum transfer can be varied over nearly a full hemispherical range, but very little radiation is intercepted at large obliquity angles. Transmission optics such as diffraction gratings can overcome this limitation, although these structures are more technologically complex than a simple reflective film [https://doi.org/10.1364/JOSAB.34.000C25].

An alternative propulsion concept, illustrated below, uses a large Fresnel lens to concentrate radiation onto one or two small beam-steering mirrors. The lens itself does not effect significant momentum transfer from the photon flux; it only functions as a condenser, which allows the use of much smaller mirrors as momentum-transfer elements.



A lens of low numerical aperture (e.g. 0.1-NA) would have shallow Fresnel facets, which would be advantageous in terms of manufacturability, optical efficiency, and low weight. The lens weight can also be minimized by using facets of narrow width, but facet diffraction effects would be problematic if the widths are too small. The aperture diffraction spread from a facet of width w, with radiation wavelength λ, is roughly λ / w radian. The diffraction will be insignificant if this angle is small in comparison to the sun subtend angle, e.g. about 0.01 radian at 1 AU solar distance ($\lambda / w << 0.01$). Based on this criterion, millimeter-size facets would exhibit insignificant diffractive spread at or within 1 AU solar distance.

The maximum facet angle, for a lens of numerical aperture NA and refractive index n, with facets on only one side, is approximately $NA/(n-1)$ radian (e.g., 0.2 radian with $NA = 0.1$ and $n = 1.5$).

Aside from its use for propulsion, the Fresnel lens could also be used as a concentrator for photovoltaic power generation. In this mode of operation, it may be advantageous to form a phase-Fresnel diffraction grating on the lens's Fresnel facets in order to mitigate chromatic dispersion over the visible spectrum and to separate the visible and infrared spectra. (US Patent 5161057) Alternatively, a phase-Fresnel line grating could be formed on one of the lens surfaces to spectrally disperse the spectrum across a photovoltaic cell with a laterally-graded band gap, for high-efficiency power generation with minimal heat gain.

With the very high amount of radiant flux collected by the Fresnel lens, sufficient power for spacecraft operations might be generated using only a narrow wavelength band, which can be separated out via grating diffraction while the remaining radiation is used only for propulsion.