gleaned by a simple analysis using the above rays where it is found that for large primary lens $f$-numbers, the concentration is

$$C = \frac{nF_1}{F_2} = \frac{n}{2(F_2/D_2)\sin\theta_i}$$

For two-axis concentration, this relation is squared. The combination of Fresnel primary and silo secondary is seen to be ideal if the $f$-number of the secondary is 1/2. Note that it can be shown that a lens with $f$-number less than 1/2 cannot be realized, preventing the above from violating the maximum concentration law.[15] Nevertheless, concentration ratios of around one-fourth the maximum are readily obtained. Despite the loss of some acceptance angle, the uniform output provides significant advantages to this approach.

## 11.4.8 Static Concentrators

The necessity of tracking concentrators has long been considered a disadvantage. While there is little doubt that tracking systems can be made cost-effectively when manufactured in very large volumes and installed in large "energy parks" with 50-MW or more capacity [57], the existing markets for PV systems are for smaller installations. This has lead to considerable research to find a nontracking or static concentrator. Most of the early work was for solar thermal concentrators in which the basic principles were established [58].

Static concentrators rely on three factors to generate concentration greater than unity. First, the region of the sky where most of the energy falls within a band $\pm 24^\circ$ of a plane normal to the Earth's axis of rotation. Figure 11.33 shows a typical yearly average distribution of light falling on a plane tilted at the latitude angle, for a latitude of $34^\circ$ south [59]. This is representative of what is found at most locations, where the bulk of the energy falls in a band of angles around the normal to a plane that is tilted at the latitude angle. An ideal one-axis concentrator with an acceptance angle of $24^\circ$ has a concentration of 2.5. When the details of such concentrators are examined, it is found that they do not receive all the light early in the morning or late in the evening when the sun is near the solstices, but most of the energy can be harvested if the acceptance angle is opened slightly [2].

The second reason that the concentration can be increased is that the cell can be immersed in a dielectric with index of refraction greater than unity. This can typically provide another factor of 1.5X for one-axis and 2.25X for two-axis concentrators.[16] Unfortunately, such dielectric-filled concentrators are rather heavy and expensive if the cells are large. One possibility is to make very small cells coupled with small dielectric concentrators [60]. The practicality of this "microconcentrator" approach depends on the ability to highly automate the assembly of many small cells into the module. Finally, solar cells can be made bifacial, that is, sensitive to light from both sides. This provides

[15] More correctly, this should be thought of as proof that it is impossible to make a lens shorter than $f/0.5$.

[16] Sometimes it is also overlooked that immersing a cell in a dielectric medium that is not a thin planar surface (such as in a glass module) will increase the escape probability of rays reaching the cell's top surface from within and, hence, reducing the impact of light trapping. This type of effect also happens in dielectric secondaries, and results in the loss of several percent in current for silicon cells that rely on light trapping.