OBSERVING SUNSPOTS USING A PINHOLE CAMERA
Or, Could the Ancient Egyptians have Observed Sunspots?
(A Project by Barry D. Malpas – © 2014 BDM)

> You may be wondering, at a time when the bigger the optic, the better the observing (otherwise known as aperture fever) why study the sun using a pinhole. Some years ago (ca. 1990-91) I wanted to know what the limits of observing with the minimum of optics might be, and wondered if sunspots might be visible through a pinhole camera. This turned into a small physics project that I eventually published in *The Practical Observer Magazine*.

Could the early Egyptians have viewed sunspots? Or, for that matter, is it even possible that any early peoples could have observed these solar blemishes before the discovery of the telescope and its application to astronomy by Galileo? Non-telescopic observations are not limited to just 'naked-eye' observing on a hazy day as one might surmise. There is one optical device for which the technology has been around for thousands of years if some curious individuals were only around to serendipitously stumble upon it. This technology is that of the pinhole camera, an optical instrument consisting of only a small circular hole and a screen upon which to project an image. Pinhole observation of sunspots, a hum-bug, you say? Well, maybe not.

First, let me relate a little historical trivia concerning early solar observations, and pinhole imagery, although not necessarily related to one another.

Solar Observations:

- Early Chinese astronomical records reveal that large sunspots had been visually observed a thousand or more years prior to the renaissance discoveries.
- Solar, as well as stellar, alignments of corridors in the Great Pyramid at Gisa have been interpreted by some archaeologists as having been used for astronomical observations.
- My son, an Arizona Hot-Shot, called to ask me if there were any large sunspots that day. He was fighting a fire which sent a lot of smoke into the sky acting as a filter allowing him to see them.

Pinhole Optics:

- In the late 1700s a pinhole projected image was recorded to have been accidentally observed by a Bedouin in his tent when he noticed an inverted view of the people outside appearing on his tent wall, this image being projected through a small hole in the wall opposite.
- Solar eclipse observers have noticed for hundreds of years, possibly much longer, the crescent images of the Sun produced when the light from the partial eclipse phases passed through small gaps between the leaves of trees.

Now, this short treatise is by no means a proof of some archaeological certainty. Especially in light of the circumstantial evidence just presented. It is, rather, an attempt to illustrate some of the criteria required to ascertain the degree of resolution of sunspots that might be observed using pinhole optics and to discuss a simple experiment in which the derived theoretical results are proved.

Pinhole Optics and Resolution

Most optical devices rely on refraction or reflection to provide an image on a screen or film plane. A pinhole camera is a device which uses neither lenses nor mirrors to produce its image, but rather only a small circular aperture, or 'pinhole'. This apparent lack of what one might consider an imaging optic does not mean that such an arrangement of hole and screen cannot produce an image. It does and with infinite depth of field. What it loses, when compared to other optical instruments, is its light gathering capabilities due to the relatively <u>small aperture</u> to <u>screen distance</u> ratio, i.e. the inverse square law. However, even with this shortcoming it still is a candidate for observing the brightest object in the sky, the Sun.

Now the questions begging to be answered are:

- Can such a device actually resolve details such as sunspots on the Sun's surface, and
- Is there an optimum resolution for such an instrument?

The resolution of any optical instrument is the limit established by the diffraction pattern, a property resulting from the wave nature of light, as it passes through any finite aperture (Figures 1a and 1b).
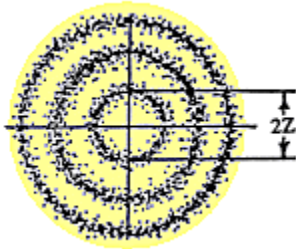

Figure 1a – Diffraction image of a point source through a small aperture.
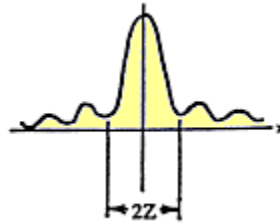
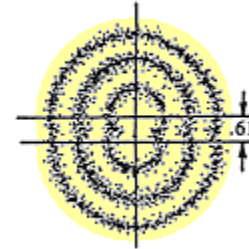Figure 1b – Plot of the diffraction pattern (x) vs. Image Intensity (y).

Figure 2 – Diffraction image from two close point sources.

Consider two point sources. Each point will be imaged through an aperture as a central maximum of intensity, or Airy Disk (after physicist George Airy, 1801-1892), surrounded by alternating dark and light diffraction rings. If the points are close, the diffraction patterns will overlap (Figure 2).

By definition, two points are resolved by an optical instrument when the image separation reaches **0.61· λ / Sin(u)**, where λ = the wavelength of light, and **u** = the angle formed by the aperture radius and the screen distance (see Figure 3).
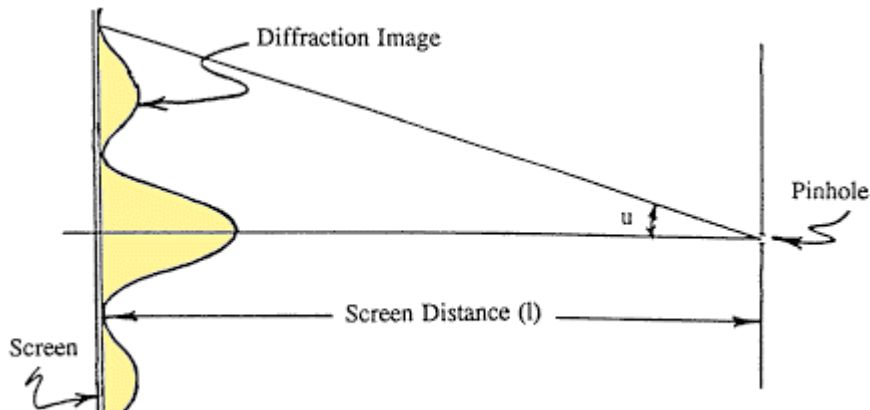

Figure 3 – Pinhole diffraction imaging at a screen

This method for determining the resolution is known as the Raleigh Criterion and is a mathematical description of when the maximum of the diffraction pattern from one point source coincides with the first dark ring by the second point source, and where there is a clear separation of the intensity maxima in the combination pattern, i.e. You can still discern two points, not two so close they appear as one.

The equation defining the radius Z from the center of the Airy Disk to the first dark ring of a diffracted point image is defined as:

$$Z = 0.61 \cdot \lambda / Sin(u) = 0.61 \cdot \lambda \cdot l/r$$

where:

Z = radius of the first dark ring of the Airy Disk
λ = wavelength of the light
l = aperture to screen distance
r = aperture radius

If a screen is placed some small distance behind a small aperture where a bright object (the Sun?) is on the other side of the aperture, an image of the object will be produced by the light rays passing from the

object straight through the 'pinhole' and onto the screen. However, if the screen is too close to the hole, no image will result since some distance is required for an image to be formed. If the screen is placed too far from the pinhole then diffraction effects (interference phenomena of the light photons due to the inherent wave nature) will come into play degrading the image. Therefore, there must be some optimum distance from the pinhole to the screen at which the image produced will be clearest, i.e. a maximum resolution.

The maximum resolution for an aperture having no lens or mirror should occur when the radius of the pinhole equals the radius of the central maximum of the Airy Disk, i.e. **Z = r**. Then the equation becomes:

$$r^2 = 0.61 \cdot \lambda \cdot l, \text{ and } r = \text{sqrt } (0.61 \cdot \lambda \cdot l)$$

Assuming visible light to have an average wavelength of approximately 550 nanometers and multiplying each side of the equation by a factor of two to obtain the pinhole diameter, the relationship of the optimum pinhole diameter to screen distance becomes:

$$d = \text{sqrt}(0.61 \cdot 0.00055 \cdot l) = 0.0366 \cdot \text{sqrt}(l), \text{ or}$$

$$l = 745d^2 \quad \text{where:}$$

$$d = \text{Pinhole aperture diameter (in mm), and}$$
$$l = \text{Aperture to screen distance (in mm)}$$

Choosing several pinhole diameters and entering them into the latter expression results in a list of optimum screen distances for each pinhole. By taking these computed distances and knowing the angular diameter of the Sun (about 32 minutes of arc), the resultant solar image diameters produced at the screen may be calculated thereby giving an indication as to which screen distance to pinhole diameter relationship might be optimum. If the resulting solar image diameter is divided by the pinhole diameter a relative resolution criteria indicator (relative to each other) is obtained since the pinhole diameter is a measure of the limit of the resolution in our situation (when we substituted **Z = r**).

Plotting the <u>Relative Resolution</u> vs. <u>Pinhole Diameter</u> (Figure 4) results in a distinct proportional relationship which forces us to the, seeming odd sounding, conclusion that the larger the pinhole, the better the relative resolution of the solar image.
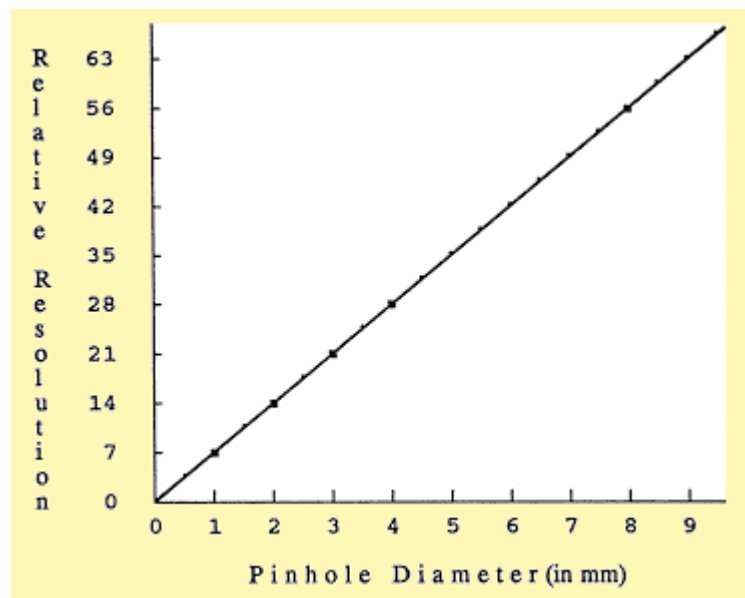

Figure 4

The limit then is the distance at which the solar image becomes too dim to see due to increased hole-to-screen distance.

Testing the Optimum Resolution and Screen Distance

To test the aperture diameter to screen distance theory, I first simulated the Sun by taking a 375 watt flood lamp, placing a mask in front of it having a circular opening of 3.0 cm diameter and positioning it 3.2 meters from a sheet of aluminum foil into which had been poked three holes of 1, 2 and 3 mm diameter (Figure 5).
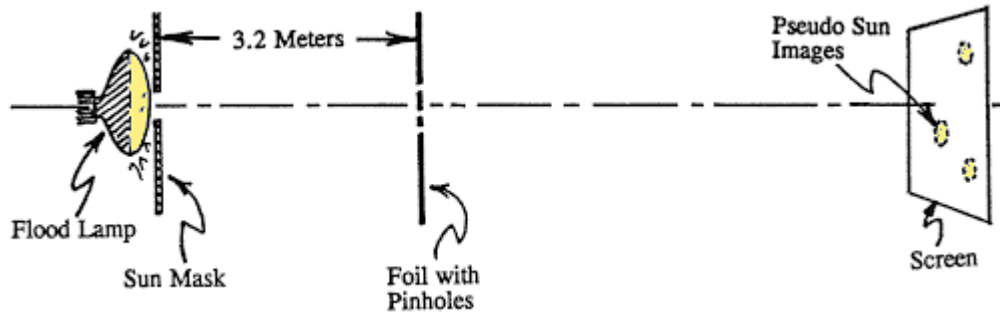

Figure 5 – Simulated sun/pinhole experiment

The mask diameter to distance ratio simulated the same angular diameter as the Sun (about 0.5 degrees). I then placed a screen behind the pin-holed foil and searched for the optimum distance at which each projected image appeared clearest. The distances obtained were 0.7-0.8 m, 2.8-3.1 m and 6.5-7.0 m, respectively. These results correspond reasonably well with the calculated results in Table I.

Table I

Pinhole Dia. in mm	Screen Dist. in M	Solar Image Dia. in cm	Relative Resolution
1	0.745	0.69	6.9
2	2.98	2.8	14.0
3	6.2	6.2	20.6
4	11.9	11.1	17.8
8	47.7	44.4	55.5
16	190	177	111
32	760	707	221

I then placed a strip of paper 1.5 mm in thickness across the simulated Sun to see if the projected images would resolve this 1/20 solar diameter object. It did in all cases, and very clearly, which lead me to believe that at least large sunspots would be visible in a pinhole projection.

The Sunspot Projection Experiment

Rather than build a huge stone observatory pyramid, or other clumsy pinhole observing device, since long pinhole to screen distances were required, and my research budget was minimal, I decided to 'cheat'. I decided to use a reflection pinhole. I acquired a first-surface mirror which would allow me to direct the Sun's light with very little effort over the long distance needed to attain a sufficiently large projected solar image.

The small mirror was mounted with masking tape on the head of a camera tripod for stability, positioning, and maneuverability. I then chose a sufficiently large hole by taking another strip of black masking tape, punching a hole in it with a commercial paper hole-punch, and affixing the tape to the mirror surface. This produced a mini-mirror pinhole aperture (d) of 5.9 mm diameter. I then calculated the optimum screen distance (l) for the clearest image resolution (25.9 m). I placed the tripod behind the observatory so that I could reflect the Sun's image through the rear door onto a white paper screen set up in the darkened building (Figure 6).
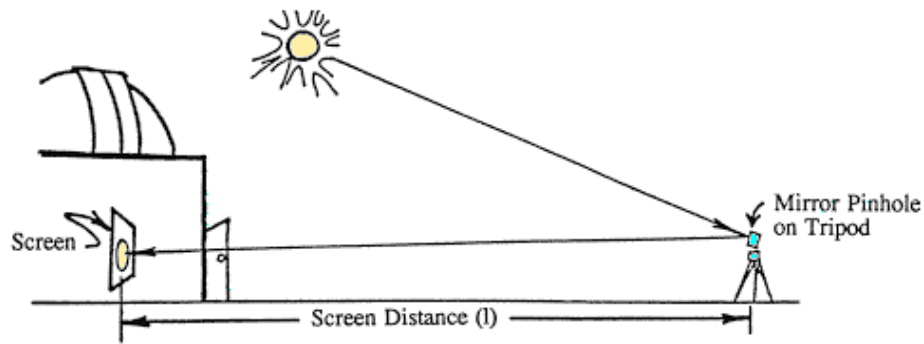
Figure 6 – Sunspot Experiment Set-Up

The resulting solar image was 24.1 centimeters in diameter. Noting several sunspots visible, I proceeded to trace their images onto the screen (This is much more difficult than it sounds since the Sun is a fast moving target, particularly at this projection size and no tracking involved. Several attempts were made at marking the sunspot positions, and shapes, to assure reasonable accuracy.) Five sunspots were easily identified (Fig. 7a), two very large and three moderately sized ones. After acquiring this data I made projection drawings for comparison onto a standard size solar observing sheet using a 4-½ inch reflector.

To make the two sets of data comparable, I photo-reduced the pinhole projected data using the proper reduction ratio to make the two drawings of equal size. Also, instead of copying onto paper, the reduction was made onto clear sheet Mylar which allowed me to flip the image over since the pinhole projected image was left-right reversed with respect to the standard drawing.

Comparison of the drawings reveals very similar images. The only differences are: 1) The three very small sunspots in the 4-½ drawing do not appear in the data from the pinhole projection; and 2) The degradation of detail around the pinhole projected spots is of much lesser quality.

Notes and Conclusions

The only optical imaging problem of any consequence I encountered was thermal air turbulence due to the solar image being projected parallel to the ground from the cold outdoors into the warm observatory. This, however, did not appear to degrade the image in any great detail.

The intensity of the 24 cm solar image was easily bright enough for viewing and a larger pinhole could have been chosen, at least one producing twice the projected solar diameter. However, increasing it much beyond this would decrease the image intensity to the point that much of the gained detail (due to the greater relative resolution) would probably be lost to a dim image since the intensity of the image decreases geometrically as a function of d / l^2. Comparing the results in Figure 7 clearly shows that the large sunspots, and those of moderate size, could easily have been viewed using pinhole projection by some ancient observers had they been so inclined.
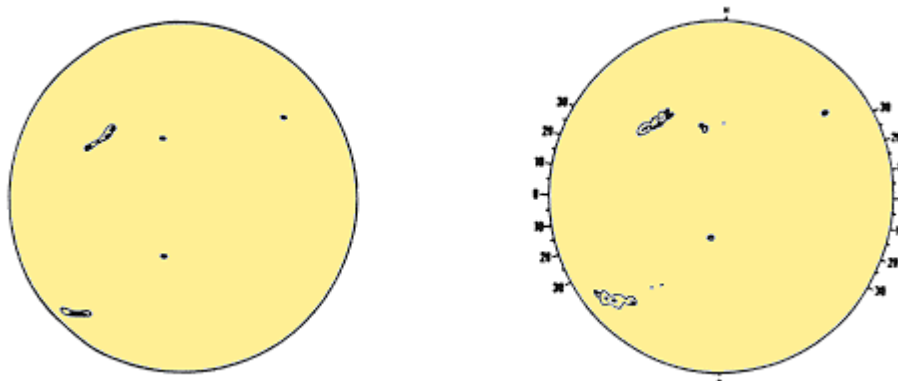

Figure 7a – Sunspots Imaged from Pinhole   Figure 7b – Sunspots Imaged from 4-½" Reflector