An Empirical Review of Solar Equipment for the Non Professional Solar Observatory

Of the many commercial telescopes available on the market today, most are unsuitable for serious solar work. A number of factors are involved - visual - photographic - monochromatic - and spectroscopic.

Refracting vs. Reflecting Optics:

The refracting optical system has proved to be far superior to any reflecting system due mainly to the scatter effects present with aluminized surfaces. This includes not only primary mirrors, but also flat mirrors if used in Heliostat or Coelostat input optics. Catodioptric telescopes, even the most expensive ones are very inferior to even small lens systems.
For white-light observation of the solar disk, uncoated (non aluminized), reflecting optics should be used. The use of unaluminized flats or even primary mirrors reduce light acting as a partial filter, reduce scatter, and heat turbulence. Any form of metal coating on a mirror surface tends to increase the mirror surface temperature with consequent changes in its optical properties. (If one does require the use of mirrors for solar work it is strongly suggested that the mirror substrate be of fused quartz).

A number of trials were made with mirror vs. lens optics. A 4 inch diameter concave mirror - aluminized - with a 9 foot focal length was used as a primary solar objective. The 4 inch mirror was in a horizontal position, south of the observing room, and fed with a 6 inch optical flat also aluminized. The results were very poor, even under good seeing conditions. The mirror was reduced to 1 inch in aperture, with little significant improvement. Turbulence and change of focus were very pronounced due to thermal effects. No real steady image could be obtained. A 4 inch diameter - 62 inch focal length achromat was substitued for the conacve mirror, and the results were dramatic. The solar image was steady, resolution excellent, and white light disk details very clear. A 3 inch achromat was then tried, stopped down to 1½ inch to give an f/20 beam and also produced excellent images. The results of this experiment verified that in all cases the refractive optics gave the better results.

A final test was made with the use of a 3½ inch Questar telescope, and the 3 inch cemented achromat. Both systems working at about f/10. The Questar was used with a full aperture Inconel filter, which was of the same type used with the 3 inch lens objective. Both systems were examined together under the same sky conditions. Again the lens objective gave the more stable image. Eventually the Questar instrument came up to the image quality produced by the achromat. However turbulence within the Questar's closed tube, and changes of focus due to heating of the internal reflective optics took far too much time to stabilize.

Focal Length to Aperture Ratio:

f-ratios are most important considerations for solar telescopes. Long f-ratios are invariably in use where solar structure of very small size on the order of 1 second of arc is under investigation. Most effective solar instruments operate at f-ratios of from f/20 to f/50, which produces an image of moderate size and brightness. Additional advantages of long f-ratios is that the light cone is less sharp in angle, and focus changes due to thermal effects due to the much greater depth of field is much less. F-ratios of f/20 or more are desired for monochromatic work with Birefringent or interference filters as well.

The actual limit to the resolution of the sun's surface structure is normally set by the scintillation of the image due to moving striations of the earth's atmosphere, a condition far more pronounced in daytime vs. night time astronomy. Since it is only rarely that the atmosphere is steady enough to allow details 1 second of arc in diameter to be seen clearly, there is not any problem about obtaining telescopes with sufficient resolving power. Tests at Yerkes Observatory extending over several months showed that when the 40 inch refractor was reduced in aperture by a diaphram to 10 inches, the theoretical resolving power of about 0.5" was always below the limit set by atmospheric smearing! At that location, the improvement in image with decreasing aperture continued down to an opening of between 6 to 8 inches, even under the best conditions of seeing, presumably because of the gain in making the lens area as small as possible, in comparison to the size of the convective elements in the lower atmosphere more than counterbalanced the loss in optical resolving power.

It seems to be evident, that even under the most favorable terrestrial conditions and locations, a telescopic aperture of abount 12 inches would be the maximum. In tests and actual practice, I have found that apertures from 2 to 5 inches are very effective, all working at f-ratios of f/20 or more.

Some solar observers have used relatively short f-ratios (under f/10), with the use of eyepiece or projection optics to obtain the longer focal lengths and larger image size. This was done as early as 1877 by Janssen for photographic use. However, as Janssen discovered, and I have verified, this may not be the best system to use in that convection effects take place in the heated air near the projection lens at the objective focal plane. The distortion is suggestive of convection cells of the Bénard type, which are either not present or very greatly reduced when long focal length optics are used in place of projection optics. If such projection optics are required, consideration must be given to remove turbulence at the focal plane by means of blowers or fans.

Some solar telescopes consist of only a single element refractive primary lens. This is most often used for monochromatic work to spectroscopic of filter input optics. Since monochromatic observation takes place at a single narrow wavelength spectral point, chromatic abberation of the primary O.G. is no longer a consideration. Such an objective lens can be made from a single "Red Glass" element - if the monochromatic work is to be done in Hydrogen-alpha. A plano-convex lens corrected for spherical aberration as described by Pettit. Such "Red Glass" blanks or even finished lenses are available from several sources. If the glass chosen has the spectral transmission required, it can also serve as an energy reduction filter (ERF) for use with a H-a monochromatic filter. ERF's have a band pass similar to a glass Wratten #29 photographic filter.

ERF Filters, Objective and other types"

The use of some kind of Energy Reduction filtration is always desired with solar work. For white light observation the Inconel on glass is prefered to the various Mylar plastic filters. The color rendition with the Inconel type is far superior to the Mylar. In my opinion the glass filter introduces less optical distortion, and has less tendancy to break when in use. Such filters when used with unaluminized mirrors can give a cool image. The observer should be sure that the metalized filter also reduced Infrared radiation as well as UV and visible.

Such ERF filters can be used in front of the objective which has the advantage of keeping heat effects down within the optical system. In addition, objective filtration will reduce the total ultra-violet radiation on the objective. Some cemented achromatic objectives will develop a "Haze" in thecement used between the elements. This is due to "Solarization" from the sun's UV radiation. I have experienced this condition with an older cemented objective that used Canada Balsam as the cementing material. More modern objectives use a thermo-plastic cement which seems not to be affected by UV. Again objective filtration removes this problem.

The ERF filter can be moved down the optical path with some advantage. This allows for smaller diameter filter plates, and reduces the higher optical precission that is required for objective filters. (In any event, the wave front for any filter should be no less than ¼ wave!) Again, for monochromatic work an ERF filter is an absolute requirement as the monochromatic filter can have permanent damage to it without the use of a pre-ERF filter!

For white light observation of the sun perhaps the best and most convenient filter is the Polarizing filter which is an adjustable density device used at the eyepiece or output end of the optical system. This device operates upon the polarization effects of plane glass reflections which when mounted at the Brewster angle of 57^{o} angle of incidence will allow a brightness control from full solar disk brightness to extinguishment of the image. Further, there is no change or alteration of color with this instrument. The solar disk resembles a full moon in color with very high contrast and detail. Only four small plane mirrors (unaluminized) are required with a rather simple mechanical assemby for rotation, and is inserted into the eyepiece tube of the telescope. This device is described in detail in Bell's "The Telescope" - McGraw-Hill Book Co. I have used this polarizer and have been very impressed with its operation! However, this device only attenuates, does not remove radiation. The I.R. is not filtered out only reduced. An additional IR filter should be considered for visual work. As pointed out by Mr. Richard Hill in his "Contributions of LaEstrella Obervatories" Nr.1, some solar filters available on the commercial market can in fact be quite dangerous to the observer.

Monochromatic Observations:

One of the most interesting facets of solar observation is the study of the sun in monochromatic light at Hydrogen-alpha, or Calcium-K wavelengths. This requires specialized auxillary equipment to the telescope. Either the use of a spectrohelioscope, or a narrow band birefringent or interference filter is used. There is now available interference filters centered upon the H-a wavelength of 6562.8 Å in the visible red portion of the spectrum. These can be obtained as narrow as 0.5Å band-pass.

The filter "purity" which also applies to the spectroheliοscope can be defined as the ratio of the central wavelength transmitted by the device to the width of its passband. Monochromatic disk features are not well shown unless the "filter purity" is greater than 10,000. Solar prominences however, are revealed with purity ratios as low as 1,000.

For example: A bandpass of 0.1Å at H-a would provide a "purity" of 65,630. A 0.6Å filter bandpass gives a "purity" of 10,938 which is most adequate to show both disk and prominence features together. Thus a filter with approximatly 5.0Å bandpasswould allow the observation of prominences. I have on occasion, and with the use of an occulting disk in the optical train observed limb prominences under good seeing conditions with a 10Å bandpass filter. In some cases, the wider bandpass is an advantage in that for prominence observation the Doppler effect is reduced with the wider band filter. The narrower band filter requires bandpass change at times to compensate for prominence motion. Such adjustments are built into the narrow band filter by a change in its operating temperature. Interference filters will show a change in the center wave length by either a change in the operating temperature, or a tilt along the optical axis. The filters are designed and callibrated to work at a specific temerature for the center band wavelength. The filter is enclosed in a insulated heated cell which does operate higher than ambiant temperature. An adjustment is provided to allow a change in the operating temperature so that the observer can shift the center band about +/- one Å. to either the blue or red wing of the H-a wavelength. Filters for use in the visible violet spectrum at Ca-K are available, but quite expensive at the present time. In addition the calcium wavelengths are just at the border line of visible radiation (near UV), and while excellent for photography, is quite difficult for visual observation. However, the Ca-K line is much broader than the H-a radiation, and gives an image of much higher contrast. A point of interest, is that if a video detector is used with Ca-K, the results are excellent! The video (TV) camera acts as a spectral image converter. In general, a narrow band interference filter can provide a bright, high contrast solar image, with both disk and limb features visible together.

In addition, such interference filters are small, light weight, and compact. They can be used with portable telescopes with good results, but do require a source of electrical power for the heater unit. One is restricted to only one spectral wavelength for each filter, but since the majority of monochromatic work is done with either H-a, or Ca-K this is of small inconvenience.

Spectrohelioscopic Instrumentation:

While the basic design of this instrument is rather simple, it does involve some rather complex mechanical-optical components. The production of an image requires scanning of the solar disk with a spectroscope/graph. The optical speed is quite slow because of this factor. The basic requirement of scanning can be accomplished in any one of three ways. For photographic use as a spectroheliograph, the solar image may be in a fixed position, along with the photographic plate or film, and the entire spectrograph moved to scan the solar image, projected by the primary objective. The second alternative is to have the spectrograph in a fixed position, and both the solar image and photographic plate moved together to scan the image. The third possibility is to have the spectrograph, film, and solar image in a fixed position, and to move both the input and exit slits together scanning the solar image. The actual choice is a mechanical convenience matter for any given installation. If, and as it is desired to be, the spectrograph is of very long focal length to obtain high dispersions, the instrument itself must be in a fixed position. The movement of the two slits is probably the best system for that application. The only difference between a spectrohelioscope and spectroheliograph is in the method of detection - eye vs. photographic film. Both types are identical in all other requirements excepting that the silts for visual work must have a movement, or oscillation of 25 or more cycles per second. This can be obtained by several methods such as rotating silts, oscillating slits, or the best I have experienced a square glass rotating prism (Anderson prism), which gave the brightest image and the least flickering of the output image.

One of the <u>most</u> important requirements for the spectrohelioscope/graph and one that is probably least mentioned is that of as high a linear dispersion as possible! High dispersion puts a great deal of optical space between the various spectral lines - spreads out the wavelengths - which in turn reduces sky scattering and spurious light. High dispersion can be obtained several ways. First, long focal ratios in the spectroscopic equipment. A focal length of 3 meters is not any too great. Dual, bandpass spectral systems are of help. A grating with 30,000 lines will give greater dispersion that one of 15,000 lines. When gratings are used, work in the higher orders, and if possible obtain a grating that is "Blazed" into high order. (This is not always easy to find!) A combination of prism and grating will also provide higher dispersions. The consideration of prism vs. grating is important. Prisms as a rule give much brighter images, and do not have the problem with order overlapping. Prisms on the other hand are not linear in dispersion. They give very good dispersion in the violet-blue portion of the spectrum, but down in the red visible portion the dispersion is very low. This applies to any type of conventional prism even with very dense flint glass. This can be overcome to some extent by the use of compound cemented prism combinations such as the so called "Direct vision" combination which consists of a train of cemented glass prisms of different flint and crown units at rather large refracting angles in numbers up to 10 or more elements. These while providing satisfactory dispersion have some loss in absorption, and the problem of curvature of the spectral lines can be serious. It should be pointed out, that the conventional 60° prism or even several such prisms working together do not as a rule prove to have enough dispersion for solar spectroheliographic work. Extreme focal lengths would be required and the physical size of the instruments gets quite out of hand. Combinations of both prism and grating have been used allowing reasonable instrument size. I have used with very good results various concave gratings in both Eagle, and Wadsworth stigmatic mountings. Both gave good results. Plane gratings in a Littrow mount or other more modern mounts have also proved to be satisfactory.

The advantage of the spectrohelioscope over the various monochromatic filters is the availability of wavelength change over the entire spectrum, and adjustment of the bandpass at any given wavelength. If one has such instrumentation at hand, it can also be used to quite good advantage for normal spectroscopic observation of the solar spectrum and in particular of lines of interest in disk features and spots. Doppler motions can be observed and measured -The solar constant can be recorded - and many other possibilities are open to the observer including Zeeman effects in the magnetic solar fields. Every serious solar observatory should have some form of spectroscopic equipment on hand. This can be visual, photographic, or photoelectric detection. We use a photoelectric monochromator with photomultiplier detection and strip chart recording to measure the solar spectrum. Some of the results obtained in 1984 are shown on the attached data sheets of measurements obtained at Kitt peak Arizona vs. Parma, Ohio at the summer soltice. As can be seen, the UV radiaion is much higher at Kitt Peak than here at low levels in Ohio. Be this a warning to the prosfessionals at Kitt Peak regarding Erythemal effects during the daylight hours! It is quite evident, that higher elevations do make for greater sky transparency. Note the much higher W/Cm^2 radiation value shown at H-a at Kitt Peak.

Horizontal vs. Vertical Fixed Input Optics:

For many years experiments and discussions have been conducted to establish the Pro. and Cons. of these two optical configurations. Hale had established that the vertical or "Tower - Pit" instrumentation was superior to horizontal optical mounts. Hale at Mt. Wilson designed and used vertical instrumentation. However, for the average non-professional observer can not afford the costs or provide the physical installation of such instrumentation. His only option is to use horizontal designs if fixed optics at the output is desired. It should be mentioned, that fixed optics at the output end of the telescope is to be highly recommended. The output image is fed into the observing room, with the objective, and Heliostat mirrors and drives located outdoors. This gives the observer a comfortable viewing station, allowing all sorts of heavy additional optics to be located in a fixed position. Only a light drive is required to slew and drive the Heliostat or Coelostat mirrors, and the observing room can be darkened, and heated or air conditioned as required - and most important no "Bugs" to bother ones observing concentration.

Some of the disadvantages of horizontal installations can be overcome by the provision of blowers and/or fans at strategic places to remove air turbulence and heating effects. This to stir the air to prevent stratification parallel to the light beam's direction. Vertical instrumentation shows that the air does tend to stratify in horizontal layers, which are transversed in nearly perpendicular incidence by the light beam.

If a spectrograph is being used, the residual "seeing" arising from convection currents is most often the limiting factor in the spectrographic or even the visual resolving power. This then indicates the observatory should be provided with many and much blower and fan units to keep such turbulence at a minimum! This consideration can often make the difference between good and bad seeing results at any given location!

Some consideration can be given to what type of mirror system should be used with the fixed bench optical instrumentation. Either Heliostat, or Coelostat. I use both types at this observing location. The Coelostat requires two flat mirrors vs. only one for the Heliostat. Both seem to give equal optical results. The rule of thumb is to keep as many optical surfaces to a minimum, so the single mirror Heliostat offers the better advantage in this respect. Also, at Parma, Ohio the single mirror Heliostat is at the polar angle of $41\frac{1}{2}^{o}$ which allows the observer to look down a comfortable viewing angle. The Heiliostat is used for white light observing at this location, while the Coelostat which is a modified design is used for monochromatic work.

Gadgetry and "Show and Tell":

While the basic instrumentation used at this location had been described, most individuals continue to add refinements, extras, and more to their equipment as time goes on. The hope being to extend the observing program, add optical capacity, or just to impress the visitor to the observing station and its program. Of the many "Gadgets" we have tried at this location, some worked, some did not, but all were interesting to try. One item that did prove to be of value was the installation of Video detection as a read out and recording system.

A black & white TV camera is used to detect and feed several closed ckt. TV monitors in addition to a VCR recorder. I have found that the video camera gives excellent results at H-a wavelengths at prime focus of the system. I can see everything on the TV monitor that I can see by eye in the eyepiece, and in fact have the very desired advantage of being able to increase the image contrast on the TV screen by electronic adjustments to the TV camera. (This is a simple adjustment of beam and target controls for maximum constrast and resolution). In this way, I can monitor the solar disk all through the day by a glance at the TV monitor screen, and as mentioned with several B&W TV monitors located around the house as well. If a particular event should start to occur during the monitoring day, a simple quick switch allows the VCR to start video recording such events in real time. The audio channel of the VCR is connected to either WWV, or CHU so that time signals are recorded directly with the video events. Originally the design was to record solar monochromatic events with 16mm motion picture equipment on film either as single frame time lapse or time bursts of several frames. However, such 16mm motion picture recording is not only expensive, but does not represent Real Time observation. By the time the film is developed and returned it is historical. Video tape can allow instant "Replay" and is inexpensive compared to motion picture film. Thus the Bolex 16mm film camer was replaced with B&W video TV camera and VCR recorder. Both VHS and Betamax formats are available for this use. I have one several occasions been able to record both flares and a rather large recent surge prominence with excellent results with video equipment! I am now in the process of obtaining photographic equipment which will allow taking photos on 35mm film directly from the TV monitor. With this system I should be able to obtain a specific event from either actual real time, or from the replay of the video tape.

The use of a black & white TV camera is suggested over a color camera. Our tests with color vs. B&W video cameras indicate that the B&W units have higher resolution and detail, and in addition, there is no particular advantage to seeing a red colored H-a image rather than a high detail B&W image! Also such B&W TV cameras are much more inexpensive than color units. The cameras are not commercial units, but is one offered for the home video market and is a ½ inch videcon. Some years ago we used a commercial B&W image orthicon camera which had a great deal better resolution and detail, but is no longer available. While this facet of solar image recording is rather new to the non professional solar observer, it can in my opinion be a viable and inexpensive system which in future may also be of value to the professional solar observer.

Summary:

Optics:

Use refractive rather than reflective input optics. Apertures larger than 5 inch are not required, except for prestige in the telescope "Horse power" race. Use a focal lenght f-ratio as long as possible, but not under about f/20. Try to avoid projection or eyepiece amplification of the primary image. If such projection is used, be sure you have adequate blowers to reduce turbulence.

Use metal coated on glass filters rather than plastic Mylar types for objective filtration. If monochromatic filter is used, be sure to have a ERF filter to remove UV and unwanted visible light prior to the monochromatic filter itself. If white light only observations are to be made, consider the use of uncoated (non aluminized) reflective optics as a light reduction system.

Fixed bench optics is a great advantage, with the telescope in a horizontal fixed position fed with a Heliostat. Slow motions to position the solar image are easy to fabricate and a convenience. Automatic sun guiders are also simple to construct - only 4 simple photo-cells are required in a simple bridge configuration to allow corrections for image drift.

A few comments for those observers who do have monochromatic filters:

While it is quite satisfactory to use a H-a filter in the primary f/20 or longer beam, an advantage can be obtained if the filter is used in a "collimated" optical system. Collimation allows the use of an occulting disk if desired, variable magnification of the image which is good for the examination of some small sized disk or limb event, and allows the filter to be used in full aperture with minimal optical distortion. This then allows the single exception for shorter f-ratio of the primary. If a short f-ratio primary is used with a collimation system, the filter always operates in parallel light. Caution must be observed because of the high light concentration into a very small area present with short f-ratios. The filter-collimator when used with a long f-ratio is the ideal system with all of the advantages the observer might require.

Practical Equipment Considerations:

A solar optical system that I use and have found practical is a cemented achromat - 2 inch in diameter, with a 50 inch focal length. This is a commercial achromatic lens available at reasonable cost from several sources. (A. Jaegers and others). The objective has a 52 mm ERF filter - red glass similar to the Wratten #29 placed over the surface facing the sky. The objective looks south, and is fed by a modified 2 mirror Heliostat. Two 4 inch aluminized optical flats (1/10 wave) are used in the Heliostat. One mirror is mounted in polar configuration driven at solar rate once in 48 hours by a simple and inexpensive gear system from a 1 RPM sync. motor. Slewing is provided in R.A. and Dec. by two small 12 volt DC motors which are geared down to 5 RPM on each motor shaft working into a 40:1 gear reduction on each mirror shaft. Only a few minutes are required to slew the mirror from horizon to horizon.

The second flat mirror is located several feet away from the equitorial first mirror so its shadow does not obstruct the first mirror. The second mirror is mounted vertically and faces the objective. It also has two of the same DC gear motors to allow up-down-right-left posistioning of the 2nd mirror axis. The 5 RPM motors work into a 50:1 gear reduction for each of the 2nd mirror axis. This allows the observer to position any part of the image with a fine motion.

The objective lens with its ERF filter is mounted in a 2 inch ID plastic heavy wall tube. (This is a standard plastic pipe available from any plumbing supply house). The 2 inch tube is mounted coaxially within a 4 inch thin wall white plastic pipe which is also available as a standard item. The outer 4 inch pipe or tube serves as a thermal barrier, and a support for the inner 2 inch optical tube. The inner pipe has several wood disk spacers between it and the 4 inch outer tube. The entire inner tube can be moved back and forth with a rack & pinion from inside the observing room. This is so various optical additions to the telescope can be positioned at a desired place within the observing room. The output end can also be rotated 360^{o} so that any optical position is available.

The "tail" or output end terminates in a standard 1¼ inch tube. The H-a filter is inserted into this "eyepiece" tube. The filter is fixed to a ball-race support which moves with the focus and tube motion rack & pinions. A dial guage is attached to the focus rack which allows re-setting of the focus tube to within .001 inch of a predetermined focus position. This is a help for 35 mm photography when required.

A right angle flat is inserted into the output end of the H-a filter and feeds the video camera which is fixed to another ball race system so that the entire optical system can be moved in any direction and always remains in a fixed optical path.

The various electrical controls are mounted at the observing table and easy to use. The TV camera can be moved out of the way on its ball race and various eyepieces can be inserted into the filter for visual observation. 35 mm SLR camera can be used by inserting it directly into the filter. It mounts onto the focus ball race and remains in a fixed optical plane with the objective lens. The SLR camera had its "ground glass" view screen removed and replaced with a clear plate. It is impossible to use the conventional ground glass view screen on most SLR cameras for sharp focus of the solar image!

The video camera feeds several small TV monitors as well as a VCR. The monitors are connected together with coaxial cable and use the RF output of the camera. The VCR has direct video and audio input from the camera, and a radio receiver set to WWV or CHU for time signal recording. The observing room is a attachment Patio to the house. The telescope tube is fed through the south wall of this room at about 36 inches from the ground. The room interior is darkened to allow for better viewing contrast. This telescope system has been in use for some time with excellent results. Recently, another telescope has been added. It is a 5 inch RFT fed from an 8 inch aluminized optical flat mounted in a polar Heliostat form. This instrument was designed as a night-time telescope, but is also used to provide a concentrated solar image for use with the spectroscopic equipment. It feeds at present a B&L large constant deviation visual spectroscope. It can also feed a dual grating photoelectric monochromator with strip chart recording.

All in all we have derived much pleasure and information from our solar installation, in particular with hydrogen-alpha observations. The sun is never static, but always has change and activity even now when it is in the minimum spot cycle. Unlike night time astronomy, every new day presents a new feature on the sun - and at times the most exciting that can be seen in astronomy!

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