

# MEASURING SEEING FROM SOLAR SCINTILLOMETRY AND THE SPECTRAL RATIO TECHNIQUE

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**Abstract.** In principle, the optical transfer function can be described by a single parameter, the Fried parameter  $r_0$ , which reveals the net effect of the turbulence along the line of sight. We present measurements of the Fried parameter obtained from the spectral ratio technique and compare them to data from solar scintillometry and from angle-of-arrival fluctuations. The measurements were performed at the Big Bear Solar Observatory (BBSO) in 1997 and 1998 – before and after a series of steps were taken to reduce dome seeing. The results show that the dome seeing was considerably reduced and now approaches the seeing conditions measured outside the dome. The Fried parameter as measured by the spectral ratio technique now frequently exceeds  $r_0 = 10$  cm at our lake site observatory. Accounting for the remaining dome and window seeing, the scintillometer and the angle-of-arrival data imply the potential for an  $r_0 > 20$  cm for BBSO during days of good seeing.

## 1. Introduction

Qualitative measurements of daytime seeing have become more important in recent years, in part, because of the search for the best site for a future, large aperture solar telescope. In this paper, we present the results of a comparison between the spectral ratio technique, solar scintillometry, and angle-of-arrival measurements that were obtained in the process of sharply reducing the dome seeing at Big Bear Solar Observatory (BBSO).

The first speckle interferometric observations at BBSO (Denker and Wang, 1998) indicated that almost diffraction limited observations could be obtained from the 65 cm vacuum telescope, although there was a strong dome seeing problem prevailing at that time. The major source of the problem was the gradual increase of the heat load on the observing floor over the years, while changing detectors from photographic film cameras to video cameras and, finally, to digital CCD cameras – many new control computers and monitors were added to the observing floor.

BBSO is one of the sites of a Mark I CLEAR scintillometer (Beckers *et al.*, 1997). One scintillation sensor is located atop an 11 m high mast on the causeway that connects the small observatory island to the lake shore. This outdoor scintillometer is pointed in a fixed direction towards zero declination and an hour angle of  $20^\circ$  east of the meridian. A second sensor is mounted in front of the 65 cm vacuum telescope behind the dome slit, i.e., it is always pointing directly towards the Sun.



The two sensors are about 25 m apart, they allow us to simultaneously monitor both the outside and the dome seeing.

The correlation between scintillation in the solar irradiance and the resulting image quality was discovered by Seykora (1993). A detailed description of the CLEAR scintillometer network and its data calibration was given by Beckers *et al.* (1997). Since the Fried parameter derived with the spectral ratio technique (von der Lühe, 1984) is an important by-product of speckle interferometric image reconstruction, it is only natural to compare it with the results from solar scintillometry. The spectral ratio technique provides an easy way to obtain  $r_0$  from a time series of a spatially resolved object of arbitrary shape which has been degraded by seeing. The basic idea is to compute the ratio of the observed squared modulus of the average Fourier transform to the observed average power spectrum.

In the next sections, we show the results of solar scintillometry and the spectral ratio technique, followed by a comparison of these results. In the final section, we discuss the discrepancies between the imaging (speckle interferometric) and non-imaging (scintillometric) techniques.

## 2. Solar Scintillometry

From data of 28 October 1997 and 16 August 1998, we compared the seeing conditions at BBSO by means of solar scintillometry and the spectral ratio technique. In 1997, the inside sensor was mounted approximately 2 m in front of the entrance window of the 65-cm telescope – somewhat more than a meter behind the dome slit. Because of the approximately 4 mm lower scale of turbulence, the scintillation sensor is not very sensitive to seeing variations in the first meter, we decided to move it further back for the 1998 measurements. Now, it is mounted just 50 cm in front of the entrance window which makes it much more sensitive to dome seeing. Therefore, the 1998 set-up represents a ‘worst case scenario’ for measuring dome seeing. Thus, our subsequent argument that dome seeing has been significantly reduced is stronger than the numbers indicate.

Figure 1 shows the evolution of the daytime seeing at BBSO on 28 October 1997 and 16 August 1998 measured with both the inside (dashed curve) and the outside (solid curve) scintillometer. A median filter has been applied to the curves to remove some of the short-lived fluctuations and show more clearly the long-term trend. Note that the outside scintillometer signal shows very little variation during the day which is the outstanding feature for BBSO, and results in a large average Fried parameter. Mountain site observatories usually show a distinct dawn minimum for 1–2 h with the seeing decaying rapidly afterwards (e.g., Figures 1 and 4 in Beckers *et al.* (1997) and note the scale). The early morning mountain site voltages are comparable to those at BBSO but the low readouts at BBSO persist all day long. Since the daily observations at BBSO do not start immediately after sunrise, the inside scintillometer record starts later. In the early morning, the inside

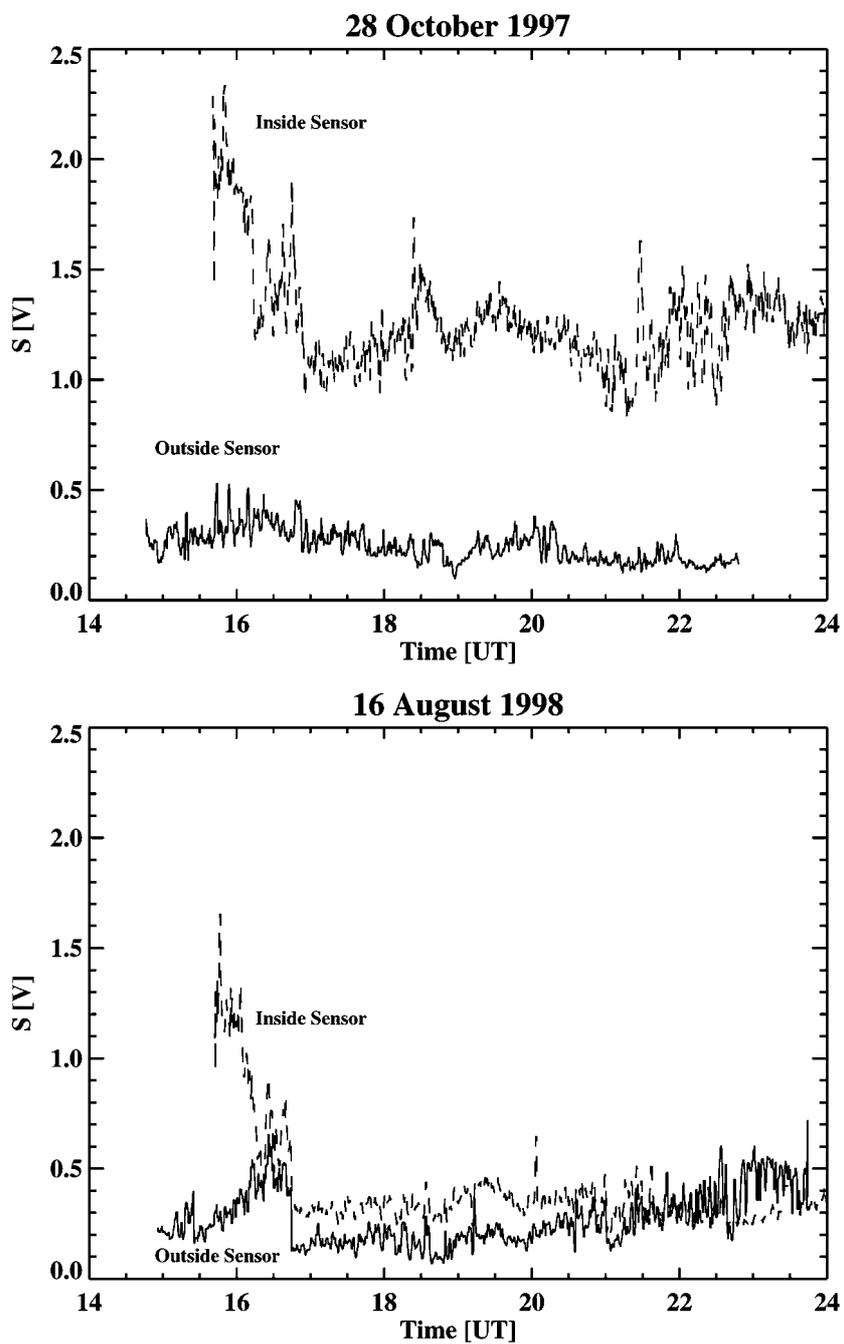


Figure 1. Signal of both scintillometers on 28 October 1997 and 16 August 1998.

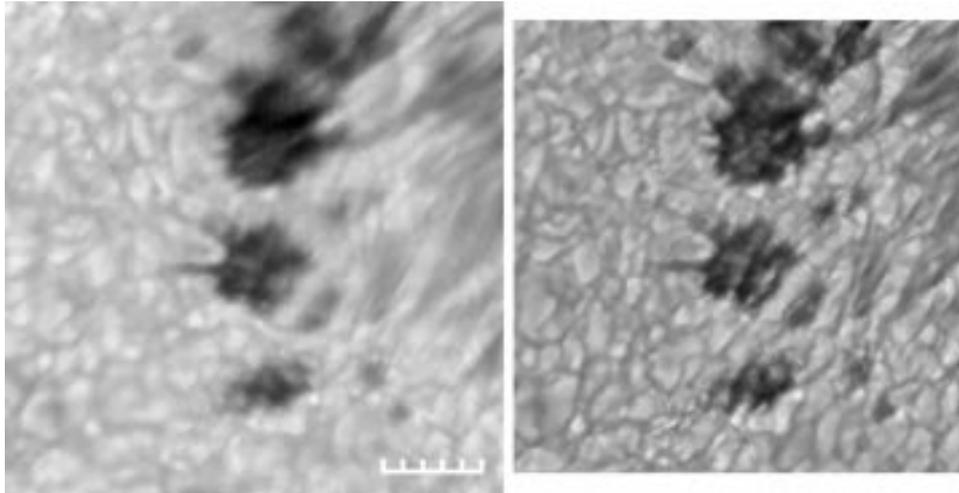


Figure 2. NOAA 8299 observed at 18:48 UT on 16 August 1998. The separation between the tick marks is  $1''$ . The right-hand image is the speckle reconstruction of 100 frames, the best of which is shown in the left-hand image.

record also shows a distinct drop off which is caused by reflection of sunlight from the lake surface. This effect is more pronounced for the inside scintillometer, since it is pointing almost directly to the horizon. Because of the  $20^\circ$  tilt eastward of the outside scintillometer, its record ends between 22:30 UT and 24:00 UT.

### 3. Spectral Ratio Technique

The speckle observations were taken with a  $256 \times 254$  pixel, 12-bit Dalsa CCD camera running at  $90 \text{ frames s}^{-1}$ . The optical set-up, data processing, and data analysis were the same for both the 1997 and 1998 observations. This same set-up was used by Denker and Wang (1998) for a high spatial resolution study of a small  $\delta$ -spot on 31 August 1997. The 1997 and 1998 images were obtained at  $\lambda = 520 \pm 3 \text{ nm}$ . The corresponding spatial resolution of the 65 cm vacuum reflector is, according to the Rayleigh criterion,  $\alpha = 1.22\lambda/D = 0.201''$ , whereas the diffraction limit is reached at  $\lambda/D = 0.165''$ . The image scale is  $0.098'' \text{ pixel}^{-1}$  which corresponds to a field of view of  $25.0'' \times 24.8''$ . We took 150 sequences of 100 short exposure images on 28 October 1997 and 98 sequences of 100 short exposure images on 16 August 1998. The time interval between consecutive sets of short exposure images was approximately 1 min. Since the camera control software was still somewhat experimental during the 1997 observing run, we had to interrupt the observing run three times for a few minutes each to change to different hard disk partitions.

In Figure 2, we show typical high spatial resolution observations obtained at the very beginning of the 1998 observing run. The left panel depicts the best image out

of sequence of 100 images, and the right panel depicts the corresponding speckle reconstruction derived from the whole sequence. The images were scaled individually, thus brightness and contrast may not be directly comparable. The granular rms contrast during the time series was  $4.79 \pm 0.26\%$ . We emphasize that the standard deviation reflects the temporal evolution of the seeing. The rms image motion was  $0.11 \pm 0.05''$ . It was derived from a rigid alignment of the images with respect to the image with the highest rms contrast by means of cross-correlation. The average image motion has been used to compute the Fried parameter from angle-of-arrival fluctuations according to Equation (3) in Brandt, Mauter, and Smartt (1987). Both images exhibit a variety of fine-structures, such as the tips of penumbral filaments, umbral dots and filigree – all at the diffraction limit of the 65 cm telescope. Since the high-frequency information has been amplified in the speckle interferometric process, they become more clearly discernible in the speckle reconstruction. However, close examination of the frame selected image show that these structures are also present in the best single frame.

#### 4. Solar Scintillometry vs Spectral Ratio Technique

In Figure 3, we show a comparison of the seeing measurements obtained by solar scintillometry to those from the spectral ratio technique. The two top panels show the scintillometric results, while the bottom panels show the results from speckle interferometry. The output signal of the scintillation sensors is given in volts. The calibration of the scintillation sensor is such that a 1 V signal roughly corresponds, by experience, to approximately  $1''$  seeing at Sacramento Peak (Beckers *et al.*, 1997). The scintillation sensors record the scintillation signal every 10 s. High clouds and, sometimes even birds can cause sharp peaks in the scintillometer signal. We deleted such spikes and linearly interpolated to obtain the same sampling interval of approximately 1 min – the interval in the spectral ratio technique. The linear correlation coefficients between the outside seeing and the inside seeing are  $\rho_{1997} = 0.24$  and  $\rho_{1998} = 0.53$ , respectively. The correlation in 1997 is just marginally significant whereas the 1998 measurements are statistically significant. However, a 100% correlation is not expected since the two scintillation sensors are 25 m apart and one looks through a slit. The two look at different, but overlapping parts of the Earth's turbulent atmosphere. The increase in the correlation coefficient is a clear indication that the dome seeing has improved (in spite of our efforts to make it appear worse by moving the scintillometer deeper into the dome in 1998). Note that the observations were taken around local noon.

This improvement is also underlined by the fact that the average Fried parameter obtained with the spectral ratio technique increased by about 70% from  $\bar{r}_0 = 6.0 \pm 0.5$  cm to  $10.1 \pm 1.0$  cm, while the outside scintillometer signal is basically the same for 28 October 1997 and 16 August 1998. We emphasize that the data processing and algorithms used in the spectral ratio technique were exactly the same as in

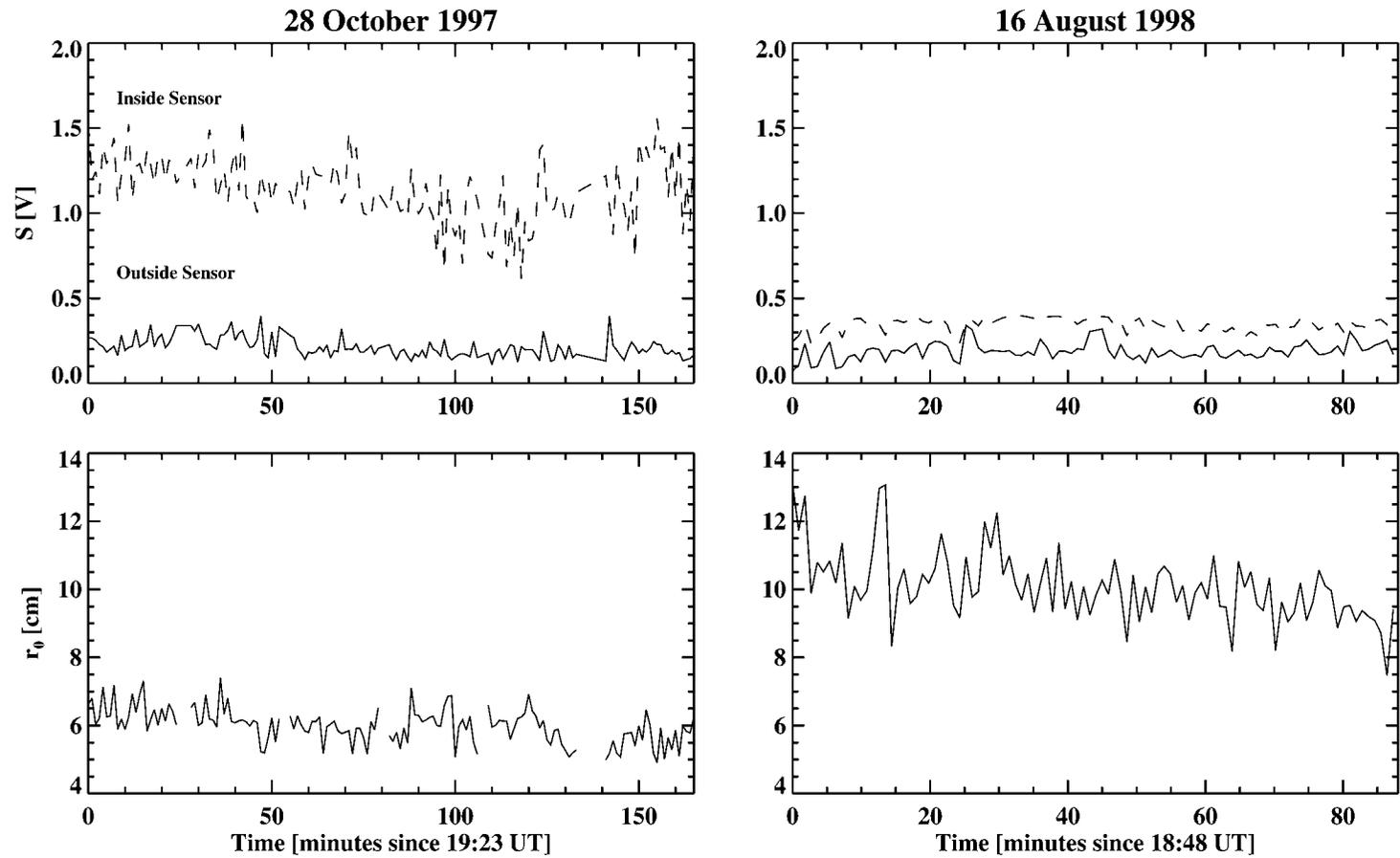


Figure 3. Comparison of solar scintillometry and spectral ratio technique before and after improving the dome seeing. The upper panels were from scintillometry and the lower panels from the spectral ratio technique.

Denker (1998) for the Observatorio del Teide/Izaña and the results from mountain and lake sites show no apparent differences. Although, we only show snapshots of the scintillation sensor data, the trend is clear and can be studied in the daily records of the scintillometer data: before improving the dome seeing, we found a weak correlation between the inside and outside scintillometer signal at best, whereas after improving the dome seeing, we almost always find a clear correlation.

In the following comparison, we ignore window seeing and some of the dome seeing which appear in speckle interferometry, but not in scintillometry. Nonetheless, we make the comparison starting from Equation (8') of Beckers *et al.* (1997) to convert the scintillometer output to the Fried parameter in cm:

$$r_0 = 10(S^{1.2} \cos^{-0.2} \zeta C + 0.075)^{-1}, \quad (1)$$

where  $S$  is the scintillometer signal in volts,  $\zeta$  the zenith angle and  $C$  a site-specific constant. Many assumptions on the seeing quality are folded into the site-specific constant  $C$ , e.g., the weighted integral with height over the index structure function  $C_n^2(h)$ , atmospheric transparency changes, and boundary layer effects. The  $C_n^2(h)$  profile and seasonal and possibly daily variations thereof should be reflected in this calibration 'constant'. Further studies over longer periods of time are necessary to clarify this aspect but are beyond the scope of this paper. A constant,  $C = 1.18$ , was chosen for Sacramento Peak Observatory so that the median seeing as measured by the scintillation sensor corresponds to the median value of  $r_0 = 8.7$  cm observed from limb motion by Brandt, Mauter, and Smartt (1987). Since the measurements were not simultaneous (taken more than 10 years apart), a systematic error might occur, resulting in an uncertainty in the scale for the Fried parameter  $r_0$ .

Our measurements were simultaneous. Since the Fried parameter  $r_0$  is given by the spectral ratio technique and the scintillometer signal  $S$  is provided by the interior scintillation sensor for each time step, we can compute the site specific constant, e.g., 16 August 1998, 18:48 UT,  $r_0 = 13.1$  cm,  $S = 0.25$  and  $\zeta = 24.2^\circ \Rightarrow C = 3.57$ . For the 1997 and 1998 time series, we obtain  $C_{1997} = 1.40 \pm 0.35$  and  $C_{1998} = 3.35 \pm 0.63$ , respectively. This indicates that changing the  $C_n^2(h)$  profile just within the first few meters, i.e., inside the dome, has dramatic effects on the calibration constant  $C$ .  $C_{1997}$  is basically indistinguishable from  $C = 1.18$  for the Sacramento Peak Observatory given by Beckers *et al.* (1997). The roughly 2.5 times larger value  $C_{1998}$  might be explained by the sharp reduction of the dome seeing. The remaining seeing is likely to be closer to the telescope entrance aperture and window, a location where the scintillometer is insensitive to the seeing. Despite this fact, it is interesting to see what happens if we use  $C_{1997}$  and  $C_{1998}$  to cross-calibrate the two scintillometers. The average Fried parameters for 1997 and 1998 are  $\bar{r}_0 = 35.4 \pm 7.8$  and  $20.0 \pm 6.1$  cm, respectively. The result for the 1998 time series is shown in Figure 4 which indicates clearly the potential for a Fried parameter of  $r_0 > 20$  cm for BBSO during days of good seeing. Taking properly into account dome and window seeing should even allow for higher values of the

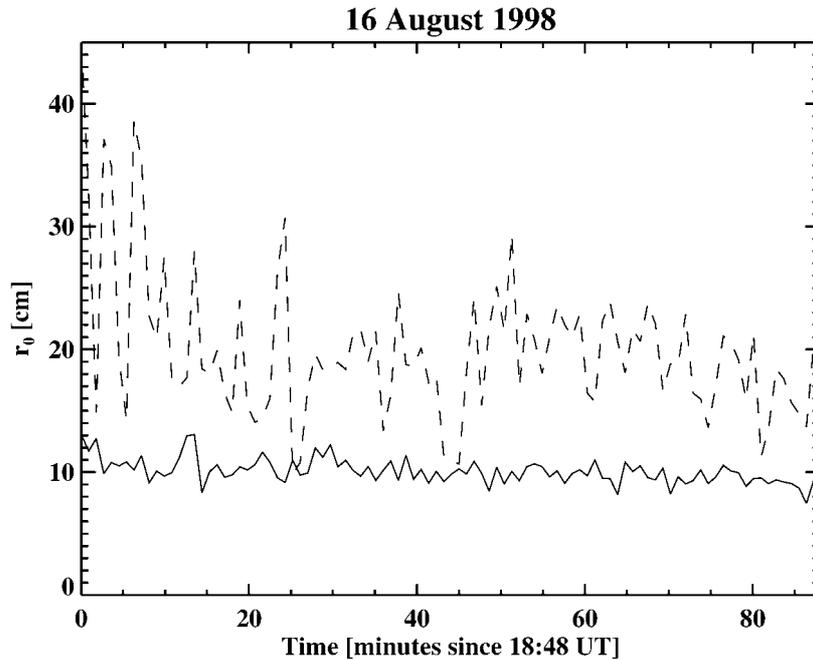


Figure 4. Solid line: Fried parameter derived with the spectral ratio technique. Dashed line: Fried parameter corresponding to the exterior seeing derived from solar scintillometry after cross-calibration with the dome scintillation sensor.

Fried parameter as implied by the  $\bar{r}_0 = 35.4$ . This value is consistent with the result for BBSO reported by Beckers *et al.* (1997).

Both, spectral ratio technique and solar scintillometry, demonstrated individually that we drastically reduced the dome seeing at BBSO. However, we failed to show a clear correlation between the data from both techniques. The correlation coefficient between the Fried parameters from both techniques is  $\rho = 0.21$  which is just marginally significant. A scatter plot of the 1998 data is shown in Figure 5(a). In addition, we show in Figure 5(b) a scatter plot between the Fried parameter from the spectral ratio technique and angle-of-arrival measurements. The correlation coefficient is slightly higher  $\rho = 0.35$ . However, we find a good correlation between the Fried parameter from the spectral ratio technique and the average rms contrast of the raw images  $\rho = 0.61$ . The average Fried parameter derived from angle-of-arrival fluctuations is  $\bar{r}_0 = 15.0 \pm 7.0$ , where the standard deviation reflects the temporal evolution. It is interesting to note that the ratio of the Fried parameters from angle-of-arrival measurements and spectral ratio technique of 1.5 is close to the value of 1.4 quoted in a similar study by Ricort *et al.* (1982). We emphasize that the lack of correlation can be explained in terms of boundary layer seeing which is dominant for mountain sites, but suppressed at lake sites such as BBSO, i.e. scintillometry is more susceptible to near ground than high altitude turbulence.

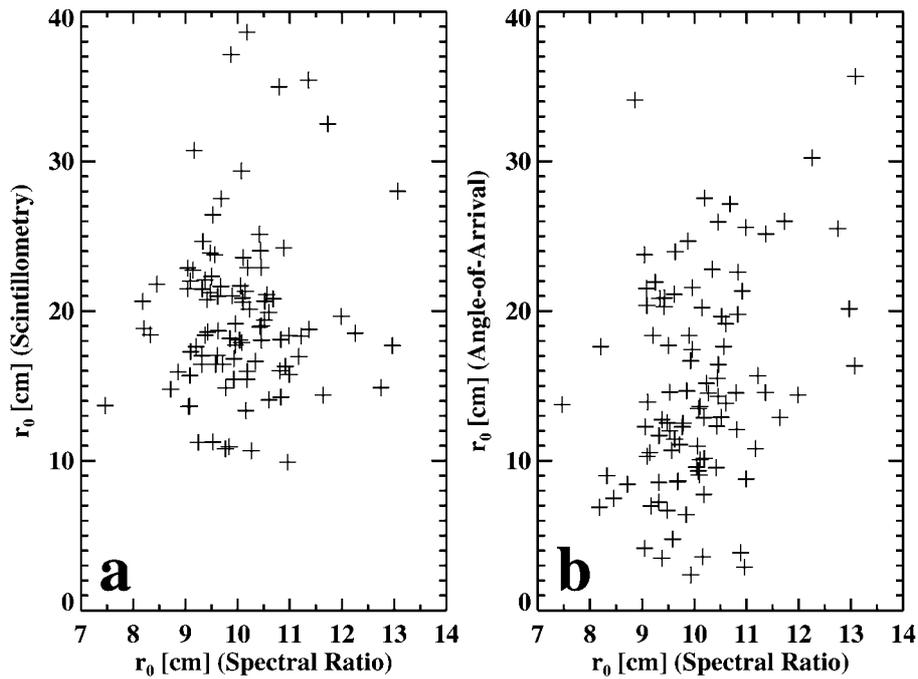


Figure 5. Scatter plots of the Fried parameter derived from scintillometry, angle-of-arrival measurements, and spectral ratio technique in 1998.

A good correlation between scintillation and the Fried parameter  $r_0$ , e.g., derived from image motion, was found at mountain sites (Seykora, 1993; Coulter, Kuhn, and Rimmele, 1996).

## 5. Discussion and Conclusions

The scintillometer has a low frequency cut-off at 0.3 Hz. Therefore, it might miss some of the very slow seeing effects. However, knife-edge tests at BBSO show our Schlieren pattern to be moving at much higher frequencies. They originate mainly from the dome shutter. The flexible textile panels of the dome shutter heat up and are responsible for a significant part of the residual seeing. The old panels are being replaced by solid,  $\text{TiO}_2$  painted, water cooled metal panels. In addition, the cross-section of the shutter opening will be reduced to minimize the heat load in the dome. The knife-edge test also shows that window seeing is not the primary problem. As rule of thumb for nighttime telescopes, a 1 K temperature gradient for optical surfaces causes  $0.4''$  seeing. Since we exhaust the warm air from the dome, there is a steady air flow, minimizing temperature gradients and in addition, a water-cooled heat shield protects the mount of the entrance window. Further tests are necessary to determine the magnitude of the window seeing, especially

after the dome shutter has been replaced. Placing one of the scintillometers at the location of the primary mirror, e.g., would make a comparison of the spectral ratio technique with solar scintillometry easier since they would see exactly the same seeing variations (assuming there is no instrument seeing).

Finally, a few remarks with regard to the accuracy of the spectral ratio technique. The observed spectral ratio (see Equations (3) and (4), von der Lühe, 1984) is

$$\epsilon(\bar{q}) = \frac{|\langle S_i(\bar{q}) \rangle|^2}{\langle |S_i(\bar{q})|^2 \rangle}, \quad (2)$$

where  $\bar{q}$  is a spatial frequency,  $S$  is the OTF and  $\langle \dots \rangle$  denotes an ensemble average.  $\epsilon(\bar{q})$  is independent of the object transform and the telescope's MTF and basically allows us to extract the atmospheric cut-off. However, in order to obtain the Fried parameter, we use expressions for  $|\langle S_i(\bar{q}) \rangle|^2$  and  $\langle |S_i(\bar{q})|^2 \rangle$  based on Fried's (1966) and Korff's (1973) theories which assume an ideal, unaberrated telescope with circular aperture. This is often overlooked when fitting observed spectral ratio curves to their theoretically expected counterparts. The effect on the Fried parameter, however, should still be small, since it is mainly encoded in the decaying part of the curves at the seeing cut-off, and not their overall shape. The problem becomes more severe when the corresponding theoretical speckle transfer functions are used in speckle reconstructions.

We used the 1997/1998 winter season to sharply reduce the dome seeing at BBSO. The electronics and computer equipment were removed from the observing floor to reduce the heat load, and the observing floor was thermally insulated from the rest of the building. In addition, the interior of the dome was coated with  $\text{TiO}_2$  paint to reduce the local turbulence and a fan gently pulls air out the dome to ensure that there are no large temperature gradients with respect to the ambient air. As Figure 3 shows, the results were quite dramatic. At last, we can see a clear correlation between inside and outside seeing, not only during moments of excellent seeing.

Even though qualitative seeing measurements are extremely important, there is only a sparse record of daytime seeing conditions in the literature. By means of photo-electric measurements of angle-of-arrival fluctuations at the solar limb, Brandt, Mauter, and Smartt (1987) found a log-normal distribution (cf., Figure 2, Brandt, Mauter, and Smartt, 1987) of  $r_0$  with a median at 8.7 cm measured at  $\lambda = 510$  nm at Sacramento Peak. A frequency distribution of the Fried parameter obtained using the spectral ratio technique at Observatorio del Teide/Izaña is shown in Figure 6 of Denker (1998). The median of the distribution is  $r_0 = 9.2$  cm measured at  $\lambda = 550$  nm. The results of the original Caltech solar site survey from 1965–1967 directed by R. B. Leighton, which led to the off-lakeshore siting of BBSO, were published by Zirin and Mosher (1988) and are based on visual estimates of the seeing conditions and on various meteorological factors. These early results already indicated the superior seeing at lake site observatories. In

this context, the qualitative results from a network of solar scintillometers become very important. However, independent methods, such as the spectral ratio technique should be used to validate these results.

The perception of high spatial resolution observations becomes highly controversial when it comes to the comparison of seeing conditions at different sites. Many interlinked factors play a role, such as the observing site, the telescope, the post-focus instrumentation, the camera system, the opportunity to observe an interesting feature at the right time, and last but not least, advertising the scientific results. The intention of this paper is to show that important progress has been achieved in reducing the dome seeing at BBSO, and the necessity of cross-comparing various techniques to measure the seeing quality. Since fast frame rate CCD cameras are nowadays standard equipment of solar observatories, and the implementation of the spectral ratio technique is straightforward, it should be possible to obtain simultaneous observations at different sites, enabling a solid cross-comparison of solar scintillometry and spectral ratio technique.

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