Celebrating the 2017 Great American Eclipse: Lessons Learned from the Path of Totality
ASP Conference Series, Vol. 516
Sanlyn Buxner, Linda Shore, and Joseph Jensen, eds.

Qualitative Shadow Band Observations from Three Sites in the Southeast

Gordon Telepun,[1] Dennis Gallagher,[2] Mitzi Adams,[2] and H. Philip Stahl[2]
[1]*Solar Eclipse Timer, Decatur, AL 35601*

[2]*NASA Marshall Space Flight Center, Huntsville, AL 35812*

Abstract. **Abstract:** Shadow bands were successfully videotaped at three observation sites within a 176-mile region of the umbral path in Kentucky and Tennessee. At each site, the direction of the path of totality and north were marked on a background for the video (a sheet). Elongated shadows were observed to be in parallel rows at each site, but the movement of the parallel rows of shadows was different at each site. There are many potential explanations for shadow bands, including atmospheric scintillation and refraction. We theorize that the cause of the different movement of the parallel lines of shadow bands at each site is due to variations introduced by atmospheric effects since the umbral path direction, the orientation of the crescent and the small azimuth change of the Sun at the sites cannot explain what was documented.

1. Witnessing Shadow Bands

There are a number of theoretical reasons for the generation of shadow bands during the thinnest portion of the crescent phase just before second contact (C2) and just after third contact (C3). These include discussions of atmospheric scintillation caused by turbulence in the upper atmosphere, in which regions of warm and cold air produce striations that change the plane waves of light passing through the air. The result is atmospheric refraction by the striae (see for example, Codona, 1986, Gladysz et. al., Jones, 1999; 2005, Marschall et. al., 1984; Seykora, 1979).

As the path of the eclipse moves across the surface of the Earth there are two opportunities for observers to witness shadow bands. The first is when the last sliver of the Sun is visible, just before being occulted by the Moon, beginning about 90 seconds before C2. The second occurs with the first sliver of Sun reappearing after C3, and lasting about 90 seconds (see Figure 1).

Shadow bands are not always visible at an observing location and even when present they can be missed by observers who are concentrating on other things at this crucial time during the eclipse. However, even when shadow bands are not seen visually by an observer, solar scintillations have been detected with photodetectors (Seykora 1979). When planning to document shadow bands with video there are many variables, and the quality of the images is difficult to predict, but capturing shadow bands with a camera requires a plan and a dedicated video-camera setup.

The period of time when shadow bands occur is thought to be due to a combination of the slit-like solar illumination and the steadily decreasing light level that enables visibility of the resulting low contrast bands of light and gray shadows. The size and

Figure 1. The movement of the Moon creates a sliver of crescent Sun when seen by the observer looking up. The space perspective demonstrates the column of light that precedes (C2) and trails (C3) the moving umbra. The column of light is not perturbed until encountering the Earth's atmosphere. At that point, shadow bands can be created.

shape of the crescent is the one element in shadow band creation that is consistent through all eclipses. The crescent Sun is very small at this point. Not only is it thin, it is also shorter, as shown in Figure 2.

2. Planning For Shadow Band Video Capture

Prior to the August 21, 2017 eclipse, our team had discussions that stressed the need to mark the compass direction north and axis of the path when trying to capture shadow bands in a video. The exact observing position coordinates must also be documented. If fortunate enough to obtain video capture of shadow bands, directional information would be crucial when analyzing the videos after the eclipse. The importance of this planning was based on the experience of one of the authors (Telepun) who witnessed shadow bands in Africa in 2002. The bands appeared to have a clear direction of motion of the entire group of parallel lines of the elongated shadows. It is this overall parallel line motion that we wanted to understand better.

The "shadows" during the shadow band phenomena are very low contrast when projecting onto a surface. The chance of seeing them and videoing them is improved if the background surface is white. A white tightly woven fabric sheet stretched out on the ground is usually a good material for a background. Since shadow bands can have a relatively low spatial frequency a large sheet has the benefits of creating a large surface to see more rows of shadow bands and better analyze directional movement. Fabric sheets are inexpensive, easily transportable and easy to set up at the eclipse observing site. Fabric has the pitfalls of having wrinkles from being folded, it's difficult to stretch it out and make perfectly smooth and the texture in the fabric weave interferes with the ability to photographically capture crisp edges of the shadows. A much better

Figure 2. From the observers perspective, the size and shape of the crescent Sun at 60 seconds before and after totality is thin and short. This thin sliver of light is thought to be necessary for creating shadow bands. These images were taken at a latitude of 34.801N and 1,100 miles east of the point of Greatest Eclipse so there is crescent rotation relative to the umbral path. Image credit: Gordon Telepun.

background would be a white smooth solid surface like a large sheet of plastic or painted plywood but large solid objects are difficult to transport to the observing site. The three observing sites discussed in this paper used white fabric sheets.

To help try to understand whether or not viewing location affects observed shadow band behavior, there are two points of reference that must appear on the background material, and will be unique for each observing site along the path of an eclipse. First, mark the orientation of the observing surface relative to the eclipse path. A line should be marked down the center of the background that represents the axis of the path. The direction of north should also be marked on the background. Use a compass at the observing site to orient the center line with the direction of the axis of the umbral path. Set up the video camera so that it captures the entire background, is aligned with the axis of the path, and is pointed in the direction of the umbra exit. An optional addition can be some type of grayscale pattern that helps correlate the color and contrast of the shadows for later analysis. We had this available at two of the sites. A second optional addition is some type of measuring reference; we had yardsticks laid out at one of the sites.

3. Constants For All Three Sites

Because the three sites were within 206 miles of the point of Greatest Eclipse and within 176-miles of each other (Figure 3) the crescent phase was high in the sky, vertically oriented and had minimal rotation between the sites. Therefore, the angle of the crescent creating shadow bands was relatively similar at all three sites.

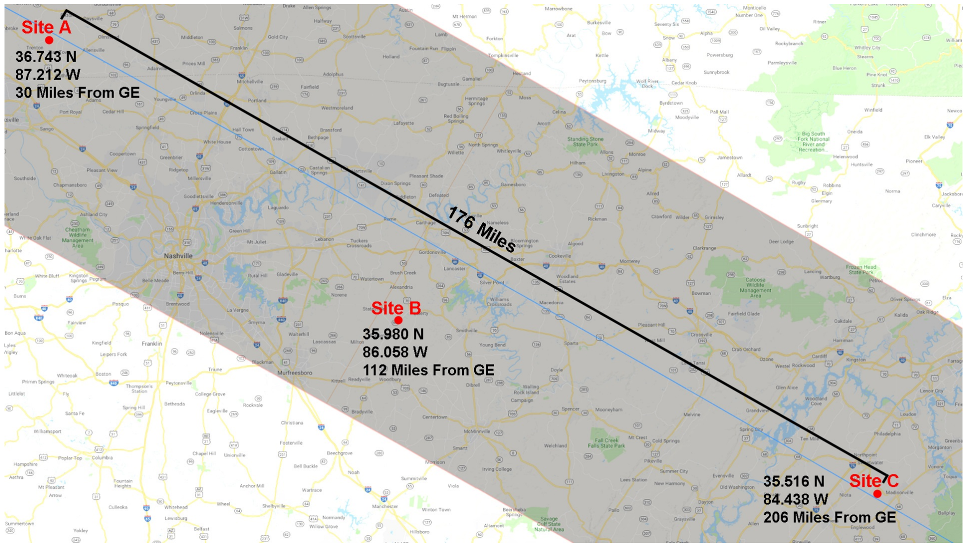

Figure 3. Three observation sites along the eclipse path in the southeast. Site A: Guthrie, KY. Site B: Auburntown, TN. Site C: Madisonville, TN. Path map image credit: Xavier Jubier.

The direction of the path of totality went from 300 degrees from due north at umbral approach, to 120 degrees at umbral exit for all sites. For the purposes of discussion later, it is important to visualize that a 90 degree offset to the path line, (perpendicular to the path) would be a line from 30 degrees to 210 degrees. The solar azimuth for all threes sites at C2 and C3 was towards the south-southwest ranging between 199 degrees and 211 degrees. Site A—199/200.4 degrees; Site B—203.9/205.2 degrees; Site C—209.7/211 degrees.

The Sun altitude for all sites was in the range of the maximum for this eclipse, between 63.6 and 64.1 degrees. Figure 4 shows the relevant geometry.

4. Observing Site Set Up

4.1. Site A

This site was located near Guthrie, Kentucky at the coordinates 36.743 north and 87.212 west. A white sheet was used as the background. The relevant directions were marked by laying a printed custom compass rose on the sheet. This compass rose was created specifically for orientation in this region of the path by Telepun. When this compass rose was aligned with north, the axis of the umbral path would be marked, 300 degrees for the umbral approach and 120 degrees for the exit of the umbra. The camera at this site was positioned on the southeastern side of the sheet facing northwest toward the direction of umbral approach. The camera was not perfectly in line with the umbral path. The video was captured with a mobile phone using completely automatic settings. The quality of the video captured was the clearest of the three sites.

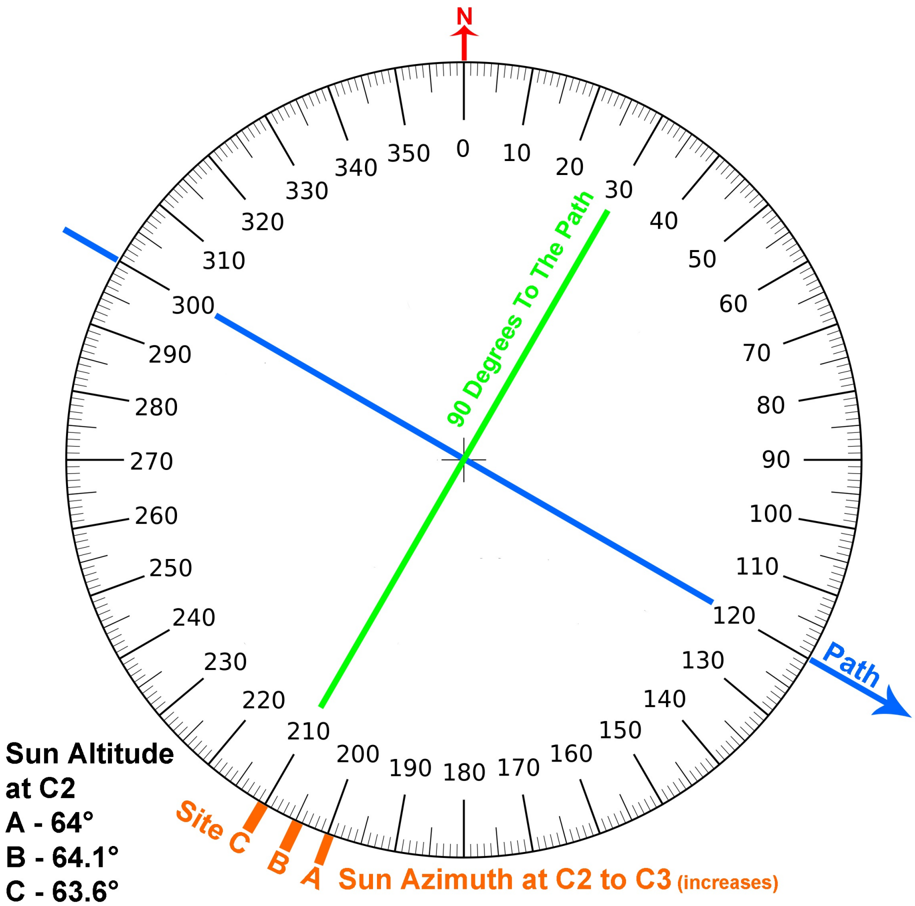

Figure 4. The important compass rose directions for the three sites. The path axis was negligibly different for the sites. The Sun azimuth differed by 12 degrees. The Sun altitude differed by 0.5 degrees. This information needs to be documented for any observing site when attempting to video shadow bands.

4.2. Site B

This site was located in Auburntown, Tennessee. at the coordinates 35.980 north and 86.058 west A white sheet was used as the background. The relevant directions were marked by laying the long axis of the sheet in line with the umbral path and marking the center of the sheet with a strip of tape. The axis of the umbra path was 300 degrees for the umbral approach and 120 degrees for the umbral exit. A strip of tape also marked the direction of north. The camera at this site was positioned on the northwestern side of the sheet facing southeast toward the direction of the umbra exit. The camera was perfectly in line with the umbral path. The video was captured with a consumer model video camera set on a semi-manual mode that allowed the observer to do exposure adjustments during the time that shadow bands were visible in an attempt to improve the capture quality. The adjustments were not really helpful with improving the contrast.

At this site, the video captured after C3 was the best video we obtained revealing visible movement of the parallel rows of shadow bands.

4.3. Site C

This site was located in Madisonville, Tennessee. at the coordinates 35.516 north and 84.438 west A white sheet was used as the background. The relevant directions were marked by laying the long axis of the sheet in line with the umbral path and marking the center of the sheet with a strip of tape. The axis of the umbra path was again 300 degrees for the umbral approach and 120 degrees for the exit of the umbra. A strip of tape also marked the direction of north. The camera at this site was positioned on the northwestern side of the sheet facing southeast toward the direction of the umbra exit. The camera was perfectly in line with the umbral path. The video was captured with a consumer model video camera set on a semi-manual mode using shutter priority at a 1/500 second shutter speed. These settings were determined by practicing prior to the eclipse, after sunset, with the video camera pointing at the grayscale pattern (see Figure 7) and trying to determine a good exposure for what was guessed to be the lighting around the time of shadow bands. It was not adjusted during the time that shadow bands were visible. This background design including the grayscale was developed by the author Telepun and reproduced by the observer at Site B.

5. Video Analysis From The Three Sites

Shadow bands are very low contrast and difficult to capture so the quality of the videos obtained from the three sites was usable for video analysis of movement but useless for trying to capture still image screenshots that showed the shadows. Therefore, the observation analysis diagrams in this paper have the shadow bands artistically simulated. The original videos were painstakingly reviewed so the directions and angles presented on the diagrams are believed to represent the movements as seen in the original videos as accurately as possible.

Because visually observed shadow bands display complex movements the authors have introduced nomenclature to describe them. This nomenclature will help standardize the discussion of shadow band movement from future eclipses because when possible, a compass direction is assigned to each type of motion.

1. *Elongated Axis of the Individual Shadows.* Shadow bands will have a long axis, either rectangular or serpentine. The compass direction of the long axis of the shadows should be documented.

2. *Axis of the Rows of Shadows.* The individual shadows will form rows which may be ill-defined or well defined. The compass direction of the axis of the rows should be documented.

3. *Direction of the Apparent Motion of the Individual Shadows.* The individual shadows forming the rows will flutter or fluctuate giving the appearance of motion. The compass direction of the apparent motion should be documented.

4. *Direction of the Movement of the Rows of the Shadows.* The parallel rows can move in unison towards a direction. The compass direction of the movement of the rows should be documented.

6. Analysis of Video From Site A

The site was 30 miles southeast from the point of Greatest Eclipse. Measured perpendicularly to the centerline, this site was 1.45 miles off the centerline to the southwest. The compass direction of the umbral path was from 300 degrees to 120 degrees. Therefore, perpendicular to the path would be a line from 30 degrees to 210 degrees. At this observing position the Sun altitude was 64 degrees at C2. The Sun azimuth was 199 degrees at C2 and 200.4 degrees at C3.

6.1. Site A Shadow Bands Before C2 (Figure 5)

Elongated Axis of Individual Shadows: The elongated axis of the individual gray shadows was approximately 20 degrees to 200 degrees. This makes the elongated axis shifted approximately 10 degrees from perpendicular to the path.

Axis of Rows of Shadows: The gray shadows were roughly aligned in rows that matched the elongated axis of the individual shadows (20 to 200 degrees). But these rows were not well defined.

Direction of Apparent Motion of Individual Shadows: The fluttering of the individual shadows gave the impression of motion toward the 20-degree direction. This was dramatic at this site for C2 and C3.

Direction of the Movement of the Rows of Shadows: The rows had a very slow movement in the direction of the path towards 110 degrees which was close to the direction of umbra exit. The velocity was slow and difficult to perceive. Enhanced and differenced processing by one of the authors (Gallagher) improved the ability to see the movement of the rows (Figure 6).

6.2. Site A Shadow Bands After C3

No discernable change from characteristics observed before C2

7. Analysis of Video From Site B

The site was 112 miles southeast from the point of Greatest Eclipse. Measured perpendicularly to the centerline, this site was 16.31 miles off the centerline to the southwest. The compass direction of the umbral path was from 300 degrees to 120 degrees. Therefore, perpendicular to the path would be a line from 30 degrees to 210 degrees. At this observing position the Sun altitude was 64.1 degrees at C2. The Sun azimuth was 203.9 degrees at C2 and 205.2 degrees at C3.

7.1. Site B Shadow Bands Before C2 (Figure 7)

Elongated Axis of Individual Shadows: The elongated axis of the individual gray shadows was perpendicular to the path, 30 degrees to 210 degrees, but they were not individually well defined.

Axis Of Rows of Shadows: The gray shadows were roughly aligned in rows that were perpendicular to the path. But these rows were not well defined.

Direction of Apparent Motion of Individual Shadows: The individual shadows did not have enough contrast and clarity in this video to make a comment about fluttering and direction of motion.

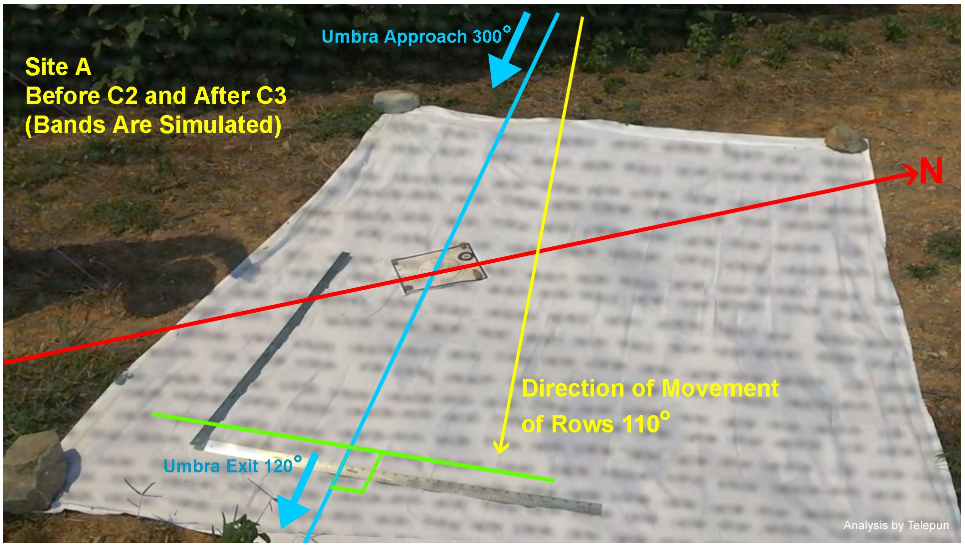

Figure 5. The axis of the rows of shadows was rotated approximately 10 degrees from perpendicular to the path (green line) as was the direction of the movement of the rows of shadows (110 degrees). The “fluttering” of the individual shadows was dramatic towards the direction of 20 degrees. Original video capture by Michaela Mason.

Figure 6. To assist in the analysis of the direction of the movement of the rows of shadow bands the Site A video was enhanced and differenced. This technique removed the distraction of the shadows “fluttering” towards 20 degrees and confirmed the movement of the rows toward 110 degrees. Processing credit: Dennis Gallagher.

Direction of the Movement of the Rows of Shadows: The rows had a movement in the direction of the path exit towards 120 degrees. The velocity of the row movement was faster than seen at Site A.

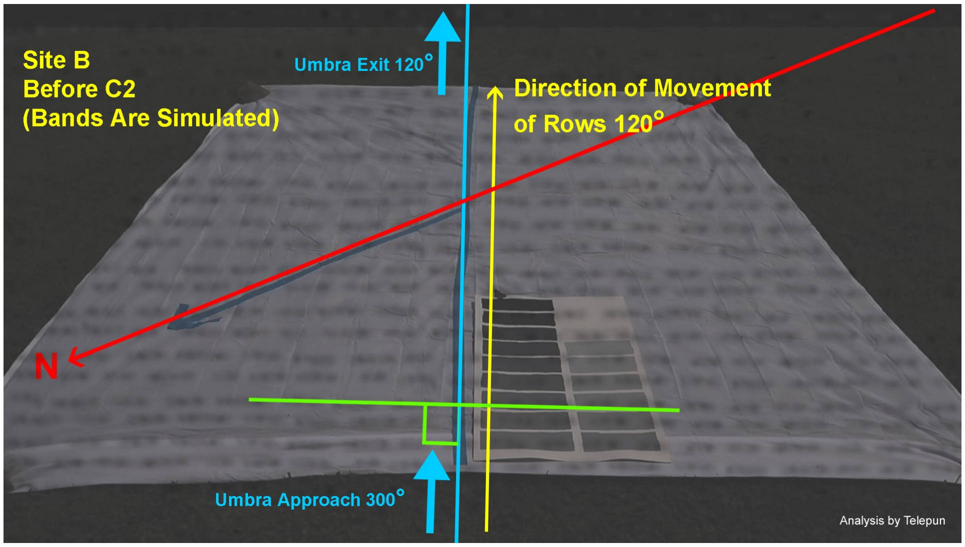

Figure 7. The axis of the rows of shadows was roughly perpendicular to the path (green line). The direction of the movement of the rows of shadows was in line with the axis of the path toward the umbra exit, 120 degrees. Original video capture by Chris Askew.

7.2. Site B Shadow Bands After C3 (Figure 8)

Elongated Axis of Individual Shadows: The elongated axis of the individual gray shadows rotated 30 degrees from being perpendicular to the path. They were now oriented 0 degrees to 180 degrees.

Axis Of Rows of Shadows: The gray shadows were aligned in rows that were oriented 0 to 180 degrees and the rows were much better defined than the video before C2

Direction of Apparent Motion of Individual Shadows: The individual shadows had more contrast and clarity than the video obtained before C2 but there was no visible fluttering in a direction.

Direction of the Movement of the Rows of Shadows: The rows were much more defined after C3 and were clearly rotated 30 degrees. The movement was in the direction of 90 degrees (due east). The velocity of the rows was similar to that seen prior to C2.

8. Analysis of Video From Site C

The site was 206 miles southeast from the point of Greatest Eclipse. Measured perpendicularly to the centerline, this site was 0.75 miles off the centerline to the northeast. The compass direction of the umbral path was from 300 degrees to 120 degrees. Therefore, perpendicular to the path would be a line from 30 degrees to 210 degrees. At this observing position the Sun Altitude was 63.6 degrees at C2. The Sun azimuth was 209.7 degrees at C2 and 211 degrees at C3.

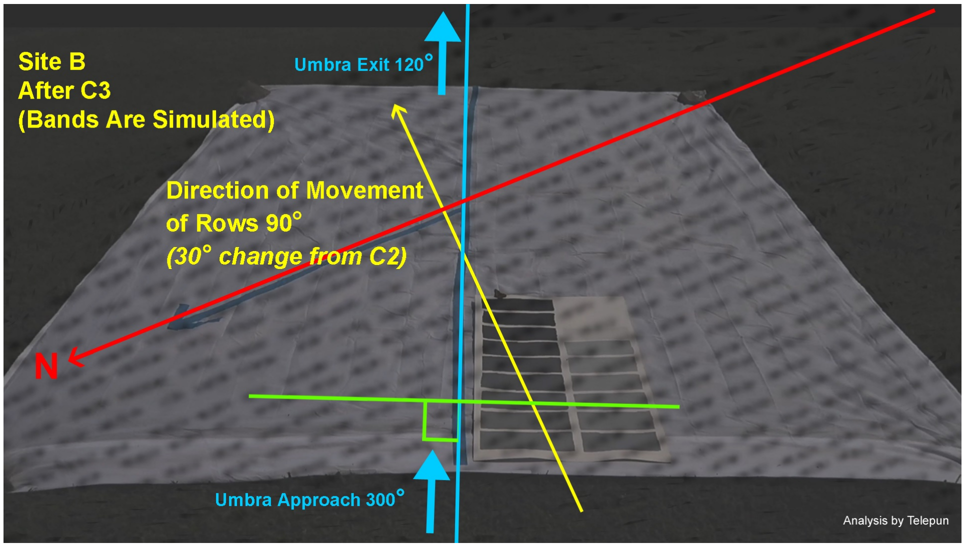

Figure 8. The axis of the rows of shadows changed to be rotated 30 degrees and was no longer perpendicular to the path (green line). They were moving due east to 90 degrees. The change in direction at C3 was totally unexpected. Original video capture by Chris Askew.

8.1. Site C Shadow Bands Before C2 (Figure 9)

Elongated Axis of Individual Shadows: The elongated axis of the individual gray shadows was perpendicular to the path, 30 degrees to 210 degrees but they were not well defined individually.

Axis Of Rows of Shadows: The gray shadows were roughly aligned in rows that were perpendicular to the path. But these rows were not well defined.

Direction of Apparent Motion of Individual Shadows: The individual shadows did not have enough contrast and clarity in this video to make a comment about fluttering and motion.

Direction of the Movement of the Rows of Shadows: The rows had a velocity opposite the direction of the path towards 300 degrees which was the direction of umbra approach. The velocity of the rows was similar that seen in Site B

8.2. Site C Shadow Bands After C3

No discernable change from characteristics observed before C2.

9. Discussion

The shadow band video data presented in this article was obtained at three different sites, 176 miles apart, during the August 21, 2017, total solar eclipse. All threes sites used different video capturing techniques including the cameras, exposure settings, pixel density and camera height position. The clarity and the quality of the videos were adequate to watch and analyze the motion of the shadow bands but inadequate to cap-

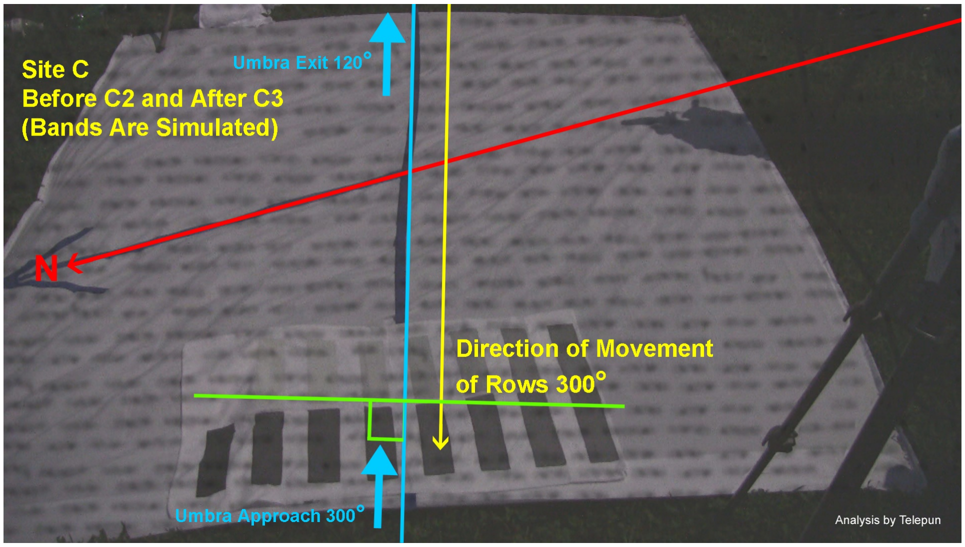

Figure 9. The axis of the rows of shadows was roughly perpendicular to the path (green line). The direction of the movement of the rows of shadows was in line with the axis of the path toward the umbra approach, 300 degrees. The movement of the rows towards the direction of umbra approach was totality unexpected. Original video capture by Gordon Telepun.

ture still screenshots. Therefore, measurements of the shadow band size and measuring actual velocity of movement was not possible with the data obtained.

However, qualitative observations of movement direction was excellent since all three sites provided video documentation of the orientation of the umbral path and the direction of north. Considered as a group, these three sites provided six videos of shadow bands, which has given us valuable information. To our knowledge documentation of shadow bands from three sites sequentially along the path of an eclipse has never been presented before.

Prior to the eclipse, our team had discussions about the need to clearly document important directions in the videos. If shadow bands were visible during the eclipse and were successfully captured one of our primary goals was to have directional data. One author (Telepun) devised two techniques for achieving this. One was a simple modification of a paper compass that was marked with the path axis and the Sun azimuth for a group of students (NASA supervised students) who would be observing the eclipse in the region of Clarksville, Tennessee. The second was a white sheet with a tape mark for the axis of the path and the direction of north combined with a grayscale pattern to help analyze contrast afterward if shadow bands were captured in the video.

The recollection of the appearance of shadow bands in Zimbabwe, Africa in 2002 was that the shadow bands made "serpentine-shaped" rows, "fluttered dramatically linearly" and moved away from the author (Telepun) in line with the path in the direction of the umbra exit. Photographs of the 2002 observation site provided compass alignment and allowed correlation with computerized eclipse path mapping and an approximate re-creation of the orientation and movement of those shadow bands. The rows were roughly perpendicular to the path.

For 2017 the pre-eclipse discussions and training were based on the expectation that the experience in 2017 would be very similar to the 2002 shadow band observation. We expected to see rows that would be perpendicular to the path and have movement toward the direction of umbra exit. We were prepared to see "fluttering" of the individual shadows within the rows. What we documented with our videos was exceedingly more interesting than that.

Site A captured shadow band video that was anticipated. It showed rows of shadows that were roughly perpendicular to the path and the rows had a movement roughly in the direction of the path exit. The individual shadows had dramatic fluttering but were straight, not forming a serpentine shape. Not exactly like the 2002 experience, but similar.

Site B provided video is extremely interesting. The shadow band rows before C2 were perpendicular to the path (30 to 210 degrees) and had movement toward the direction of the umbra exit as was seen at Site A. What was not expected was the rotation of the rows after C3. The rows of shadow bands shifted by 30 degrees making the new axis 0 degrees to 180 degrees. The change in angle is clearly seen in the video. The angle of the crescent would have had a negligible change during the 2 minute and 22-second totality since the Sun azimuth only changed from 203.9 degrees to 205.2 degrees. The camera position and camera angle did not change. Therefore, we conclude that unique characteristics in the atmosphere, at some level, affected the direction of the movement of the shadow band rows projected on the ground. The level of the atmosphere which caused shadow bands at Site B must have had had a significant change in characteristics between C2 and C3 to cause the rotation.

Site C also provided surprising video data. At this site, the parallel rows of shadow bands were perpendicular to the axis of the path which the authors expected during eclipse planning. However, what was completely unexpected was the rows of shadow bands had a movement direction that was towards the direction of the approaching umbra (300 degrees). This movement was the same before C2 and after C3. Our conclusion for this observation is similar to Site 3. We conclude that this shadow band movement on the ground was due to the unique characteristics of the atmosphere, at some level, creating the shadow band movement at Site C.

Data from the GOES-16 satellite (Figure 10) for this region on eclipse day shows that the low-level weather pattern was similar for all three sites. It was a rather typical southeastern summer day creating low-level convective clouds. Significant convective cloud dissipation occurred in this region as the umbra approached. Other authors have attempted to correlate wind data to shadow band behavior with limited conclusions. (Gladysz et al. 2005; Jones 1999) We believe that atmospheric influence of shadow band movement occurs at a different level in the atmosphere than the level of the observed convective clouds.

Further work is required to correlate atmospheric disturbances with what is seen on the ground at the observing sites. The atmosphere analysis must consider that the region of interest is not at the observer's zenith or local conditions, but is the atmosphere in line with the Sun's altitude, the Sun's azimuth, and the observer's position. Therefore, the pertinent atmosphere can be miles away from the observing site.

The videos of shadows bands at each of these sites independently would by themselves be interesting. But when taken as a group and analyzed, the data offers unique insight to study of shadow bands. The most obvious and significant variable that could explain the differences we documented are characteristics in the atmosphere at some

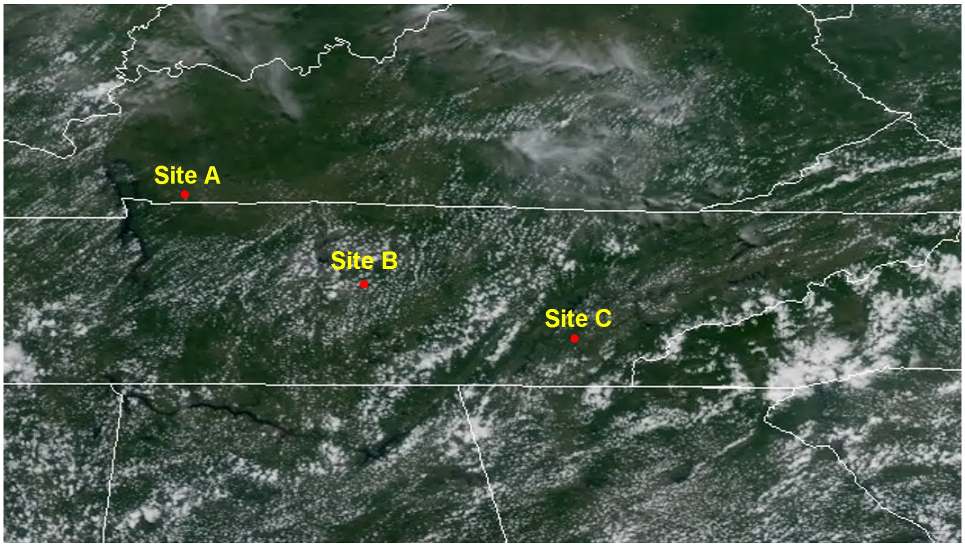

Figure 10. The low-level weather on eclipse day was similar for all three sites. This GOES-16 image is taken about 1 hour before C2 at Site A. The sites marked on this image are estimated. Image credit: Colorado State University, Cooperative Institute for Research in the Atmosphere.

level. Our analysis indicates that each site was affected in a unique way by the atmosphere that was creating the shadow bands at that site. It seems that the atmosphere affects the size and shape of the individual elongated shadows, the motion of the individual shadows, the formation of rows and can create directional motion of the rows. (Figure 11).

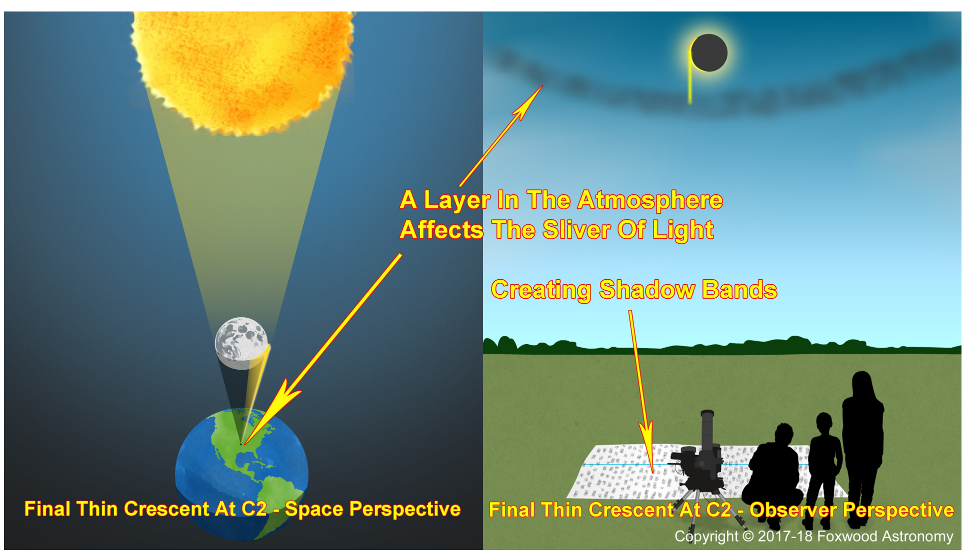

Figure 11. The column of light gets altered by the atmosphere and creates the projection of shadow bands on the ground. The atmosphere in line with the observer and the Sun is the relevant portion of the atmosphere.

10. Conclusion

More videos of higher quality and at planned locations relative to the eclipse centerline from upcoming eclipses are needed to evaluate potential explanations for shadow bands. We have offered a standardization of terms for describing shadow bands that can guide discussion of specific behaviors that are sought from observations. These terms: "Elongated Axis of the Individual Shadows," "Axis of the Rows of Shadows," "Direction of the Apparent Motion of the Individual Shadows," and "Direction of the Movement of the Rows of the Shadows" are all related to specific compass directions that must be determined for each observing site and eclipse event.

We also present a plan for a standardized background that will orient the features observed in a shadow band video, as shown in Figure 12.

1. Document the observing site coordinates in the decimal degrees (DD.dddd).
2. A rectangular white sheet placed with its long axis in line with the axis of the path.
3. A tape line down the center of the sheet marking the axis of the path.
4. Use a compass to orient the line on the sheet with the axis of the path.
5. Mark the direction of north.
6. Use a high definition or 4k video camera on automatic exposure settings.
7. Have the video camera in line with the tape marking the axis of the path.
8. Point the video camera in the direction of the umbra exit.
9. Have a gray scale pattern on the background.
10. Have an object on the background of a known size for relative scale measurements after the eclipse.

More eclipse information may be found at:

- `http://www.solareclipsetimer.com/`
- `https://eclipse.gsfc.nasa.gov/eclipse.html`

The equation for converting a color image to black and white used in this work can be found on page 4, item 3.2 in the following document:

- `http://www.itu.int/dms_pubrec/itu-r/rec/bt/R-REC-BT.709-6-201506-I!!PDF-E.pdf`

More information regarding the GOES satellite image:

- `https://journals.ametsoc.org/doi/10.1175/BAMS-D-15-00154.1`

Acknowledgments. NASA is acknowledged for their participation in observing shadow bands during the 2017 eclipse and that their participation does not imply endorsement by NASA employees of any commercial product. Space and landscape artwork by Bethany Gano.

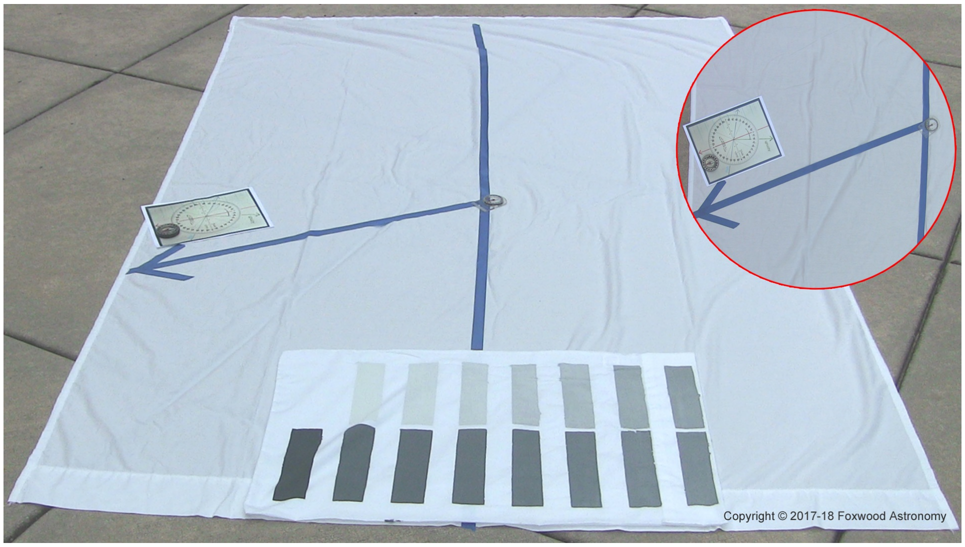

Figure 12. Suggested standard background. A compass is used to align the long axis with the direction of the path. Video camera points towards the direction of the umbra exit. The compass rose printed on a sheet of paper provides a relative size. Grayscale pattern in the foreground. Image credit Gordon Telepun.

References

Codona, J. I. 1986, “The scintillation theory of eclipse shadow bands,” Astronomy and Astrophysics, 164, 425

Gladysz, S., Redfern, M.,& JJones, B. W. 2005, “Shadow bands observed during the total solar eclipse of 4 December 2002, by high resolution imaging,” Journal of Atmospheric and Terrestrial Physics 67, 899

Jones, B. W. 1999, “Shadow bands during the total solar eclipse of 26 February 1998,” Journal of Atmospheric and Terrestrial Physics 61, 965

Marschall, L. A., Mahon, R., & Henry, R. C. 1984, “Observations of shadow bands at the total solar eclipse of 16 February 1980,” Applied Optics 23, 4390

Sekora, E. J. 1979, “Observations of Eclipse Shadow Bands and Related Phenomena,” Applied Optics, 18, 21, 3538