Measurement of atmospheric scintillation during a period of Saharan dust (Calima) at observatorio del Teide, Izãna, Tenerife, and the impact on photometric exposure times

Hale, S. J.; Chaplin, W. J.; Davies, G. R.; Elsworth, Y. P.; Howe, R.; Pallé, P. L.

DOI:
10.1088/1538-3873/ab6753

Measurement of atmospheric scintillation during a period of Saharan dust (Calima) at Observatorio del Teide, Iz̃ana, Tenerife, and the impact on photometric exposure times

S J Hale[1,2], W J Chaplin[1,2], G R Davies[1,2], Y P Elsworth[1,2], R Howe[1,2], P L Pallé[3]

[1] School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham B15 2TT, United Kingdom

[2] Stellar Astrophysics Centre, Department of Physics and Astronomy, Aarhus University, Ny Munkegade 120, DK-8000 Aarhus C, Denmark

[3] Instituto de Astrofísica de Canarias, and Department of Astrophysics, Universidad de La Laguna, San Cristóbal de La Laguna, Tenerife, Spain

E-mail: `s.j.hale@bham.ac.uk`

Abstract.

We present scintillation noise profiles captured at the Observatorio del Teide, Izaña, Tenerife, over a one-week period in September 2017. Contemporaneous data from the Birmingham Solar Oscillations Network (BiSON) and the Stellar Activity (STELLA) robotic telescopes provides estimates of daily atmospheric extinction allowing the scintillation noise to be placed within the context of overall atmospheric conditions. We discuss the results both in terms of the impact on BiSON spectrophotometer design, and for astronomical observations more generally. We find that scintillation noise power reduces by half at about 5 Hz, and is reduced to one tenth between 20 Hz to 30 Hz even during periods of mild Calima, where visibility is reduced due to high concentrations of mineral dust in the atmosphere. We show that the common accepted exposure time of $<$10 ms for limiting the effect of scintillation noise in ground based photometry may be increased, and that depending on the application there may be little benefit to achieving exposure times shorter than 50 ms, relaxing constraints on detector gain and bandwidth.

Keywords: atmospheric effects, atmospheric scintillation, saharan dust, calima

1. Introduction

The Birmingham Solar Oscillations Network (BiSON) is a six-site ground-based network of spectrophotometers observing oscillations of the Sun [Hale et al., 2016]. For many ground-based photometers, the dominant noise source is that from atmospheric scintillation [Osborn et al., 2015]. The BiSON spectrophotometers seek to reduce the effect of atmospheric scintillation by making use of a multi-wavelength polarisation switching technique. The basic measurement is Doppler velocity, determined from the changes in intensity at two points in the wings of the potassium absorption line at 770 nm. Two short (≈5 ms) exposures are taken consecutively and the ratio, R, of intensity between the two wings is determined,

$$R = \frac{I_{\mathrm{b}} - I_{\mathrm{r}}}{I_{\mathrm{b}} + I_{\mathrm{r}}} , \tag{1}$$

where I_{b} and I_{r} are the intensities measured at the blue and red wings of the solar absorption line, respectively. The ratio is proportional to the observed line-of-sight Doppler velocity shift. Integrating many short exposures and calculating the ratio in this way allows common intensity fluctuations to cancel, reducing the effect of atmospheric scintillation noise.

The BiSON node located at Izaña on the island of Tenerife, at the Instituto de Astrofísica de Canarias (IAC) [Roca Cortés and Pallé, 2014], suffers additional complications in terms of visibility and atmospheric noise due to the proximity of the Western Sahara, just 100 km from the North African coast. During the summer months the Canary Islands frequently experience high concentrations of mineral dust in the atmosphere, known as Calima, where the Saharan Air Layer passes over causing a fog-like reduction in visibility and a change in atmospheric characteristics. The aim of this paper is to determine the contribution of atmospheric scintillation noise to the overall noise budget in BiSON observations, and to investigate the change in atmospheric noise characteristics with periods of Calima. There are several techniques for estimation and approximation of the effect of scintillation noise – see, e.g., Young [1967, 1969], Dravins et al. [1997, 1998], Kenyon et al. [2006], Kornilov et al. [2012], Shen et al. [2014], Föhring et al. [2019]. Here, we take an empirical approach to exploring the temporal frequency spectrum of the scintillation. The scintillation noise measurements presented will be of general interest to astronomers at Izaña, however it should be noted that these day-time results will be worse than night-time conditions.

In Section 2 we look at two methods of estimating atmospheric conditions, and in Sections 3 and 4 we present scintillation noise data captured over several days in September 2017 during a period of mild Calima. Finally, in Section 5 we discuss the results both for the impacts on BiSON spectrophotometer design, and for astronomical observations more generally.

2. Atmospheric conditions

In order to interpret the changes in atmospheric scintillation noise characteristics it is essential to also estimate the overall atmospheric conditions. This is particularly relevant to Izaña, where placing results on scintillation in context requires an understanding of the impact of the Calima. The atmospheric extinction coefficient was determined each day using the technique described by Hale et al. [2017]. In brief, this involved logging the

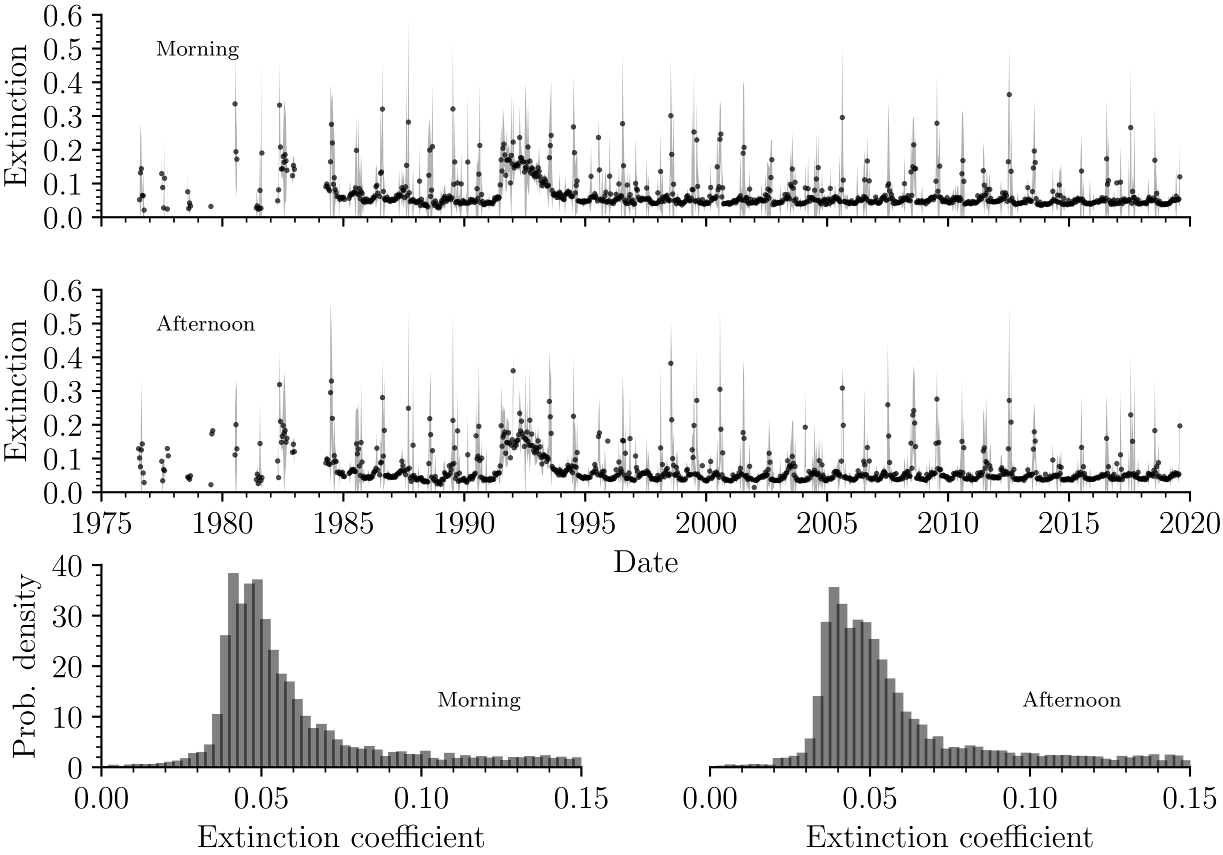

Figure 1. Extinction coefficients and statistical distribution from Izaña, Tenerife, estimated with the Mark-I BiSON instrument using the technique described by Hale et al. [2017]. Morning and afternoon extinction values are estimated separately, shown in the top and middle panel. Each dot represents the median value over 14 days. The grey shading represents ±3 times the standard-error on each median value. The large increase in extinction during the period between 1991 and 1994 was caused by the eruption of the Mount Pinatubo volcano in the Philippines. The bottom two panels show the statistical distribution of extinction, which is Gaussian with a long-tail caused by the effects of Calima.

changing solar intensity measured throughout the day by our BiSON instrument, and fitting this for both morning and afternoon periods against the airmass calculated from the known solar zenith angle,

$$\ln(I/I_0) = -\tau A \ , \tag{2}$$

where I is the direct-Sun radiance, I_0 the maximum intensity measured on a given day, and A the airmass. The gradient of the fit, τ, is a measure of the column atmospheric aerosol optical depth (AOD) per unit airmass, calibrated in terms of magnitudes per airmass. Figure 1 shows the estimated atmospheric extinction coefficients determined from the archive of data from the Mark-I BiSON instrument at Izaña. The typical extinction coefficient at Izaña on a clear day is about 0.05 magnitudes per airmass. During mineral dust events, often between June and October, extinction can rise to values between 0.1 and 0.8 magnitudes per airmass.

A real-time estimate of ground-level dust at Izaña is provided by the Stellar Activity (STELLA) robotic telescopes [2019], a Leibniz Institute for Astrophysics Potsdam

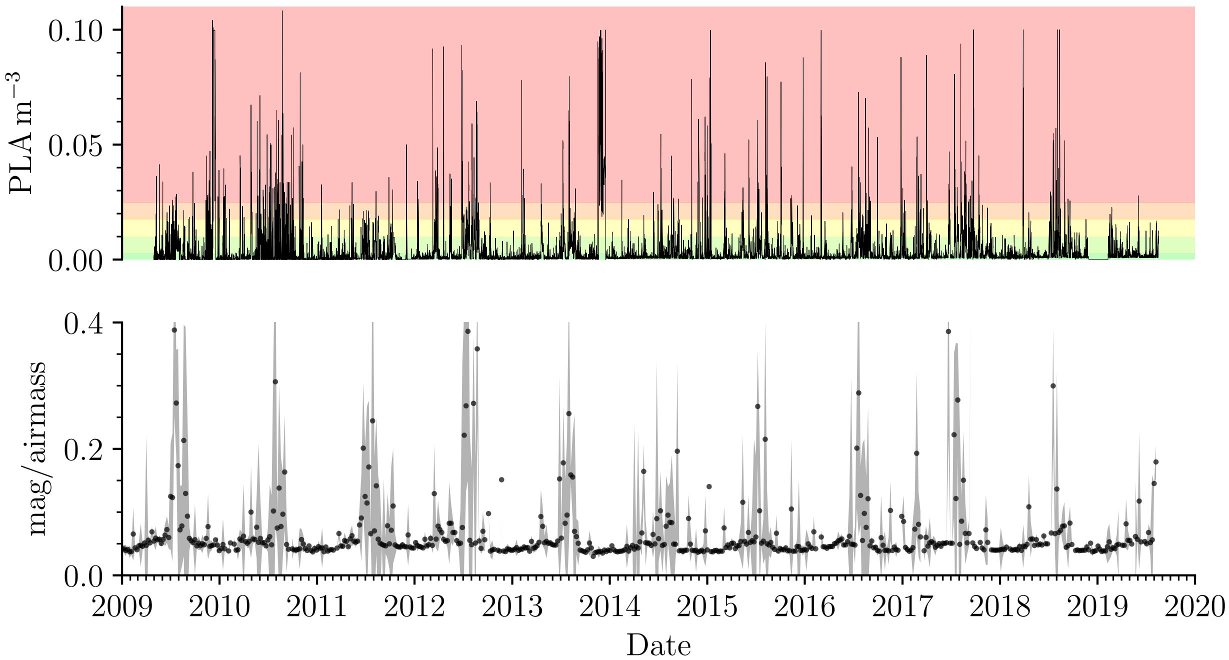

Figure 2. Top: Dust data obtained with the STELLA robotic telescopes [2019] at Izaña, an AIP facility jointly operated by AIP and IAC. The coloured bands indicate the qualitative limits described in Table 1. Towards the end of 2018 a fault was discovered with the wiring of the sensor, which following the repair resulted in a cleaner signal and calibration change. Bottom: Average daily extinction coefficients at Izaña estimated with the BiSON instrument over the same time period. Each dot represents the median value over 7 days. The grey shading represents ±3 times the standard-error on each median value. The Spearman rank-order correlation coefficient for the two datasets is 0.5 with an infinitesimally small false-alarm probability.

(AIP) facility. STELLA make available, amongst other parameters, measurements from a VisGuard 2 In-situ Visibility Monitor manufactured by SIGRIST Photometer [2019]. The VisGuard is a photometer that measures the intensity of scattered light from an air sample drawn into the instrument by a fan. The output is a measure of Polystyrol-Latex-Aerosols (PLA) per cubic metre, and when the instrument is installed in its intended use case monitoring visibility in vehicle tunnels, this value can be converted to an extinction coefficient. When used in open-air observations, the factory calibration is uncertain. The IAC have therefore defined some threshold levels for what is considered to be low and high, and these are detailed in Table 1. The archive of data from the VisGuard is shown in Figure 2 with coloured banding to indicate the IAC thresholds. The period of unusually high values towards the end of 2013 results from a sensor glitch, and at the end of 2018 a repair to the wiring of the sensor has reduced the noise level and resulted in a change of calibration.

The two results do not necessarily show perfect correlation, since the BiSON atmospheric extinction measurement is estimating the column aerosol optical depth through the entire atmosphere, and the VisGuard is estimating the amount of dust at only ground level. In general, when the extinction is high the PLA tends to be high, and the Spearman rank-order correlation coefficient is 0.5 with

Table 1. Qualitative limits used at the IAC in calibration of ground-level dust measurements from the STELLA robotic telescopes [2019].

Qualitative Value		Range (PLA m^{-3})	
Spanish	English	Min	Max
Poca	Little		<0.0025
Media	Medium	0.0025	<0.0100
Bastante	Quite a lot	0.0100	<0.0175
Mucha	A lot	0.0175	<0.0250
Fuera limites	Outside limits	0.0250	

an infinitesimally small false-alarm probability. When considered together the two measurements provide a good qualitative judgement of atmospheric conditions, and this allows us to better understand the following frequency-dependent scintillation measurements, which show significant variation.

3. Scintillation measurement

The scintillation noise was measured at about the same time each morning over a one-week span in 2017. This period captured several days of marked variation in sky quality. Independent measures of sky quality were available on each day from BiSON (extinction) and STELLA (dust PLA).

Sunlight was collected using the Solar Pyramid coelostat at the Observatorio del Teide, and a small bespoke instrument (independent of the BiSON spectrophotometer) was used to log intensity fluctuations. The instrument consisted of a 25.4 mm objective lens, filtered to a bandwidth of 700 nm to 900 nm, with sunlight fed through an optical fibre to a simple photodiode and transimpedance amplifier. The wavelength bandwidth was selected to match existing BiSON instrumentation. The input power with this configuration was approximately 0.05 mW, producing an output of approximately 700 mV after amplification with a 30 kΩ gain resistor and 0.45 A W^{-1} photodiode quantum efficiency. The detector bandwidth was approximately 50 kHz. The light intensity was logged using a digital oscilloscope for 10 s at 6.25 kHz. A total of 24 realisations of noise were captured consecutively each morning, producing four minutes of data in 10 s segments. The spectral density of each 10 s segment was calculated and then stacked to improve the final atmospheric “signal” to noise ratio.

4. Results

The results from the scintillation measurements are shown in Figure 3, where each panel shows the amplitude spectral density (ASD) of scintillation noise measured each day, with annotations indicating dust level and frequencies of power roll-off. The effects of Calima are most pronounced below 5 Hz, equivalent to exposures of ≥200 ms. Photometry techniques making use of multi-wavelength observations to reduce the effect of scintillation noise typically require high-speed (<10 ms) exposures [Dravins et al., 1997], and we can see from the profiles in Figure 3 that the effect of scintillation noise has indeed almost completely decayed at frequencies above 100 Hz, even during days of medium to high Calima. The mean value of the “white” band of scintillation noise between 0.5 Hz to 1.0 Hz was measured, and this value was used as the baseline to determine the frequencies of the −3 dB to −10 dB points, listed in Table 2. For comparison, the IAC telescope operator night-time logs are also included for each day. Exposures shorter than 200 ms, equivalent to 5 Hz, see the scintillation noise power reduced by half (−3 dB) over that of longer exposures. A reduction in scintillation noise of −6 dB is

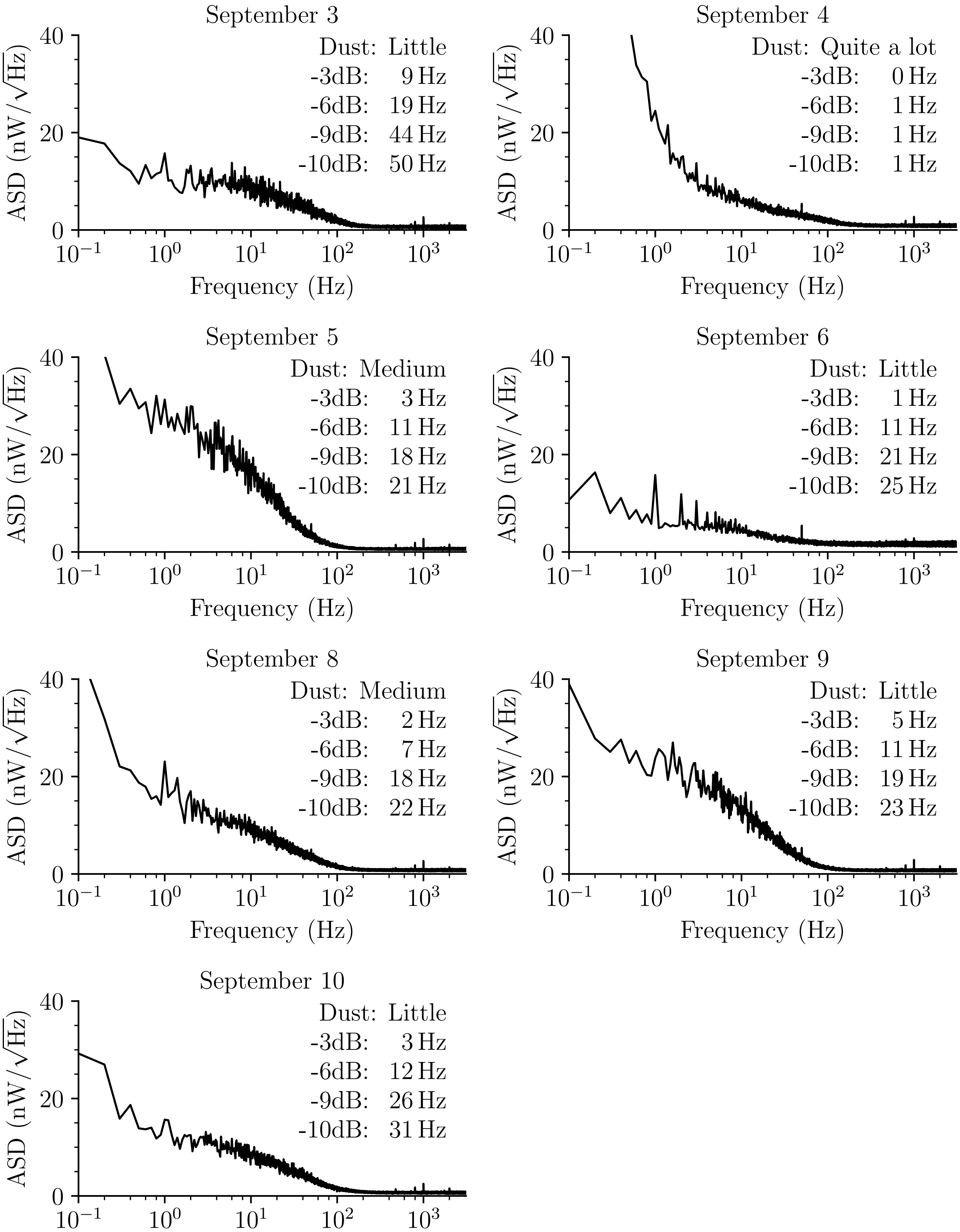

Figure 3. Daily scintillation measurements collected during 2017 September, using the technique described in Section 3. The qualitative dust levels are described in Table 1. The absolute values for September 6 are low due to a temporary change in collection optics.

Table 2. Day-time scintillation noise characteristics and atmospheric conditions, including telescope operator notes on night-time observations.

Date	Mean ($nW/\sqrt{Hz}$)	−3 dB (Hz)	−6 dB (Hz)	−9 dB (Hz)	−10 dB (Hz)	Dust ($PLA\,m^{-3}$)	Extinction (mag/airmass)
2017/09/03	12.3	9	19	44	50	0.0017	0.044 ± 0.004
Not photometric, thin cirrus.							
2017/09/04	47.3	0	1	1	1	0.0150	0.111 ± 0.014
100% clear. Variable night, with rising calima and almost full moon. Loose wind and medium humidity. Photometric except for the moon.							
2017/09/05	30.4	3	11	18	21	0.0080	0.322 ± 0.032
100% clear. Almost no calima and full moon. Moderate wind and very low humidity. Photometric except for the moon.							
2017/09/06	8.5†	1	11	21	25	0.0009	0.048 ± 0.004
100% clear. No calima and almost full moon. Moderate wind and very low humidity. Photometric except for the moon.							
2017/09/07						0.0100	0.046 ± 0.004
100% clear. Excellent seeing. Photometric except for the moon.							
2017/09/08	19.7	2	7	18	22	0.0025	0.222 ± 0.020
Not photometric, thin cirrus. Excellent seeing.							
2017/09/09	24.0	5	11	19	23	0.0015	0.172 ± 0.023
Not photometric, thin cirrus.							
2017/09/10	15.4	3	12	26	31	0.0017	0.096 ± 0.008
100% clear. Photometric except for the moon.							

†This value is low due to a temporary change in collection optics.

typically achieved at about 11 Hz, and reduction of −10 dB between 20 Hz to 30 Hz, which means depending on the application there may be little benefit to achieving exposure times shorter than 50 ms, relaxing constraints on detector gain and bandwidth. It is expected that results will differ between day- and night-time observations, and for instruments with different aperture size.

5. Discussion

BiSON spectrophotometers have made use of various optoelectronic components to achieve computer-controlled wavelength selection via polarisation switching, with rates varying from 0.5 Hz to 50 kHz. Modern BiSON spectrophotometers use Pockels effect cells switched at 90.9 Hz. The data acquisition subsystem takes 5 ms exposures per polarisation phase, plus 0.5 ms stabilisation time at each switching point, making an 11 ms period. This is repeated 340 times for 3.74 s, giving a total exposure integration of 3.4 s within each 4 s sample. Faster switching has the detrimental effect of reducing the overall integration time due the need for stabilisation periods at each switching interval. Slower switching is less effective at removal of scintillation noise but reduces the dead time. In order to determine the optimum switching rate it is necessary to know the characteristics of atmospheric scintillation noise.

Many polarisation switching techniques are not capable of reaching rates as high as 100 Hz, and so during instrumentation design it is essential to know the potential impact of atmospheric scintillation on the overall noise levels, and how this compares with other noise sources in the system.

Table 3. Velocity-calibrated white noise level and noise equivalent velocity (NEV) for five BiSON spectrophotometers over a 2018 summer observing campaign.

Site	White noise $(\mathrm{ms}^{-1})^2\,\mathrm{Hz}^{-1}$	NEV $\mathrm{cm\,s}^{-1}$ RMS
Sutherland	4.3	23.1
BiSON:NG	9.9	35.2
Narrabri	10.4	36.1
Las Campanas	13.5	41.1
Mark-I	61.6	87.7

Electronic noise, photon shot noise, and noise from thermal fluctuations each contribute less than $1\,\mathrm{pW}\,\sqrt{\mathrm{Hz}}^{-1}$ to the overall noise level, and by comparison with the values shown in Table 2, we see the system is dominated by scintillation noise as is expected for ground-based photometric measurements.

Throughout 2018, a next generation prototype BiSON spectrophotometer was commissioned at Izaña alongside the Mark-I instrument, sharing light from the pyramid coelostat [Hale, 2019c]. The aim of BiSON:NG is to miniaturise and simplify the instrumentation as much as practical, typically though the use of off-the-shelf components, whilst maintaining performance comparable with the existing network. The prototype spectrophotometer makes use of an LCD retarder for wavelength selection, and such devices are much slower to change state than bespoke Pockels effect cells and drivers. The prototype instrument switches polarisation state at 5 Hz, consisting of a 50 ms stabilisation period followed by 50 ms exposure time per polarisation phase, a total of 200 ms per observation data point. Table 3 shows the noise performance for five BiSON spectrophotometers over a 2018 summer observing campaign. Mark-I at Izaña switches at 0.5 Hz. Three instruments at Las Campanas in Chile, Narrabri in Australia, and Sutherland in South Africa, all switch at 90.9 Hz. Comparing the faster switching instruments with the slow-switching Mark-I instrument, we see reduction in white noise power of −6.6 dB to −11.5 dB which as we have seen here is of the order expected through reduction in scintillation noise alone. The prototype instrument produces mid-range performance inline with the faster switching instruments, and is consistent with the scintillation noise profiles and variability we have shown here.

Having such low noise is essential to allow the detection of very-low frequency solar p-mode oscillations, which have amplitudes of a centimetre-per-second or less [Davies et al., 2014].

6. Open Data

All code and data are freely available for download from the University of Birmingham eData archive [Hale, 2019a], and also from the source GitLab repository [Hale, 2019b].

Acknowledgments

The authors are grateful for the financial support of the Science and Technology Facilities Council (STFC), grant reference ST/R000417/1. The BiSON node on the island of Tenerife is based at the Observatorio del Teide operated by IAC, and we give particular thanks to Antonio Pimienta and the team of operators who have contributed to running the Mark I instrument over many years. Telescope operator logs provided courtesy of Alex Oscoz, Head of Telescope Operations. Dust data was obtained with the STELLA robotic telescopes at Tenerife, an AIP facility jointly operated by AIP and IAC.

References

G. R. Davies, A. M. Broomhall, W. J. Chaplin, Y. Elsworth, and S. J. Hale. Low-frequency, low-degree solar p-mode properties from 22 years of Birmingham Solar Oscillations Network data. MNRAS, 439:2025–2032, April 2014. doi: 10.1093/mnras/stu080.

D. Dravins, L. Lindegren, E. Mezey, and A. T. Young. Atmospheric Intensity Scintillation of Stars, I. Statistical Distributions and Temporal Properties. PASP, 109:173–207, Feb 1997. doi: 10.1086/133872.

D. Dravins, L. Lindegren, E. Mezey, and A. T. Young. Atmospheric Intensity Scintillation of Stars. III. Effects for Different Telescope Apertures. PASP, 110:610–633, May 1998. doi: 10.1086/316161.

D. Föhring, R. W. Wilson, J. Osborn, and V. S. Dhillon. Atmospheric scintillation noise in ground-based exoplanet photometry. MNRAS, 489(4):5098–5108, Nov 2019. doi: 10.1093/mnras/stz2444.

S. J Hale. Measurement of atmospheric scintillation at Observatorio del Teide, Iz̃ana, Tenerife, December 2019a. URL `https://edata.bham.ac.uk/412/`.

S. J Hale. Measurement of atmospheric scintillation at Observatorio del Teide, Iz̃ana, Tenerife, December 2019b. URL `https://gitlab.com/drstevenhale/izana-scintillation/-/tags/v1.0`.

S. J Hale. *Birmingham Solar Oscillations Network: The Next Generation*. PhD thesis, School of Physics and Astronomy, University of Birmingham, UK, July 2019c. URL `https://etheses.bham.ac.uk/id/eprint/9010/`.

S. J. Hale, R. Howe, W. J. Chaplin, G. R. Davies, and Y. P. Elsworth. Performance of the Birmingham Solar-Oscillations Network (BiSON). Sol. Phys., 291(1): 1–28, January 2016. ISSN 1573-093X. doi: 10.1007/s11207-015-0810-0. URL `https://link.springer.com/article/10.1007%2Fs11207-015-0810-0`.

S. J. Hale, W. J. Chaplin, G. R. Davies, Y. P. Elsworth, R. Howe, M. N. Lund, E. Z. Moxon, A. Thomas, P. L. Pallé, and E. J. Rhodes, Jr. Atmospheric extinction coefficients in the I_c band for several major international observatories: Results from the BiSON telescopes, 1984-2016. *The Astronomical Journal*, 154(3):89, 2017. doi: 10.3847/1538-3881/aa81d0. URL `https://iopscience.iop.org/article/10.3847/1538-3881/aa81d0`.

S. L. Kenyon, J. S. Lawrence, M. C. B. Ashley, J. W. V. Storey, A. Tokovinin, and E. Fossat. Atmospheric Scintillation at Dome C, Antarctica: Implications for Photometry and Astrometry. PASP, 118: 924–932, June 2006. doi: 10.1086/505409.

V. Kornilov, M. Sarazin, A. Tokovinin, T. Travouillon, and O. Voziakova. Comparison of the scintillation noise above different observatories measured with MASS instruments. A&A, 546:A41, October 2012. doi: 10.1051/0004-6361/201219954.

J. Osborn, D. Föhring, V. S. Dhillon, and R. W. Wilson. Atmospheric scintillation in astronomical photometry. MNRAS, 452: 1707–1716, September 2015. doi: 10.1093/mnras/stv1400.

T. Roca Cortés and P. L. Pallé. The Mark-I helioseismic experiment - I. Measurements of the solar gravitational redshift (1976-2013). MNRAS, 443:1837–1848, September 2014. doi: 10.1093/mnras/stu1238. URL `http://adsabs.harvard.edu/abs/2014MNRAS.443.1837R`.

Hong Shen, Longkun Yu, and Chengyu

Fan. Temporal spectrum of atmospheric scintillation and the effects of aperture averaging and time averaging. *Optics Communications*, 330:160 – 164, 2014. ISSN 0030-4018. doi: 10.1016/j.optcom.2014.05.039. URL `http://www.sciencedirect.com/science/article/pii/S0030401814004969`.

SIGRIST Photometer. VisGuard 2 In-situ Visibility Monitor. Technical Report 14289E/4, SIGRIST Photometer AG, Hofurlistrasse 1, 6373 Ennetbürgen, Switzerland, 2019. URL `https://classic.photometer.com/svc/document.axd?id=14761&hl=E`.

STELLA robotic telescopes. Environmental Status (Dust), 2019. URL `http://stella.aip.de/stella/status/getdetail.php?typ=24`.

A. T. Young. Photometric error analysis. VI. Confirmation of Reiger's theory of scintillation. AJ, 72:747, August 1967. doi: 10.1086/110303.

A. T. Young. Photometric error analysis. VIII. The temporal power spectrum of scintillation. Appl. Opt., 8:869–885, 1969. doi: 10.1364/AO.8.000869.