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Toward a global earthshine network: First results from two stations

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[1] Big Bear Solar Observatory is building the world's first global earthshine network to measure Earth's large-scale reflectance. Our first remote station was deployed in late 2003 at the Crimean Astronomical Observatory. Here we compare the data obtained from the two earthshine stations, Crimea and Big Bear. We find that the retrieved quantities from both stations are consistent and that the data may be easily combined into a single data set expanding the temporal and geographical coverage of our Earth reflectance measurements from California. We also detail our plans and the expected coverage with a larger network of stations.

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1. Introduction

[2] The net sunlight reaching the Earth, which is the ultimate source of energy driving the climate, depends critically on the solar irradiance and the Earth's albedo. Since late 1998, the Earth's reflectance has been monitored continuously from Big Bear Solar Observatory (BBSO) by measuring the earthshine (ES). This is a revitalization of an old method, using modern technologies on a manual telescope. In previous publications [*Qiu et al.*, 2003; *Pallé et al.*, 2003; *Montañés-Rodriguez et al.*, 2005; *Goode et al.*, 2001], we have shown that we can measure the Earth's reflectance with a precision comparable to that of satellites. *Pallé et al.* [2004a] have also shown that the Earth's albedo changes over the past two decades have been larger than previously suspected, with a significant decline from the mid 1980's to 2000. These decadal changes in reflectance are climatologically significant and derive mainly from changes in cloud properties. The next step for the ES project is a global network giving better temporal and spatial coverage.

[3] The most important single-site historical programs of earthshine measurements were carried out by *Danjon* [1928, 1954] and *Dubois* [1942, 1947] from a number of sites in France. Simultaneous observations from several sites were attempted during the 1958 international geophysical year [*Bakos*, 1964], although the project suffered from systematic errors among the uncalibrated photometers.

[4] In this paper, we outline plans for the development of a global earthshine Network that would make a crucial contribution in determining the relative roles of a modestly variable sun, evolving cloud cover, and a varying Earth in global climate change. The precision of the Earth's albedo determination by means of the earthshine, strongly depends on the number of nights for which we have data [*Pallé et al.*, 2003]. In this sense, we know that increasing the number of earthshine stations (a process already underway), and judiciously spacing them in longitude will significantly increase precision. The fact that the morning and evening earthshine measurements from BBSO are almost identical [*Pallé et al.*, 2003, 2004b] suggests that data from different stations may be easily combined to derive a 24-hour annual Bond albedo with a precision better than one percent, and monthly albedos with a precision close to a percent. Further, we anticipate determining regional albedos of large slices of the Earth, to about a percent. These will allow us to confidently distinguish between changes in the albedo arising from variations in solar activity from variations in weather phenomena, while reducing, or even eliminating calibration problems.

[5] As the first implementation of our plan to build a network of earthshine observing stations, in November 2003, we deployed a side-by-side calibrated, manual earthshine telescope (hereafter ES2), twin to that at BBSO (hereafter ES1), at the Crimean Astronomical Observatory (CrAO). After a testing phase, regular measurements at CrAO started in February 2004.

[6] In the next section, we will describe the calibration process between ES1 and ES2 when both telescopes were at BBSO. In section 3, we will compare the available data from the two stations during 2004. In section 4, we will discuss our plans for a global earthshine network and what measurements we expect to perform with it. Our conclusions will be given in section 5.

2. Intercalibration Between ES1 and ES2

[7] Over the period April to August 2003, the ES2 earthshine telescope was mounted on top of the BBSO solar telescope side-by-side with ES1. Simultaneous observations of the earthshine were taken with both telescopes for a period of five months allowing a complete intercalibration of the two instruments. By observing from the same place and at the same time, our albedo measurements must be identical, after accounting for instrumental differences.

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Table 1. Mean Nightly p^* Measurements for ES1 and ES2 During the 2003 Calibration Period of Both Telescopes at BBSO[a]

Night	p^* ES1	p^* ES2	Δp^*, %	Lunar Phase
Jul 24	0.2648	0.2676	1.0	123.9
Aug 02	0.2298	0.2288	−0.4	−131.2
Aug 03	0.2316	0.2319	0.1	−118.2
Aug 04	0.2330	0.2258	−3.1	−104.9
Aug 20	0.2840	0.2720	−4.2	93.5
Aug 22	0.2565	0.2498	−2.6	115.8
Aug 24	0.2766	0.3212	16.1	139.1
Sep 02	0.2255	0.2175	−3.5	−108.1

[a] Also given is the size of the discrepancy (in percentage) of the ES2 data with respect to ES1. Excluding the night of August 24th, the correlation coefficient between the two sets of measurements is r = 0.97 ($P \gg 99.99\%$), and of r = 0.87 ($P > 99.5\%$) if included.

[8] The ES2 telescope is a refracting telescope with an optical setup very similar, although slightly shorter than ES1, see *Qiu et al.* [2003] for a detailed description of ES1. The ES1 detector is a back-illuminated Apogee-7 CCD camera. This particular camera model is no longer commercially available and for ES2 an Apogee-47p CCD was chosen because of its similarity in design and quantum efficiency to the no-longer-available Ap-7. Still some differences remain as the Ap-47p camera sensitivity is much greater than the Ap-7 and exposures times are much shorter.

[9] An exact determination of the bright side filter transmission is crucial for our measurements [*Qiu et al.*, 2003]. The theoretical generic transmission value of the ES2 bright side filter (a Melles Griot metallic neutral-density filter, 03FNQ023), is 1.0 ± 0.05% (over the 200–700 nm range). We determined empirically (for ES2 measurements to coincide with ES1) an overall transmission value of 1.32% between 400 and 700 nm (the range covered by our photometric observations), which is in modest agreement with the wavelength-dependent transmission measurements provided by Melles Griot for our specific filter, especially when combined with the Ap-47p quantum efficiency curve. Note that these calibrations are relative, i.e., if the albedo using the ES1 filter value is wrong by some factor, then the albedo using ES2 will be wrong by the same factor. For our future telescopes, we are testing new camera systems that will allow us to eliminate the bright side filter, which to-date is our major source of uncertainty in the intercalibration of the network. When data from these telescopes working side by side with ES1 are available, we will be able to absolutely re-calibrate the filter values for ES1 and ES2 and post-facto eliminate any possible systematic errors in our albedo determinations.

[10] The simultaneous ES1 and ES2 p^* measurements from BBSO are tabulated in Table 1. While on a typical night of observations with good weather conditions we obtain about 1% precision in our earthshine measurements, nights with a precision accuracy of 2–3% are not uncommon. In Table 1, for half of the nights ES1 and ES2 p^* measurements agree within 2.5% or less, and within 3.5% for two other nights, all values within our error bars. On the night of August 20th, which has the second largest discrepancy between ES1 and ES2 (4.2%), weather conditions were not good at BBSO leading to noisy data and a larger discrepancy in the determination of the atmospheric absorption coefficients for the two telescopes. The same happened for the night of the 24th of August which has the largest discrepancy. Note, that this night has a lunar phase value of 139°, when the bright side is a very small crescent. Data at such extreme lunar phases are not used in long-term trend analysis [i.e., *Pallé et al.*, 2004a]. For all nights (not shown), including Aug 24th, the hourly variations in our retrieved earthshine measurements track each other extremely well.

3. Results

[11] The ES2 telescope has been continuously taking data from CrAO since February 2004. Unfortunately an anomalously bad winter at that station, combined with technical difficulties in both telescopes reduced the number of available nights of simultaneous observations at BBSO and CrAO. Nevertheless, we already have enough data to carry out an initial analysis of the retrieved measurements.

[12] In Figure 1 (top), the mean nightly p^* values from BBSO from 1999 to 2005 are plotted against lunar phase value. Over-plotted are the nightly p^* measurements for ES1 and ES2 for 16 simultaneous (same UT day) nights of observations. We have determined the mean value of p^* at each lunar phase angle over the 1999–2005 period (solid line), and we have subtracted these mean values to derive the mean p* anomalies, Δp^*, for each of these 16 nights. In Figure 1 (bottom) the Δp^* values at the two stations are plotted against each other.

[13] The apparent albedo values taken by ES2 in CrAO fall well within the range of variability observed at BBSO, suggesting that the data for both stations can be combined to derive global albedo measurements with a larger geographical coverage than a single station. The p^* values for ES1

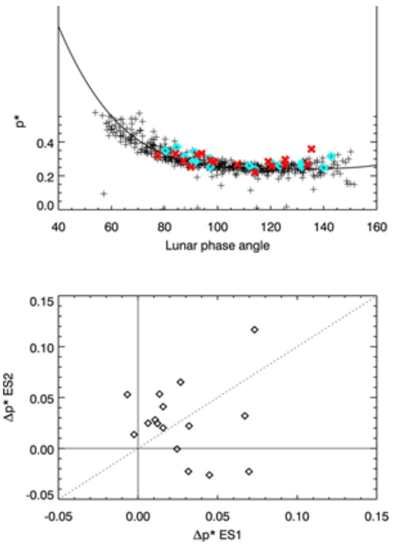

Figure 1. (top) Apparent albedo values 1999–2005 measured at BBSO (crosses)plotted against lunar phase angle. Over-plotted are ES1 (blue) and ES2 (red) mean nightly apparent albedo for 16 simultaneous nights of observations from BBSO and CrAO respectively. The solid line represents a fourth degree polynomial fit to all the BBSO data. (bottom) Apparent albedo anomalies measured at BBSO against apparent albedo anomalies measured at CrAO for the same UT days. The broken line corresponds to that of a 45° straight line.

and ES2 for the same UT dates, however, do not coincide. This is not surprising because there is a 10 hour difference between CrAO and BBSO, which means that different parts of the Earth are being observed for the same UT day. Further, the two stations will have lunar phase angles differing about 6–7°, further changing the retrieved p^* values. While the overall annual mean albedo values of these two regions are very similar [*Goode et al.*, 2001], the seasonal variability is not because of the different latitudinal land mass distributions of the two regions, and the global cloud patterns tied to it, i.e., for a night in which observations from BBSO cover the area centered in the Atlantic (Figure 2a), the observations from CrAO will cover the area centered over Asia (Figure 2c). E. Pallé et al. (Seasonal and interannual trends in Earth's reflectance 1999–2004, submitted to *Journal of Geophysical Research*, 2005) have shown opposite seasonalities for the two large regions observed from BBSO. This is why there is no correspondence between the anomaly values retrieved by the two telescopes neither. When a long-term data set is available from both stations a comparative seasonal and interannual trend analysis will be possible. Finally, we note how for both telescopes the anomalies are mostly positive, indicating larger albedo values for 2004 than the mean value over the 1999–2004 period.

4. The Need for a Global Network

[14] Presently, we are working on developing a network of automated earthshine telescopes capable of monitoring the Earth's reflectance 24 hours a day. The proposed network would have eight stations ideally located in California, Hawaii, Australia, China, Kazakhstan/India, Crimea/South Africa, the Canaries and Chile, each station being separated by 45^{o} degrees in longitude from its neighbor, and including some of the best sites for nighttime astronomy in the world. It is worth noting that we get a greater number of observing nights in the summer than in any other period because of local weather conditions at Big Bear, where it is cloudier at night in winter. Thus, locating some of our new stations in the southern hemisphere and in sites with different weather patterns will increase our global coverage on any particular night.

[15] With these stations, we would have full global coverage each night, thereby giving us the ability to make differential measurements of the Earth's regions, as well as some redundancy to mitigate against local bad weather. The increase in precision with eight stations is essential in determining the longer term variations (such as during the roughly five year rise, or decline of a solar cycle) because of the sizable night-to-night weather fluctuations of the Earth's cloud cover. Each of the robot telescopes would be calibrated against one another in the same way as ES1 and ES2.

[16] As the first step toward a global network, we are deploying a set of four manned stations and at the same time developing an automated telescope at BBSO. In a second phase, the manned telescopes will be replaced by automated telescopes and the number of stations increased. At present, two stations, BBSO and CrAO, are already in operation. A third earthshine telescope has been calibrated at BBSO and is scheduled to be deployed in Yunnan during 2005. In Figure 2, the weighted area contributing to the earthshine observations from BBSO over the period 1999–2001 is shown. The weight includes the number of times that each region has contributed to the earthshine observations, multiplied by the lunar cosine angle at that time. The two nodes correspond to morning (rising moon) and evening (setting moon) observations. To simulate what the observational coverage would have been at the other three stations of our first phase, we have displaced the two BBSO nodes in longitude according to each station's location. One can see that BBSO and CrAO stations have similar area coverage, but on a given night, while BBSO may be measuring the western hemisphere (Atlantic Ocean and South America), CrAO will be measuring over the eastern hemisphere (Asia and Indian Ocean). The two planned stations at Yunnan and the Canaries are also complementary to each other and complete the geographical coverage of the whole Earth.

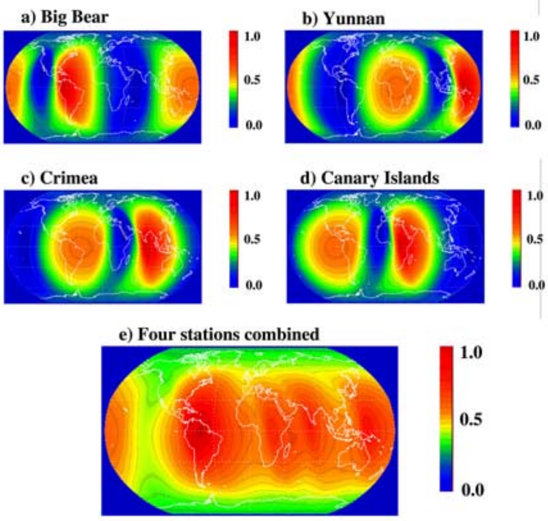

Figure 2. (a)–(d) Earthshine contributing areas for each of the first four manned network stations (BBSO, longitude = 118°W; CrAO, lon = 34°E; Yunnan, lon = 102°E; and the Canaries, lon = 28°W). The data are real for the Big Bear station and have been longitudinally displaced to match what the observations would have been for each of the other 3 stations. The contributions are arbitrarily normalized. (e) Earthshine contributing area when measurements from all four stations are combined into one single data set. Note how the coverage becomes more uniform as several of the nodes overlap one another. Also note that the contribution of the polar regions increases with the number of stations. This is due to the fact that one of the polar regions will be visible from all the stations for a given date, while this is not true for lower latitude regions.

[17] On the lower panel of Figure 2, the combined coverage of these four stations is given. The resulting coverage encompasses the entire surface of the Earth except for a band in the Pacific and is quite uniform, except over the polar regions where the coverage is poorer. Nevertheless the relative contribution of the polar regions is higher than with a single station. Still, these areas contribute relatively less to the albedo because the sunlight is always oblique.

[18] One should note that the two nodes, as measured from BBSO, are not exactly symmetric. This is due to two factors:

i) local weather at BBSO, which over the past few years has made it more likely to have clear skies in the morning than in the evening, has resulted in a greater sampling to the east than to the west (with respect to BBSO). We do not expect to have this same pattern of local weather at other stations; ii) to calculate the weighted contribution we have multiplied by the lunar cosine, and we take the value of that cosine at the end of the observations, which makes the two nodes artificially narrow and compressed toward western longitudes. The over-sampling of South America and under sampling of the eastern Pacific ocean shown in the composite figure is a consequence of these two effects (plus the fact that our four stations are not exactly 45° apart in longitude). Thus, we expect a more uniform coverage from real data.

5. Conclusions

[19] The role of clouds in the Earth's changing albedo is largely unknown, but understanding it is essential for studying climate change. Sustained measurements of the earthshine are an ideal probe of this critical, evolving parameter of climate, and provide an excellent complement to satellite measurements. We have shown in this paper how we performed the calibration between two earthshine telescopes. Earthshine measurements from these two telescopes from two different locations on the planet can be combined together to allow a longer time line with broader geographical coverage of the Earth's albedo. We find that earthshine measurements at BBSO and CrAO stations are consistent with what we would expect a priori, although a full consistency test on seasonal and interannual scales awaits the availability of a larger data set.

[20] We have also shown how our proposed global earthshine network would cover the whole Earth and continuously monitor the Earth's reflectance. The overlapping of the several stations will provide a more homogeneous sampling of the Earth's surface and will make a crucial contribution in determining the relative roles of a modestly variable sun, an evolving cloud cover, and the increasing atmospheric greenhouse gases in global climate change.

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