

1. EXECUTIVE SUMMARY

This report contains the final results of the ATST site survey, initiated in 2000 to determine the location of the Advanced Technology Solar Telescope. This report is a replacement of ATST RPT-0016, *ATST Site Survey Working Group Interim Report*. The interim report contained results from analyses that are now known to be incomplete. Note that even with this final report, it should not be construed to definitively prove that any one site is the best in the world. The data presented here were collected over too short a period to reflect long-term temporal variations. Also, the tests were limited to only six promising sites.

The results of this report come from a measurement and analysis technique that uses an array of scintillometers to estimate the seeing as a function of height above the ground. A considerable amount of effort has gone into testing and verifying the method, and the Working Group is of the opinion that the method gives an acceptable estimate up to a height of 50 m above the ground. This report contains the results of the verification tests, as well as two independent approaches to the analysis to allow the reader to judge the level of uncertainty in the results.

The ATST Site Survey Working Group (SSWG) has overseen the development and construction of instrumentation to measure daytime solar seeing, sky brightness, clear time fraction, dust levels, and water vapor content. These quantities have been measured at six candidate sites:

- Big Bear Solar Observatory, California
- Mees Solar Observatory, Haleakala, Hawaii
- Observatorio Roque de los Muchachos, La Palma, Canary Islands, Spain
- Panguitch Lake, Utah
- Sacramento Peak Observatory, Sunspot, NM
- Observatorio Astronomico Nacional, San Pedro Martir, Baja California, Mexico

These six sites were selected from an initial list of 72 candidates. The list was culled down primarily by considerations of feasibility and observing conditions. In a few cases, site visits eliminated candidates on the basis of changing environmental conditions, particularly drought. The six tested sites represent a cross-section of geographical locales: continental mountain (Sac Peak), continental mountain lake (Panguitch), peninsula mountain (San Pedro), coastal mountain lake (Big Bear), Atlantic island mountain (La Palma), and Pacific island mountain (Haleakala).

With the release of the interim report it became clear that the six sites could be grouped into two classes based on the observing conditions. A meeting of the ATST Science Working Group in November 2003 resulted in the recommendation that testing be continued only at the top group of sites (Big Bear, Haleakala, and La Palma). Thus those sites have an additional year of data included in this report, and are the main subject of the final report. Note that the overall classification of the sites into two groups remained unchanged as the seeing analysis continued to evolve.

As of August 31, 2004 data have been collected over various time periods at the six sites ranging in length from 0.5 to 2.1 years (1.9 to 2.1 years for the top group of sites) to determine which sites fulfill the scientific site requirements for the ATST. Those requirements are:

- Clear daytime fraction of 70%, 3000 hours annual sunshine.
- 1800 annual hours with r_0 (500 nm) > 7 cm (measured at the telescope aperture), including at least 100 continuous 2-hr periods.

- 200 annual hours with r_0 (500 nm) > 12 cm (measured at the telescope aperture) including at least 10 continuous 4-hr periods.
- Large isoplanatic angle, i.e., good atmospheric conditions at high altitudes.
- 480 annual hours with a sky brightness less than or equal to 25 ± 10 millionths at 1.1 radii at 1 micron with a radial profile equal to or steeper than $R^{-0.8}$, including at least 40 continuous 4 hour periods.
- 600 annual hours with the precipitable water vapor below 5 mm, including at least 40 continuous 4-hour periods.

The instrumentation used for the survey comprised two major pieces – a seeing monitor, and a sky brightness monitor. The seeing monitor included two components: a solar differential image motion monitor (S-DIMM), and an array of six scintillometers known as the shadow band ranger (SHABAR). Both seeing monitor components were designed and developed by Jacques Beckers and constructed at Sac Peak Observatory. The S-DIMM measures the total value of r_0 integrated from the observing height to the top of the atmosphere with no $C_n^2(h)$ weighting. The SHABAR measures the steady and fluctuating intensity of sunlight in six detectors giving the clear time fraction and a measure of the seeing with $C_n^2(h)$ weighted towards lower heights h by a factor $h^{-1/3}$. The SHABAR also measures the cross-covariance of scintillation between the 15 possible pairs of detectors which are arranged in a non-redundant array. These covariances are used to estimate $C_n^2(h)$ and hence r_0 as a function of height above the 8-m height at which the seeing monitor entrance aperture is mounted. Since the height of the ATST primary mirror is expected to be around 25 m, the inferred $r_0(h)$ is a vital piece of information. The seeing monitor is mounted on a substantial 6-m tall test stand that is designed such that the dominant motion of the instrument platform is a horizontal translation without tilting. The additional height of the telescope pier and telescope itself places the entrance aperture of the seeing monitor at 8 m above the ground. The sampling time and cadence of the seeing monitor is 10 sec.

The sky brightness monitor (SBM) comprises a miniature coronagraph that compares the sky brightness in three wavelength bands (450, 530, and 890 nm) to the solar disk intensity. It is sensitive to sky brightness below 1×10^{-6} of disk center intensity with a field of view of 4 to 8 solar radii. It also provides an intensity measurement in the 940-nm water vapor absorption band. In addition to the SBM, a commercial dust counter was installed to count particulates in five size ranges (0.3, 0.5, 1, 2, and 3 microns). The dust counter was mounted at the 6-m height of the top of the seeing monitor test stand, while the SBM was located at ground level. The SBM was designed and developed by Haosheng Lin and constructed at the Institute for Astronomy in Hawaii.

In addition to the seeing monitor and SBM, a weather station recorded wind speed, wind velocity, pressure, relative humidity, and temperature at two locations (top and bottom of the test stand).

Calibration of the S-DIMM instrument consisted of measuring the plate scale of the detector using observations of double stars. The SHABAR detectors were tested using generated laboratory signals as inputs and standard electronic measuring devices and techniques for the outputs. In addition, all field units were run for a brief period co-located with a constant “standard” unit at Sac Peak. Similar tests were performed for the SBM in Hawaii before shipment.

The data analysis to estimate $r_0(h)$ proved to be challenging. It essentially comprises the fitting of the observed cross-covariances as a function of detector separation with a model of the structure function, $C_n^2(h)$, composed of weighting functions derived from the theory of atmospheric turbulence. In addition, the integral of the model over the atmosphere is required to fit the observed S-DIMM value of r_0 , and the total observed scintillation. This requires the inclusion of an estimate of high-altitude seeing. Several tests of the analysis have been performed -- simulations, comparisons between simultaneous SHABAR/S-

DIMM r_0 estimates at different heights, and comparison with in-situ measurements of C_n^2 . In all cases the analysis appears to provide a reasonable estimate of $r_0(h)$. This report contains the results of the verification tests as well as two independent inversions of the seeing data so that the reader can judge the reliability of the results.

The SBM analysis to obtain sky brightness measurements involves the extraction of portions of the recorded images, averaging, correction for extinction and air mass, and fitting for radial and wavelength power laws. These power-law exponents are then used to extrapolate the sky brightness at the location and wavelength specified in the science requirements. This analysis also was challenging, primarily due to instrumental difficulties.

The clear time fraction is estimated from the steady intensity level of the scintillometers in the Shabar. The time derivative of the intensity I is computed and the number of sign changes of dI/dt in a 5-minute block is used to discriminate between clear and cloudy samples. This measurement was clearly impacted by the short length of the survey. In particular, Big Bear has been experiencing a long unusually cloudy period since mid-2002, which lowered the clear time fraction measured by this survey.

An effort was made to reduce the impact of site-specific observing habits, equipment outages, and bad weather on the extrapolation of the measured seeing statistics to estimates of annualized hours of quality observing conditions. Once the relevant measurements are estimated for each sample, statistics are performed on the data to obtain the summary quantities that are shown in the following figures and table. The figures show a few of the seeing and sky brightness characteristics of the sites, as summarized in the captions. The table represents the statistical outline of the results. In addition to these overall summaries, this report contains detailed information on the statistical dependence of seeing as a function of time of day, time of year, wind speed and wind direction.

The ATST site survey is one of the few comparative studies of solar site characteristics, and has been done with new instrumental and analysis techniques that can provide new details about the height dependence of the atmospheric turbulence. The reader should keep in mind the limitations of this work: the short observational time span, and the limited number of sites that have been tested.

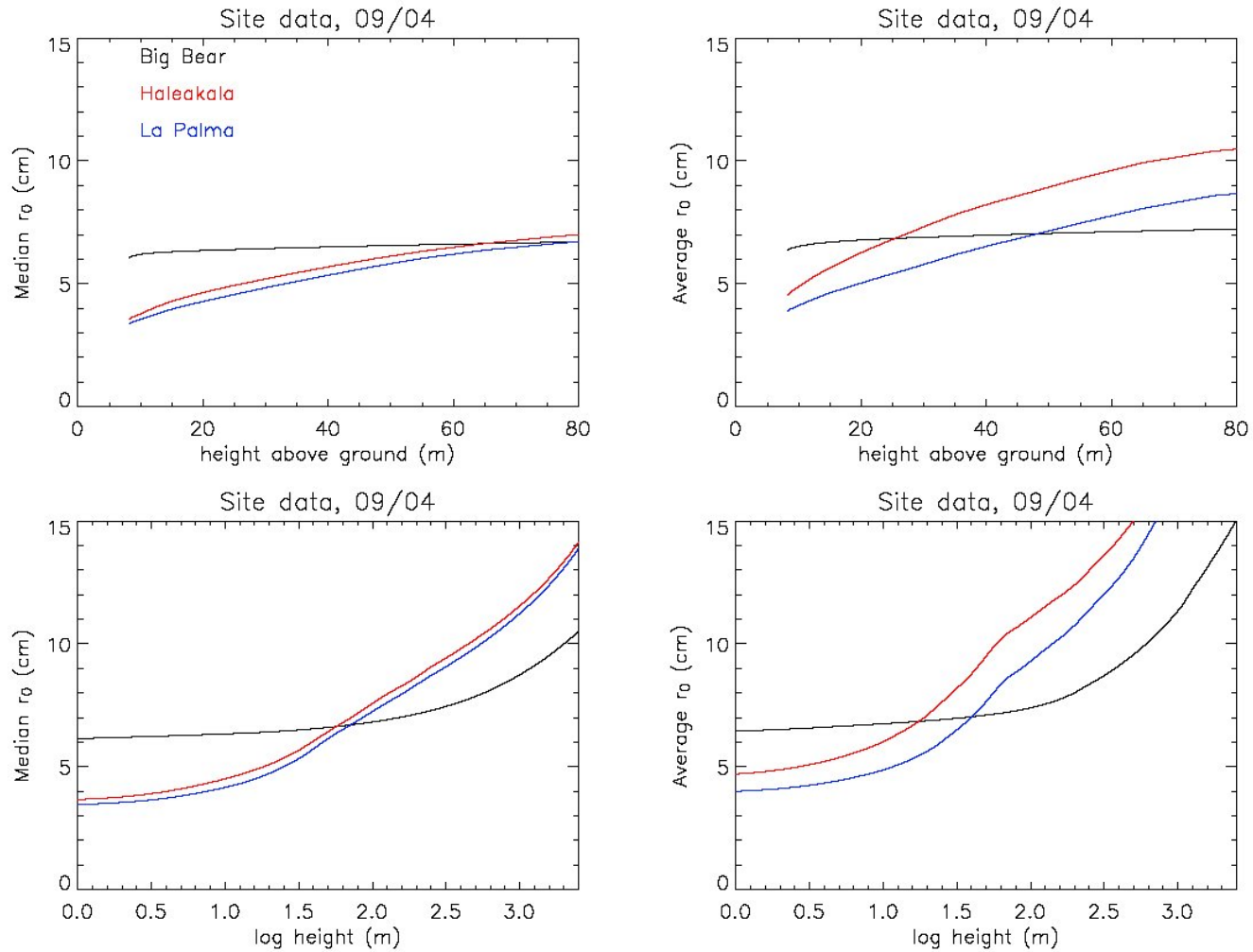


Figure ES.1 – These plots show the behavior of r_0 as a function of height as derived from the SHABAR and S-DIMM analysis. The left column shows the median values for each site; the right column shows the average r_0 . The bottom row is on a logarithmic height scale to show high-altitude seeing, and the top row is on a linear scale to show the low-level seeing.

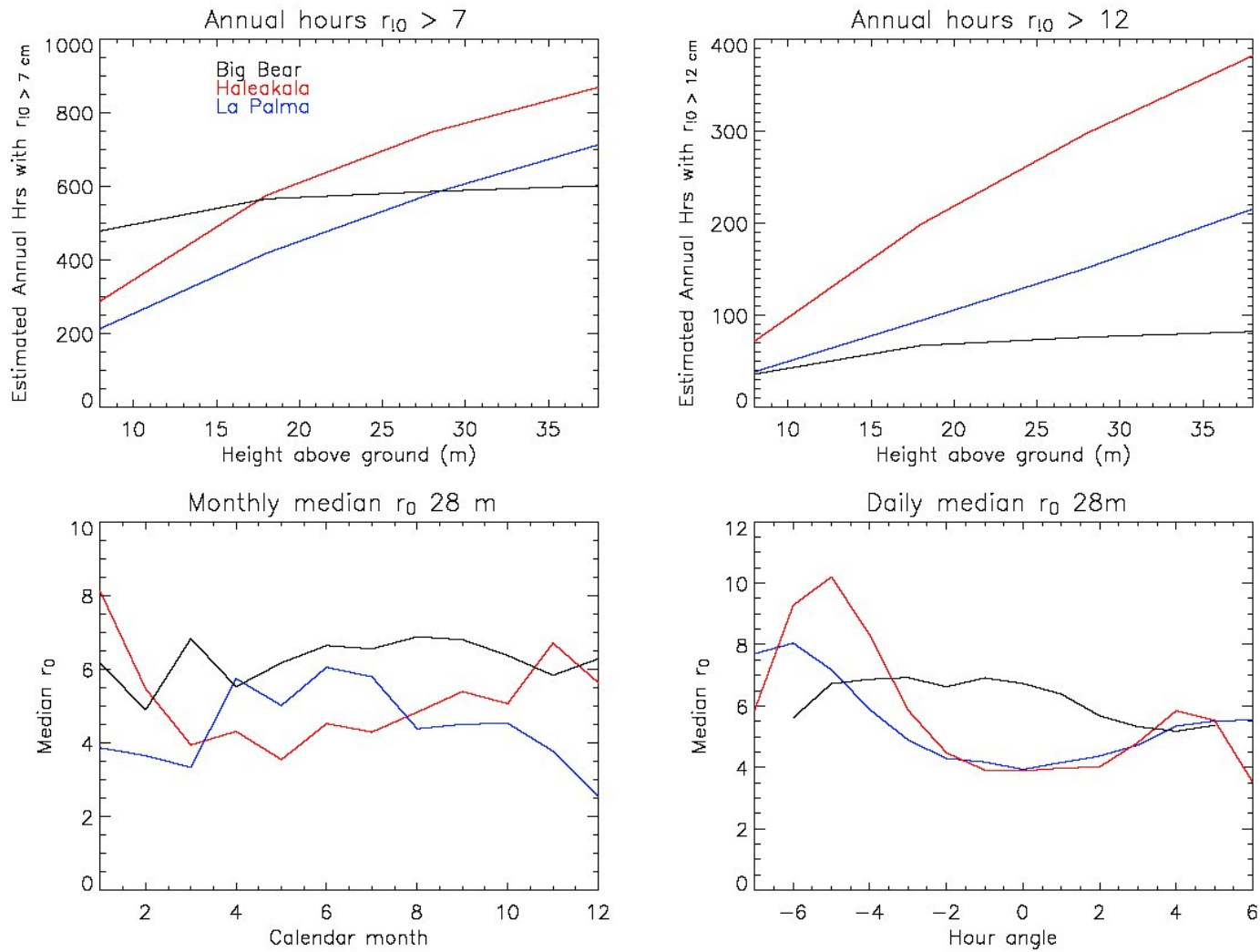


Figure ES.2 – These plots show some temporal characteristics of r_0 at the sites. The top row shows the estimated annual number of hours during which r_0 was greater than 7 cm (upper left panel) or 12 cm upper right (right panel) as a function of height above the ground. The lower row shows the median values of r_0 as a function of calendar month (lower left) and hour angle (lower right).

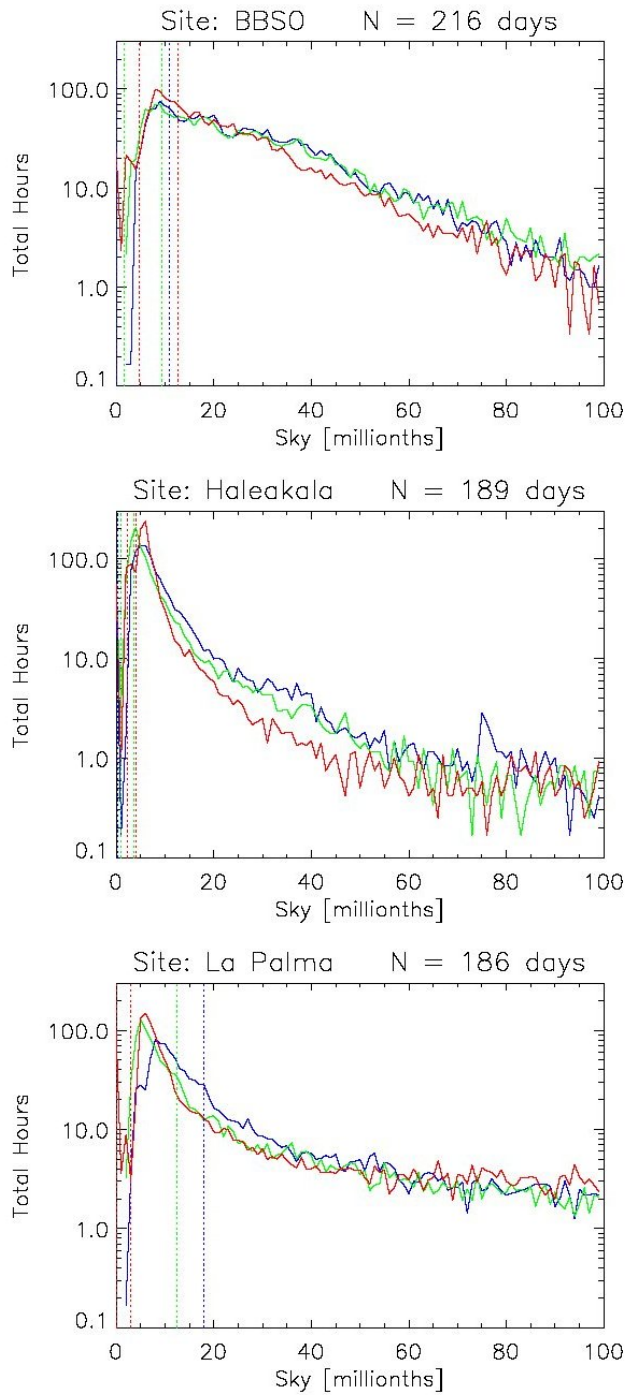


Figure ES.3 – These plots show histograms of the sky brightness measurements for the three sites. The colors of the lines indicate that the measurements have been obtained in the 450 nm (blue), 530 nm (green), or 890 nm (red) bands.

Seeing	Big Bear	Haleakala	La Palma
Time Period Start	18-Jul-2002	6-Aug-2002	28-Sep-2002
Time Period End	30-Aug-2004	30-Aug-2004	30-Aug-2004
N days observed	774	755	702
N valid seeing measurements	820434	713678	718370
Smoothed S-DIMM r0 Median (5-min running mean)	6.04	3.53	3.42
Results from MCV analysis			
S-DIMM/SHABAR r0 8 m Median, cm	6.06	3.50	3.37
S-DIMM/SHABAR r0 18 m Median, cm	6.33	4.42	4.15
S-DIMM/SHABAR r0 28 m Median, cm	6.42	4.99	4.73
S-DIMM/SHABAR r0 38 m Median, cm	6.49	5.48	5.25
S-DIMM Corrected Annual hours r0 >7 cm	496	290	214
S-DIMM/SHABAR 8 m Corrected Annual hours r0 >7 cm	500	288	213
S-DIMM/SHABAR 18 m Corrected Annual hours r0 >7 cm	590	575	418
S-DIMM/SHABAR 28 m Corrected Annual hours r0 >7 cm	611	747	580
S-DIMM/SHABAR 38 m Corrected Annual hours r0 >7 cm	628	868	713
S-DIMM Corrected Annual hours r0 > 12 cm	37	72	38
S-DIMM/SHABAR 8 m Corrected Annual hours r0 > 12 cm	37	72	38
S-DIMM/SHABAR 18 m Corrected Annual hours r0 > 12 cm	70	199	94
S-DIMM/SHABAR 28 m Corrected Annual hours r0 > 12 cm	79	298	151
S-DIMM/SHABAR 38 m Corrected Annual hours r0 > 12 cm	85	382	215
S-DIMM Corrected Annual N 2-hr blocks r0 > 7 cm	36	12	10
S-DIMM/SHABAR 8 m Corrected Annual N 2-hr blocks r0 > 7 cm	28	12	12
S-DIMM/SHABAR 18 m Corrected Annual N 2-hr blocks r0 > 7 cm	42	34	29
S-DIMM/SHABAR 28 m Corrected Annual N 2-hr blocks r0 > 7 cm	48	61	40
S-DIMM/SHABAR 38 m Corrected Annual N 2-hr blocks r0 > 7 cm	49	79	53
S-DIMM Corrected Annual N 2-hr blocks r0 > 12 cm	1	1	0
S-DIMM/SHABAR 8 m Corrected Annual N 2-hr blocks r0 > 12 cm	0	1	0
S-DIMM/SHABAR 18 m Corrected Annual N 2-hr blocks r0 > 12 cm	1	2	1
S-DIMM/SHABAR 28 m Corrected Annual N 2-hr blocks r0 > 12 cm	1	8	3
S-DIMM/SHABAR 38 m Corrected Annual N 2-hr blocks r0 > 12 cm	1	13	2

Summary Table 1: Seeing results from the S-DIMM and for one of the inversion methods at heights of 8, 18, 28, and 38 m above the ground.

	Big Bear	Haleakala	La Palma
Weather			
Clear Time fraction	0.460	0.561	0.476
Corrected annual clear hours	1428	2211	2062
Wind Speed median m/s			
Sky Brightness			
Time Period Start			
Time Period End			
N days observed			
N valid measurements			
Sky brightness median, 1.e-6 extrap to 1.1 r, 1 micron			
Sky brightness median, 1.e-6 at 4 r and 890 nm			
Sky brightness median, 1.e-6 at 4 r and 530 nm			
Sky brightness median, 1.e-6 at 4 r and 450 nm			
Radial exponent median at 890 nm			
Wavelength exponent median at 4 r			
Water vapor absorption median at 950 nm			
Corrected annual hours satisfying sky brt req			
Corretced Annual N 4-hour blocks satisfying sky brt req			
0.3 Dust Median			
0.5 Dust Median			
1.0 Dust Median			
2.0 Dust Median			
5.0 Dust Mean			
N measurements			

Summary Table 2: Weather and sky brightness quantities.