Potential of the McMath-Pierce 1.6-Meter Solar Telescope for Speckle Interferometry

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Abstract We explored the aiming and tracking accuracy of the McMath-Pierce 1.6 m solar telescope at Kitt Peak National Observatory as part of an investigation of using this telescope for speckle interferometry of close visual double stars. Several slews of various lengths looked for hysteresis in the positioning system (we found none of significance) and concluded that the 1.6 m telescope would make a useful telescope for speckle interferometry.

Introduction

Atmospheric conditions play a vital role in resolving binary stars. On some nights, the sky is so turbulent that it is impossible even at mountain top locations to obtain good resolution of stars closer than an arcsecond or so using conventional imaging technology. Variations in the local temperature of the atmosphere cause changes in the index of refraction, which in turn cause differences in the starlight's wave front phase. The temperature variations are random and have the spectrum of Kolmogorov turbulence. One often characterizes the effect of turbulence with a single parameter, the Fried cell diameter, which is a measure of the coherence length of the wave front passing through the atmosphere. Wind causes these "Fried cells" to pass across the aperture of the telescope, causing scintillation and distortion of the point spread function (PSF). The effect is known as atmospheric seeing distortion (ASD).

If short integrations are taken, typically less than 30 milliseconds, the averaging effect of the wind is greatly reduced, and the captured image is then composed of "speckles." Even though distorted, the image still contains a high degree of correlated information at the resolution limit of the optics. Labeyrie (1970) first proposed the method of speckle interferometry to recover the high-resolution information in the image. In this technique, many images are taken at high speed.

The power spectrum of each image is computed by forming the modulus squared of the Fourier transform. The ensemble average of all the power spectra is then calculated, and from this averaged power spectrum, the autocorrelation is found by Fourier inversion. Since the image phase is lost in this process, the autocorrelation has inversion symmetry about its center, causing the companion star of a double to appear in two places, 180 degrees apart. This ambiguity must be resolved by other methods. In the case of close double stars, the position angle is usually approximately known in advance based on previous observations; this knowledge resolves the ambiguity. Speckle interferometry has been highly successful for imaging and measuring double stars with separations close to the theoretical resolution limit of a telescope's optics. All one needs is a high-speed camera, a telescope operating at an appropriately long focal length, and a program to perform the fast-Fourier transformation. Programs such as PlateSolve 3 (Rowe 2014) and REDUC (Losse 2015) perform this function.

Obtaining time on large-aperture telescopes (i.e. telescopes with high resolution) is problematic; most large telescopes are oversubscribed due to the needs of other observers. This motivated Genet to investigate the use of solar telescopes, such as the McMath-Pierce Solar Telescope, in hopes that while daytime use might be fully subscribed, nighttime use might be available. Thus was born the experiment described in this paper.

The McMath-Pierce as a Stellar Telescope

The McMath-Pierce Telescope was not built to serve as a stellar telescope but rather as a solar telescope for imaging and spectroscopy (see Fig. 1). During its long career it has done (and is still doing) outstanding work in this capacity. More recently, it has also been employed in stellar spectroscopy (Washuettl et al. 2009), suggesting the possibility of using this telescope for other stellar work.

The slewing and tracking requirements of this telescope for solar imaging and long exposure spectroscopy are rigorous. However, the acquisition requirements for finding the sun are not nearly as constraining as those for finding faint stars. Acquisition is especially difficult when the star's image must fall on the small CCD sensor of a high-speed camera used for speckle interferometry.

For instance, Andor Technology's Luca-R EMCCD camera's chip is just 8mm by 8mm, which, at the focal length of the 1.6 meter McMath-Pierce telescope, is 20 X 20 arcseconds. The Andor Luca-S, another EMCCD camera, would only have a field-of-view of 12 arcseconds. Our research question was: Can the 1.6 m telescope slew to targets with enough accuracy (and repeatability) to be useful as a speckle interferometry instrument?

Figure 1. The 1.6 meter heliostat.

Method

Our experimental protocol and equipment were simple and straight-forward. The crew (consisting of Richard Harshaw, Ed Wiley, Pat Boyce, and Detrick Branston) used a round white target marked with crosshairs placed at the focus of the 1.6 meter telescope north port, utilizing an experimental setup (Figure 2) already in place in the observing room. (This setup is used by Ron Oliversen of the NASA Goddard Space Flight Center, and it was used with his kind permission.) Projection of the light beam onto the reticule allowed us to visually detect stars to about 5th magnitude in a totally darkened room.

Their displacement from center was marked and measured. Knowing the image scale of the telescope (approximately 2.36 arcseconds/mm), we were able to measure the angular pointing error of bright target stars.

In each of two experiments, a bright star was taken as the reference, centered on the crosshairs via paddle control, and the telescope was initialized (encoders reset to the star's coordinates). From this reference location, we slewed the telescope to another bright star (e.g. Sirius to Procyon, Table 1) and recorded where on the target plate the star was located. This was taken as the slewing error (Table 1, Acquisition). This displacement was measured from the crosshairs using a metric straightedge and was also photographed (Figure 3). The star was then centered using the hand paddle and the telescope encoders zeroed to the star's position. Slewing north and then returning to the original coordinates yielded the North Displacement; slewing south and returning to the original coordinates yielded the South Displacement (Table 1). The second star was then returned to the center via the hand paddle controls, the telescope was reinitialized, and the telescope was slewed to the coordinates of the third star (see Tables 1 and 2). Four slews were made using Sirius as the starting point and three with Spica as the starting point. The Spica experiment was designed to see if there was an indication that a slew of two degrees yielded smaller pointing errors than the ten degree slew used for the Sirius experiment.

Figure 2. D. Branston (McMath-Pierce T.O) adjusts the target reticle for the slewing tests while P. Boyce, R. Harshaw, and E. Wiley look on.
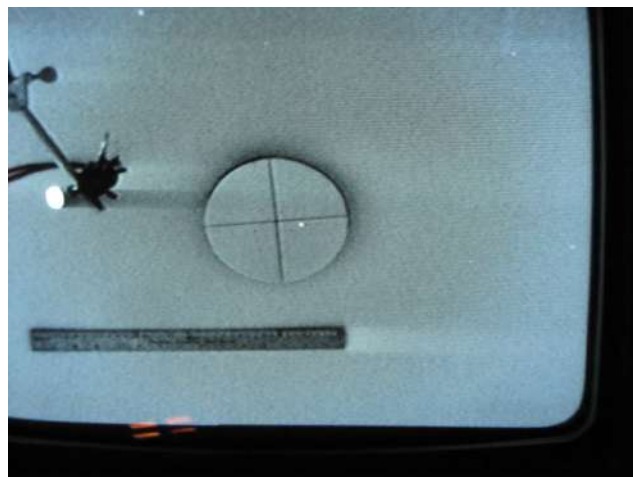

Figure 3. Sirius near the crosshair of the foam core target board.

Slew Test of the 1.6m McMath-Pierce Telescope

Run 4/15/14 3:15-5:15 UT

Star	Acquisition Error	10 deg drift	
		Slew from North	Slew from South
Sirius	n/a	not applicable; starting point reference star	
Procyon	30mm	12mm E	8mm E
Pollux	35mm	4mm E	0mm
Arcturus	60mm	2 mm *(?)*	2mm *(SE)*
Spica	22mm	2mm NW	13mm WNW

| *started 2 deg tests at Spica*		2 deg drift	
Star	Acquisition Error	Slew from North	Slew from South
Spica	n/a	4mm SE	3mm SE
Sirius	*350mm (E)*	not applicable; returned to reference star	
Pollux	*56mm (NW)*	2mm NW	3mm W
Arcturus	*45mm (SE)*	4mm S	11 mm W

Table 1. Results of experiments as a function of displacement in millimeters and slew angle.

Star	Acquisition	photo	Acquisition Aiming Error	Distance to North	10 Degree Offset				
					Slew from North	Slew Aiming Error	Distance to South	Slew from South	Slew Aiming Error
Sirius	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a
Procyon	30mm (70.8")	1	70.8"/92,525"	11° 00' 00"	28.3" E	28.3"/39,600"	11° 00' 00"	18.9" E	18.9"/39,600"
Pollux	35mm (82.6")	4	82.6"/82,245"	11° 47' 00"	9.4" E	9.4"/42,420"	10° 00' 00"	0"	0"/36,000"
Arcturus	60mm (141.6")	7	141.6"/206,855"	10° 31' 50"	4.7" ??	4.7"/5,510"	10° 05' 24"	4.7" SE	4.7"/3,924"
Spica	22mm (51.9")	10	51.9"/118,054"	10° 51' 43"	4.7" NW	4.7"/6,703"	10° 44' 33"	30.7" WNW	30.7"/ 6,273"

| *started 2 deg tests at Spica*					2 Degree Offset				
Star	Acquisition		Acquisition Aiming Error	Distance to North	Slew from North	Slew Aiming Error	Distance to South	Slew from South	Slew Aiming Error
Spica	n/a		n/a	2° 04' 42"	4mm SE (9.4")	9.4"/7,482"	2° 13' 23"	7.1" SE	7.1"/8,003"
Sirius	350mm E	A	826"/346,251"	n/a	n/a	n/a	n/a	n/a	n/a
Pollux	56mm NW	15	132.2"/169,391"	2° 13' 00"	4.7" NW	4.7"/7,980"	2° 18' 22"	7.1" W	7.1"/8,302"
Arcturus	45mm SE	18	106.2"/304,055"	1° 58' 35"	9.4" S	9.4"/7,115"	1° 55' 35"	26.0" W	26"/6,535"

Table 2. Errors in acquisition. (Interpretation of Acquisition Aiming Error: 70.8″/92,525″ signifies that the acquisition error was 70.8″ out of a total slew of 95,525″.)

Plate 1. Graphical Representation of the Data

(+ HA from meridian means the star was west of the meridian; - HA means the star was east of the meridian. The data clearly show a systemic error with the telescope's aim. However, it appears the error is proportional to the distance from the meridian, so adjustments in pointing should be possible.)
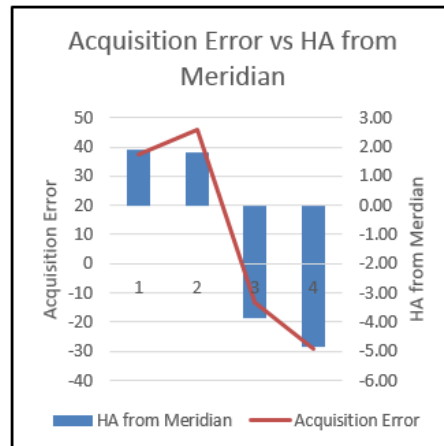
Graph 1. Acquisition Errors (arc seconds).
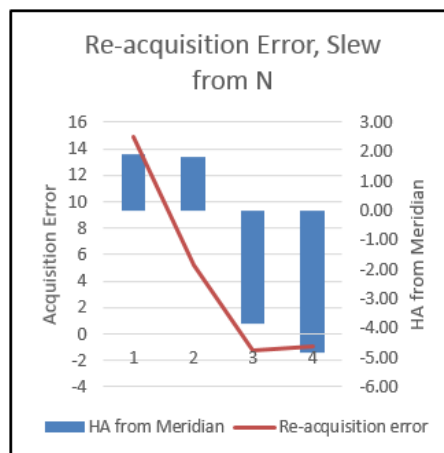
Graph 2. 10° Slewing errors, approach from the north.
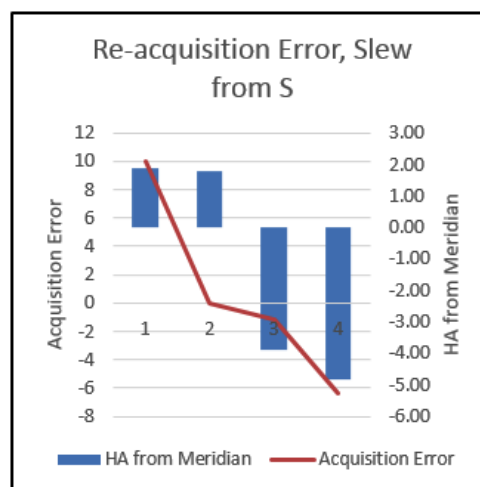
Graph 3. 10° Slewing errors, approach from the south.

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Discussion

The primary function of the 1.6 m telescope is for solar observations, which does not require exceptional pointing accuracy. Nevertheless, we were encouraged to find that the largest pointing error was approximately 30″ after a slew of 1.74^o, while the smallest error was close to zero. Additionally, our slew tests, although too small for statistical analysis, suggests that there is not much difference in accuracy between a 10° slew and a 2° slew. Slews longer than 10 degrees were not attempted at this time.

Subsequent to our experiment, we learned that a T-Point telescope pointing model had not been updated for a number of years (and is not really required for solar research). With a new model it may be possible that much of the residual pointing errors reported here could be reduced. In addition, there is a suggestion in the data (see Plate 1) that the error vector of the star is consistent with the side of the meridian on which it was observed. For acquisitions west of the meridian, in three cases the star was to the east of the crosshair and once it was to the west. For acquisitions east of the meridian, there was one case where the star was to the southeast of the crosshair and three cases of it being to the west or northwest. It is clear that these acquisition errors are virtually mirror images of each other and suggest that the error is in the pointing model of the telescope. Thus a new model may allow quick and accurate acquisition of double stars.

We are currently designing several methods to improve telescope pointing in case a new pointing model proves insufficient, or if significant hysteresis is found in the positioning system of the heliostat. A leading candidate is to place a small acquisition telescope with a CCD camera in the main tunnel, pointed at the heliostat but out of the light beam of the main telescope. A USB cable from the camera to the observation room would be used to control the camera and download images. An all-sky plate solving program, such as PlateSolve 3, would be used to find the exact pointing direction of the main telescope after appropriate initialization. From this, either an open-loop or closed loop pointing algorithm would be implemented. A second candidate would utilize a wide-angle acquisition system at the focal plane of the telescope. The location of the target star would be determined from an image of the wider field, and the telescope would be slewed to center the target in the science camera. The choice of an acquisition method would depend on the outcome of a new pointing model.

Recommendations for Future Work

A two or three night experimental observing run could accomplish several things. A new pointing model could be made, and the model tested by slewing to bright stars over a substantial portion of the sky. The vector offsets from the center of the target plate would be recorded and analyzed. (This would involve acquisition of many stellar targets and the updating of the T-Point database.)

If the RMS pointing error of the new model was less than 15 arcseconds for target stars within one hour of the meridian and appropriate declination, no further acquisition work would be necessary. If the pointing error was larger than this, but less than 30 arcseconds RMS, a square-spiral search algorithm could be implemented. If the pointing error was greater than 30 arcseconds RMS then we could install the auxiliary telescope in the main tunnel and develop a pointing model. The pointing offset between the main telescope and the auxiliary telescope would be determined by slewing a bright star to the center of the field and plate solving. We would then use open- and closed- loop algorithms to point the telescope to bright stars, recording the location of the star at the focal plane.

If this still does not yield accurate acquisition, then we could install, at the focal plane, a wide-field image acquisition camera and test the ability to move the image of a bright star to the center of the science camera using very short offset slews. After the acquisition system was set up and working, we would make a number of observations using the science camera on known, close double stars to prove the feasibility of the overall system.

In the future, to semi-automate the acquisition and imaging of double stars, it would be useful to input telescope coordinates directly without the intervention of an operator. This could be accomplished if an interface was developed between our control computer and the telescope positioning system as currently pointing commands must be manually entered via keyboard.

Conclusion

Based on the initial experiments documented in this paper, it is likely that the 1.6 meter McMath-Pierce telescope could be useful for semi-automated double star observations using high-speed, low read-noise cameras. At R-band, the resolution of this telescope should allow measurements of double stars down to approximately 0.1 arcsecond separation, opening the possibility for discovery and measurement of thousands of new and existing targets.

Acknowledgments

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