Solar Observations Using Total Stations – Phenomenal Results

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Abstract

Today's electronic total stations have all the features that make them the most desirable instruments for solar and astronomic observations. This paper describes retrofitting a Leica total station with Roelof's prism for solar observations. The observations were performed as a class project by the Surveying Engineering students at Ferris State University. The results show phenomenal agreements with those obtained by GPS. One of the most significant sources of error in solar and/or astronomic observations is the error due to dislevelment of the horizontal axis of the instrument. Using conventional instruments, this error cannot be eliminated by making face left and face right observations. This error can only be corrected by recording the left and right ends of the horizontal level vial at the time of observation. Knowing the sensitivity of the instrument's level vial this correction can be calculated and applied to the observed horizontal angle. A total station with dual-axis compensators corrects the horizontal angle for error due to the dislevelment of the horizontal axis. Furthermore, the total station's built-in timing device can further improve the time synchronization with the epoch when the sun or the star is on the cross hairs.

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I. Introduction

Azimuth determination from solar observations has been around and practiced by surveyors and navigators for centuries. While some technologies such as GPS have made azimuth determination from observing celestial bodies less common, others such as electronic theodolites with powerful onboard computers and timing devices have made solar and stellar observations more convenient and accurate. Although at this time no instrument manufacturer has an onboard solar ephemeris and reduction programs whereby the observer would point to a reference mark and the Sun/star and read the azimuth of the line instantly, the technology, however, is here now to achieve this. This paper discusses using the Leica Total Stations retrofitted with Roelof's Prism for solar observations. Observations made by several different student groups reveal very consistent results that compare very favorably with azimuths obtained from GPS.

http://maia.usno.navy.mil/search/search.html
http://www.boulder.nist.gov/timefreq/pubs/bulletin/leapsecond.htm

II. Roelof's Prism and The Leica Total Station

A Roelof's Prism is designed to fit on the objective lens of optical theodolites such as the WILD T2s enabling an observer to view the sun directly. The intersections of four images of the sun create a diamond shaped figure as shown in the figure.

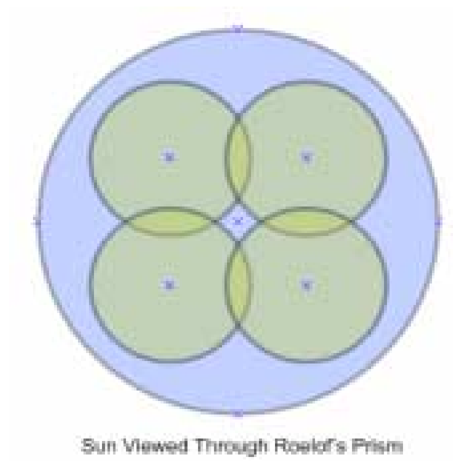
 Roelof's Prism and adapter for Leica total station	

Table 1

For direct viewing of the sun the diamond shape provides for more accurate observations of the sun's center. The only difficulty in using the Roelof's prism with a total station is that the objective lens of Leica Total Station is larger than the Roelof's prism and therefore it does not fit the total station. With the help of Mr. Rick Sauve, Leica Geosystems representative in Michigan, an adapter is made to accommodate the use of Roelof's prism with Leica total station. See Table 1.

III. Preparations For Observations

For places where the position of the observer is known within 1 second of arc in latitude (~101 feet), and 1 second of arc in longitude (~78 feet at 40^o latitude), and the time can be obtained within one second of time it is best to use azimuth by hour angle method. In the United Sates where USG quadrangle maps are available and positions can be scaled reliably, observing the sun using the hour angle method is the preferred technique. This eliminates the need for correcting the observed altitude for parallax and refraction. Table 2 shows the error in azimuth in seconds of arc resulting from an uncertainty of one second of arc in latitude for declinations (d) 23^o, 0^o, -23^o, and at ten-degree intervals of hour angle, from 0^o to 100^o.

Hour angle in degrees	**Error in azimuth resulting from 1" of arc error in latitude**			**Error in azimuth in arc sec. resulting from 1" of arc & 1^s of time errors in longitude**					
	d = 23^o	d = 0^o	d = -23^o	d = 23^o		d = 0^o		d = -23^o	
				*	**	*	**	*	**
0^o	0.0	0.0	0.0	3.1	47.2	1.6	23.3	1.0	15.5
10	1.4	0.3	0.1	2.6	38.7	1.5	22.4	1.0	15.2
20	1.7	0.5	0.2	1.7	26.0	1.3	20.0	1.0	14.5
30	1.5	0.6	0.2	1.2	17.8	1.1	17.2	0.9	13.5
40	1.3	0.6	0.2	0.9	13.4	1.0	14.7	0.8	12.4
50	1.0	0.5	0.1	0.7	10.9	0.8	12.7	0.8	11.3
60	0.8	0.4	0.1	0.6	9.6	0.8	11.3	0.7	10.3
70	0.6	0.3	0.0	0.6	8.9	0.7	10.4	0.6	9.6
80	0.4	0.1	0.1	0.6	8.7	0.7	9.8	0.6	9.0
90	0.2	0.0	0.2	0.6	8.7	0.6	9.6	0.6	8.7
100	0.1	0.1	0.4	0.6	9.0	0.7	9.8	0.6	8.7

Table 2

* This column indicates error in azimuth in arc seconds for 1 second of arc change in longitude.

** This column indicates error in azimuth in arc seconds for 1 second of time change in longitude

Prior to Leica TPS1200 total station model the record mask of the total station must be set to include: horizontal angle, time and date. The new TPS1200 series the instrument records everything and therefore no special settings are required. It is important, however, to set the system clock using NIST (National Institute of Standards and Technology) time service. Accurate time can be obtained from WWV, WWVB radio stations in Fort Collins, Colorado and WWVH radio station in Kauai, Hawaii. The broadcast information includes time announcements, standard time intervals, standard frequencies, UT1 time corrections, marine storm warnings, and Global Positioning System (GPS) status reports. The audio portions of the WWV and WWVH broadcasts can also be heard by telephone. To hear these broadcasts, dial **(303) 499-7111** for WWV (Colorado), and **(808) 335-4363** for WWVH (Hawaii). Callers are disconnected after 2 minutes. These are not toll-free numbers; callers outside the local calling area are charged for the call at regular long-distance rates. A very useful site by NIST is http://www.boulder.nist.gov/timefreq/.

The master clock pulses of the NIST's time service by WWV, WWVH, and WWVB are called UTC. The time that should be used for azimuth reduction is called UT1 (astronomical time scale). The difference between UTC and UT1 is a fraction of a second and it is referred to as DUT1 which can be obtained from the United States Naval Observatory (USNO) at http://www.boulder.nist.gov/timefreq/pubs/bulletin/leapsecond.htm address. The relationship is UT1 = UTC + DUT1. The DUT1 corrections are available from the above site on a monthly basis and from the archived data correction for any day going back to 5-19-1976 can also be queried.

IV. Observations and Reductions

Table 3 contains 12 sets of observations where a set consists of one pointing direct and one reverse making a total of 24 pointings made by three different students. Leica TPS 1100 series total station was used for the observations where the total station onboard clock was set in the classroom before the observations began. The current time via internet can be obtained from http://nist.time.gov/timezone.cgi?Eastern/d/-5/java site. If the animated clock cannot seen clicking the "Disable Java Animation" at the bottom right hand corner of the dialog box will enable a static clock to appear or the current version of Java can be downloaded from Sun Microsystems site http://www.java.com/en/download/installed.jsp. The average of the reduced azimuth of the line is 259^{o} 18' 22" and compares favorably with the azimuth obtained from GPS observations with the difference of 15 seconds of arc. It is important to note that the observations were made approximately one hour before the apparent noon which according to Table 2, a one second of time uncertainty in time could cause an error of roughly 15 seconds of arc in azimuth. Much better results could have been obtained by observing earlier in the day or later in the day.

	Solar Observation Data and Reduction from point 1 to 2									
Date of observation: Novemver 13, 2002										
GHA @ 0 hour UT:		183.56513		Declination @ 0 hour UT			-17.51221			
GHA @ 24 hour UT:		183.54455		Declination @ 24 hour UT			-18.0717			
Latitude of station:		43.41085	(ddd.mmss)			DUT1:	-0.28	seconds		
Longitude of station:		-85.28375	(ddd.mmss)							
BS	SUN	Time	UTC	UT1	LHA	declination	Az. of sun	Az of Line	Az of Line	
ddd.mmss	ddd.mmss	hh.mmss	hh.mmss	in hours	in degrees	in degrees	in degrees	in degrees	ddd.mmss	
137.3037	37.0602	11.0620	16.0620	16.1055	340.0292	-18.0341	158.88874	259.29846	259.1754	OK
317.3046	217.2017	11.0717	16.0717	16.1213	340.2667	-18.0343	159.12982	259.30454	259.1816	OK
137.3039	37.5420	11.0930	16.0930	16.1583	340.8208	-18.0347	159.69363	259.29891	259.1756	OK
317.3041	218.2444	11.1128	16.1128	16.1910	341.3124	-18.0351	160.19535	259.29451	259.1740	OK
137.3038	39.0335	11.1402	16.1402	16.2338	341.9540	-18.0356	160.85220	259.30303	259.1811	OK
317.3046	219.2647	11.1533	16.1533	16.2591	342.3332	-18.0358	161.24142	259.30781	259.1828	OK
137.3034	40.0350	11.1755	16.1755	16.2985	342.9248	-18.0363	161.85035	259.29590	259.1745	OK
317.3035	220.1635	11.1846	16.1846	16.3127	343.1372	-18.0364	162.06950	259.30284	259.1810	OK
137.3028	40.5736	11.2126	16.2126	16.3571	343.8038	-18.0369	162.75860	259.30638	259.1823	OK
317.3035	221.0929	11.2210	16.2210	16.3694	343.9872	-18.0371	162.94851	259.30017	259.1801	OK
137.3032	41.4355	11.2426	16.2426	16.4071	344.5538	-18.0375	163.53656	259.31350	259.1849	OK
317.3035	221.5710	11.2518	16.2518	16.4216	344.7704	-18.0376	163.76183	259.31877	259.1908	OK
137.3044	42.2820	11.2717	16.2717	16.4546	345.2662	-18.0380	164.27820	259.31820	259.1906	OK
317.3042	222.3933	11.2800	16.2800	16.4666	345.4453	-18.0381	164.46508	259.31758	259.1903	OK
137.3020	43.2628	11.3100	16.3100	16.5166	346.1953	-18.0387	165.24899	259.31344	259.1848	OK
317.3040	223.4952	11.3228	16.3228	16.5410	346.5619	-18.0390	165.63317	259.31317	259.1847	OK
137.3035	44.2617	11.3448	16.3448	16.5799	347.1452	-18.0394	166.24558	259.31725	259.1902	OK
317.3025	224.3603	11.3523	16.3523	16.5896	347.2910	-18.0395	166.39892	259.30503	259.1818	OK
137.3029	45.0329	11.3707	16.3707	16.6185	347.7243	-18.0398	166.85506	259.30506	259.1818	OK
317.3030	225.1340	11.3745	16.3745	16.6291	347.8826	-18.0399	167.02192	259.30247	259.1809	OK
137.3034	45.3304	11.3900	16.3900	16.6499	348.1951	-18.0402	167.35154	259.30987	259.1836	OK
317.3015	225.4033	11.3927	16.3927	16.6574	348.3076	-18.0402	167.47030	259.29863	259.1755	OK
137.3032	46.0412	11.4057	16.4057	16.6824	348.6825	-18.0405	167.86652	259.30541	259.1819	OK
317.3015	226.0959	11.4118	16.4118	16.6883	348.7700	-18.0406	167.95905	259.29683	259.1749	OK
						Mean azimuth:		259.30616	259.1822	
						Standard deviation:		0.007525	0.00271	
		Azimuth obtained from GPS (No corrections for deflection of the vertical):							259.1807	
		Difference between GPS derived azimuth and solar observations:							0.0015	

Table 3

The second point to note is that the students conducting the observations are second year students with the first time experience doing solar observations, yet of the 12 sets observed none were rejected using ±two standard deviations from the mean. The students experience level can be seen in the observations where back sight direct and reverse readings vary by as much as 31 seconds. Furthermore, the length of line 1 to 2 is 108 meters. Another very important consideration is the fact that the instrument recorded time to nearest second plays a major role when observations are made close to apparent noon as is in this case. In short, with proper precautions observation standard deviation can easily be less than 10 seconds of arc.

V. Conclusion

The use of electronic total stations for solar and stellar observations provides the following benefits:

- The instrument's dual axes compensators are extremely useful in minimizing the error due to the dislevelment of the horizontal axis. This is a significant contaminant for solar and stellar observations where the back sight point and the foresight point (sun or stars) are at different altitudes.
- The synchronization of recording the observation epoch with instrument's onboard clock provides a much more accurate time of observations.
- The total station's ability to automatically record the observations further reduces the chance of misreading the instrument and misreporting the observations.

Further considerations include:

- Observations should be made early in the day or later in day, a minimum of three hours prior to or after the apparent noon if at all possible.
- Check the instrument clock after the observations are made to insure there is no clock drift. A reasonable clock drift can be prorated to correct the recorded times.
- Use the hour angle method to reduce the observations when all possible.
- Select a back sight no less than 250 feet and use a fixed target.
- Observe several sets, not just one or two. More observations provide better analysis and better results and with a total station it does not take much longer to observe eight or ten sets as opposed to two or three.
- Apply the DUT1 (Leap second correction) to the UTC.

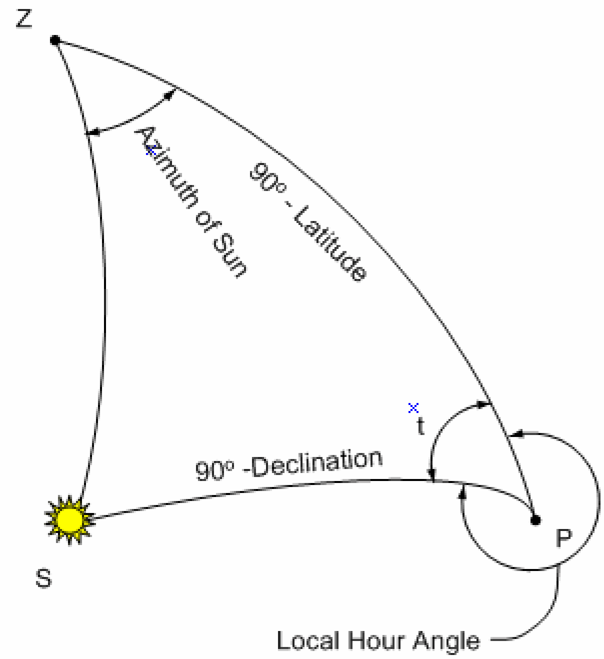
References

National Institute of Science and Technology, Feb. 6, 2005
http://www.boulder.nist.gov/timefreq/

Appendix

Solar Azimuth Reduction Using Hour Angle Method

The PZS spherical triangle shown in Figure 2, depicts the pole (P), point of observation (Z), and the sun (S). Any three elements of a spherical triangle must be known in order to find the any of the remaining elements. In this case, the three known elements of the spherical triangle are:



1. Side PZ which is equal to 90°-latitude (ϕ) of the station.
2. Side PS which is to 90°-declination (δ) of the sun. Declination of the sun for the time of observation is interpolated from a solar ephemeris.
3. Local hour angle of the sun is the angle at the pole from the observer's meridian clockwise to the hour circle of the sun. It is calculated from the observed time, tabulated Greenwich of the sun and the longitude of the observation station.

Knowing the above three elements of the PZS spherical triangle, the azimuth of the sun at Z can be computed from the following equation:

$$Z = ArcTan\left[\frac{Sin(t)}{Cos(\varphi)\cdot Tan(\delta) - Sin(\varphi)\cdot Cos(t)}\right]$$

Where, "t" is the interior angle of the spherical triangle at P.

Reduction Procedures

Latitude of station: 43° 41’ 08.”5 N	**Longitude of station:** 85° 28’ 37”.5 W

Back sight	**Sun**	**Time**
137° 30’ 37”	37° 06’ 02”	$11^h\ 06^m\ 20^s$ Eastern Standard Time

Step #	**Explanation of Calculations**	**Calculations**
1	UTC (Coordinated Universal Time) of Observation	$11^h\ 06^m\ 20^s + 5^h$ **$16^h\ 06^m\ 20^s$**
2	UT1 = UTC + DUT1 The DUT1 correction can be obtained from: http://www.boulder.nist.gov/timefreq/pubs/bulletin/leapsecond.htm	$-0^s.27$ **$16^h\ 06^m\ 19^s.73$**
3	G.H.A. @ 0^h UT, From Ephemeris, on 11/13/2002	183° 56’51”.3
4	G.H.A. @ 24^h UT, From Ephemeris, on 11/14/2002	183° 54’ 45”.5
5	Change in G.H.A. since 0^h UT = $\frac{UT1^h}{24}(GHA@24^h - GHA@0^h + 360)$	241° 33’ 31”.38
6	G.H.A. @ Time of Observation = G.H.A @ 0^h + Change = Step 3 + Step 5	425° 30’ 22”.68
7	+ West Longitude of station	+ (-85° 28’ 37”.5)
8	Local Hour Angle of The Sun = Step 6 + Step 7 Subtract 360 if LHA > 360 or add 360 if LHA is negative	340° 01’ 45”
9	The angle of the spherical triangle “t” is = 360° - LHA, Sun is East of North. If LHA < 180° , t = LHA, Sun is West of North	**19° 58’ 15”**
10	Declination of Sun @ 0^h UT “δ_0” on 11/13/2002 From Ephemeris	-17° 51’ 22”.1
11	Declination of Sun @ 24^h UT “δ_{24}” on 11/14/2002 From Ephemeris,	-18° 07’ 17”.0
12	Declination at the time observation $\delta = \delta_0 + \frac{UT1}{24}(\delta_{24} - \delta_0)$	**-18° 02’ 02”.8**
13	$Z = ArcTan\left[\frac{Sin(t)}{Cos(\varphi)\cdot Tan(\delta) - Sin(\varphi)\cdot Cos(t)}\right]$ The azimuth of Sun from North	**-21° 06’ 41”** **158° 53’ 19”**
14	Horizontal angle = Fore sight – Back sight	259° 35’ 25”
15	Azimuth of Line “1” to “2” = 180° – Z - Horizontal angle	**259° 17’ 54”**