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Aerodynamics Experimental Facility Upgrade: Downrange Distance Measurements

by Joseph Haire and Ilmars Celmins

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14. ABSTRACT
The Aerodynamics Experimental Facility (AEF) is a spark shadowgraph range located at Aberdeen Proving Ground, Maryland, used to determine aerodynamic coefficients of projectiles in free flight. To accurately extract the coefficients, precise knowledge of the projectile’s 6-degrees of freedom coordinates as it travels downrange is required. These coordinates are obtained by taking orthogonal photos of the projectile in free flight at numerous stations along the length of the range. A fiducial notch is located at each range station and is used as a reference for the projectile position in each photo. At the time of publication, the AEF range is undergoing an upgrade from analog to digital hardware. After the installation of the new hardware, the downrange position of the fiducial notches must be surveyed to provide position inputs for the aero data reduction software. This report discusses the procedure used to determine the downrange location (Z direction) of each station’s fiducial notch relative to the first station’s notch. The notch locations were measurable with an uncertainty of less than 0.04 inch (1 mm).

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Weapons Sciences, Aerodynamics Experimental Facility, AEF, measurement, fiducial, coordinates, rangefinder, survey

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1. Introduction and Background

The US Army Combat Capabilities Development Command (DEVCOM) Army Research Laboratory (ARL) Aerodynamics Experimental Facility (AEF) is a spark shadowgraph range located in Aberdeen Proving Ground, Maryland (Schmidt 1983). This range is used to study in high fidelity the flight dynamics and fundamental flow phenomena of projectiles in free flight. To accurately characterize a projectile's flight dynamics, precise knowledge of the projectile's 6-degrees of freedom (6-DoF) position and orientation as it travels downrange is required. These are obtained by taking orthogonal photos of the projectile in free flight at 39 stations along the length of the range (Will 2017). A fiducial notch is located at each range station and is used as a reference to calibrate projectile position in each photo.

Prior to 2024, the photographs were taken with physical wet film through direct exposure. Large pieces of 11- × 14-inch film were placed on the horizontal and vertical station surfaces and the range was kept in total darkness to prevent light saturation of the film (Braun 1958). Each range station featured an optical break screen that would produce a voltage transient as the projectile passed through, triggering a spark source. The spark source would then directly expose the vertical piece of film and would indirectly expose the horizontal piece of film via reflection off a mirror. Each piece of film fit under the edge of the fiducial bar by 1/8 inch, allowing the film to capture the location of the fiducial notches. The shadow of the projectile was also captured on both the horizontal and vertical pieces of film, allowing the position of the projectile relative to the fiducial notches to be measured.

In 2024, the AEF range was upgraded to use digital image capture and data reduction. Blank white backdrops replaced the film plates and digital cameras were implemented to take photographs. The spark sources were also updated to allow for a shorter pulse duration and to eliminate large obsolete high-voltage power supplies.

The AEF range stations are nominally spaced 5 ft apart with larger gaps between groups. The first two groups have secondary stations that are spaced 2 ft from primary stations. The precise spacing between station fiducial notches (Z direction) must be known to generate an accurate reduction of a projectile's trajectory.

This report discusses the procedure used to determine the downrange location (Z direction) of each station's fiducial notch relative to the first station's notch. Figure 1 shows the nominal spacing of stations, while Fig. 2 shows a station with its local coordinate system.

Nominal Station Locations (feet)					
Group:	1	2	3	4	5
	15	75	150	210	280
	20	80	152	215	285
	22	85	155	220	290
	25	87	157	225	295
	27	90	160	230	300
	30	92	162		
	32	95	165		
	35	97	170		
	37				
	40				
	42				
	45				
	47				

Fig. 1 **AEF range station nominal locations**

Fig. 2 **AEF range station coordinate system**

2. Procedure

To determine the precise downrange (Z-direction) distances of each station in the AEF range, three methods were considered. The first was a 100-ft tape measure. The second was a simple handheld laser rangefinder mounted to a camera tripod. The third was a more complicated laser survey device.

To explore the validity of the proposed measurement devices, several stations (15, 37, 47, 75, and 95) within the first two groups were measured and compared to historical data from 1968. Since the laser rangefinder and laser survey device functioned similarly, the laser survey device was omitted from this preliminary observation. Two models of rangefinders (Leica DISTO E7500i and Leica DISTO A8) were used for comparison. We found that both rangefinders produced values within 0.090 inch of the historical values independent of downrange distance, while the tape measure deviated from the historical values by more than 0.250 inch. We believe that the sag in the tape measure could not be sufficiently reduced to allow for accurate measurements over large distances. Based on these findings, we used the Leica DISTO E7500i and the laser survey device (Sokkia FX103) to measure the downrange distances of all 39 AEF range stations. The Leica uses a visible red laser to aim, while the Sokkia uses an infrared laser and portable targeting computer to aim. Specifications for the measurement equipment are included in Appendix A.

When measuring each of the AEF range stations, the laser rangefinder and laser survey device were positioned on tripods at the opening of the AEF range (Fig. 3). A white paper target was attached to a fixture that mated with each station's fiducial notch, allowing relative distances between fiducial notches to be measured. White paper was found to be an effective target material, while reflective targets overload the rangefinder sensor and dark targets are insufficiently emissive.

At the outset of measuring, the target was placed at the farthest station (300) and the measurement devices were aimed at the target, establishing a shot line through the range. The position of the measurement devices was not adjusted after this alignment. We found that at station 300, the spot size of the Leica diverged to an approximately 2.5-inch diameter (Fig. 4).

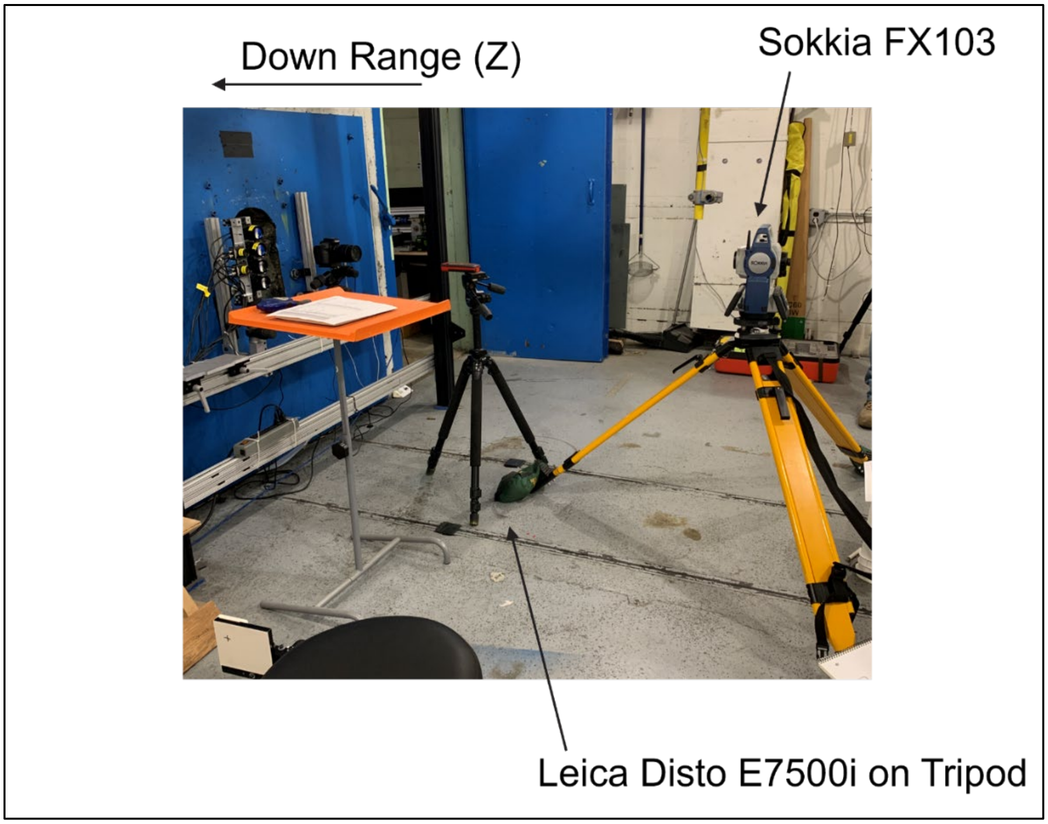

Fig. 3 Leica rangefinder and Sokkia laser survey device setup

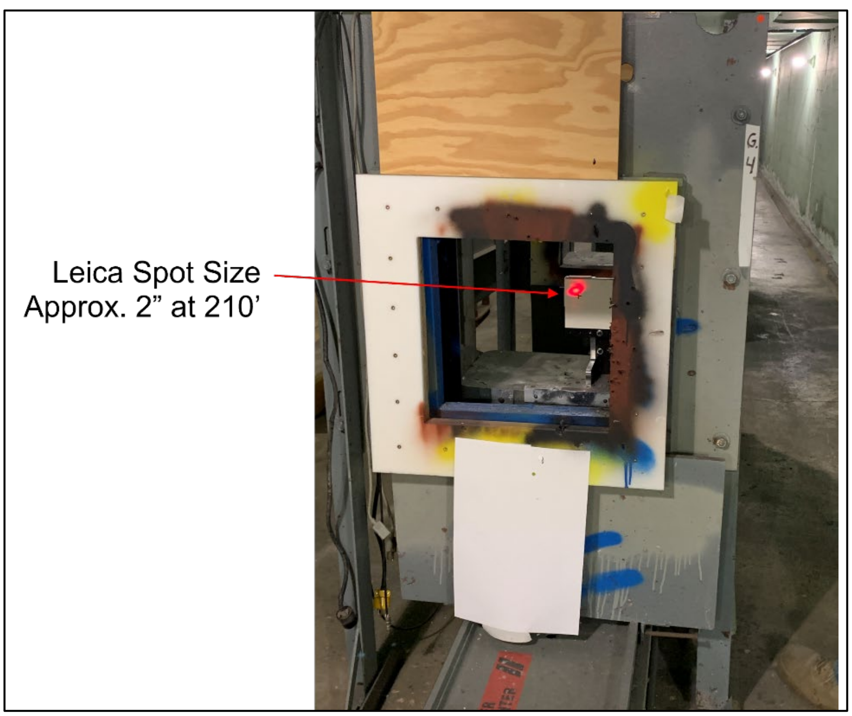

Fig. 4 Laser survey target

With the shot line established, we placed the target at the closest station (15) and recorded the distances between the measurement devices and the target. We then moved the target to the next station (20) and again recorded the distances between the measurement devices and the target. We repeated this process until every station had been measured.

3. Results

After measuring the downrange distance to each of the stations with the Leica E7500i and Sokkia FX103, we compared the measurements of the two devices to each other and to the historical measurements from 1968. We found that the two devices agreed well with each other and with the historical measurements. Both the Leica and the Sokkia deviated from the historical measurements by 0.039 inch on average when excluding stations 285–300 from the Sokkia measurements. The Sokkia showed significant deviations from historical measurements (±0.25) at these stations while the Leica did not, so these points were considered outliers. This deviation may have been caused by overspill or underspill of the laser spot or by disruption of the tripod position. Three stations (152, 165, and 300) deviated from the historical measurements by more than 1/8 inch, so they were marked for adjustment. Also, station 152 deviated from its nominal position by approximately 2 inches. This is because the mounts that hold station 152 to the support channel interfered with the support rail anchors at the nominal position. All measurements are included in Appendix B.

4. Conclusion

After measuring the downrange distances of the AEF stations with two independent laser measurement devices, we determined that the AEF stations had not moved significantly since 1968. Also, since the Leica showed better accuracy than the Sokkia at range and was easier to operate, we concluded that the station positions could be rapidly and accurately measured with simple handheld equipment (Leica E7500i) on a tripod. This experiment gave us confidence that we could measure the downrange positions of the AEF stations after completion of the spark range upgrade with ±1/32-inch precision, reducing the need for station bias offsets.

5. References

Braun WF. The free flight aerodynamics range. Army Ballistic Research Laboratory (US); 1958 Dec. Report No.: 1048.

Schmidt E. The aerodynamics range: a national historic mechanical engineering landmark. Army Ballistic Research Laboratory (US); 1983. Report No.: ARBRL-SP-00028.

Will E. Analysis of survey systems and data reduction for spark shadowgraph ranges. DEVCOM Army Research Laboratory (US); 2017 Aug. Unpublished Summer Research Technical Report.

Appendix A. Measurement Device Specifications

Leica Geosystems

E7500i Technical Data – US Standard

Range	0.2” up to 656’
Accuracy	±0.04”
Measuring units	m, ft, in, decimal, fractions
Smallest unit displayed	0.04”
X-Range Power Technology	Yes
Angle measurements using tilt sensor	360º
Tilt sensor	Yes
Tilt sensor accuracy to the laser beam	± 0.2°
Tilt sensor accuracy to the housing	± 0.2°
Units in the tilt sensor	0.0º, 0.00%, mm/m, in/ft
Laser class	2
Laser type	635nm, <1mW
IP class	IP 65
Pointfinder with zoom	4 x
Pointfinder contrast adjustment	Yes
Memory	For last 30 measurements
Display illumination	Yes
Free software for Windows	Yes

Fig. A-1 Leica DISTO E7500i data sheet
(Source: https://shop.leica-geosystems.com/measurement-tools/disto/leica-disto-e7500i/buy)

MODEL		FX-101	FX-102	FX-103	FX-105
Telescope					
Magnification / Resolving power		30x / 2.5"			
Length		171 mm			
Objective aperture		45 mm (48 mm for EDM)			
Image		Erect			
Field of view		1°30' (26 m/1,000 m)			
Minimum focus		1.3 m			
Reticle illumination		5 brightness levels			
Angle Measurement					
Display Resolution		0.5" / 1"	1" / 5"		
Accuracy (ISO 17123-3:2001)		1"	2"	3"	5"
Dual-axis compensator / Collimation compensation		Dual-axis liquid tilt sensor, working range: ±6' (±111 mgon) / Collimation compensation available			
Distance Measurement					
Laser output[*1]		Reflectorless mode: Class 3R / Prism / sheet mode: Class 1			
Measuring range (under average conditions[*2])	Reflectorless[*3]	Reflectorless[*3] 0.3 to 500 m			
	Reflective sheet[*4/*5]	RS90N-K: 1.3 to 500 m, RS50N-K: 1.3 to 300 m, RS10N-K: 1.3 to 100 m			
	Mini prisms	CP01: 1.3 to 2,500 m, OR1PA: 1.3 to 500 m			
	One AP prism	1.3 to 4,000 m/ Under good conditions[*6]: 5,000 m			
	Three AP prisms	to 5,000 m / Under good conditions[*6]: to 6,000 m			
Display Resolution		Fine/Rapid: 0.001 m / 0.01 ft. / 1/8 in. Tracking: 0.01 m / 0.1 ft. / 1/2 in.			
Accuracy[*2] (ISO 17123-4:2001) (D=measuring distance in mm)	Reflectorless[*3]	(3 + 2 ppm x D) mm[*7]			
	Reflective sheet[*4]	(3 + 2 ppm x D) mm			
	AP/CP prism	(2 + 2 ppm x D) mm			
Measuring time[*8]		Fine: 0.9s (initial 1.7 s), Rapid: 0.7 s (initial 1.4 s), Tracking: 0.3 s (initial 1.4 s)			
OS, Interface and Data management					
Operating System / Application		Microsoft Windows® CE 6.0 / MAGNET® Field			
Display / Keyboard		3.5 in., Semi-transmissive TFT QVGA color LCD with LED backlight, Touch screen, Automatic brightness control / 26 keys with backlight			
Control panel location*9		Dual Display (Face 2 is only touch screen display)			Single with control panel
Data storage	Internal memory	500MB internal memory (includes memory for program files)			
	Plug-in memory device	USB flash memory (max. 8GB)			
Interface		Serial RS-232C, USB 2.0 (Type A / mini B)			
Bluetooth® modem (optional)[*10]		Bluetooth® Class 1, Ver.2.1+EDR, Operating range: up to 300 m[*11]			
General					
Laser-pointer[*12]		Coaxial red laser using EDM beam			
Guide light[*12]		Green LED (524 nm) and Red LED (626 nm), Operating range: 1.3 to 150 m[*2]			
Levels	Graphic	6' (Inner Circle)			
	Circular level	10' / 2 mm			
Optical plummet		Magnification: 3x, Minimum focus: 0.3 m from tribrach bottom			
Laser plummet (optional)		Red laser diode (635 nm ±10 nm), Beam accuracy: ≤1.0 mm at 1.3 m, Class 2 laser product			
Dust/Water Rating		IP65 (IEC 60529:2001)			
Operating Temperature[*13]		-20 to +50°C			
Size with handle[*9] (w x d x h)		Control panel on both faces: 191 x 190 x 348 mm Control panel on one face: 191 x 174 x 348 mm			
Weight with battery and tribrach		Approx. 5.7 kg			

Fig. A-2 Sokkia FX series data sheet
(Source: https://geonetworking.com/sokkia-fx-103-3-second-reflectorless-total-station.html)

Appendix B. Downrange Measurement Data

	1968-08	2023-05			2023-05			
Station	Measured	**Sokkia FX103 [ft]**	Shifted to Station 20 [ft]	δ From Historical [in]	**Leica Disto E7500i [ft]**	Shifted to Station 20 [ft]	δ From Historical [in]	δ From Nominal [in]
15	14.9924	14.9114	14.9933	-0.0103	6.8409	14.9938	-0.0164	0.0748
20	20.0000	19.9182	20.0000	0.0000	11.8471	20.0000	0.0000	0.0000
22	22.0000	21.9163	21.9981	0.0223	13.8451	21.9980	0.0236	0.0236
25	24.9956	24.9151	24.9969	-0.0159	16.8409	24.9938	0.0220	0.0748
27	26.9893	26.9033	26.9851	0.0502	18.8327	26.9856	0.0448	0.1732
30	29.9968	29.9184	30.0003	-0.0417	21.8448	29.9977	-0.0108	0.0276
32	32.0403	31.9625	32.0443	-0.0482	23.8865	32.0394	0.0112	-0.4724
35	35.0008	34.9218	35.0036	-0.0338	26.8468	34.9997	0.0135	0.0039
37	36.9970	36.9165	36.9984	-0.0167	28.8435	36.9964	0.0073	0.0433
40	39.9875	39.9054	39.9872	0.0033	31.8386	39.9915	-0.0476	0.1024
42	41.9774	41.9035	41.9853	-0.0949	33.8317	41.9846	-0.0862	0.1850
45	44.9774	44.8990	44.9808	-0.0408	36.8284	44.9813	-0.0468	0.2244
47	46.9804	46.8970	46.9788	0.0189	38.8278	46.9806	-0.0029	0.2323
75	74.9889	74.9055	74.9874	0.0181	66.8333	74.9862	0.0322	0.1654
80	80.0079	79.9252	80.0071	0.0098	71.8533	80.0062	0.0200	-0.0748
85	85.0095	84.9351	85.0169	-0.0891	76.8602	85.0131	-0.0435	-0.1575
87	86.9993	86.9233	87.0051	-0.0698	78.8514	87.0043	-0.0596	-0.0512
90	90.0070	89.9285	90.0104	-0.0404	81.8543	90.0072	-0.0026	-0.0866
92	92.0117	91.9265	92.0084	0.0397	83.8530	92.0059	0.0695	-0.0709
95	94.9999	94.9220	95.0038	-0.0469	86.8471	95.0000	-0.0012	0.0000
97	97.0066	96.9266	97.0084	-0.0216	88.8533	97.0062	0.0044	-0.0748
150	149.9978	149.9154	149.9972	0.0066	141.8428	149.9957	0.0248	0.0512
152	151.8452	151.7461	151.8280	0.2069	143.6742	151.8271	0.2172	2.0748
155	154.9913	154.9088	154.9907	0.0074	146.8369	154.9898	0.0176	0.1220
157	157.0015	156.9167	156.9986	0.0353	148.8448	156.9977	0.0456	0.0276
160	159.9930	159.9121	159.9940	-0.0116	151.8419	159.9948	-0.0210	0.0630
162	161.9916	161.9102	161.9920	-0.0048	153.8376	161.9905	0.0134	0.1142
165	164.9811	164.9088	164.9907	-0.1150	156.8376	164.9905	-0.1126	0.1142
170	169.9760	169.8957	169.9776	-0.0187	161.8235	169.9764	-0.0045	0.2835
210	209.9700	209.8859	209.9677	0.0272	201.8153	209.9682	0.0219	0.3819
215	214.9826	214.8990	214.9809	0.0209	206.8248	214.9777	0.0589	0.2677
220	219.9852	219.8990	219.9809	0.0521	211.8284	219.9813	0.0468	0.2244
225	224.9899	224.9023	224.9841	0.0691	216.8356	224.9885	0.0166	0.1378
230	229.9910	229.9089	229.9907	0.0036	221.8369	229.9898	0.0140	0.1220
280	280.0218	279.9449	280.0268	-0.0599	271.8760	280.0289	-0.0849	-0.3465
285	285.0140	284.9089	284.9907	0.2796	276.8678	285.0207	-0.0800	-0.2480
290	290.0122	289.9089	289.9907	0.2580	281.8576	290.0105	0.0204	-0.1260
295	295.0071	294.9351	295.0169	-0.1182	286.8507	295.0036	0.0419	-0.0433
300	299.9990	299.9384	300.0202	-0.2547	291.8560	300.0089	-0.1183	-0.1063
			avg deviation from historical [in]	0.0392		avg deviation from historical [in]	0.0391	0.1839
			avg deviation from historical [mm]	0.9953		avg deviation from historical [mm]	0.9943	4.6718