NATIONAL TRANSPORTATION SAFETY BOARD
Vehicle Recorder Division

July 28, 2020

Sound Spectrum Study

Specialist's Study Report
By Christopher Babcock

1. EVENT

Location:	Fort Lauderdale, Florida
Date:	March 1, 2019
Aircraft:	Piper PA-25-235, N145AB
Operator:	Aerial Banners North, Inc
NTSB Number:	ERA19FA112

2. GROUP

No group was formed.

3. ACCIDENT DESCRIPTION

On March 1, 2019, about 1141 eastern standard time (EST), a Piper PA-25-235, N145AB, was destroyed when impacted a condominium while maneuvering in Fort Lauderdale, Florida. The commercial pilot was fatally injured. The airplane was operated by Aerial Banners North, Inc., under the provisions of Title 14 *Code of Federal Regulations* Part 91 as a local banner tow flight. Visual meteorological conditions prevailed at the time and no flight plan was filed for the flight that originated from North Perry Airport (HWO), Hollywood, Florida, about 1043. Witness video and audio of a portion just prior to the accident was forwarded to the NTSB Vehicle Recorder Division for evaluation and a sound spectrum study was performed to determine engine operating RPM prior to the accident.

4. DETAILS OF INVESTIGATION

4.1. Accident Airplane

The accident airplane was a Piper PA-25. The airplane was equipped a single Lycoming O-540-B2B5-C-A1D5 reciprocating engine, equipped with a 2-bladed fixed-pitch propeller.

4.2. Witness Video

A witness captured video and audio with a body-mounted GoPro camera as she was walking south on the beach at 26.1665° North Latitude and 80.0981° West Longitude. Figure 1 indicates her position on the beach at the time of the accident. The video segment was 46 seconds long and began just prior to the time the aircraft crossed over the beach flying westbound and ends shortly after the accident.

4.3. Aircraft Position Data

The aircraft was equipped with a flight tracking system installed by the operator. The system captured GPS position and transmitted it to a ground station every 5 seconds. The last position reported corresponds to the accident location and was used to approximate the time of impact. Figure 1 shows the aircraft's flight path just prior to the accident. While radar data was available, the GPS data provided the best information about the time of the accident and the flight path just prior to the accident. Altitude information was not recorded by this system.

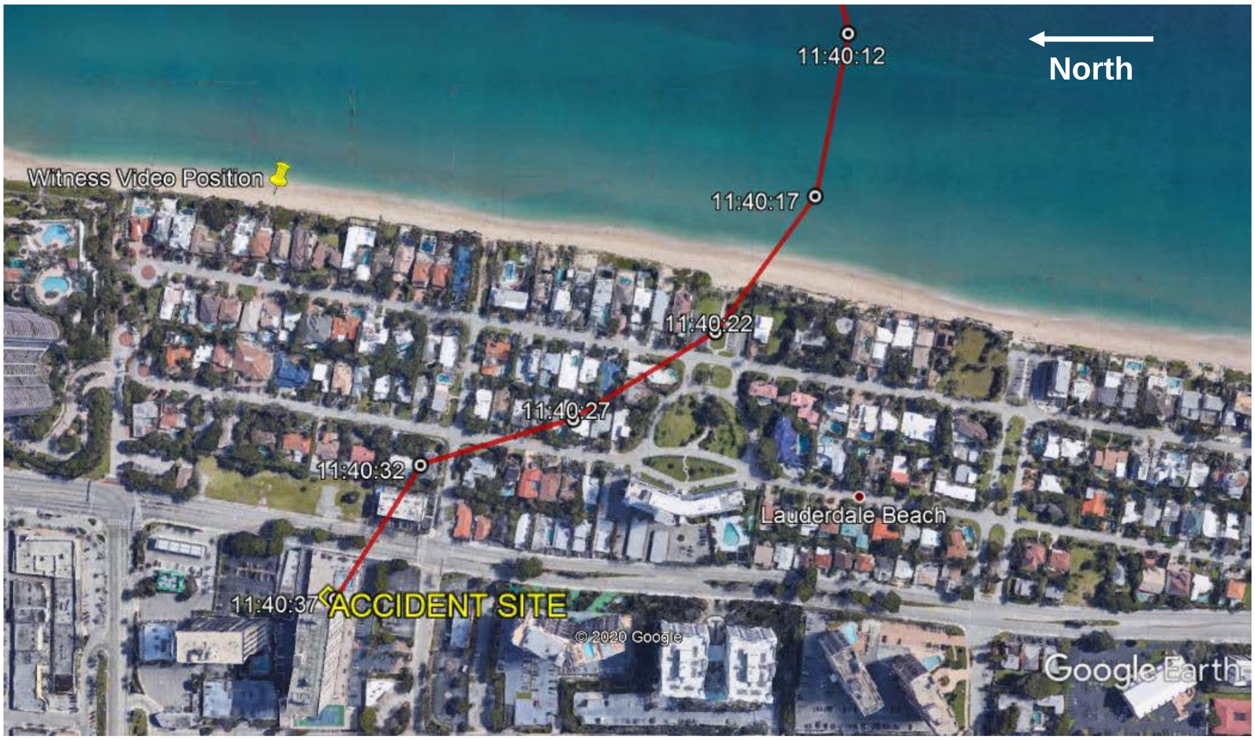

Figure 1. Aircraft flight path and location of witness video.

4.4. Time Correlation of Video and Flight Path Data

Because the video was not recorded with reference to any time base a time correlation was performed. The transmitted GPS data indicated that the aircraft impacted the building at 11:40:37 EST. While the actual aircraft impact with the building was not visible, a sound consistent with impact was audible, followed by the witness exclaiming, "oh my God." The sound of impact occurred at 22.0 seconds video elapsed time.

Equation 1 approximates the speed of sound in feet per second in still air, where γ is the specific heat ratio for air (1.4), R is the molar gas constant for air (1716 $\frac{ft*lbf}{slug*°R}$), and T is the Fahrenheit temperature. Using the 27° Celsius (80.6° F) reported temperature, the speed of sound at the time of the accident was about 1139.2 feet per second (Equation 1).

$$c = \sqrt{\gamma R(T + 459.67)} \quad (1)$$

The witness was approximately 1022 feet away from the point of impact at a bearing of 81°. The reported wind was out of 110° at 8 knots (13.5 feet per second). Taking the wind speed and direction into account, the effective speed of sound between the accident site and the witness was 1126 feet per second. The sound of the impact would have taken 0.9 seconds to reach the witness. The actual impact sound in the video occurred at 21.1 seconds elapsed time and the video began at 11:40:15.9 EST.

4.5. Doppler Effect

Because the source of engine sound is moving with respect to the witness, the Doppler Effect must be quantified. The Doppler Effect states that, for a source with constant emitted frequency, the measured frequency is higher than the emitted frequency as the source approaches, identical as the source passes, and lower as the source moves away. For a stationary receiver the Doppler Effect is:

$$f_S = \frac{c - v_S \cos\theta}{c} f_O \tag{2}$$

where f_O is the observed frequency, f_S is the source frequency, c is the speed of sound, v_S is the magnitude of the source velocity, and θ is the angle between the source velocity vector and the line of sight vector from the source to the sensor. To solve for the source frequency, the flightpath and velocity along the flightpath must be known.

4.6. Flightpath Derivation

Using the GPS data, a flightpath was interpolated in half second intervals. The interpolated flight path points and the witness location were transformed from latitude and longitude to nautical miles west and north of a datum point. The datum used for this study was the witness location. The results of the flightpath derivation can be found in Table A-1 in Appendix A.

4.7. Observed Frequency Determination

For each point in the interpolated flightpath, the time delay for the sound emitted at that point to reach the witness was calculated using Equation 3. The results of this calculation can be found in Tables A-2 in Appendix A.

$$EmittedTime + \frac{Distnce}{c} = RceivedTime \tag{3}$$

A sound spectrum study was performed to determine the observed engine frequencies recorded at the witness location. An aircraft piston engine generates tones at several different frequencies. The more prominent tones occur at the blade passage frequency, engine exhaust timing frequency, and harmonics of those frequencies. For this airplane equipped with a two-bladed propeller, the blade passage frequency would be twice the shaft frequency, and the six-cylinder, four-stroke engine exhaust timing would produce tones at three times the fundamental shaft frequency. Harmonic tones will also appear at multiples of these frequencies. At each calculated *RceivedTime*, the sound spectrum was evaluated to determine the observed frequencies of the engine sounds. Three-dimensional spectrogram and two-dimensional spectrum plots were used to identify the fundamental engine shaft speed.

A spectrogram is a 3-D plot displaying time on the x-axis, frequency on the y-axis, and sound intensity in color. It is a simple way to show differences in intensity with respect to time and frequency. Figures 2 shows a spectrogram for the period of time preceding the accident.

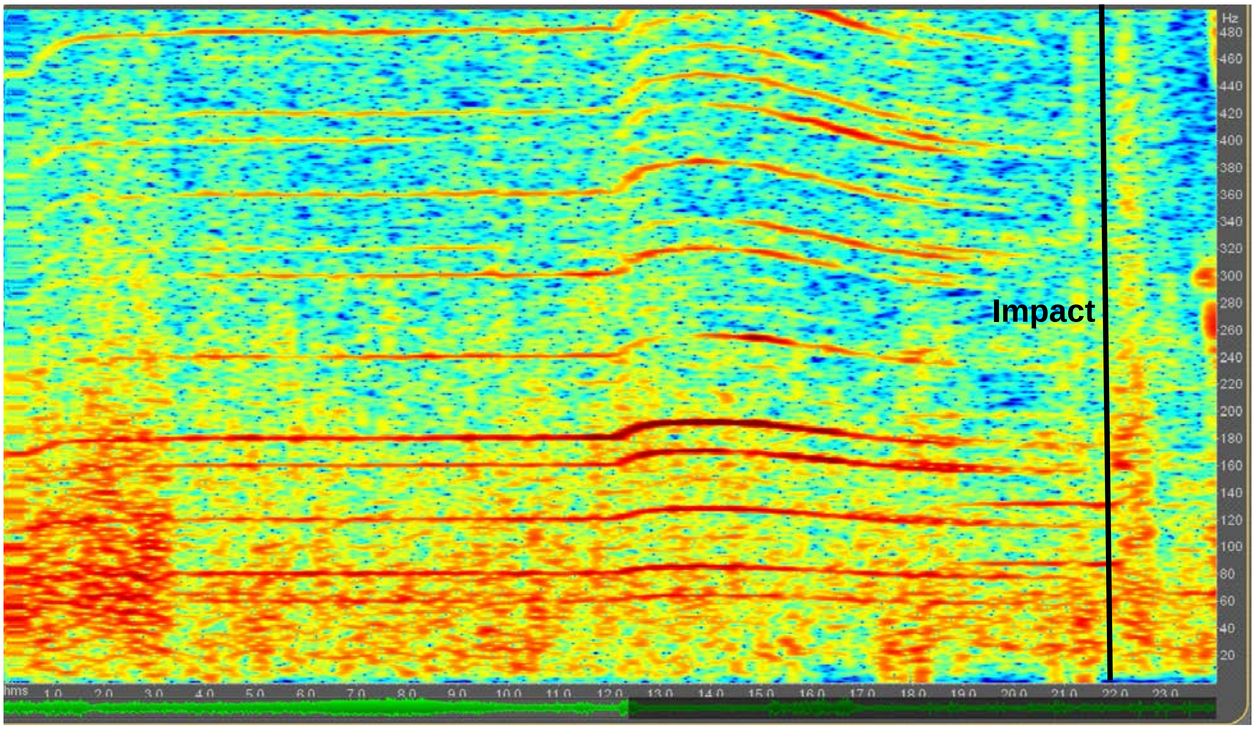

Figure 2. Spectrogram from the witness video with vertical line indicating impact at 22.0 seconds elapsed time.

Two-dimensional spectrum plots were used to determine the fundamental engine frequencies at each time. These frequencies were measured by identifying potential blade passage frequencies, exhaust valve timing frequencies, and their harmonics. For example, the Lycoming O-540-B2B5-C-A1D5, operating at maximum 2575 RPM, would have a fundamental shaft speed of 43 Hz and a blade passage frequency of 86 Hz and exhaust timing frequency of 129 Hz. Figure 6 shows a spectrum plot from the video approximately 8 seconds prior to the accident with annotated frequency values. A similar analysis was done at each calculated *RceivedTime* through the accident sequence.

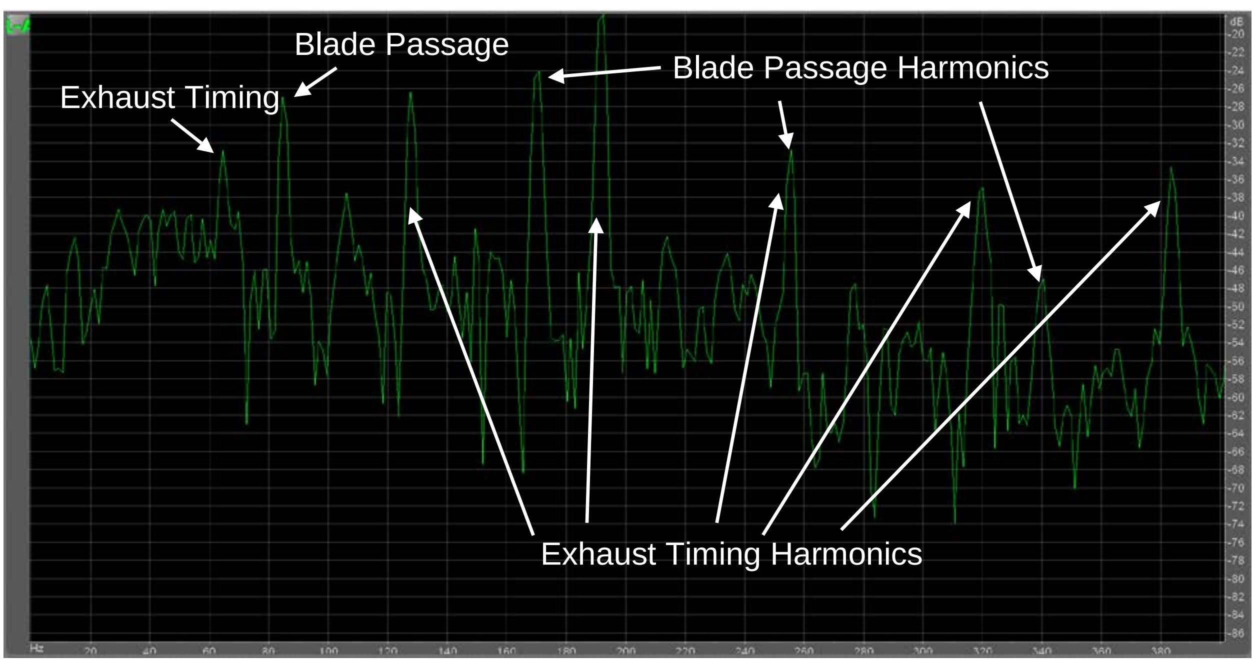

Figure 3. Sound spectrum at 13.8 seconds video elapsed time (11:40:29.7 EST)

4.8. Source Frequency Determination

The Doppler equation was solved for each point in time. The source velocity vector for each point was calculated from the interpolated flight path. Figure 4 shows the source frequency calculation converted to engine RPM using Equation 4, where BPF is the identified blade passage frequency and RPM is the calculated engine RPM. The results of this calculation can be found in Tables A-3 in Appendix A. Figure 5 shows a map with the aircraft's flight path, the location of the witness and banner, and an annotation at 11:40:28 EST where there was an increase in engine RPM.

$$\frac{BPF}{2} * 60 = RPM \tag{4}$$

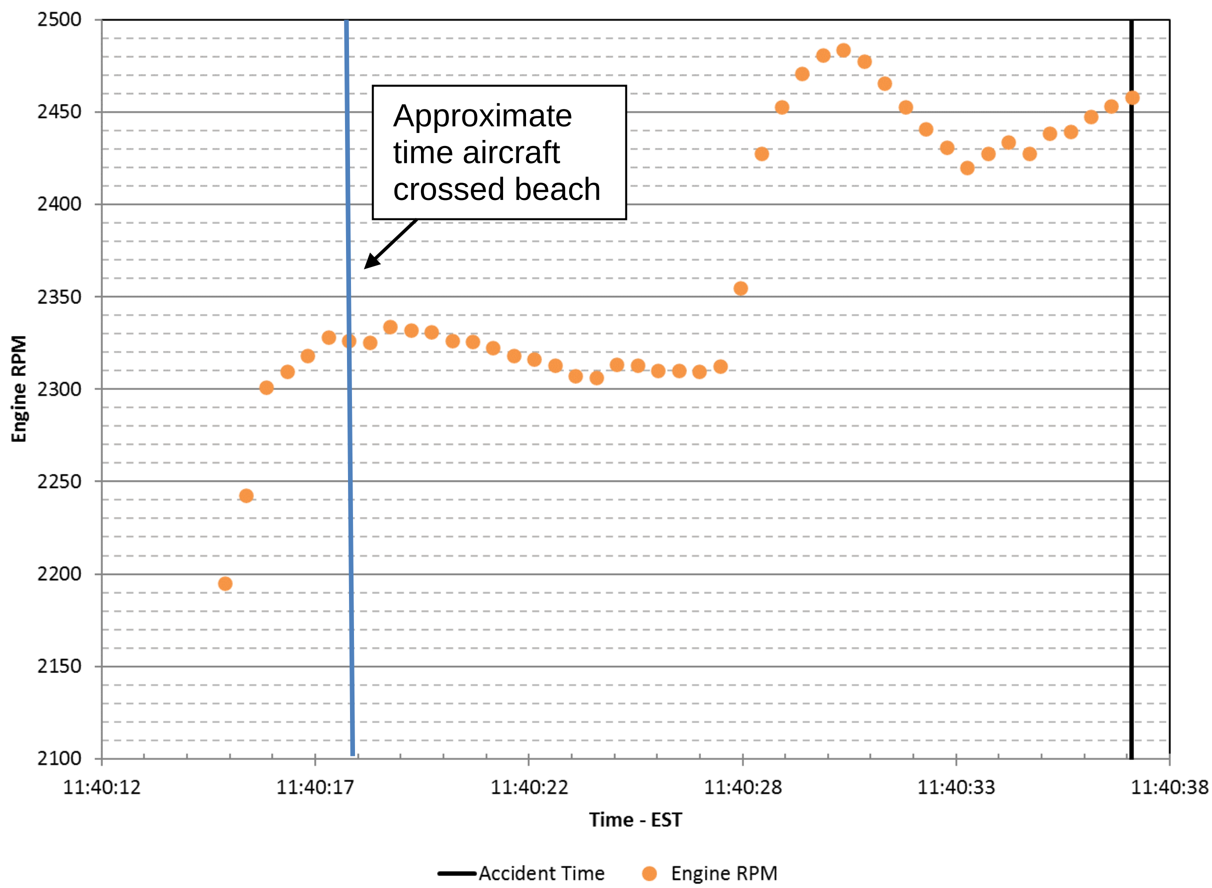

Figure 4. Source frequency time history.

Figure 5. Aircraft flight path, witness location, and location of banner.

4.9. Summary

A sound spectrum study was performed to determine the engine speed from recorded audio from a witness on the ground at the time of the accident. Because the aircraft was moving relative to the witness at the time of the accident, the Doppler frequency shift had to be calculated. The study determined the time history of engine RPM during the video recording up to building impact.

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APPENDIX A

Table A-1. Flightpath interpolation results.

Time (EST)	Groundspeed (kts)	True Track (deg)	Latitude (deg)	Longitude (deg)	North Range (nm)	East Range (nm)	VEast (kts)	VNorth (kts)
11:40:15.0	48.7	282	26.16267	-80.09751	-0.229	0.032	-47.6	10.1
11:40:15.5	48.7	284	26.16270	-80.09763	-0.227	0.025	-47.2	11.8
11:40:16.0	47.8	286	26.16274	-80.09775	-0.225	0.019	-45.9	13.2
11:40:16.5	47.8	288	26.16278	-80.09787	-0.223	0.012	-45.5	14.8
11:40:17.0	47.8	290	26.16282	-80.09799	-0.220	0.006	-44.9	16.3
11:40:17.5	46.9	292	26.16287	-80.09811	-0.217	-0.001	-43.5	17.6
11:40:18.0	47.8	294	26.16292	-80.09822	-0.214	-0.006	-43.7	19.4
11:40:18.5	47.8	296	26.16298	-80.09833	-0.211	-0.012	-43.0	21.0
11:40:19.0	47.8	298	26.16304	-80.09844	-0.207	-0.018	-42.2	22.4
11:40:19.5	48.7	300	26.16311	-80.09855	-0.203	-0.024	-42.1	24.3
11:40:20.0	48.7	302	26.16318	-80.09865	-0.199	-0.030	-41.3	25.8
11:40:20.5	49.5	305	26.16325	-80.09875	-0.194	-0.035	-40.6	28.4
11:40:21.0	49.5	307	26.16333	-80.09885	-0.190	-0.040	-39.6	29.8
11:40:21.5	49.5	310	26.16341	-80.09894	-0.185	-0.045	-37.9	31.8
11:40:22.0	50.4	313	26.16349	-80.09904	-0.180	-0.051	-36.9	34.4
11:40:22.5	49.5	316	26.16358	-80.09913	-0.175	-0.056	-34.4	35.6
11:40:23.0	49.5	319	26.16366	-80.09921	-0.170	-0.060	-32.5	37.4
11:40:23.5	49.5	323	26.16375	-80.09929	-0.165	-0.064	-29.8	39.6
11:40:24.0	48.7	326	26.16384	-80.09937	-0.159	-0.069	-27.2	40.3
11:40:24.5	48.7	329	26.16394	-80.09944	-0.153	-0.072	-25.1	41.7
11:40:25.0	47.8	332	26.16404	-80.09951	-0.147	-0.076	-22.4	42.2
11:40:25.5	47.8	335	26.16414	-80.09957	-0.141	-0.079	-20.2	43.3
11:40:26.0	46.9	338	26.16424	-80.09963	-0.135	-0.083	-17.6	43.5
11:40:26.5	46.9	340	26.16434	-80.09967	-0.129	-0.085	-16.0	44.1
11:40:27.0	46.9	341	26.16445	-80.09972	-0.123	-0.087	-15.3	44.4
11:40:27.5	46.1	342	26.16456	-80.09975	-0.116	-0.089	-14.2	43.8
11:40:28.0	46.1	342	26.16467	-80.09978	-0.109	-0.091	-14.2	43.8
11:40:28.5	46.1	342	26.16478	-80.09981	-0.103	-0.092	-14.2	43.8
11:40:29.0	46.1	341	26.16489	-80.09983	-0.096	-0.093	-15.0	43.5
11:40:29.5	46.1	340	26.16500	-80.09986	-0.090	-0.095	-15.8	43.3
11:40:30.0	46.1	338	26.16510	-80.09989	-0.084	-0.097	-17.3	42.7
11:40:30.5	46.1	336	26.16521	-80.09992	-0.077	-0.098	-18.7	42.1

Time (EST)	Groundspeed (kts)	True Track (deg)	Latitude (deg)	Longitude (deg)	North Range (nm)	East Range (nm)	VEast (kts)	VNorth (kts)
11:40:31.0	46.1	333	26.16531	-80.09997	-0.071	-0.101	-20.9	41.0
11:40:31.5	46.1	330	26.16540	-80.10002	-0.066	-0.104	-23.0	39.9
11:40:32.0	46.9	327	26.16549	-80.10009	-0.060	-0.107	-25.6	39.4
11:40:32.5	46.9	323	26.16557	-80.10017	-0.056	-0.112	-28.2	37.5
11:40:33.0	46.9	319	26.16565	-80.10027	-0.051	-0.117	-30.8	35.4
11:40:33.5	46.9	315	26.16572	-80.10037	-0.047	-0.123	-33.2	33.2
11:40:34.0	46.9	311	26.16578	-80.10048	-0.043	-0.128	-35.4	30.8
11:40:34.5	46.9	307	26.16584	-80.10059	-0.039	-0.134	-37.5	28.2
11:40:35.0	46.9	304	26.16589	-80.10071	-0.036	-0.141	-38.9	26.2
11:40:35.5	46.9	300	26.16594	-80.10082	-0.033	-0.147	-40.6	23.5
11:40:36.0	46.9	297	26.16598	-80.10093	-0.031	-0.153	-41.8	21.3
11:40:36.5	46.9	295	26.16602	-80.10103	-0.029	-0.158	-42.5	19.8
11:40:37.0	46.9	293	26.16606	-80.10112	-0.026	-0.163	-43.2	18.3

East Range = Distance East of Witness Location
North Range = Distance North of Witness Location
VEast = Eastward component of velocity
VNorth = Northward component of velocity
Vz = Vertical component of velocity
V = Magnitude of velocity vector

Table A-2. Reception times of audio at witness location.

Emitted Time (EST)	LOSNorth (nm)	LOSEast (nm)	LOS (nm)	Received Time (EST)
11:40:15.0	-0.229	0.032	0.231	11:40:16.23
11:40:15.5	-0.227	0.025	0.229	11:40:16.72
11:40:16.0	-0.225	0.019	0.226	11:40:17.20
11:40:16.5	-0.223	0.012	0.223	11:40:17.69
11:40:17.0	-0.220	0.006	0.220	11:40:18.17
11:40:17.5	-0.217	-0.001	0.217	11:40:18.66
11:40:18.0	-0.214	-0.006	0.214	11:40:19.14
11:40:18.5	-0.211	-0.012	0.211	11:40:19.63
11:40:19.0	-0.207	-0.018	0.208	11:40:20.11
11:40:19.5	-0.203	-0.024	0.204	11:40:20.59
11:40:20.0	-0.199	-0.030	0.201	11:40:21.07
11:40:20.5	-0.194	-0.035	0.198	11:40:21.55
11:40:21.0	-0.190	-0.040	0.194	11:40:22.03
11:40:21.5	-0.185	-0.045	0.190	11:40:22.52
11:40:22.0	-0.180	-0.051	0.187	11:40:23.00
11:40:22.5	-0.175	-0.056	0.183	11:40:23.48
11:40:23.0	-0.170	-0.060	0.180	11:40:23.96
11:40:23.5	-0.165	-0.064	0.177	11:40:24.44
11:40:24.0	-0.159	-0.069	0.173	11:40:24.92
11:40:24.5	-0.153	-0.072	0.169	11:40:25.40
11:40:25.0	-0.147	-0.076	0.166	11:40:25.88
11:40:25.5	-0.141	-0.079	0.162	11:40:26.36
11:40:26.0	-0.135	-0.083	0.158	11:40:26.85
11:40:26.5	-0.129	-0.085	0.155	11:40:27.32
11:40:27.0	-0.123	-0.087	0.151	11:40:27.80
11:40:27.5	-0.116	-0.089	0.146	11:40:28.28
11:40:28.0	-0.109	-0.091	0.142	11:40:28.76
11:40:28.5	-0.103	-0.092	0.138	11:40:29.24
11:40:29.0	-0.096	-0.093	0.134	11:40:29.72
11:40:29.5	-0.090	-0.095	0.131	11:40:30.20
11:40:30.0	-0.084	-0.097	0.128	11:40:30.68
11:40:30.5	-0.077	-0.098	0.125	11:40:31.17

Emitted Time (EST)	LOSNorth (nm)	LOSEast (nm)	LOS (nm)	Received Time (EST)
11:40:31.0	-0.071	-0.101	0.124	11:40:31.66
11:40:31.5	-0.066	-0.104	0.123	11:40:32.15
11:40:32.0	-0.060	-0.107	0.123	11:40:32.66
11:40:32.5	-0.056	-0.112	0.125	11:40:33.17
11:40:33.0	-0.051	-0.117	0.128	11:40:33.68
11:40:33.5	-0.047	-0.123	0.131	11:40:34.20
11:40:34.0	-0.043	-0.128	0.136	11:40:34.72
11:40:34.5	-0.039	-0.134	0.140	11:40:35.25
11:40:35.0	-0.036	-0.141	0.146	11:40:35.78
11:40:35.5	-0.033	-0.147	0.151	11:40:36.30
11:40:36.0	-0.031	-0.153	0.156	11:40:36.83
11:40:36.5	-0.029	-0.158	0.161	11:40:37.36
11:40:37.0	-0.026	-0.163	0.165	11:40:37.88

LOSEast = Eastward component of line of sight from sensor to aircraft at Emitted Time
LOSNorth = Northward component of line of sight from sensor to aircraft at Emitted Time
LOS = Magnitude of line of sight vector from sensor to aircraft at Emitted Time
Received Time = Reception time of audio at the witness location emitted from aircraft at Emitted Time

Table A-3. Doppler shift calculation.

Emitted Time (EST)	Theta (Deg)	Observed BPF (Hz)	Emitted BPF (Hz)	Engine RPM	EffC (kts)	Received Time (EST)
11:40:15.0	70.1	75.0	73.2	2195	678.5	11:40:16.23
11:40:15.5	69.6	76.7	74.8	2243	678.4	11:40:16.72
11:40:16.0	69.2	78.7	76.7	2301	678.2	11:40:17.20
11:40:16.5	68.8	79.0	77.0	2310	678.0	11:40:17.69
11:40:17.0	68.5	79.3	77.3	2318	677.7	11:40:18.17
11:40:17.5	68.1	79.7	77.6	2328	677.5	11:40:18.66
11:40:18.0	67.7	79.7	77.5	2326	677.3	11:40:19.14
11:40:18.5	67.4	79.7	77.5	2325	677.1	11:40:19.63
11:40:19.0	67.1	80.0	77.8	2334	676.9	11:40:20.11
11:40:19.5	66.8	80.0	77.7	2332	676.6	11:40:20.59
11:40:20.0	66.5	80.0	77.7	2331	676.4	11:40:21.07
11:40:20.5	65.2	80.0	77.5	2326	676.2	11:40:21.55
11:40:21.0	65.1	80.0	77.5	2326	675.9	11:40:22.03
11:40:21.5	63.8	80.0	77.4	2322	675.7	11:40:22.52

Emitted Time (EST)	Theta (Deg)	Observed BPF (Hz)	Emitted BPF (Hz)	Engine RPM	EffC (kts)	Received Time (EST)
11:40:22.0	62.7	80.0	77.3	2318	675.4	11:40:23.00
11:40:22.5	61.7	80.0	77.2	2316	675.1	11:40:23.48
11:40:23.0	60.4	80.0	77.1	2313	674.9	11:40:23.96
11:40:23.5	58.3	80.0	76.9	2307	674.6	11:40:24.44
11:40:24.0	57.3	80.0	76.9	2306	674.3	11:40:24.92
11:40:24.5	56.3	80.3	77.1	2313	674.1	11:40:25.40
11:40:25.0	55.3	80.3	77.1	2313	673.8	11:40:25.88
11:40:25.5	54.3	80.3	77.0	2310	673.5	11:40:26.36
11:40:26.0	53.4	80.3	77.0	2310	673.2	11:40:26.85
11:40:26.5	53.3	80.3	77.0	2309	673.0	11:40:27.32
11:40:27.0	54.5	80.3	77.1	2312	672.7	11:40:27.80
11:40:27.5	55.5	81.7	78.5	2355	672.4	11:40:28.28
11:40:28.0	57.6	84.0	80.9	2428	672.1	11:40:28.76
11:40:28.5	59.9	84.7	81.8	2453	671.8	11:40:29.24
11:40:29.0	63.1	85.0	82.4	2471	671.5	11:40:29.72
11:40:29.5	66.6	85.0	82.7	2481	671.2	11:40:30.20
11:40:30.0	71.1	84.7	82.8	2483	670.9	11:40:30.68
11:40:30.5	75.9	84.0	82.6	2478	670.6	11:40:31.17
11:40:31.0	81.8	83.0	82.2	2466	670.2	11:40:31.66
11:40:31.5	87.6	82.0	81.8	2453	669.9	11:40:32.15
11:40:32.0	93.6	81.0	81.4	2441	669.6	11:40:32.66
11:40:32.5	100.5	80.0	81.0	2431	669.3	11:40:33.17
11:40:33.0	107.5	79.0	80.7	2420	669.0	11:40:33.68
11:40:33.5	114.2	78.7	80.9	2428	668.7	11:40:34.20
11:40:34.0	120.5	78.3	81.1	2434	668.5	11:40:34.72
11:40:34.5	126.6	77.7	80.9	2428	668.4	11:40:35.25
11:40:35.0	131.5	77.7	81.3	2438	668.2	11:40:35.78
11:40:35.5	137.1	77.3	81.3	2439	668.1	11:40:36.30
11:40:36.0	141.5	77.3	81.6	2448	668.0	11:40:36.83
11:40:36.5	144.7	77.3	81.8	2453	667.9	11:40:37.36
11:40:37.0	147.8	77.3	81.9	2458	667.8	11:40:37.88

θ = Angle between velocity vector of aircraft and line of sight from aircraft to sensor
Observed BPF = Observed blade passage frequency measured at the witness location at Received Time
Emitted BPF = Blade passage frequency emitted from aircraft at Emitted Time

EffC = effective speed of sound at each Emitted Time