U.S. AIR FORCE

USSF

AFRL

AIR FORCE RESEARCH LABORATORY BRIEFING OVERVIEW

Paul T. Schrader, PhD

Topological Multimodal Sensor Data Analytics for Target Recognition and Information Exploitation in Contested Environments

Information Directorate (RI) 08AUG2023

Agenda

- Technical Background
  - Algebraic Topology
  - Topological Data Analysis (**TDA**)
    - Persistent Homology (**PH**)/Persistence Diagrams (**PD**)
    - Metrics of PDs
- The TDA AI/ML Pipeline (US Patent Pending)
- TDA AI/ML Pipeline Acoustic Modality Results
- TDA AI/ML Pipeline Electro-Optical (**EO**) Modality Results
- TDA AI/ML Pipeline Infrared (**IR**) Modality Results
- Future Directions

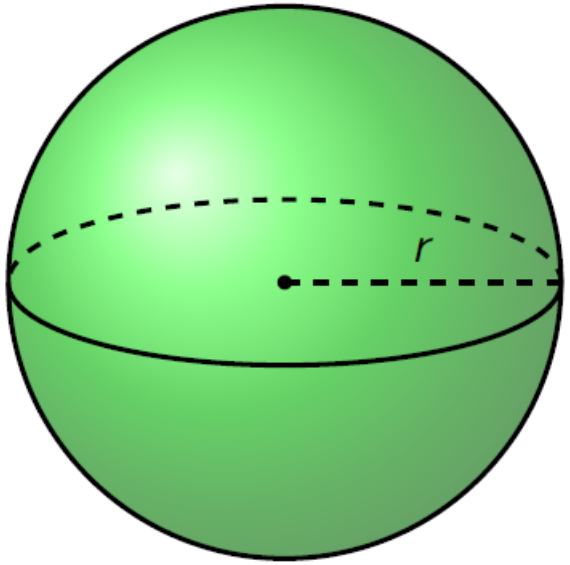
Technical Background (TB)

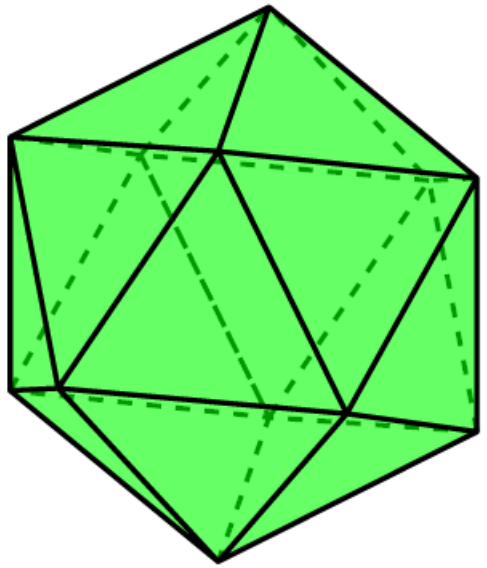
(TB1) Algebraic Topology

- **Topology** is the mathematical study of abstract spaces (set theoretical) and the continuous transformations (or deformations) between them.

- As its name implies, **algebraic topology** provides information about a topological space through its algebraic characteristics.

- **Homology** is a mature compression methodology in algebraic topology that can measure/record important topological features of a space such as connected components, holes, and voids.

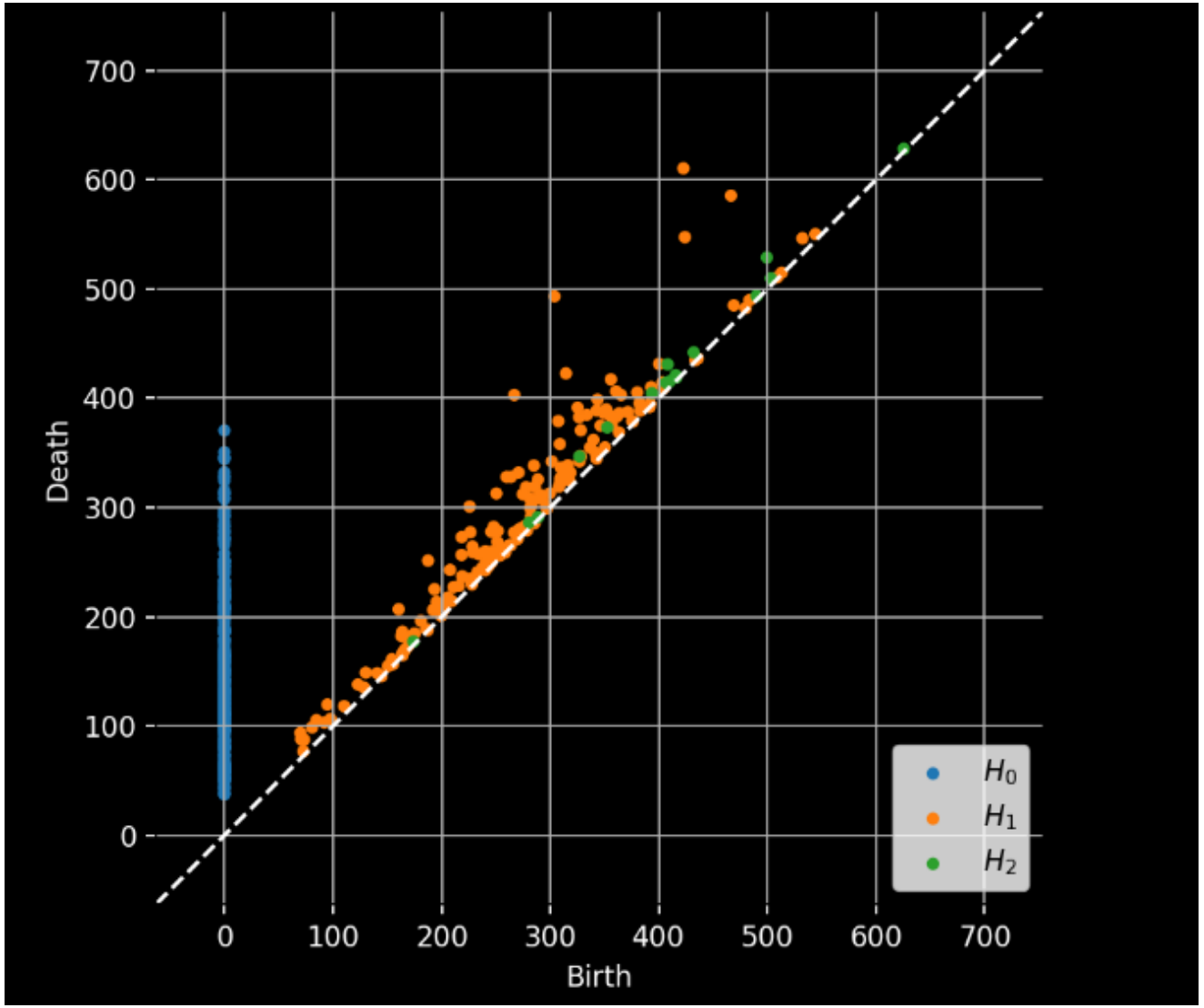




(TB2) Topological Data Analysis (TDA)

- **Topological Data Analysis** (**TDA**) is a rigorous algorithmically efficient synthesis of applied combinatorial and algebraic topology along with computational geometry motivated by the idea that topology and geometry expose qualitative and sometimes quantitative global features of a data set which are stable under small perturbations.
  - **Persistent Homology** (**PH**) is a rigorous mathematical compression scheme containing coherent algorithms which encode the developing homology for families of filtered topological spaces indexed by a set of real numbers.
  - **Persistence Diagrams** (**PD**): PH gives us a means to monitor and record changes in a filtration by identifying its top'l features (e.g., connected components, holes, and voids) as intervals or ordered pairs (b, d) representing lifespan. The collection of these (b, d) pairs by PH dimension is called a PD of that filtration.

(TB3) An Example of a Persistence Diagram (PD)



- Each sample of acoustic (time-series), EO, or IR data produces a distinct PD
- H_0 or the 0^{th} dimensional persistent homology records the lifespan of connected components
- H_1 or the 1^{st} dimensional persistent homology records the lifespan of 1D holes
- H_2 or the 2^{nd} dimensional persistent homology records the lifespan of 2D holes or voids

(TB4) The 9 Topological Metrics Used in the TDA AI/ML Feature Space

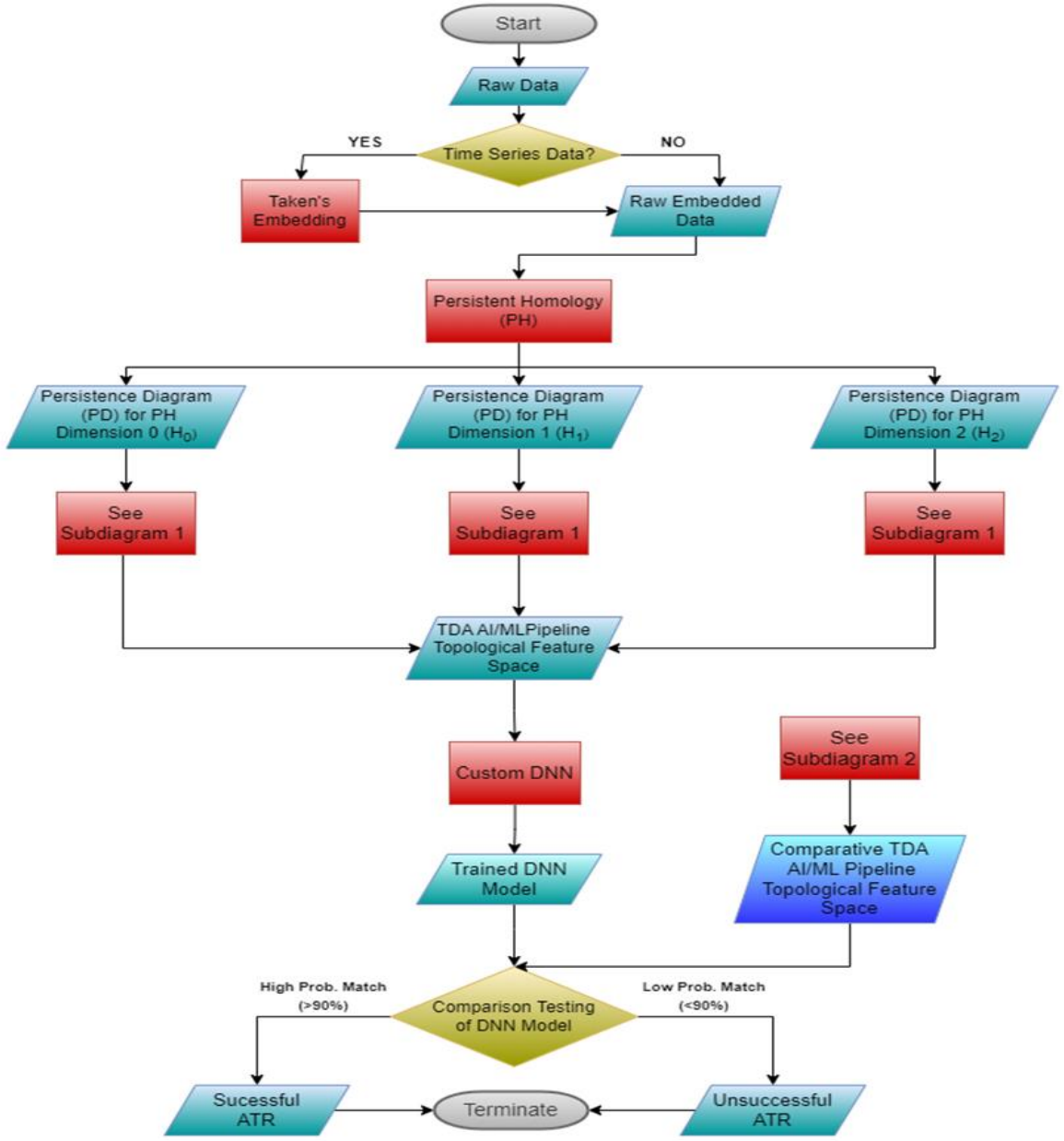
- Persistent Entropy (**PE**)
- Number of 'Off Diagonal' Points in a PD (**NoP**)
- Bottleneck Distance Amplitude (**Btl**)
- *q*-Wasserstein Distance Amplitude (**Wass**)
- Persistence Landscape Amplitude (**PL**)
- Persistence Image Amplitude (**PI**)
- Betti Curve Amplitude (**Bet**)
- Persistence Silhouette Amplitude (**Sil**)
- Persistence Heat Kernel Amplitude (**Heat**)

- In this study there are a total of 27 topological features (H_0, H_1, H_2 in each metric) in the TDA AI/ML feature space as real scalars.

(TB5) An Example TDA AI/ML Topological Feature Space

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB
1	PE_H0	PE_H1	PE_H2	NoP_H0	NoP_H1	NoP_H2	Wass_H0	Wass_H1	Wass_H2	Btl_H0	Btl_H1	Btl_H2	Land_H0	Land_H1	Land_H2	PI_H0	PI_H1	PI_H2	Bet_H0	Bet_H1	Bet_H2	Sil_H0	Sil_H1	Sil_H2	Heat_H0	Heat_H1	Heat_H2	Label
2	8.120936	6.636793	3.569075	314	175	16	1508.321	245.9354	25.79561	185.2316	94.71944	14.64574	2058.282	1136.873	68.45795	8.894664	4.590828	3.42547	3325.481	221.8408	15.59377	709.6616	91.35214	10.83805	16.20234	3.485661	1.270905	0
3	8.065631	6.586071	2.990369	302	166	10	1521.378	244.8863	17.33032	194.4319	98.3959	11.60634	2213.52	1141.324	39.47599	8.269805	4.460248	2.642513	3245.272	215.7715	11.46303	737.4084	100.7482	9.301387	15.05301	3.50141	0.963777	0
4	8.075927	6.609528	3.02445	293	133	14	1522.855	219.9112	28.87938	275.2126	91.65294	21.34821	3727.647	928.2302	92.96135	8.179313	4.084545	3.482464	3089.8	186.1696	17.0325	774.0971	72.61855	27.98288	11.65354	3.186446	1.969908	0
5	8.082969	6.644405	3.482857	302	150	15	1519.314	219.7139	19.70649	213.0252	79.94817	10.10622	2538.51	878.6841	43.27598	8.791295	4.555639	4.118668	3144.396	181.2445	14.47123	759.961	65.41485	7.954837	14.17247	3.215279	1.731117	0
6	8.048852	6.594526	3.367003	308	145	11	1482.671	221.4954	28.07171	196.0523	96.41986	17.29906	2241.249	1045.696	86.88864	9.503217	4.344963	3.697598	3167.113	185.0312	12.44111	717.3214	82.48005	20.77219	15.51491	3.253637	1.726865	0
7	8.048438	6.674642	3.328057	299	140	13	1508.77	235.961	15.49635	231.2174	107.336	10.92587	2870.537	1137.606	34.53044	8.043786	3.560279	3.587116	3111.694	189.3667	10.78599	755.1877	91.57601	7.709136	13.24211	2.937407	1.370789	0
8	8.067692	6.600194	3.185826	293	130	12	1513.211	241.5828	13.08934	205.3783	106.7394	10.96878	2403.057	1269.783	32.01847	7.916984	3.796995	3.89969	3063.402	172.4936	7.896585	771.9691	121.1789	11.31525	13.25822	2.841581	1.805277	0
9	7.983139	6.460224	2.795117	299	140	10	1493.4	230.5967	26.70388	209.7153	125.1495	14.9389	2479.576	1305.932	72.40752	8.380715	3.658335	3.98328	3114.099	170.5887	13.34266	738.985	121.4859	14.33881	13.89599	2.935464	1.858856	0
10	7.994573	6.544119	3.063234	299	138	16	1536.754	227.1846	22.70553	241.2623	106.9906	12.6673	3059.612	1142.856	51.59676	7.862798	3.755524	4.149542	3133.91	175.1996	16.65281	775.7939	94.65289	12.90549	12.62426	2.957754	1.602815	0
11	8.035353	6.545054	3.519832	293	131	13	1514.251	235.0132	20.71171	226.3366	131.5809	14.81686	2780.125	1457.259	55.34192	7.644736	3.438014	3.014431	3086.19	159.8653	12.75688	767.0318	139.3719	13.69499	13.37119	2.661144	1.096644	0
12	7.982975	6.417853	2.928583	299	144	15	1509.801	240.7848	13.97286	233.4154	126.2614	7.266144	2911.565	1496.402	27.4254	8.395251	3.762325	3.598495	3124.733	174.2628	9.796432	755.6403	137.3466	4.012698	13.1858	2.832186	1.487678	0
13	8.024474	6.521143	3.425273	296	135	14	1567.51	231.3717	21.2099	236.0932	127.8247	12.7471	2961.812	1357.285	55.0293	7.304841	3.558086	3.25954	3160.281	169.1426	12.33044	803.9133	109.5796	12.19719	12.59375	2.815714	1.048898	0
14	8.057006	6.482348	2.806518	305	166	16	1544.01	245.0558	23.1361	193.5723	109.1387	17.54482	2198.858	1195.996	67.97542	9.338198	4.496847	3.321584	3287.666	217.3261	11.05781	753.161	100.2622	19.23599	15.39841	3.666928	1.006227	0
15	8.006922	6.411167	3.288413	296	134	6	1564.583	246.752	8.416852	230.5797	141.3312	6.945587	2858.669	1555.708	17.57494	7.746278	3.326726	2.222703	3143.625	179.5566	5.555225	804.6692	137.8149	7.015067	12.38442	2.670206	0.824868	0
16	7.9756	6.197458	2.862398	299	140	9	1540.569	238.0608	11.39839	228.6034	120.555	8.436279	2821.994	1292.271	21.13981	7.58646	3.486781	2.516208	3159.685	182.1528	8.065431	774.8114	101.8457	8.67007	12.94493	2.869422	0.920299	0
17	8.01276	6.269933	2.940397	299	147	13	1575.274	238.5605	25.20135	231.8243	113.5889	18.55948	2881.845	1197.661	77.89645	7.827455	3.764517	2.688522	3187.258	191.7388	12.46557	805.1265	86.64436	21.14175	13.68886	3.078618	0.92096	0
18	8.002718	6.302862	3.30583	284	131	10	1525.316	240.5837	12.1904	217.3799	128.8676	6.95636	2616.743	1390.592	21.79749	7.203796	3.396153	2.291266	3009.4	165.6365	9.280102	799.7698	123.6877	4.360118	13.51006	2.654918	0.788226	0
19	7.984044	6.135814	3.190697	293	137	12	1539.232	239.0367	17.34093	219.1307	113.2232	10.68805	2648.421	1247.544	37.04493	7.943684	3.735604	3.784402	3120.489	172.5274	11.99291	787.0615	100.9666	9.098515	13.70705	2.777023	1.695764	0
20	8.010595	6.245618	3.446813	290	128	10	1556.098	240.5047	9.250994	215.5673	111.7799	5.75885	2584.083	1227.772	14.51963	7.438076	3.798812	2.709694	3101.733	177.548	7.221339	809.9776	111.1919	3.223692	13.83108	2.721562	0.920462	0
21	7.994118	6.305851	3.140535	290	125	5	1524.845	234.3059	3.606831	208.6989	120.5395	2.38443	2461.572	1276.634	5.890153	7.843803	3.3785	1.72596	3100.626	162.9978	3.519979	777.2275	105.74	2.027387	13.85446	2.763013	0.593085	0
22	7.990514	6.273309	2.131871	293	129	8	1513.759	229.8811	12.30956	207.8509	120.7789	8.139282	2446.584	1280.102	24.82588	7.681475	3.696762	2.23593	3124.248	156.3341	7.547349	758.8453	106.4669	5.785843	14.09326	2.584632	0.788236	0
23	8.011664	6.409231	2.711906	296	128	10	1541.086	228.0639	12.66455	204.1427	127.0321	8.153763	2381.404	1269.115	25.99878	8.371307	3.264996	3.027594	3141.611	148.4358	8.300022	784.2427	139.8422	6.037103	14.68541	2.755281	1.293293	0
24	8.011848	6.47052	2.998609	278	135	12	1517.06	241.6178	16.24124	207.9351	146.3519	10.97443	2448.07	1579.082	38.20498	7.128792	3.201206	2.920947	2994.912	150.7534	9.647354	796.5482	154.182	9.462506	13.12545	2.468176	0.911696	0
25	7.934168	6.189025	2.941505	305	167	19	1528.803	237.7353	25.32655	206.0376	102.1191	19.65916	2414.638	1155.483	77.54065	8.561906	4.494432	3.16624	3288.056	218.2812	12.44157	733.982	95.85986	19.74523	14.75909	3.81324	1.093902	0
26	7.990212	6.175491	3.117303	299	161	17	1528.799	249.1468	22.40488	219.9341	108.2269	14.54182	2662.999	1303.445	60.76505	8.054226	4.164662	3.703309	3227.321	223.8412	12.84126	749.5248	105.8166	12.48822	13.40994	3.792286	1.361851	0
27	7.97085	6.163762	2.990941	299	163	20	1527.34	222.8998	46.32722	206.4606	96.19112	29.76712	2422.078	996.5309	164.983	8.308373	4.397716	2.759752	3220.271	222.7116	21.77555	752.6282	85.55893	40.9355	14.56401	3.904002	1.288429	0
28	7.982749	6.135639	1.82328	302	166	15	1500.844	230.3723	37.7037	188.8167	99.05179	34.27011	2118.326	1057.109	165.7597	9.262203	4.605246	2.298646	3231.223	206.6441	16.01578	722.2767	91.43068	63.59877	15.93789	3.529404	1.281196	0
29	8.000831	6.109542	2.705351	293	137	16	1539.47	219.7721	42.55415	221.3662	65.20744	32.76045	2689.052	732.2867	173.3797	8.076734	4.764337	2.652428	3099.279	203.4475	17.62581	795.0732	67.2281	59.5416	12.90375	3.285914	1.460759	0
30	8.006322	6.189526	2.780178	293	144	14	1530.576	227.6499	31.66953	204.1501	92.34317	19.55872	2381.533	942.7762	91.24131	8.837417	4.123973	3.341843	3122.59	220.4738	17.90154	776.8117	81.71337	23.077	14.10076	3.332426	1.601659	0
31	7.921898	6.097011	2.950181	302	152	18	1525.68	235.8102	34.25779	207.4018	86.98174	18.51781	2438.658	1010.662	97.83098	8.250232	4.589129	3.692009	3181.248	234.933	19.21374	756.9944	78.37322	17.36329	14.51756	3.123095	1.47636	0

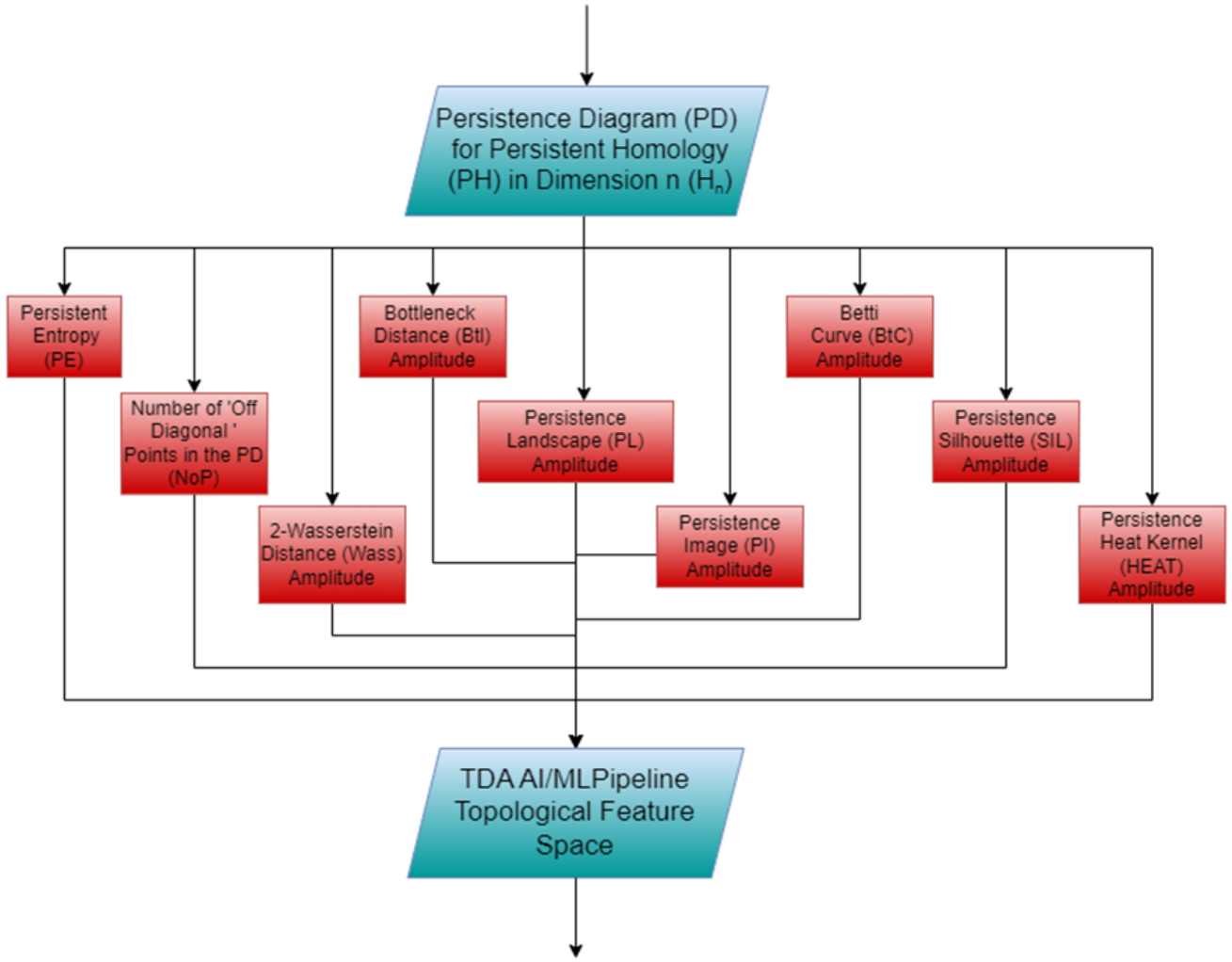
The TDA AI/ML Pipeline Architecture



The Primary TDA AI/ML Workflow Diagram (US Patent Pending)

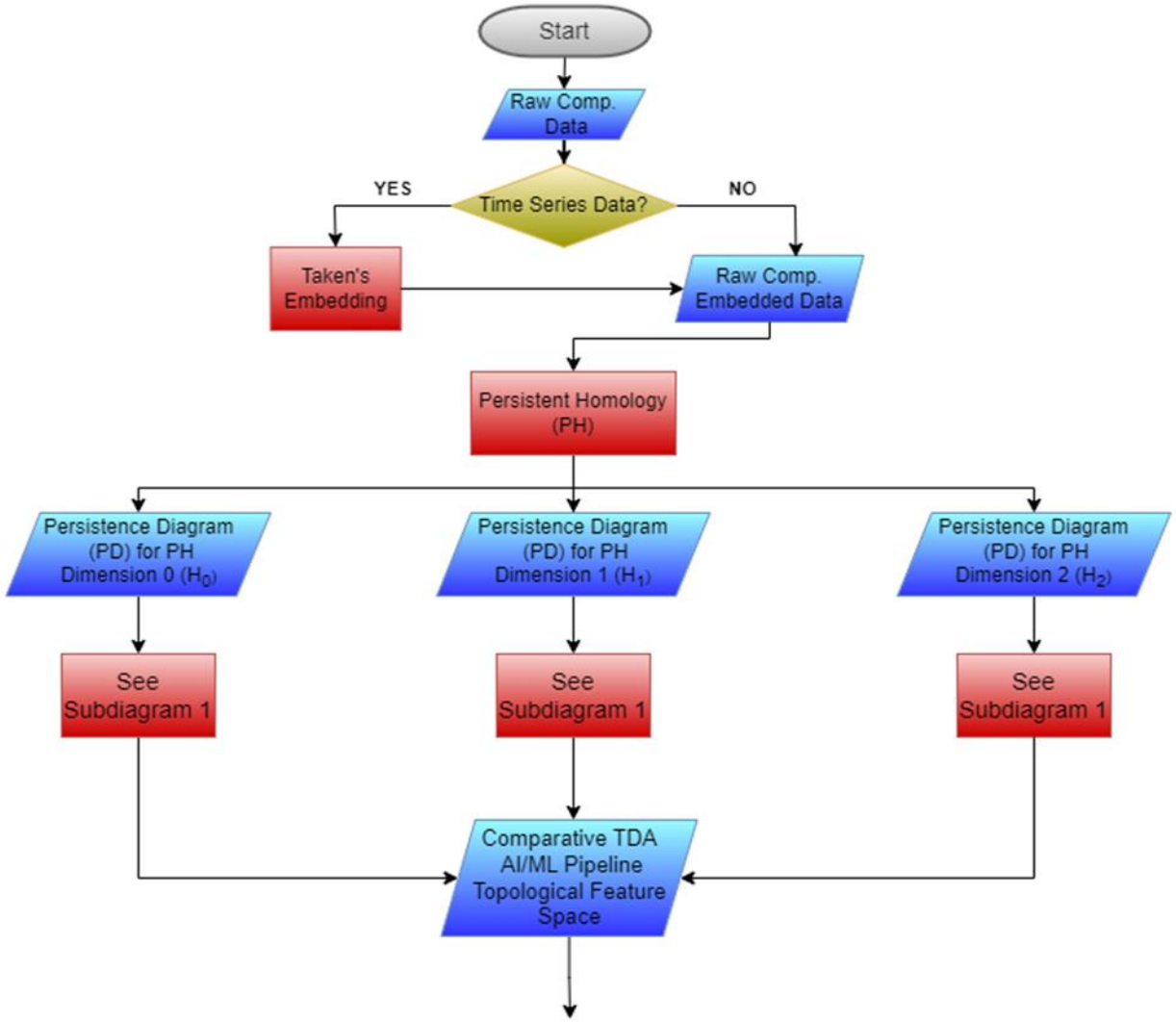
- Time Series Data = acoustic, seismic, p-RF, radar
- DNN = supervised multi-classification deep neural network
- PH dimension 0 (H_0) records and tracks connected components in the filtration
- PH dimension 1 (H_1) records and tracks 1 dimensional holes in the filtration
- PH dimension 2 (H_2) records and tracks voids (2D holes) in the filtration
- ATR = automatic target recognition

Subdiagram 1 of the Primary TDA AI/ML Workflow Diagram



- The data in each PH dimension (H_0, H_1, H_2) is processed through Subdiagram 1.
- These individual results are then collected in the 27 (9 metrics of 3 dimensions each) dimensional TDA AI/ML pipeline topological feature space.

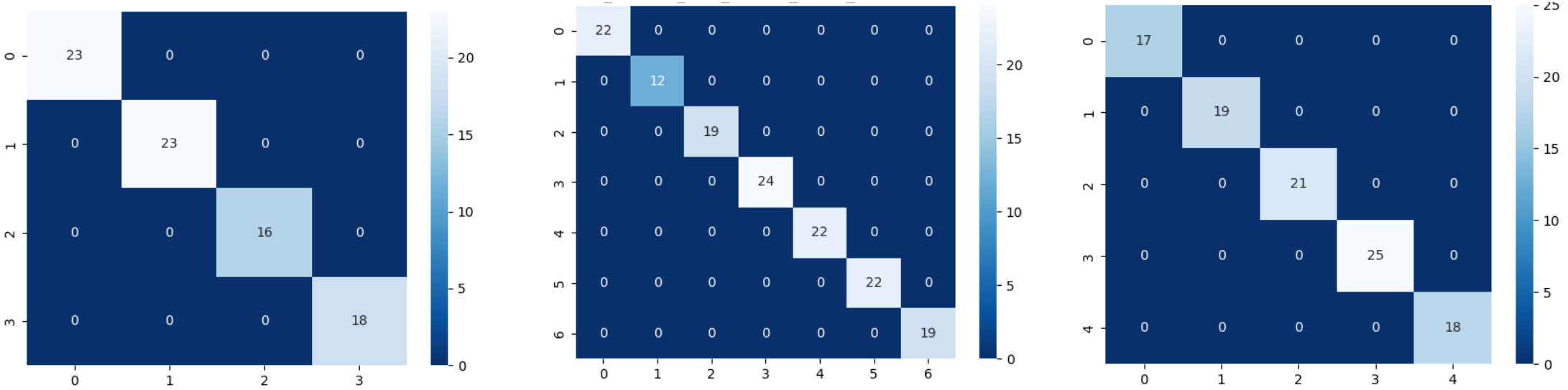
Subdiagram 2 of the Primary TDA AI/ML Workflow Diagram



- The comparative data is derived from different timestamps (1-10 seconds away from the training data) in the relative environment scenarios from the training data.
- This comparative data from Subdiagram 2 is then ingested back into the primary TDA AI/ML workflow where a random test set is extracted.

TDA AI/ML Pipeline Acoustic Modality Results

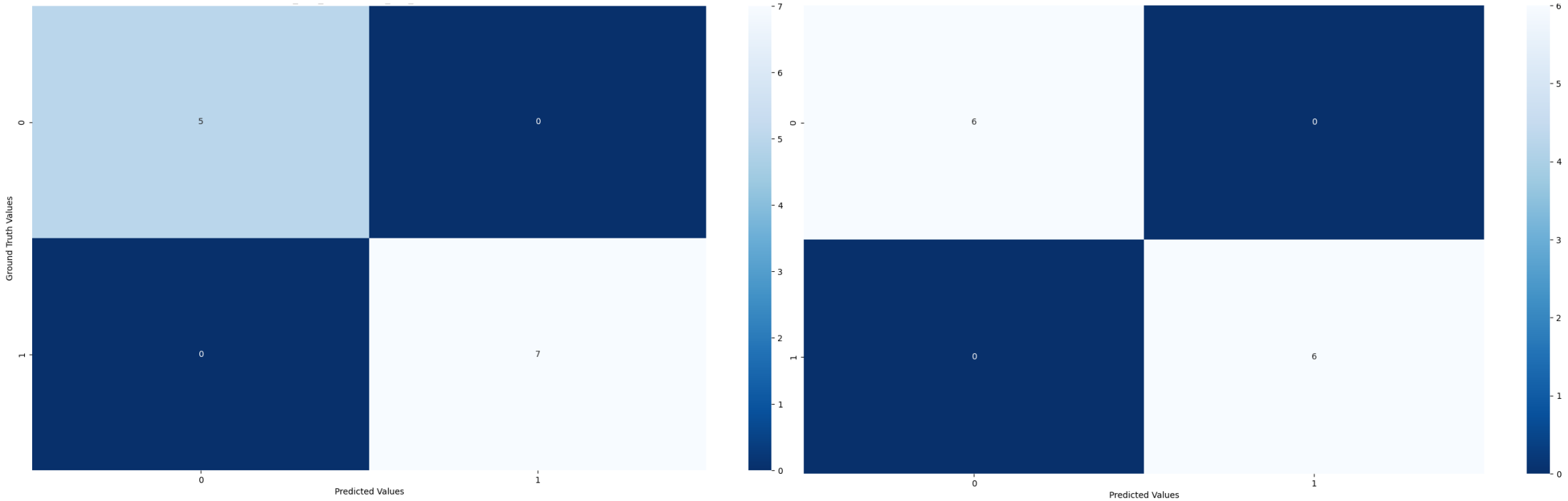
TDA AI/ML Pipeline AFRL Acoustic Modality Results



- (Leftmost) The confusion matrix visualizes the predictive ATR capability of the trained TDA AI/ML model for 4 SUAS.
- (Middle) The confusion matrix visualizes the predictive ATR capability of the trained TDA AI/ML model for 7 ground vehicles.
- (Rightmost) The confusion matrix visualizes the predictive ATR capability of the trained TDA AI/ML model for 5 ground personnel (dismounts).
- All three matrices indicate perfect accuracy, precision, and recall.

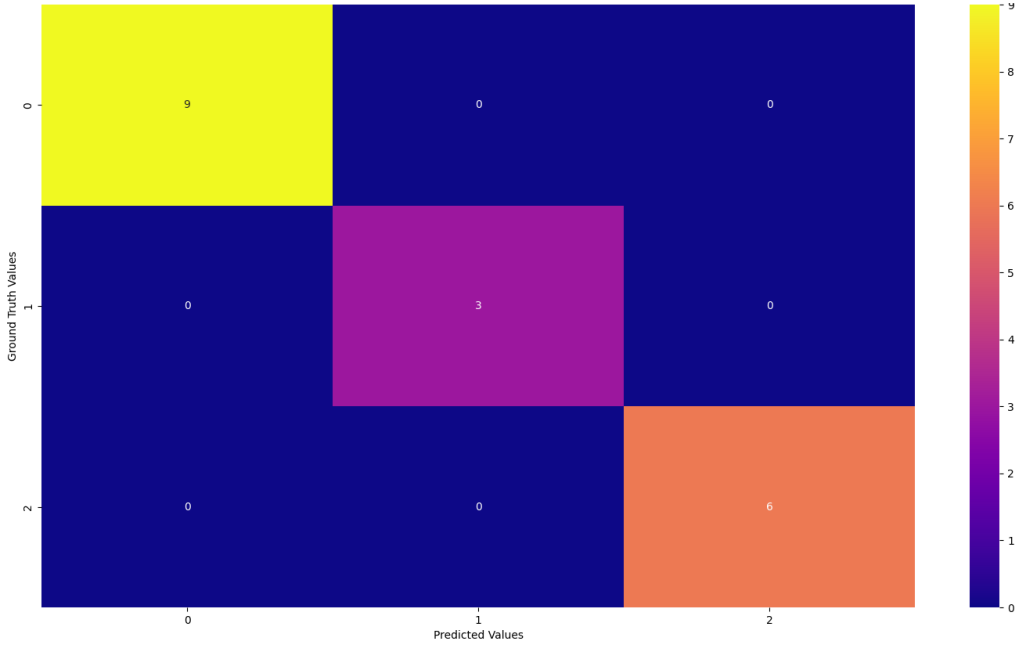
TDA AI/ML Pipeline EO Modality Results

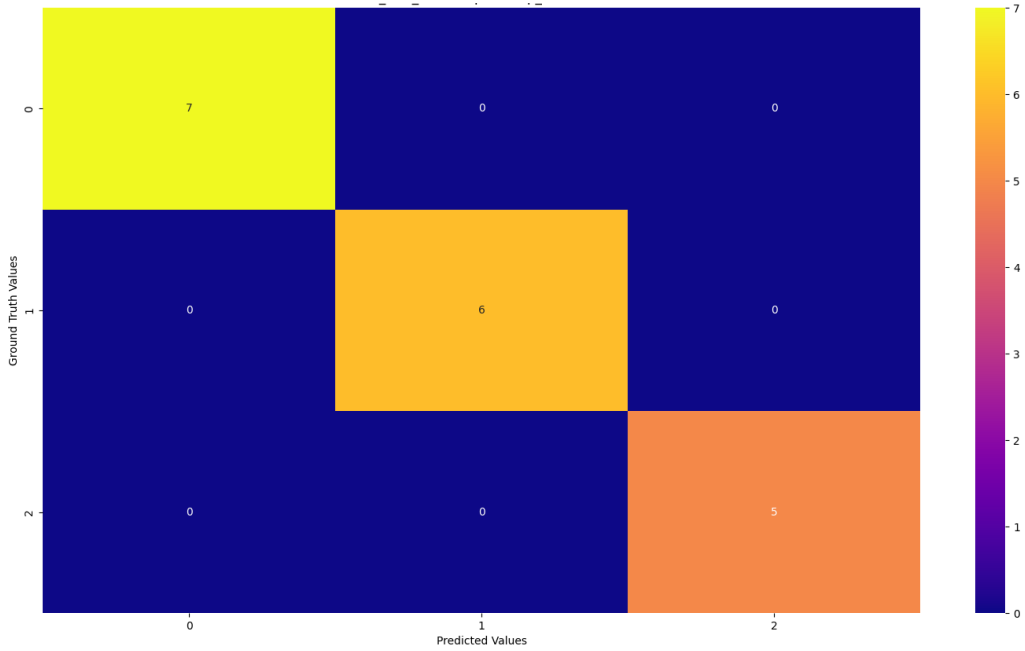
TDA AI/ML Pipeline EO Modality Results for 2 SUASs



- (Left) The confusion matrix for TDA AI/ML EO trained model ATR predictive testing on 2 SUAS RE scenario at the first comparative data timestamp.
- (Right) The confusion matrix for TDA AI/ML EO trained model ATR predictive testing on 2 SUAS RE scenario at the second comparative data timestamp.
- Both matrices indicate perfect accuracy, precision, and recall.

TDA AI/ML Pipeline EO Modality Results for 3 Ground Vehicles

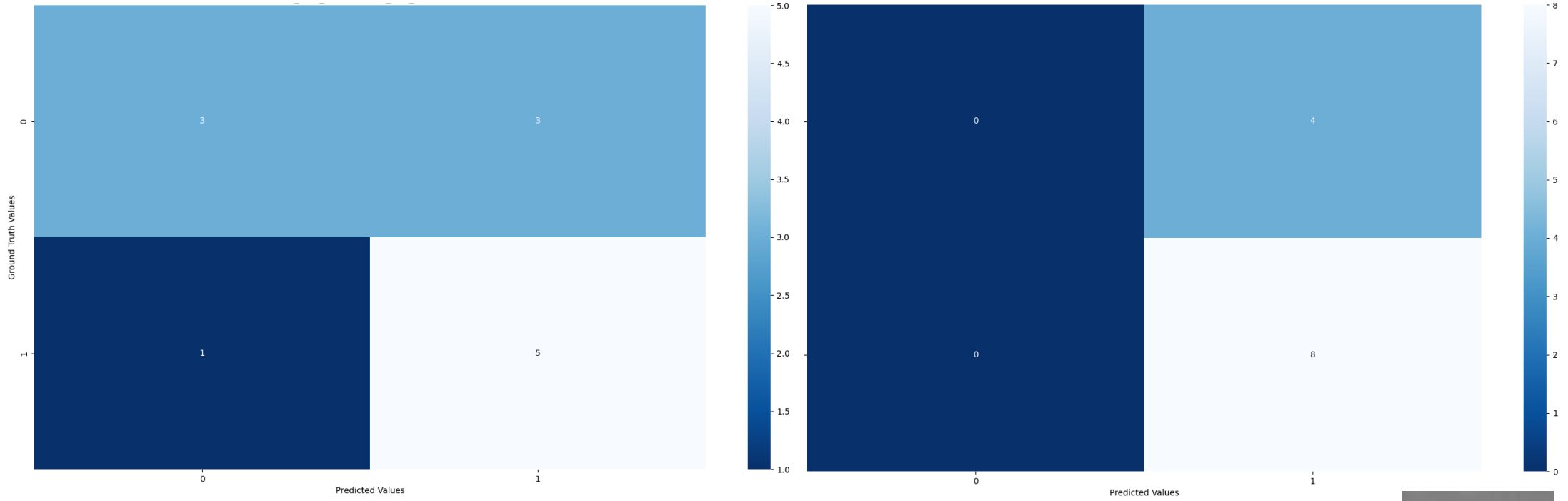




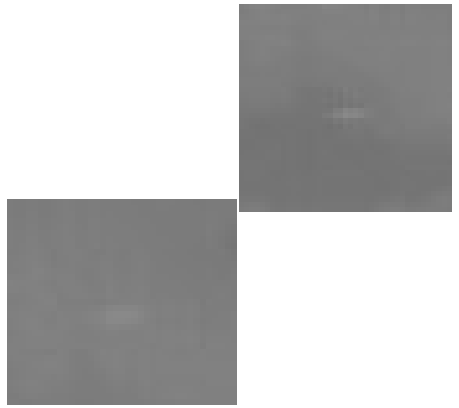
- (Left) The confusion matrix for TDA AI/ML EO trained model ATR predictive testing on 3 ground vehicle RE scenario at the first comparative data timestamp.
- (Right) The confusion matrix for TDA AI/ML EO trained model ATR predictive testing on 3 ground vehicle RE scenario at the second comparative data timestamp.
- Both matrices indicate perfect accuracy, precision, and recall.

TDA AI/ML Pipeline IR Modality Results

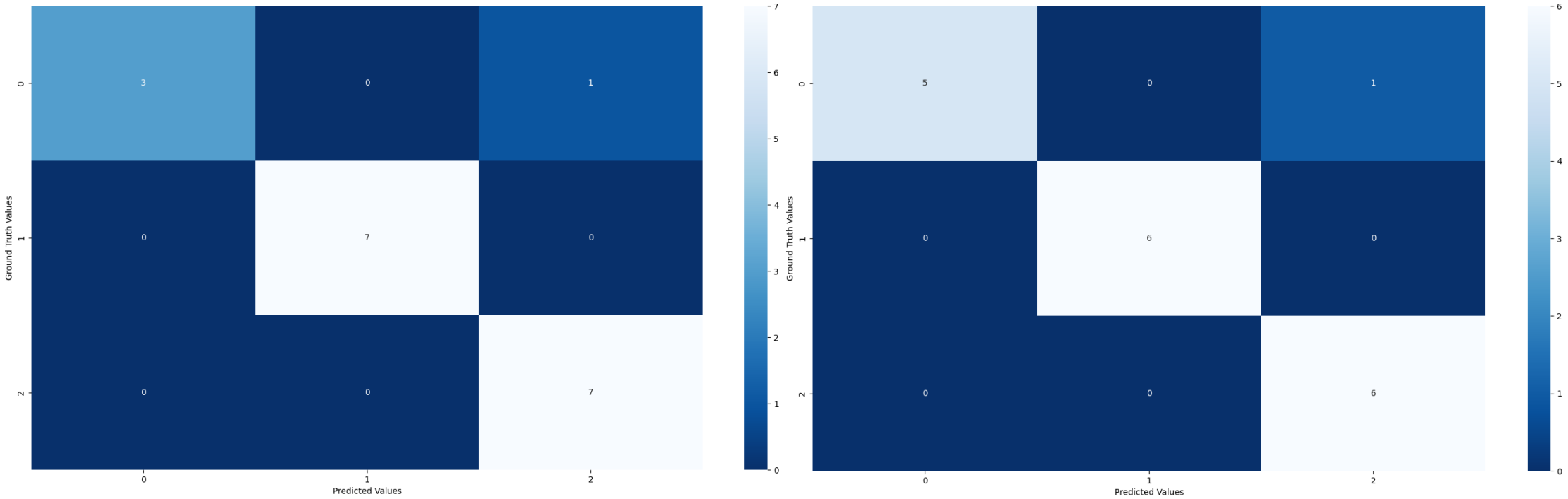
TDA AI/ML Pipeline IR Modality Results (2 SUASs)



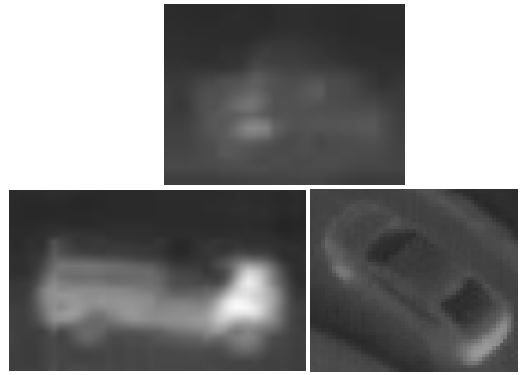
- (Left) The confusion matrix for TDA AI/ML IR trained model ATR predictive testing on 2 SUAS RE scenario at the first comparative data timestamp.
- (Right) The confusion matrix for TDA AI/ML IR trained model ATR predictive testing on 2 SUAS RE scenario at the second comparative data timestamp.
- These matrices indicate accuracies of 66.7%, precision from 33.3-68.8%, and recall from 50-66.7% in identifying the two targets involved.



TDA AI/ML Pipeline IR Modality Results (3 Ground Vehicles)



- (Left) The confusion matrix for TDA AI/ML IR trained model ATR predictive testing on 3 ground vehicle RE scenario at the first comparative data timestamp.
- (Right) The confusion matrix for the TDA AI/ML IR trained model ATR predictive testing on 3 ground vehicle RE scenario at the second comparative data timestamp.
- The matrices indicate accuracies of 94.4%, precision from 95.2-95.8%, and recall from 91.7-94.4% in identifying the three targets involved.



Future Directions

Future Directions

- Data Fusion and Multimodal Sensor Data Applications for the TDA AI/ML Pipeline
- Intrinsic clustering capability for ATR of TDA AI/ML pipeline features and other associated TDA/PD metrics
- Generalizations of the TDA AI/ML pipeline using Sheaf Theory
- Intuitive user platform/dashboard designs of TDA AI/ML data for deployment in (near) real time SA analytics

Thank You!

Questions?

paul.schrader.1@us.af.mil