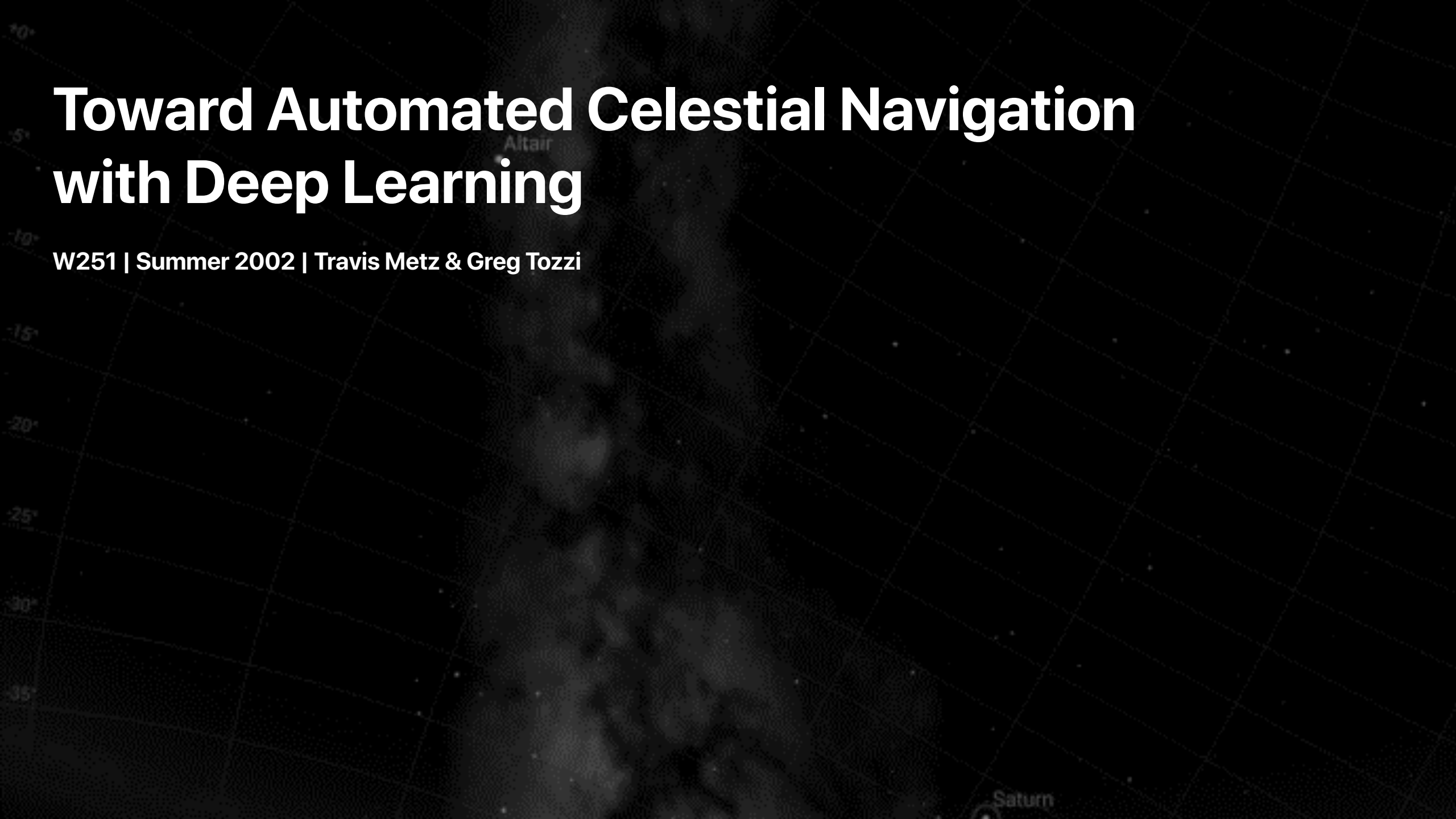
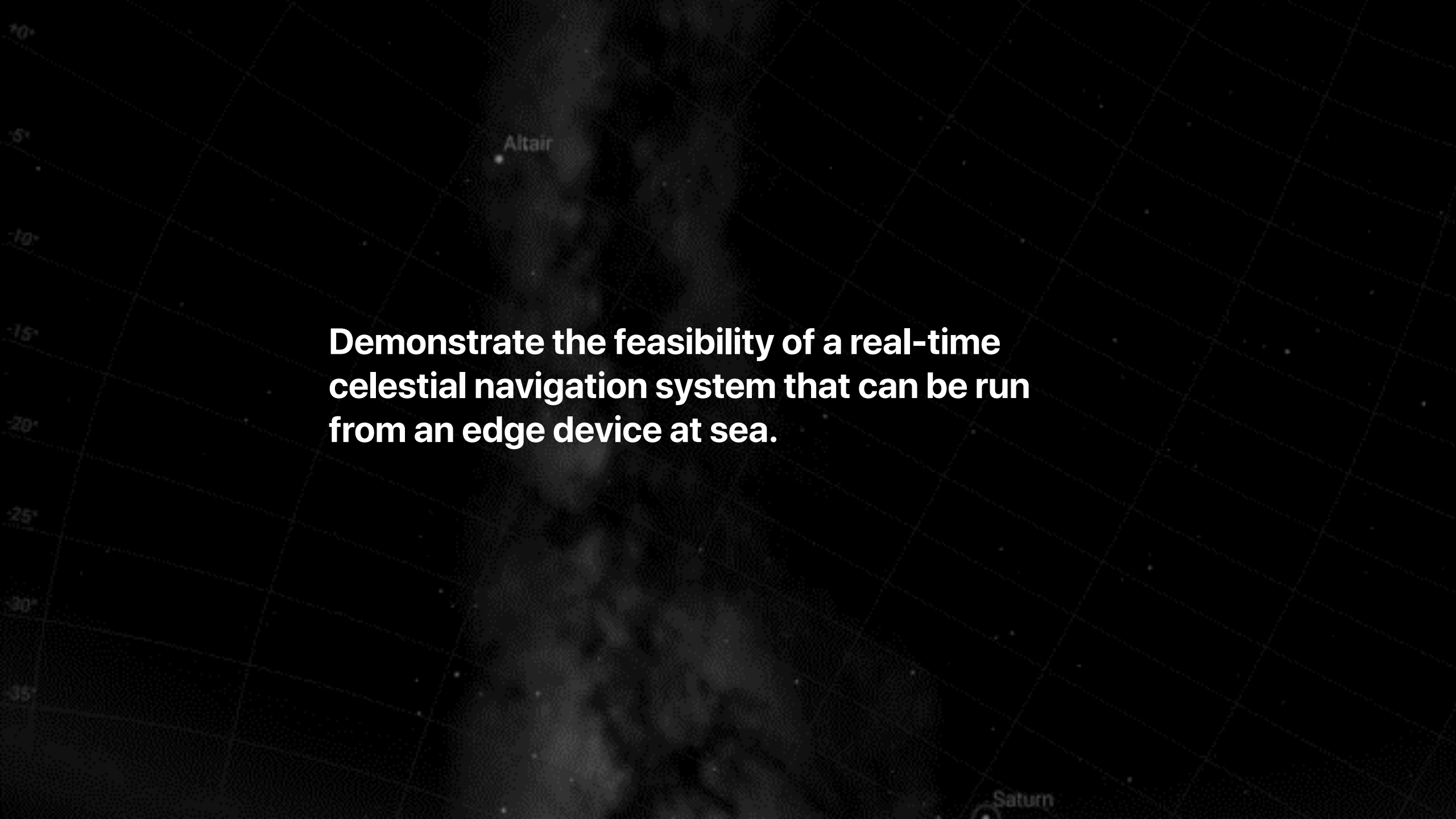
Toward Automated Celestial Navigation with Deep Learning

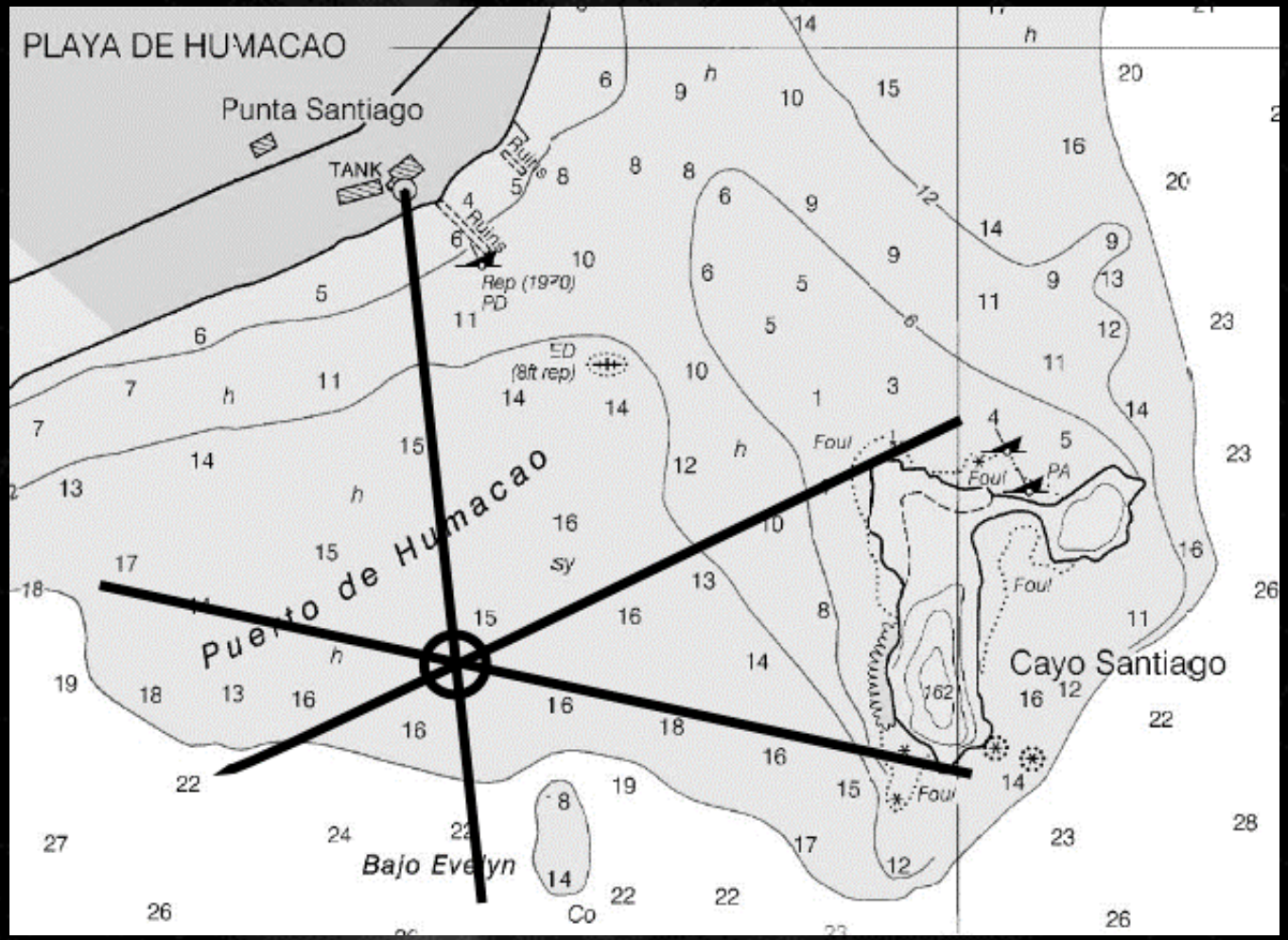
W251 | Summer 2002 | Travis Metz & Greg Tozzi



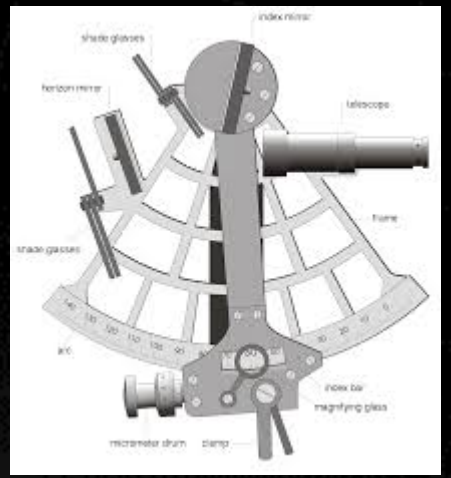


Demonstrate the feasibility of a real-time celestial navigation system that can be run from an edge device at sea.

Marine navigation



Celestial navigation



LAT 79°N

LHA ♈	Hc	Zn	Hc	Zn	Hc	Zn	Hc	Zn	Hc	Zn	Hc	Zn	Hc	Zn
	POLLUX		✦CAPELLA		Hamal		Alpheratz		✦DENEB		VEGA		✦Alioth	
0	22°38′	059	46°55′	089	32°43′	145	40°11′	177	51°46′	240	39°45′	270	45°06′	349
2	22 58	061	47 18	091	32 56	147	40 12	180	51 26	242	39 22	272	44 02	351
4	23 18	063	47 41	093	33 08	149	40 12	182	51 06	244	38 59	274	44 59	352
6	23 39	064	48 04	095	33 20	151	40 10	184	50 45	246	38 36	275	44 56	354
8	24 00	066	48 26	097	33 30	153	40 08	186	50 24	248	38 14	277	44 54	355
10	24°21′	068	48°49′	099	33°40′	156	40°05′	189	50°02′	250	37°51′	279	44°52′	357
12	24 42	070	49 12	101	33 49	158	40 01	191	49 41	253	37 28	281	44 51	359
14	25 04	072	49 34	103	33 57	160	39 57	193	49 19	255	37 06	283	44 51	000
16	25 26	074	49 56	105	34 05	162	39 51	196	48 56	257	36 44	285	44 52	002
18	25 48	076	50 18	107	34 11	164	39 44	198	48 34	259	36 22	287	44 53	003
20	26°10′	078	50°40′	109	34°17′	167	39°37′	200	48°12′	261	36°00′	289	44°54′	005
22	26 33	080	51 02	111	34 22	169	39 29	202	47 49	263	35 38	291	44 57	007
24	26 55	082	51 23	113	34 26	171	39 19	205	47 26	265	35 17	293	45 00	008
26	27 18	084	51 44	116	34 29	173	39 09	207	47 03	267	34 56	294	45 03	010
28	27 41	086	52 04	118	34 31	175	38 59	209	46 40	269	34 35	296	45 07	011
	✦Alioth		POLLUX		✦CAPELLA		Hamal		Alpheratz		✦DENEB		VEGA	
30	45°12′	013	28°04′	087	52°24′	120	34°33′	178	38°47′	211	46°17′	271	34°15′	298
32	45 18	014	28 27	089	52 44	122	34 33	180	38 35	214	45 55	273	33 55	300
34	45 24	016	28 49	091	53 03	124	34 33	182	38 22	216	45 32	275	33 35	302
36	45 30	018	29 12	093	53 21	127	34 32	184	38 08	218	45 09	277	33 16	304
38	45 37	019	29 35	095	53 39	129	34 29	187	37 54	220	44 46	279	32 57	305
40	45°45′	021	29°58′	097	53°57′	131	34°26′	189	37°39′	222	44°24′	280	32°39′	307
42	45 54	022	30 21	099	54 14	134	34 22	191	37 23	225	44 01	282	32 21	309
44	46 03	024	30 43	101	54 30	136	34 18	193	37 07	227	43 39	284	32 03	311
46	46 12	026	31 05	103	54 46	138	34 12	195	36 50	229	43 17	286	31 46	313
48	46 23	027	31 28	105	55 01	141	34 05	198	36 32	231	42 55	288	31 29	314
50	46°33′	029	31°50′	107	55°15′	143	33°58′	200	36°14′	233	42°33′	290	31°13′	316
52	46 45	030	32 11	109	55 28	146	33 50	202	35 56	235	42 12	292	30 58	318
54	46 57	032	32 33	112	55 41	148	33 41	204	35 36	237	41 51	293	30 43	320
56	47 09	034	32 54	114	55 52	150	33 31	206	35 17	239	41 30	295	30 28	322
58	47 22	035	33 15	116	56 03	153	33 20	209	34 57	242	41 09	297	30 14	323
	✦Alioth		REGULUS		POLLUX		✦CAPELLA		Alpheratz		✦DENEB		VEGA	
60	47°36′	037	11°12′	085	33°35′	118	56°13′	155	34°37′	244	40°49′	299	30°01′	325
62	47 50	039	11 35	087	33 55	120	56 22	158	34 16	246	40 29	301	29 48	327
64	48 04	040	11 58	089	34 15	122	56 31	160	33 55	248	40 10	302	29 36	329
66	48 19	042	12 21	091	34 34	124	56 38	163	33 34	250	39 51	304	29 24	330
68	48 35	044	12 44	093	34 53	126	56 44	165	33 12	252	39 32	306	29 13	332
70	48°51′	045	13°06′	095	35°11′	128	56°49′	168	32°50′	254	39°14′	308	29°03′	334
72	49 07	047	13 29	097	35 29	130	56 54	170	32 28	256	38 56	310	28 53	336
74	49 24	049	13 52	099	35 46	133	56 57	173	32 06	258	38 38	311	28 44	338
76	49 42	050	14 14	101	36 03	135	56 59	175	31 43	260	38 21	313	28 36	339
78	49 59	052	14 37	103	36 19	137	57 01	178	31 21	262	38 05	315	28 28	341
80	50°18′	054	14°59′	105	36°34′	139	57°01′	181	30°58′	264	37°49′	317	28°21′	343
82	50 36	055	15 21	107	36 49	141	57 00	183	30 35	266	37 33	318	28 15	345
84	50 55	057	15 43	109	37 03	143	56 58	186	30 12	268	37 19	320	28 09	346
86	51 15	059	16 04	111	37 16	146	56 56	188	29 49	270	37 04	322	28 04	348
88	51 34	060	16 25	113	37 28	148	56 52	191	29 26	272	36 50	324	28 00	350
	✦ARCTURUS		REGULUS		POLLUX		✦CAPELLA		Alpheratz		✦DENEB		VEGA	
90	12°41′	053	16°46′	115	37°40′	150	56°47′	193	29°04′	274	36°37′	325	27°56′	352
92	13 00	055	17 07	117	37 51	152	56 41	196	28 41	276	36 24	327	27 53	353
94	13 19	057	17 27	119	38 02	154	56 35	198	28 18	278	36 12	329	27 51	355
96	13 39	059	17 47	121	38 11	157	56 27	201	27 55	280	36 00	331	27 49	357
98	13 58	061	18 06	123	38 20	159	56 18	203	27 33	282	35 49	332	27 48	359
100	14°19′	063	18°25′	125	38°28′	161	56°09′	206	27°11′	283	35°39′	334	27°48′	001
102	14 39	065	18 44	127	38 35	163	55 58	208	26 48	285	35 29	336	27 49	002
104	15 00	067	19 02	129	38 41	166	55 47	211	26 26	287	35 20	337	27 50	004
106	15 21	069	19 19	131	38 46	168	55 35	213	26 05	289	35 12	339	27 52	006
108	15 43	071	19 36	133	38 50	170	55 22	216	25 43	291	35 04	341	27 55	008
110	16°04′	072	19°52′	135	38°54′	172	55°08′	218	25°22′	293	34°57′	343	27°58′	009
112	16 26	074	20 08	138	38 56	175	54 54	220	25 01	295	34 50	344	28 02	011
114	16 48	076	20 23	140	38 58	177	54 39	223	24 40	297	34 44	346	28 07	013
116	17 11	078	20 38	142	38 59	179	54 23	225	24 20	299	34 39	348	28 12	015
118	17 33	080	20 52	144	38 58	182	54 06	227	24 00	301	34 34	349	28 18	016
	✦VEGA		ARCTURUS		✦REGULUS		POLLUX		✦CAPELLA		Alpheratz		DENEB	
120	28°25′	018	17°56′	082	21°05′	146	38°57′	184	53°49′	230	23°41′	302	34°31′	351
122	28 33	020	18 19	084	21 17	148	38 55	186	53 31	232	23 22	304	34 27	353
124	28 41	022	18 41	086	21 29	150	38 52	188	53 13	234	23 03	306	34 25	354
126	28 50	023	19 04	088	21 40	152	38 49	191	52 54	237	22 45	308	34 23	356
128	28 59	025	19 27	090	21 50	154	38 44	193	52 35	239	22 27	310	34 22	358
130	29°09′	027	19°50′	092	22°00′	156	38°38′	195	52°15′	241	22°09′	312	34°21′	000
132	29 20	029	20 13	094	22 09	158	38 32	197	51 55	243	21 53	314	34 21	001
134	29 31	031	20 36	096	22 17	161	38 25	200	51 34	245	21 36	315	34 22	003
136	29 43	032	20 58	098	22 24	163	38 17	202	51 13	248	21 20	317	34 24	005
138	29 56	034	21 21	100	22 30	165	38 08	204	50 52	250	21 05	319	34 26	006
140	30°09′	036	21°44′	102	22°36′	167	37°58′	206	50°30′	252	20°51′	321	34°29′	008
142	30 23	038	22 06	104	22 41	169	37 47	209	50 08	254	20 36	323	34 32	010
144	30 37	039	22 28	106	22 45	171	37 36	211	49 46	256	20 23	325	34 36	011
146	30 52	041	22 50	108	22 48	173	37 24	213	49 24	258	20 10	327	34 41	013
148	31 07	043	23 12	110	22 50	175	37 11	215	49 01	260	19 58	328	34 47	015
	DENEB		✦VEGA		ARCTURUS		✦REGULUS		POLLUX		✦CAPELLA		Alpheratz	
150	34°53′	017	31°23′	045	23°33′	112	22°52′	177	36°57′	217	48°39′	262	19°46′	330
152	35 00	018	31 39	047	23 54	114	22 52	180	36 43	220	48 16	264	19 35	332
154	35 08	020	31 56	048	24 15	116	22 52	182	36 28	222	47 53	266	19 24	334
156	35 16	022	32 14	050	24 35	118	22 51	184	36 13	224	47 30	268	19 15	336
158	35 24	023	32 31	052	24 55	120	22 49	186	35 56	226	47 07	270	19 06	338
160	35°34′	025	32°50′	054	25°15′	122	22°46′	188	35°40′	228	46°44′	272	18°57′	339
162	35 44	027	33 08	056	25 34	124	22 42	190	35 22	230	46 22	274	18 50	341
164	35 55	029	33 28	058	25 53	126	22 38	192	35 04	233	45 59	276	18 43	343
166	36 06	030	33 47	059	26 11	128	22 33	194	34 46	235	45 36	278	18 36	345

LAT 79°N

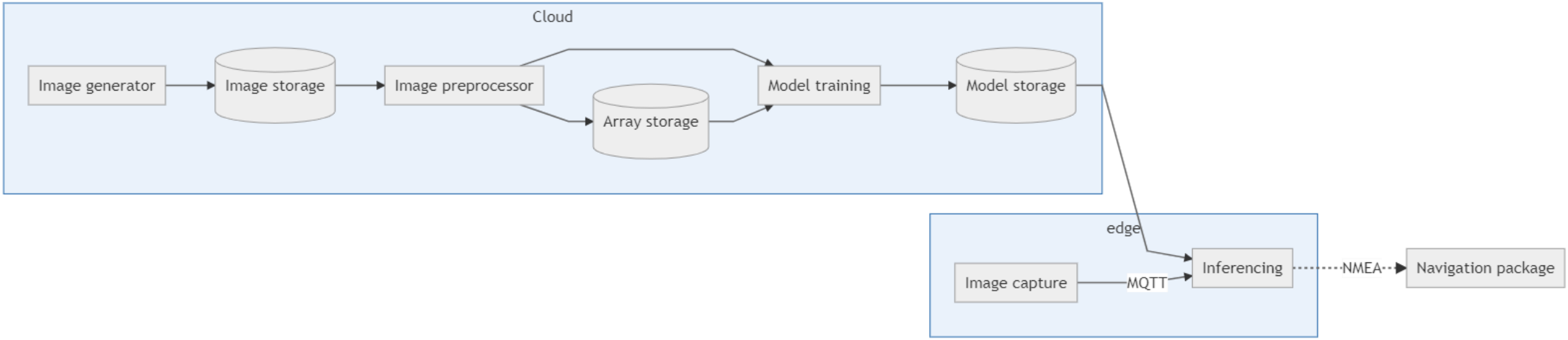
LHA ♈	Hc	Zn	Hc	Zn	Hc	Zn	Hc	Zn	Hc	Zn	Hc	Zn	Hc	Zn
	DENEB		✦VEGA		ARCTURUS		✦REGULUS		POLLUX		✦CAPELLA		Alpheratz	
180	37°41′	042	36°13′	072	28°03′	143	21°33′	209	32°25′	249	43°01′	291	18°12′	358
182	37 56	044	36 35	074	28 16	145	21 22	211	32 03	251	42 40	293	18 12	000
184	38 13	046	36 57	076	28 29	147	21 09	213	31 41	253	42 19	295	18 12	002
186	38 29	048	37 19	078	28 41	149	20 56	215	31 19	255	41 58	296	18 13	003
188	38 47	049	37 42	080	28 52	152	20 43	218	30 57	257	41 38	298	18 15	005
190	39°04′	051	38°04′	082	29°03′	154	20°28′	220	30°35′	259	41°18′	300	18°17′	007
192	39 22	053	38 27	084	29 12	156	20 13	222	30 12	261	40 58	302	18 20	009
194	39 41	055	38 50	086	29 21	158	19 58	224	29 49	263	40 39	304	18 24	011
196	40 00	057	39 13	088	29 29	160	19 42	226	29 27	265	40 20	305	18 29	013
198	40 19	058	39 36	090	29 37	162	19 25	228	29 04	267	40 02	307	18 34	014
200	40°39′	060	39°59′	092	29°43′	165	19°08′	230	28°41′	269	39°44′	309	18°40′	016
202	40 59	062	40 22	094	29 49	167	18 50	232	28 18	271	39 26	311	18 47	018
204	41 19	064	40 44	096	29 54	169	18 32	234	27 55	273	39 09	312	18 55	020
206	41 40	066	41 07	098	29 58	171	18 13	236	27 32	275	38 52	314	19 03	022
208	42 01	067	41 30	100	30 01	173	17 54	238	27 10	277	38 36	316	19 11	024
	Alpheratz		✦DENEB		VEGA		✦ARCTURUS		REGULUS		POLLUX		✦CAPELLA	
210	19°21′	025	42°22′	069	41°52′	102	30°03′	175	17°34′	240	26°47′	279	38°20′	318
212	19 31	027	42 44	071	42 15	104	30 04	178	17 14	242	26 24	281	38 05	319
214	19 42	029	43 05	073	42 37	106	30 05	180	16 54	244	26 02	283	37 51	321
216	19 53	031	43 27	075	42 59	108	30 04	182	16 33	246	25 40	285	37 36	323
218	20 06	033	43 49	077	43 20	110	30 03	184	16 12	248	25 18	287	37 23	325
220	20°18′	035	44°12′	079	43°42′	112	30°01′	186	15°50′	250	24°56′	289	37°10′	326
222	20 32	036	44 34	080	44 03	114	29 58	189	15 29	252	24 34	291	36 57	328
224	20 45	038	44 57	082	44 24	116	29 54	191	15 07	254	24 13	292	36 46	330
226	21 00	040	45 20	084	44 44	118	29 50	193	14 45	256	23 52	294	36 34	331
228	21 15	042	45 43	086	45 04	120	29 44	195	14 22	258	23 31	296	36 24	333
230	21°31′	044	46°05′	088	45°23′	123	29°38′	197	14°00′	260	23°11′	298	36°14′	335
232	21 47	046	46 28	090	45 42	125	29 30	199	13 37	262	22 51	300	36 04	337
234	22 03	048	46 51	092	46 01	127	29 22	202	13 14	264	22 31	302	35 56	338
236	22 21	049	47 14	094	46 19	129	29 14	204	12 52	266	22 12	304	35 47	340
238	22 38	051	47 37	096	46 37	131	29 04	206	12 29	268	21 53	306	35 40	342
240	22°56′	053	48°00′	098	46°53′	134	28°54′	208	62°26′	241	21°35′	308	35°33′	343
242	23 15	055	48 22	100	47 10	136	28 42	210	62 05	244	21 17	309	35 27	345
244	23 34	057	48 45	102	47 25	138	28 30	212	61 45	246	20 59	311	35 21	347
246	23 53	059	49 07	104	47 40	140	28 18	215	61 24	248	20 42	313	35 16	349
248	24 13	061	49 29	106	47 54	143	28 05	217	61 02	250	20 26	315	35 12	350
250	24°33′	063	49°51′	108	48°08′	145	27°51′	219	60°41′	252	20°10′	317	35°09′	352
252	24 54	064	50 12	111	48 21	147	27 36	221	60 19	255	19 55	319	35 06	354
254	25 14	066	50 34	113	48 33	150	27 21	223	59 56	257	19 40	321	35 04	355
256	25 36	068	50 55	115	48 44	152	27 05	225	59 34	259	19 26	322	35 02	357
258	25 57	070	51 15	117	48 54	154	26 48	227	59 11	261	19 12	324	35 01	359
260	26°19′	072	51°36′	119	49°04′	157	26°31′	229	58°49′	263	18°59′	326	35°01′	000
262	26 41	074	51 55	121	49 12	159	26 13	231	58 26	265	18 46	328	35 01	002
264	27 03	076	52 15	124	49 20	161	25 55	233	58 03	267	18 35	330	35 03	004
266	27 25	078	52 33	126	49 27	164	25 37	236	57 40	269	18 23	332	35 04	005
268	27 47	080	52 52	128	49 33	166	25 18	238	57 17	271	18 13	334	35 07	007
	✦CAPELLA		Alpheratz		✦DENEB		VEGA		✦ARCTURUS		Alioth		POLLUX	
270	35°10′	009	28°10′	082	53°09′	130	49°38′	169	24°58′	240	56°55′	273	18°03′	335
272	35 14	011	28 33	084	53 27	133	49 42	171	24 38	242	56 32	275	17 54	337
274	35 19	012	28 56	086	53 43	135	49 45	173	24 18	244	56 09	277	17 45	339
276	35 24	014	29 18	087	53 59	137	49 47	176	23 57	246	55 46	279	17 38	341
278	35 30	016	29 41	089	54 14	140	49 48	178	23 36	248	55 24	280	17 30	343
280	35°36′	017	30°04′	091	54°29′	142	49°48′	181	23°15′	250	55°01′	282	17°24′	345
282	35 43	019	30 27	093	54 42	144	49 47	183	22 53	252	54 39	284	17 18	346
284	35 51	021	30 50	095	54 55	147	49 46	186	22 31	254	54 17	286	17 13	348
286	36 00	022	31 13	097	55 07	149	49 43	188	22 09	256	53 55	288	17 09	350
288	36 09	024	31 35	099	55 18	152	49 39	190	21 47	258	53 33	290	17 05	352
290	36°18′	026	31°58′	101	55°29′	154	49°35′	193	21°24′	260	53°12′	291	17°03′	354
292	36 29	028	32 20	103	55 38	157	49 29	195	21 02	262	52 51	293	17 01	356
294	36 40	029	32 42	105	55 47	159	49 23	198	20 39	264	52 30	295	16 59	358
296	36 51	031	33 04	107	55 55	162	49 16	200	20 16	266	52 09	297	16 59	359
298	37 03	033	33 26	109	56 01	164	49 07	202	19 53	268	51 49	298	16 59	001
300	17°00′	003	37°16′	034	33°47′	111	56°07′	167	48°58′	205	19°30′	270	51°29′	300
302	17 01	005	37 29	036	34 09	114	56 12	169	48 48	207	19 07	272	51 09	302
304	17 04	007	37 43	038	34 29	116	56 16	172	48 37	209	18 45	274	50 50	304
306	17 07	009	37 57	040	34 50	118	56 19	174	48 26	212	18 22	276	50 31	305
308	17 10	011	38 12	041	35 10	120	56 20	177	48 13	214	17 59	278	50 12	307
310	17°15′	012	38°28′	043	35°30′	122	56°21′	179	48°00′	216	17°36′	279	49°54′	309
312	17 20	014	38 43	045	35 49	124	56 21	182	47 46	219	17 14	281	49 37	310
314	17 26	016	39 00	047	36 08	126	56 20	184	47 31	221	16 52	283	49 19	312
316	17 33	018	39 17	048	36 26	128	56 17	187	47 16	223	16 29	285	49 03	314
318	17 40	020	39 34	050	36 44	130	56 14	189	47 00	225	16 07	287	48 46	315
320	17°48′	022	39°52′	052	37°01′	133	56°10′	192	46°43′	228	15°46′	289	48°30′	317
322	17 57	023	40 10	054	37 17	135	56 05	195	46 26	230	15 24	291	48 15	319
324	18 07	025	40 29	055	37 33	137	55 58	197	46 08	232	15 03	293	48 00	320
326	18 17	027	40 48	057	37 49	139	55 51	200	45 50	234	14 42	295	47 46	322
328	18 28	029	41 07	059	38 03	141	55 43	202	45 31	237	14 21	297	47 32	323
330	18°39′	031	41°27′	061	28°18′	113	38°17′	143	55°34′	204	45°12′	239	47°18′	325
332	18 51	033	41 47	063	28 39	115	38 30	146	55 24	207	44 52	241	47 06	327
334	19 04	035	42 08	064	29 00	117	38 43	148	55 13	209	44 32	243	46 53	328
336	19 17	036	42 29	066	29 20	119	38 55	150	55 02	212	44 11	245	46 42	330
338	19 31	038	42 50	068	29 40	121	39 06	152	54 49	214	43 50	247	46 30	332
340	19°45′	040	43°11′	070	29°59′	123	39°16′	155	54°36′	217	43°29′	249	46°20′	333
342	20 00	042	43 33	072	30 18	125	39 25	157	54 22	219	43 07	251	46 10	335
344	20 16	044	43 55	074	30 36	128	39 34	159	54 07	221	42 46	253	46 00	336
346	20 32	046	44 17	075	30 54	130	39 42	161	53 52	224	42 24	256	45 51	338

Why do we care?

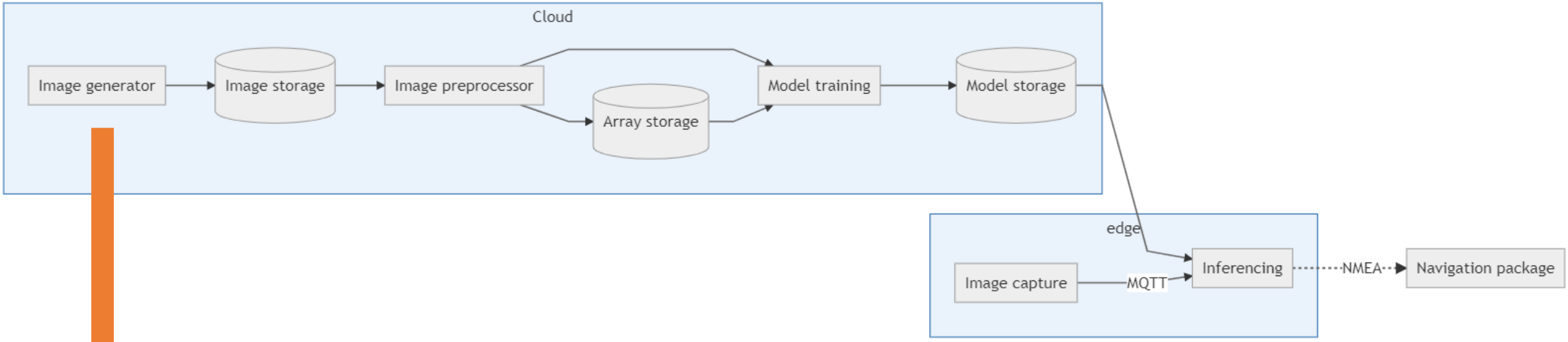
Assumptions/Simplifications

All images are synthetic
Image taken oriented 000°T with altitude = 89° & consistent height
No fouling of images by weather or superstructure
Constrained training to fixed spatial-temporal regions

Proposed system

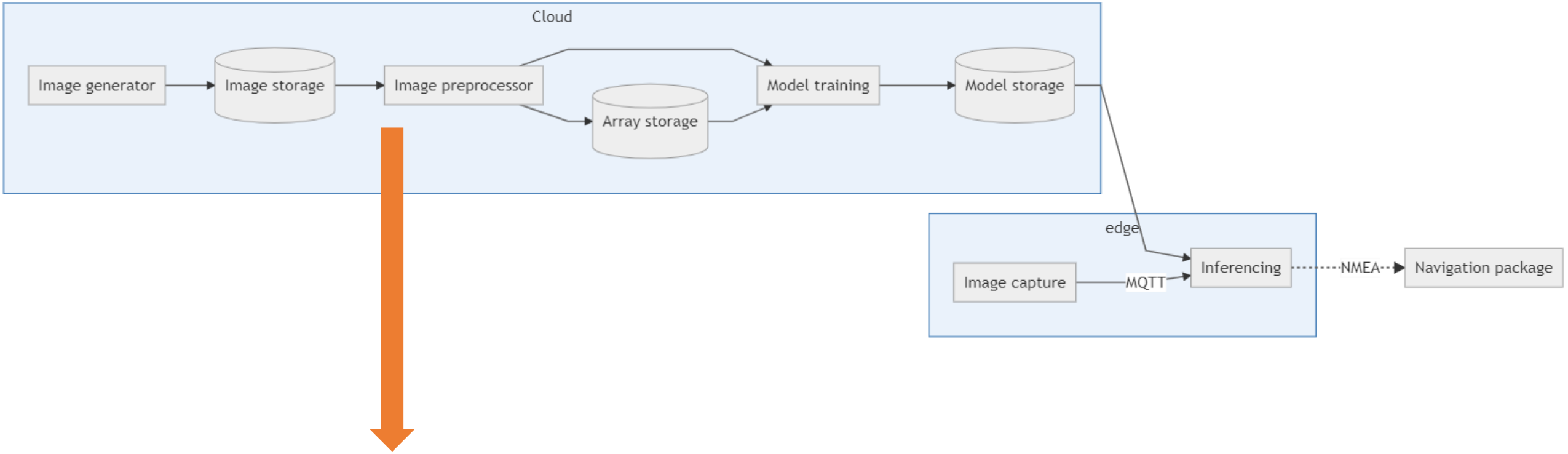


Proposed system



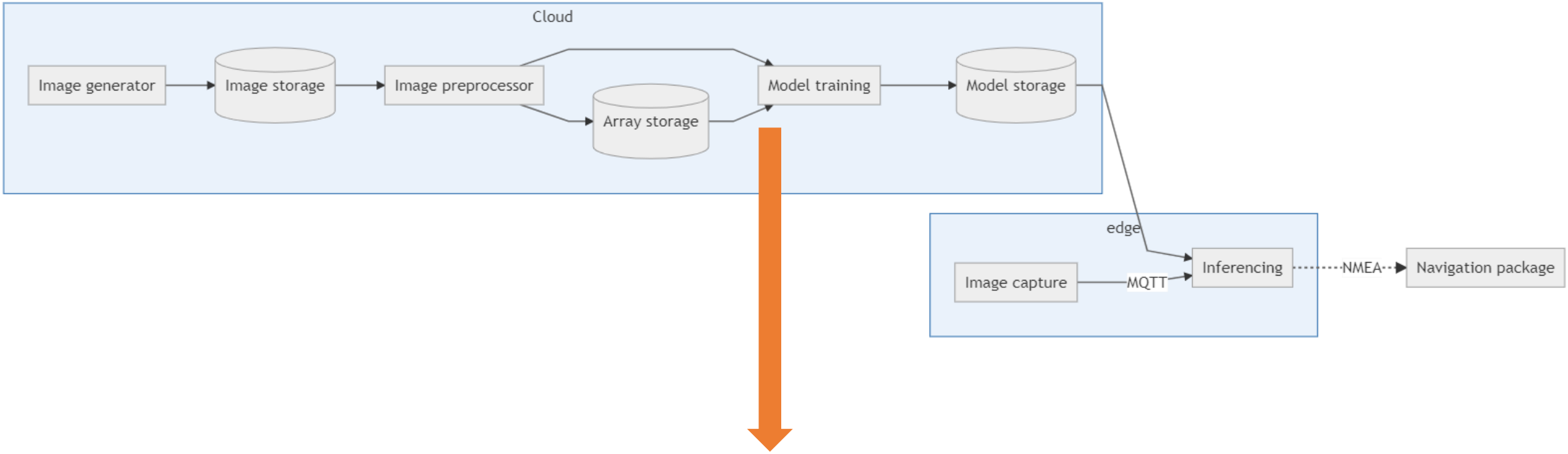
Synthetic images generated using open source astronomy application *Stellarium*

Proposed system



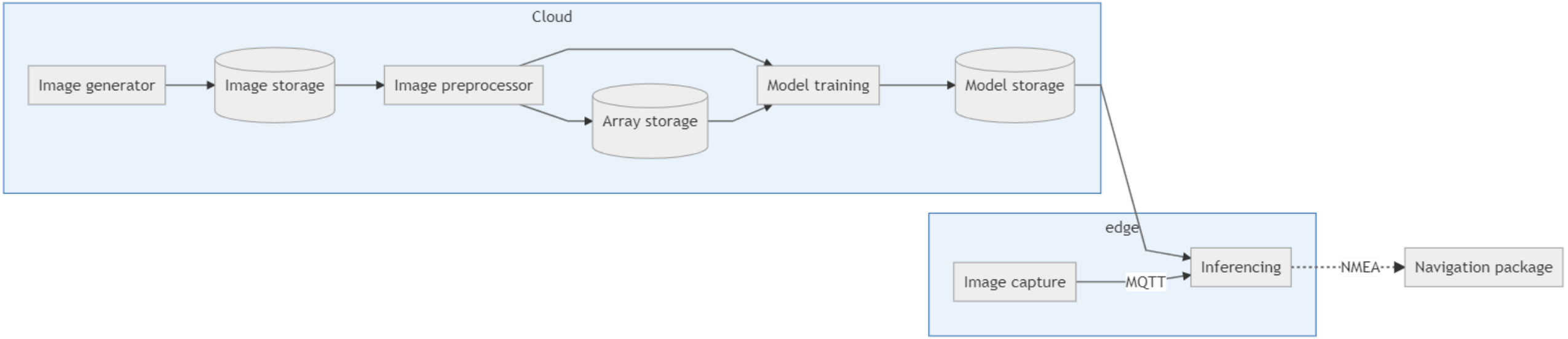
Images are processed into arrays for in-memory training

Proposed system



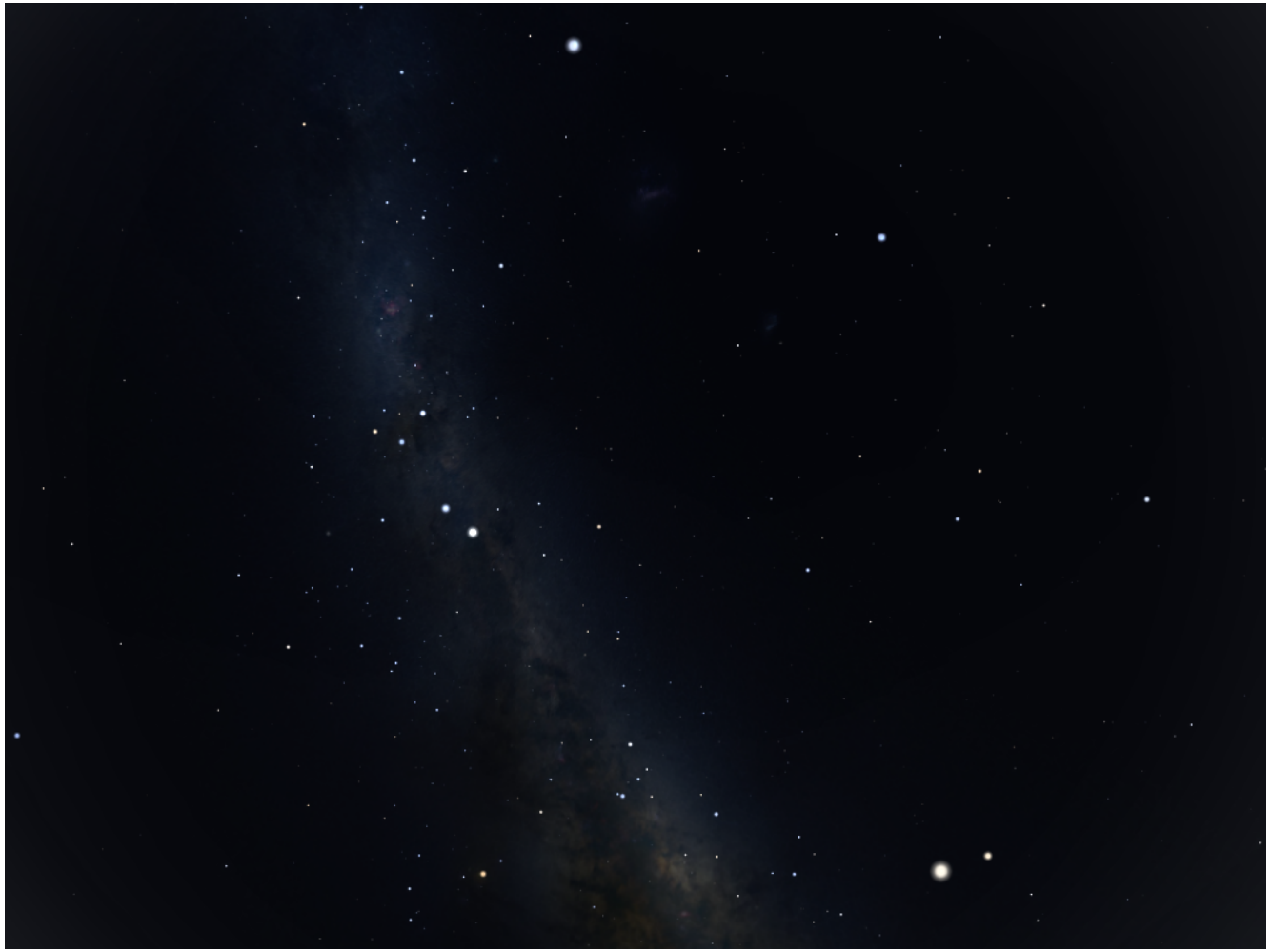
Uses ktrain package

Proposed system

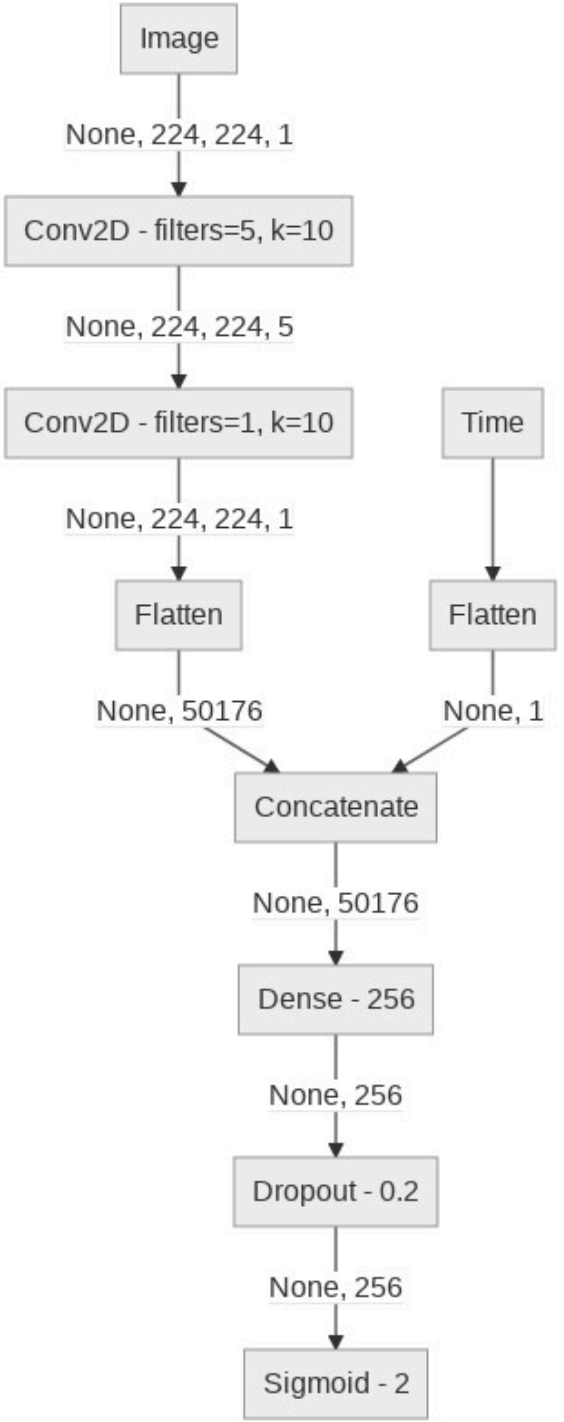


Onboard Jetson

Image generation



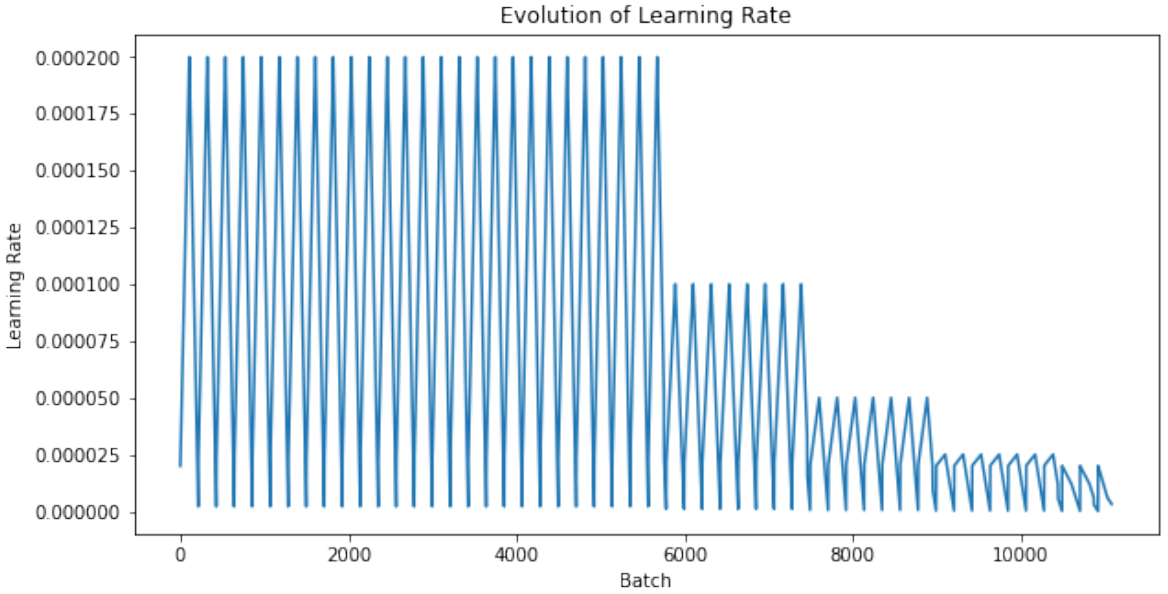
Model architecture

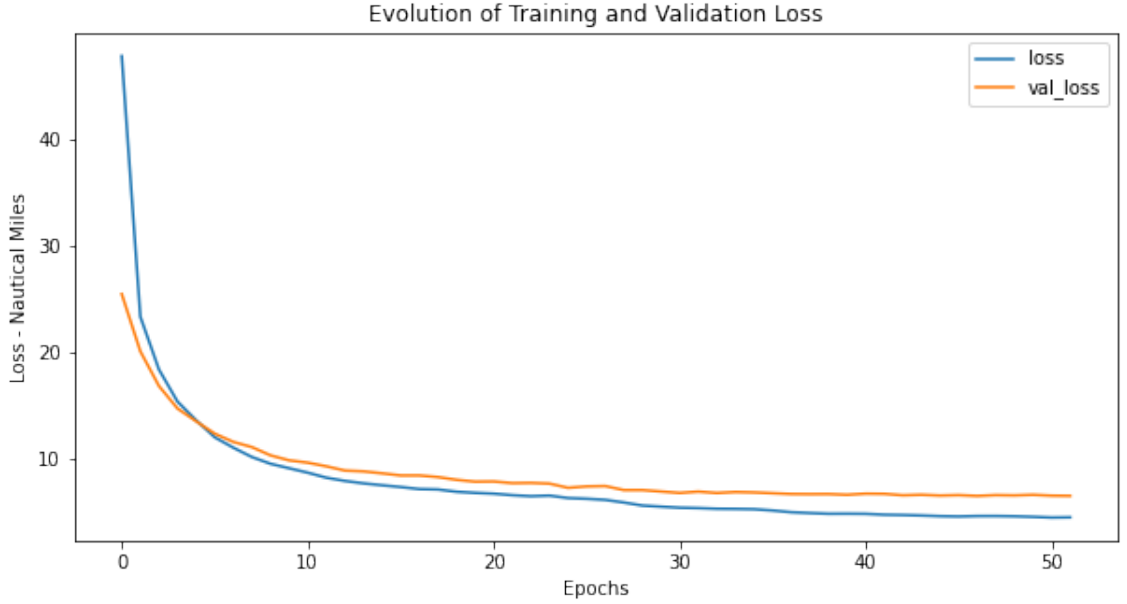


Loss function

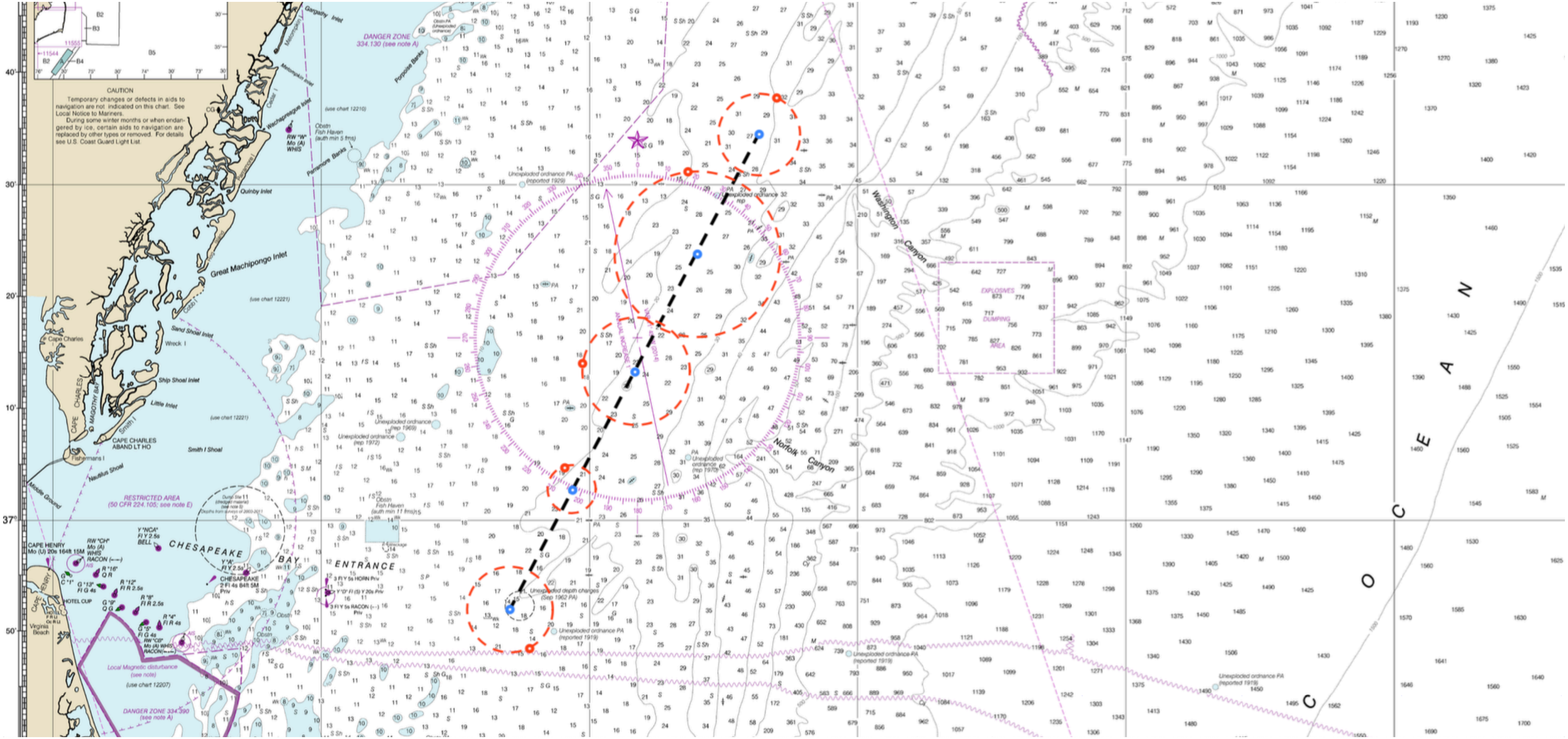
$$d = 2r \arcsin\left(\sqrt{\sin^2\left(\frac{\phi_2 - \phi_1}{2}\right) + \cos(\phi_1)\cos(\phi_2)\sin^2\left(\frac{\lambda_2 - \lambda_1}{2}\right)}\right)$$

Model training





Accuracy



CAUTION
Temporary changes or defects in aids to navigation are not indicated on this chart. See Local Notice to Mariners.
During some winter months or when endangered by ice, certain aids to navigation are replaced by other types or removed. For details see U.S. Coast Guard Light List.
DANGER ZONE 334.130 (see note A)
Great Machipongo Inlet
Quinby Inlet
Wachapreague Inlet
Sand Shoal Inlet
Ship Shoal Inlet
Little Inlet
Cape Charles
CAPE CHARLES ABAND LT HO
Smith I Shoal
Fishermans I
Nautilus Shoal
Middle Ground
RESTRICTED AREA (50 CFR 224.105; see note E)
CHESAPEAKE BAY ENTRANCE
CAPE HENRY
Virginia Beach
Local Magnetic disturbance (see note)
(use chart 12207)
DANGER ZONE 334.390 (see note A)
Washington Canyon
Norfolk Canyon
EXPLOSIVES DUMPING AREA
Unexploded ordnance PA (reported 1929)
Unexploded depth charges (Sep 1962 PA)
Unexploded ordnance PA (reported 1919)
OCEAN

Demo

Next steps

- Build generators to allow training sets that do not fit in memory
- Continue testing/refining architectures
- Account for weather
- Engineering analysis
  - Compass error
  - Camera height error
- Identify camera and test