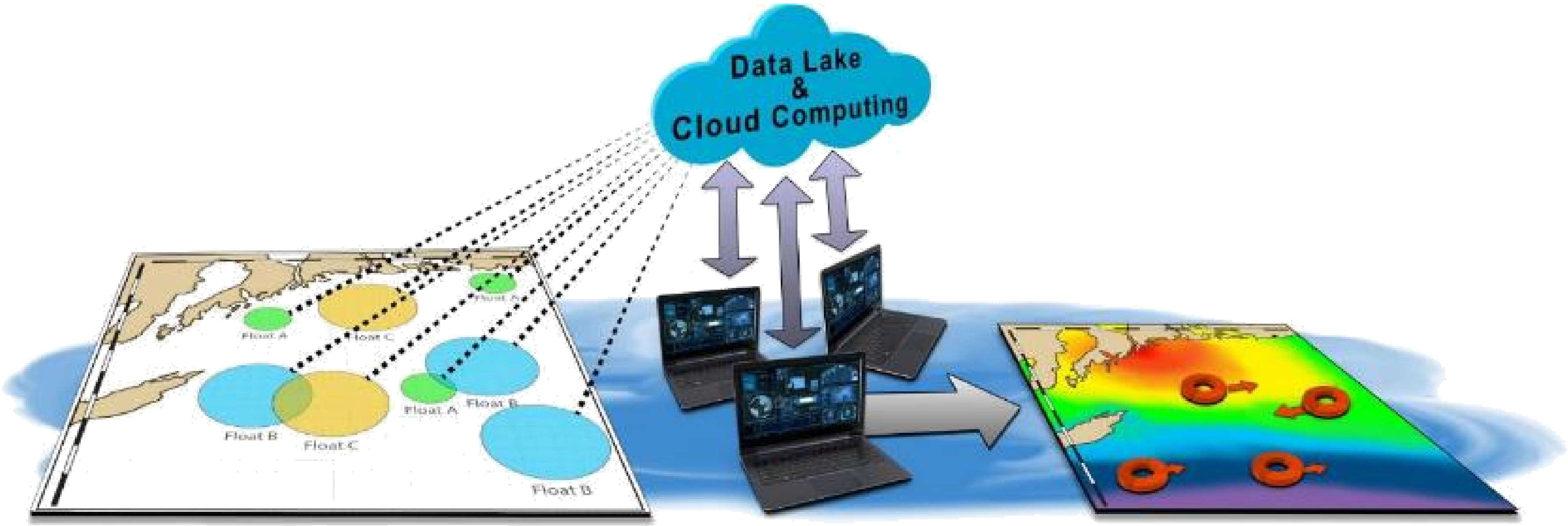
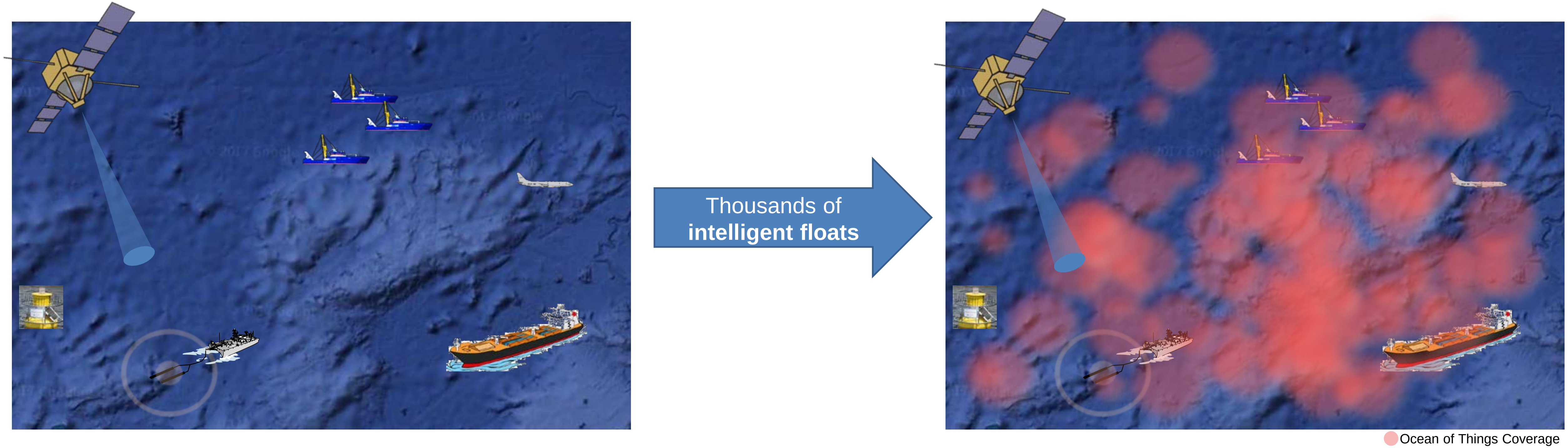
Ocean of Things: Low-cost Distributed Sensing with Scalable Analysis for Maritime Situational Awareness

Defense Advanced Research Projects Agency (DARPA)
Program Manager – John Waterston



PROBLEM: Significant gaps in ocean awareness

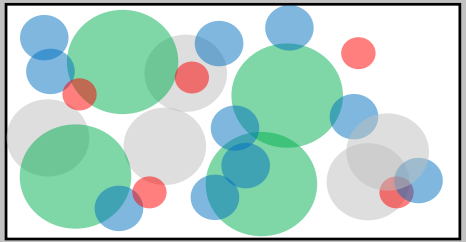
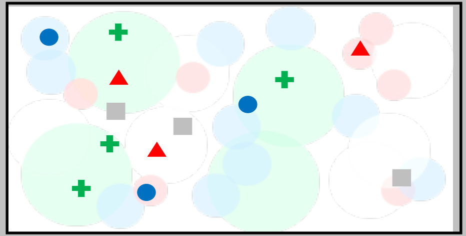
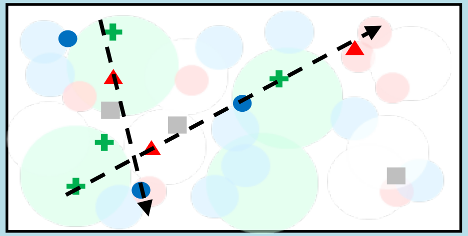
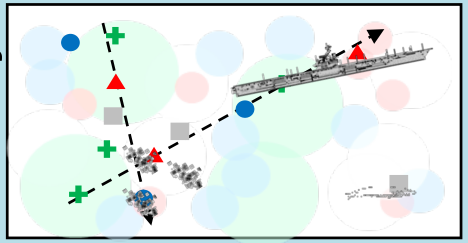
The military, commercial, and scientific communities desire additional understanding of their environment. Ocean of Things provides **persistent, wide-area, multi-modal** coverage through large scale employment of floats.

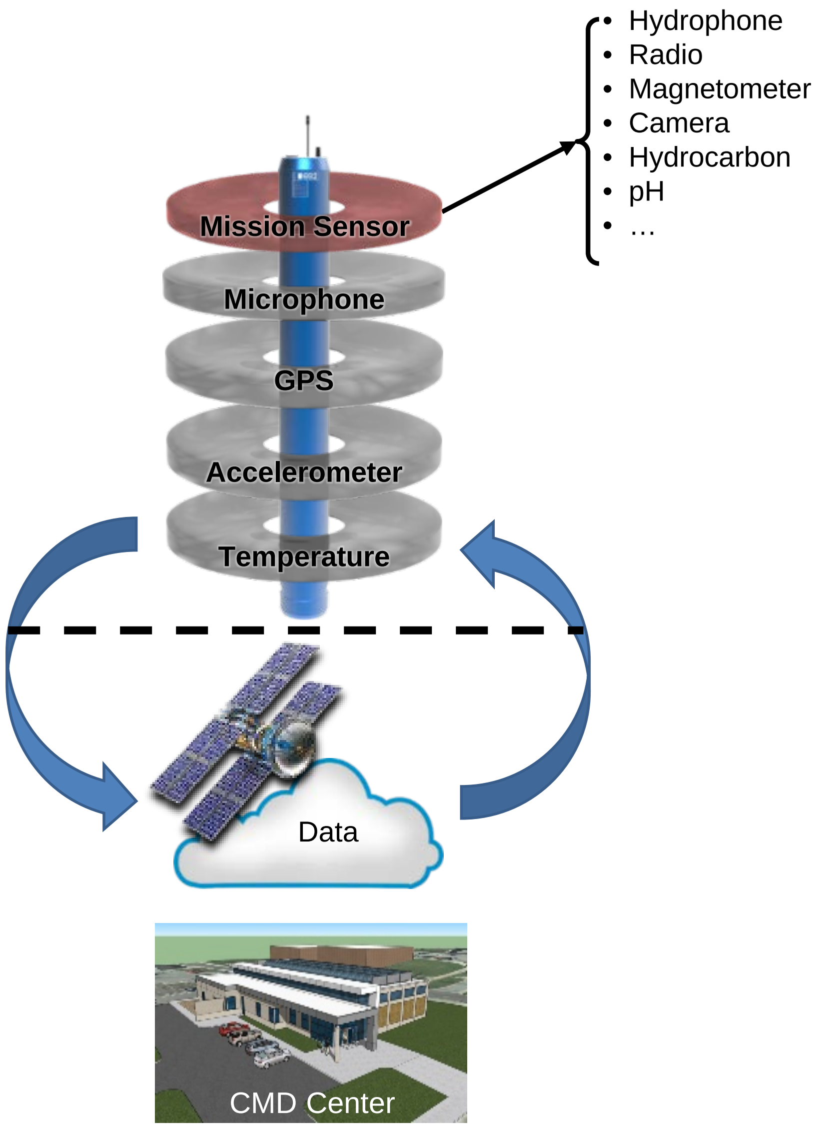


- Each float operates for > 1-year using widely available components
- Object and sensor motion allow for the collection of physical and activity-based information
- Multi-sensor fusion and machine learning techniques used to characterize maritime tracks
- Ocean of Things supports multiple missions with its heterogeneous capabilities

Affordably increasing maritime capability and coverage

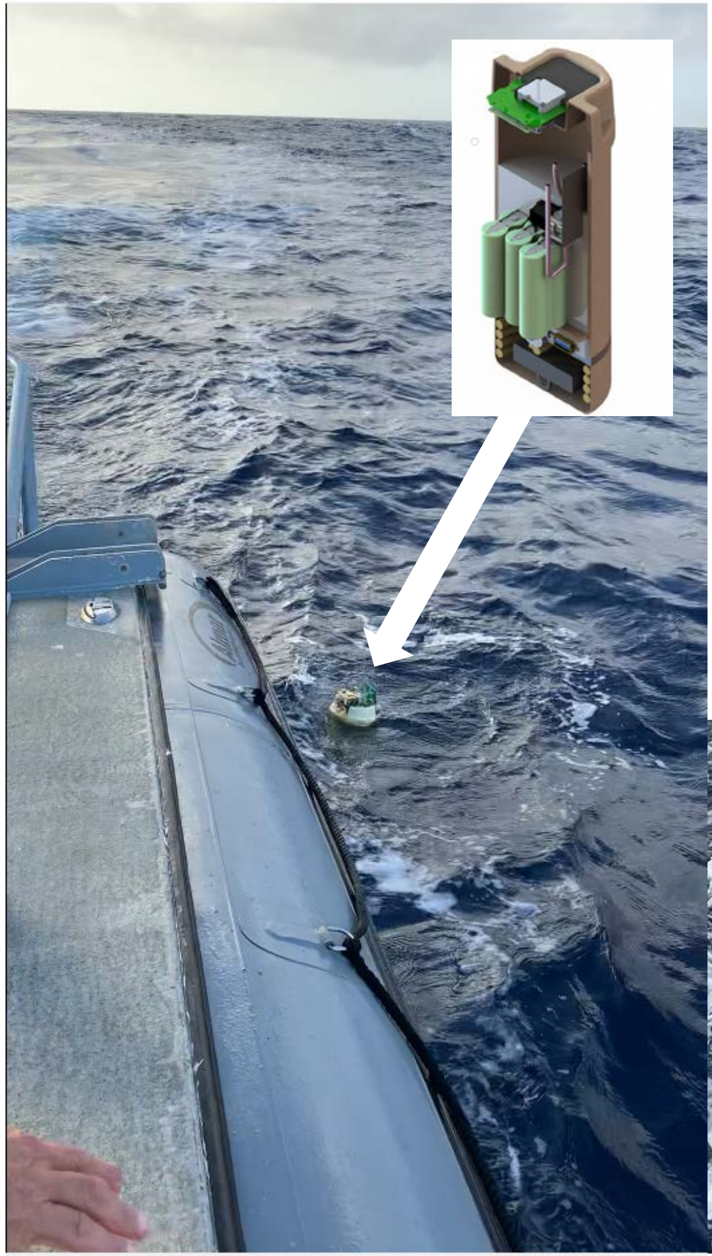
PROCESS: Collect float data to understand ocean activity & environment

	Ocean of Things Activity	Outputs	Data Products
TA-1	**Measure** 	• Periodic scalar sensor data • Float locations	• Fine resolution environmental data • Ocean of Things system performance
TA-1	**Report** 	• Episodic event declarations via Iridium	• Activity cueing • Anomaly reports • Unique bell-ringer signatures
TA-2	**Fuse** 	• Track reports	• Vessel tracks to common tactical plot • Data confidence values
TA-2	**Classify** 	• Contact signatures • Platform ID • Behavioral norms	• Object/vessel behaviors • Intelligence reporting • Indications and warnings

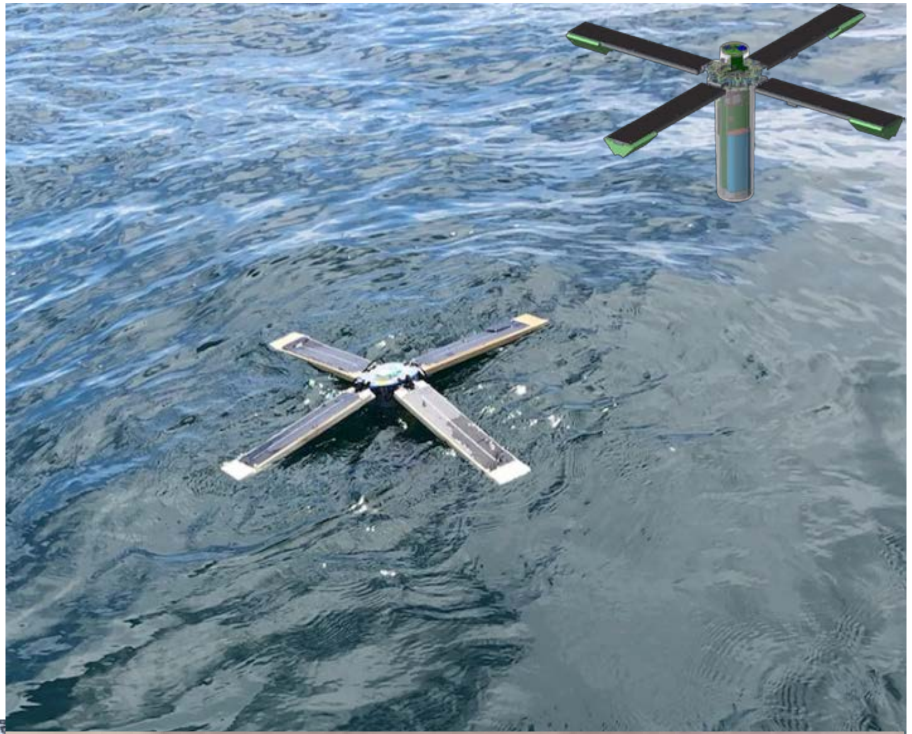


PNT: Positioning, Navigation and Timing

Float Hardware



Phase 1 Onboard Sensors:
- Sea Surface Temperature
- GPS Position
- Inertial Measurement Unit (IMU)
- AIS Receiver
- Surface Pressure
- Relative Humidity
- Cloud Cover
- Software Defined Radio (SDR)
- Microphone
- Hydrophone
- Camera
- Conductivity



Smart floats processing on the edge: Working with TA-1 Performers

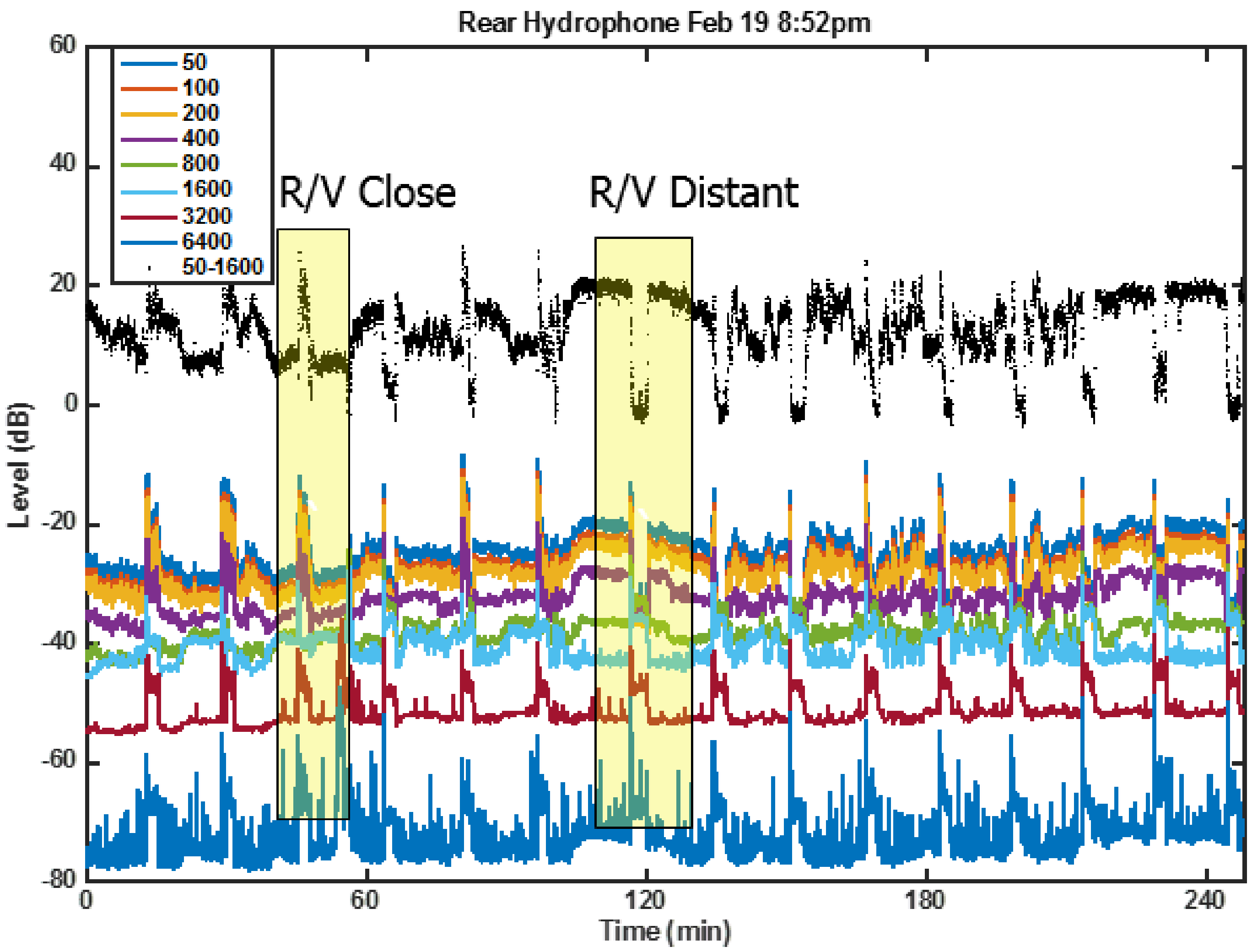
Edge processing includes detection algorithms for numerous events that could potentially correlate to tracks:

- Marine mammals and biologic activity
- Vessel activity
- Anomalies

Priority based queues manage report transmissions:

- Periodic based timelines (e.g., planned health and status)
- Event based reports (e.g., detection above a threshold)
- Queue created and re-prioritized based on observed activity

Transmission size is limited. Working with Float Hardware Performers on efficient transmission management will contribute to improved energy use by the floats while providing valuable, timely data.



Example acoustic sampling and processing

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Ocean of Things – Data Overview

Dr. Jeff Ellen

Naval Information Warfare Center (NIWC) - Pacific

Phase 2 Proposer’s Day – April 7, 2020

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Outline

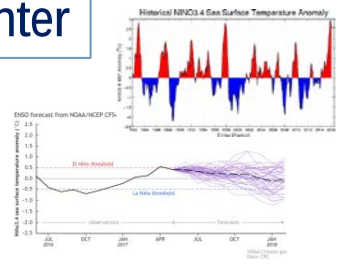
- Ocean of Things (OoT) Data flow overview
  - Float Report Generation
  - Float Command Sequence
- Data/Software Responsibilities
- Resources + Access
- Software Build Process
- Phase 1 Lessons Learned
- Summary

Ocean of Things Data Operational Diagram

Data transmitted from TA 1 floats via Iridium

Data to shore via DISA EMSS Gateway

Visualizations hosted by NIWC data center



Iridium SBD

Data stored in NIWC data center

Algorithms developed by TA2s process data

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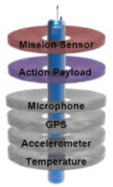
Float Report Generation

1. Raw data recorded by TA1 float sensors
2. Data condensed to reports by TA1 float encoder
   - Clever byte packing, summarization, smoothing, etc.
3. Bytes sent as Iridium Mobile Originated (MO) message
4. Bytes sent via TCP to NIWC's OoT Cloud by Iridium/DISA
5. Bytes unpacked/logged/archived by OoT Gov switchboard
6. Bytes decoded by TA1-provided REST endpoint
   - Rich Representation – Avro + JSON
7. Avro posted to Apache Kafka pub/sub streaming pipeline by OoT Gov switchboard
8. Reports consumed by TA2 Clients



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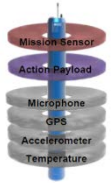
Float Command Sequence

1. Avro command posted to Kafka pipeline by <u>TA2 Client</u>
2. Command consumed by OoT Gov Switchboard
3. Command encoded (as bytes)
   <u>by TA1-provided</u> REST endpoint
4. Bytes sent via TCP to Iridium/DISA by NIWC’s OoT Cloud
5. Bytes queued as Iridium Mobile Terminated (MT) message
6. Float checks inbox after sending MO message
7. Bytes downloaded as MT message by float modem
8. MT message decoded <u>by TA1 float decoder</u>
9. Action(s) taken <u>by TA1 float logic</u> to follow command







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Data/Software Responsibilities

TA1

- Provide encoder / decoder for float messages
- Provide documentation
- Optimize useful data

NIWC

- Host infrastructure
- Provide Access
- Decide formats
- Serve Kafka + Avro
- <u>Verify decoder</u>
- <u>Generate quality test data</u>

TA2

- Use Cloud
- Leverage DevOps
- Consume Kafka
- Follow Schema
- <u>Inform TA1s (report utility)</u>
- <u>Deliver novel data ‘products’</u>

Resources + Access – NRDE GovCloud

- NRDE (Naval R&D Environment) - GovCloud
  - DoD Authorized Amazon Web Services
- Similar to public offerings, but US Hosted, security compliant etc.
- Entire OoT infrastructure is hosted on AWS
  - Primarily EC2 instances
- Potential for higher levels of security than UNCLASS
- Metered access – Paid directly by DARPA

Resources + Access - SkyDesk

- SkyDesk – Customized Citrix for access to NIWC network
- Can originate from Windows, MacOS, Linux
- Endpoint is Windows 10 instance hosted on GovCloud
- CAC card required
  - # of CAC per team limited by security principles
  - <u>Long Lead Time</u> – reissued not transferred - choose wisely
- Monthly fee paid by DARPA

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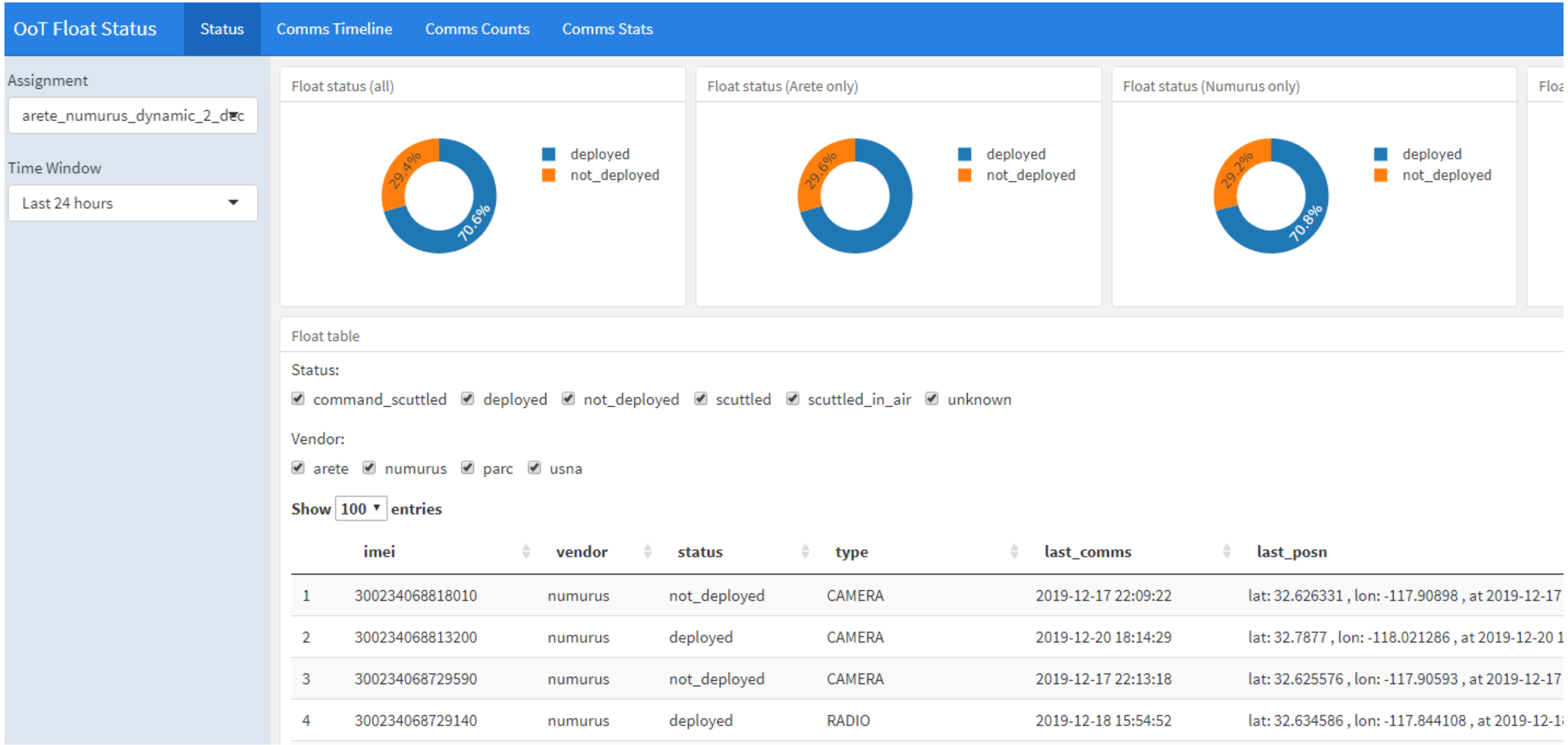
Resources + Access - Float Status Tool – Gov

- Monitor low-level comms of groups of floats
- Actively developed/supported by NSWC Dahlgren



	imei	vendor	status	type	last_comms	last_posn
1	300234068818010	numurus	not_deployed	CAMERA	2019-12-17 22:09:22	lat: 32.626331 , lon: -117.90898 , at 2019-12-17
2	300234068813200	numurus	deployed	CAMERA	2019-12-20 18:14:29	lat: 32.7877 , lon: -118.021286 , at 2019-12-20 1
3	300234068729590	numurus	not_deployed	CAMERA	2019-12-17 22:13:18	lat: 32.625576 , lon: -117.90593 , at 2019-12-17
4	300234068729140	numurus	deployed	RADIO	2019-12-18 15:54:52	lat: 32.634586 , lon: -117.844108 , at 2019-12-1

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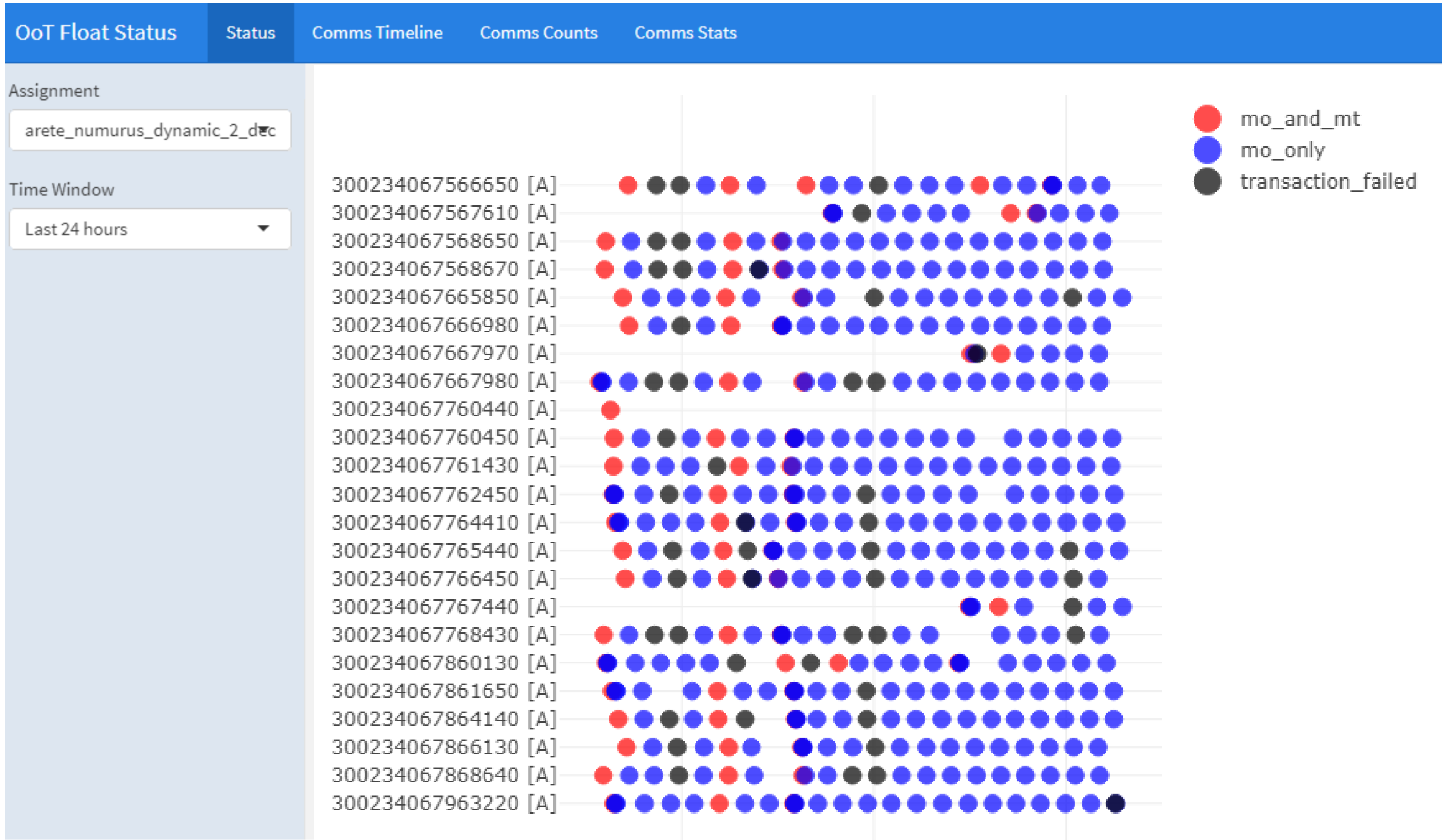
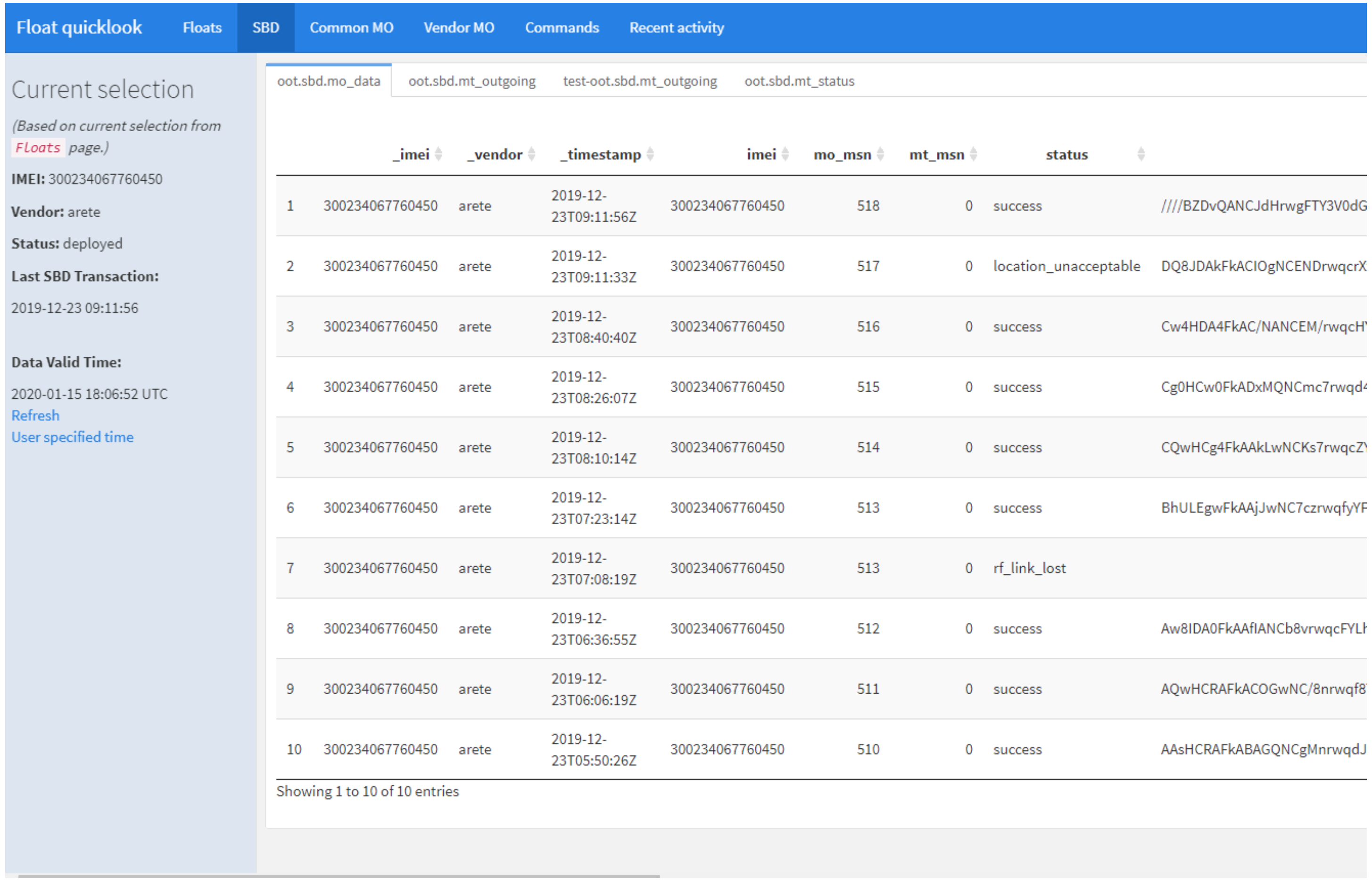
Resources + Access - Float Status Tool – Gov

- Verify float connectivity
- Ascertain status of tests + deployments



Resources + Access - Float Quicklook Tool

- Provides detailed information recent float comms
- Provides last #N messages for individual floats + OoT-wide



Float quicklook | Floats | SBD | Common MO | Vendor MO | Commands | Recent activity

Current selection

(Based on current selection from `Floats` page.)

IMEI: 300234067760450

Vendor: arete

Status: deployed

Last SBD Transaction:

2019-12-23 09:11:56

Data Valid Time:

2020-01-15 18:06:52 UTC

Refresh

User specified time

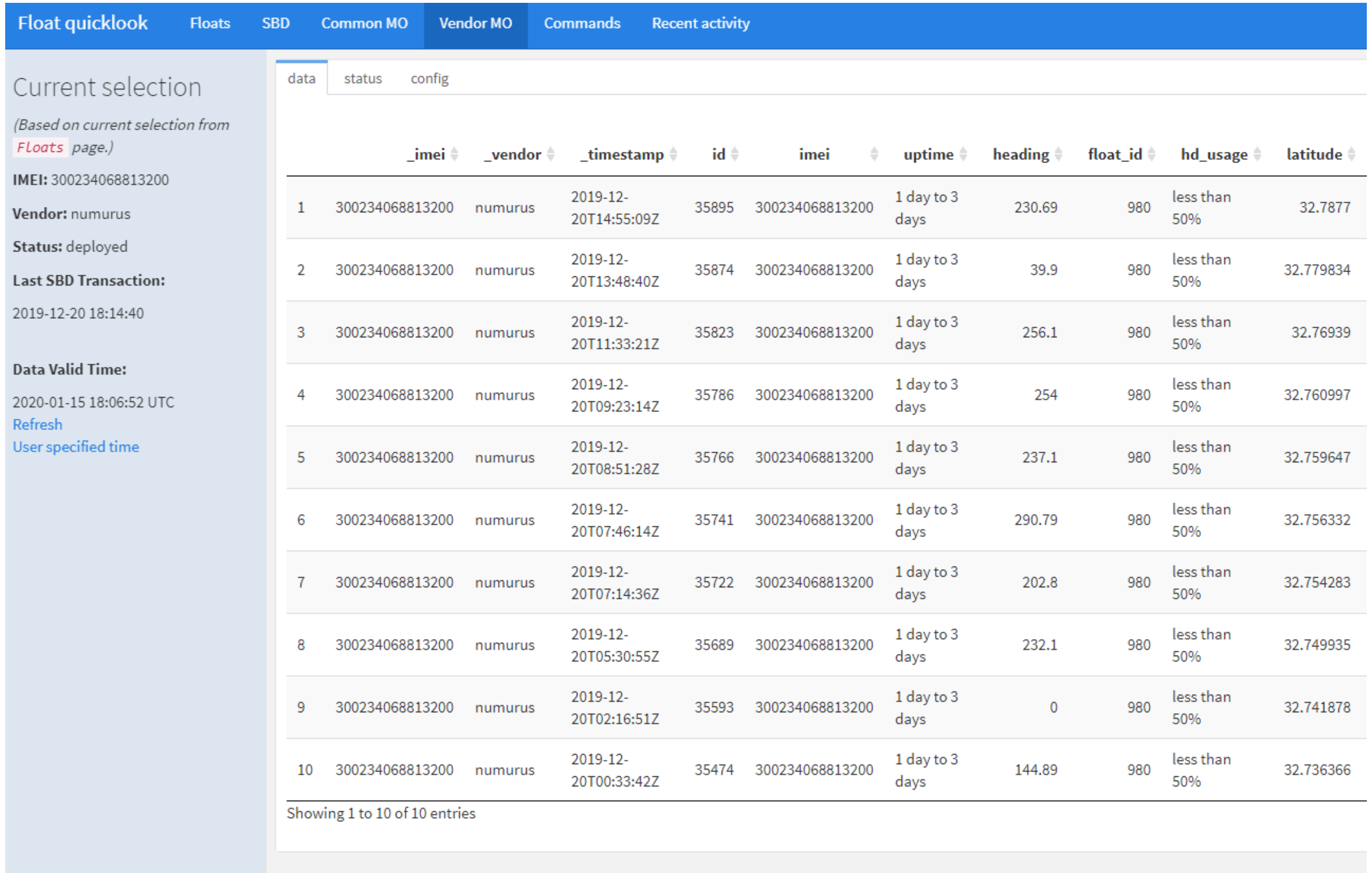
oot.sbd.mo_data | oot.sbd.mt_outgoing | test-oot.sbd.mt_outgoing | oot.sbd.mt_status

	_imei	_vendor	_timestamp	imei	mo_msn	mt_msn	status	
1	300234067760450	arete	2019-12-23T09:11:56Z	300234067760450	518	0	success	////BZDvQANCJdHrwgFTY3V0dG
2	300234067760450	arete	2019-12-23T09:11:33Z	300234067760450	517	0	location_unacceptable	DQ8JDAkFkACIOgNCENDrwqcrX
3	300234067760450	arete	2019-12-23T08:40:40Z	300234067760450	516	0	success	Cw4HDA4FkAC/NANCEM/rwqcH
4	300234067760450	arete	2019-12-23T08:26:07Z	300234067760450	515	0	success	Cg0HCw0FkADxMQNCmc7rwqd
5	300234067760450	arete	2019-12-23T08:10:14Z	300234067760450	514	0	success	CQwHCg4FkAAkLwNCKs7rwqcZ
6	300234067760450	arete	2019-12-23T07:23:14Z	300234067760450	513	0	success	BhULEgwFkAAjJwNC7czrwqfyYF
7	300234067760450	arete	2019-12-23T07:08:19Z	300234067760450	513	0	rf_link_lost	
8	300234067760450	arete	2019-12-23T06:36:55Z	300234067760450	512	0	success	Aw8IDA0FkAAfIANCb8vrwqcFYL
9	300234067760450	arete	2019-12-23T06:06:19Z	300234067760450	511	0	success	AQwHCRAFkACOGwNC/8nrwqf8
10	300234067760450	arete	2019-12-23T05:50:26Z	300234067760450	510	0	success	AAsHCRAFkABAGQNCgMnrwqdJ

Showing 1 to 10 of 10 entries

Resources + Access – Kafka + Avro

- Provides human-readable decoded messages
- Allows browsing of key topics by IMEI

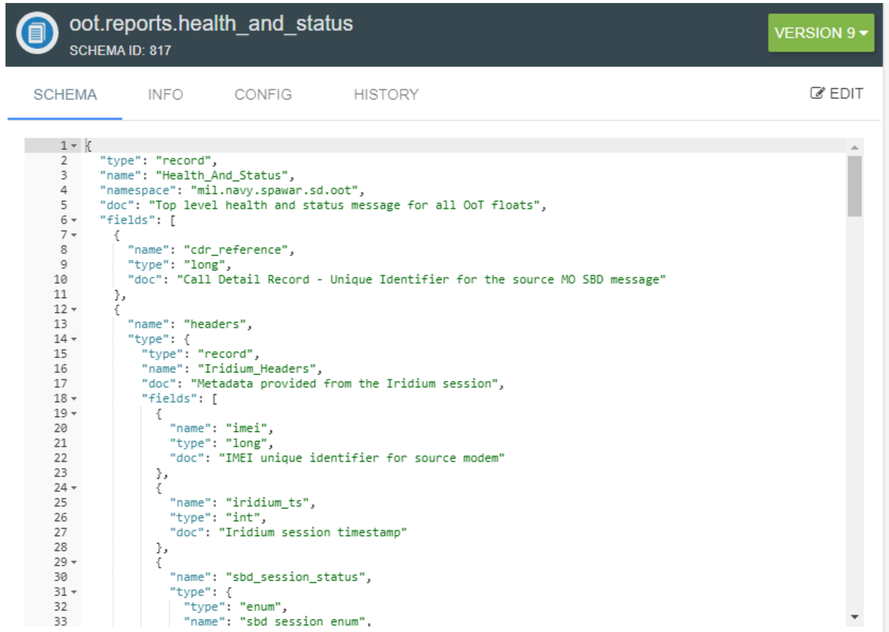


	_imei	_vendor	_timestamp	id	imei	uptime	heading	float_id	hd_usage	latitude
1	300234068813200	numurus	2019-12-20T14:55:09Z	35895	300234068813200	1 day to 3 days	230.69	980	less than 50%	32.7877
2	300234068813200	numurus	2019-12-20T13:48:40Z	35874	300234068813200	1 day to 3 days	39.9	980	less than 50%	32.779834
3	300234068813200	numurus	2019-12-20T11:33:21Z	35823	300234068813200	1 day to 3 days	256.1	980	less than 50%	32.76939
4	300234068813200	numurus	2019-12-20T09:23:14Z	35786	300234068813200	1 day to 3 days	254	980	less than 50%	32.760997
5	300234068813200	numurus	2019-12-20T08:51:28Z	35766	300234068813200	1 day to 3 days	237.1	980	less than 50%	32.759647
6	300234068813200	numurus	2019-12-20T07:46:14Z	35741	300234068813200	1 day to 3 days	290.79	980	less than 50%	32.756332
7	300234068813200	numurus	2019-12-20T07:14:36Z	35722	300234068813200	1 day to 3 days	202.8	980	less than 50%	32.754283
8	300234068813200	numurus	2019-12-20T05:30:55Z	35689	300234068813200	1 day to 3 days	232.1	980	less than 50%	32.749935
9	300234068813200	numurus	2019-12-20T02:16:51Z	35593	300234068813200	1 day to 3 days	0	980	less than 50%	32.741878
10	300234068813200	numurus	2019-12-20T00:33:42Z	35474	300234068813200	1 day to 3 days	144.89	980	less than 50%	32.736366

Showing 1 to 10 of 10 entries

Resources + Access – Kafka + Avro

- Kafka cluster provides incoming message traffic
- Avro schemas create commonality across report types
- Kafka also provides TA2← → TA2 exchange
- Provide documentation for outgoing float commands
- Provide documentation for accessing raw float data (via wifi)



Resources + Access – Kafka + Avro

▼ Existing Data flow + Kafka Topics

Topic: Oot.sbd.mo_data (json)
Content: Raw float binary payloads (+ some metadata)

Python: master_decoder
Algorithm:
- Look up decoder by TA1 (mfr)
- Call mfr REST interface
- Publish resulting Avro/Json

Python: (provided by TA1s)
Algorithm:
- Provide REST endpoint
- Accept Binary payload
- Return JSON/Avro

Topic: arete.data (json)
Content: decoded Arete data

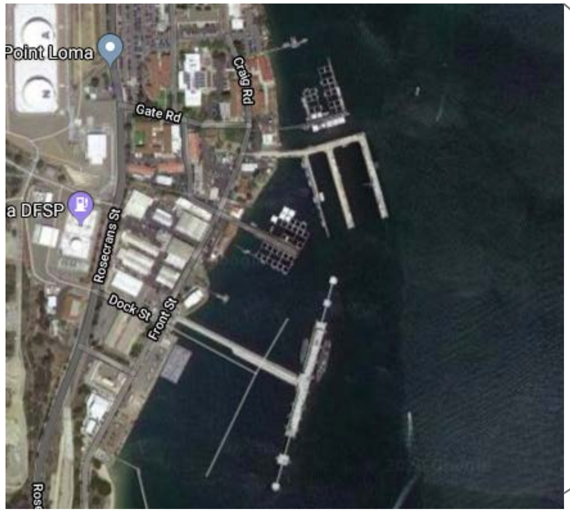

Topic: numurus.data (json)
Content: decoded Numurus data

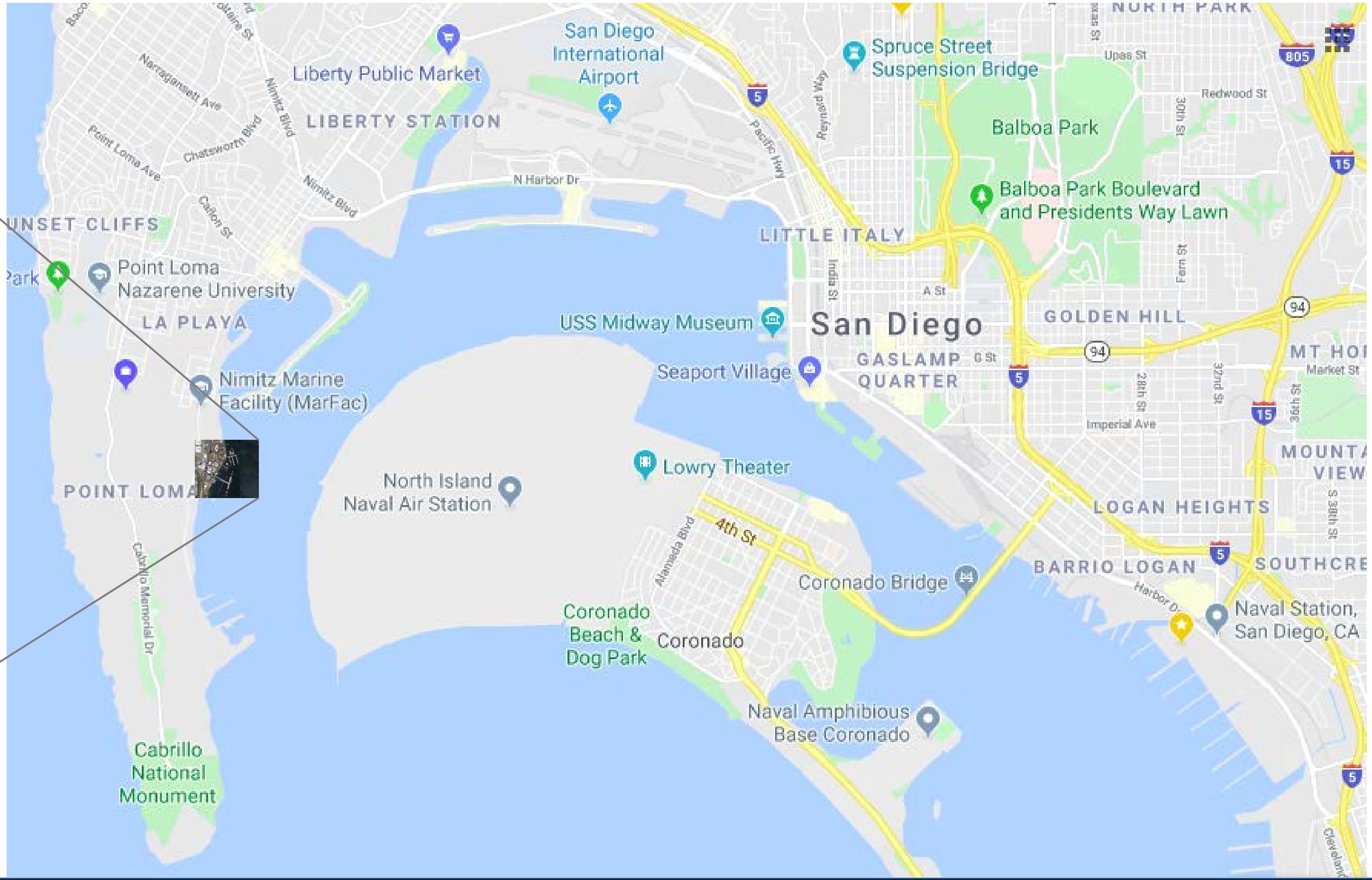
Topic: oot.reports.* (Avro)
Content: decoded PARC and USNA data

- **Topic: oot.reports.health_and_status**
- Content: float position and operations
- **Topic: oot.reports.environmental**
- Content: temp, salinity, etc.
- **Topic: oot.reports.mission_sensors**
- Content: hydrophone, camera, etc

Resources + Access - NIWC float deployment

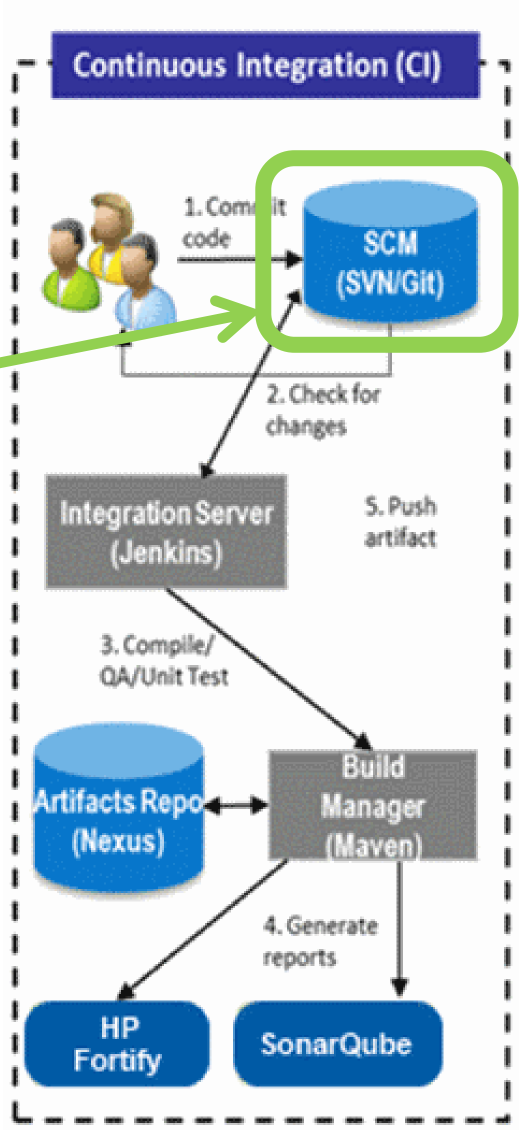
- NIWC deploys floats both pierside and in open water
- Pierside environment is signal-rich





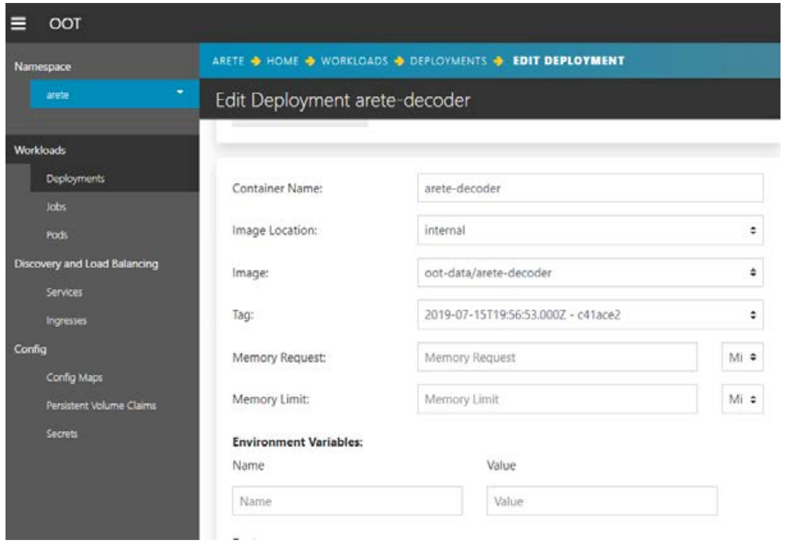
Software Build Process – DevOps Principles

- Continuous Integration / Continuous Deployment
  - No mailing discs, minimize delays
- Leveraging primarily open source technologies
- Di2e – Hosting source code repo
  - DoD instance of BitBucket, Jira, etc.
  - Accessible from internet
  - Accessible from NRDE GovCloud
  - Access controlled via CAC
  - Access limited to own team + Gov



Software Build Process - SUDOE

- SUDOE - Secure Unified DevOps Orchestration Engine
- Dashboard for managing build, deployment, monitoring
- Supports many languages (e.g. Java, JavaScript, Python)
- Deploys software and infrastructure using micro-services, containers, and virtual machine technologies
  - Currently supports AWS deployment of Docker, Kubernetes, etc.
- Manages network and access rules
  - E.g. Routing, ingress, VPC
- Provides view of console/errors
- Actively being developed by NIWC



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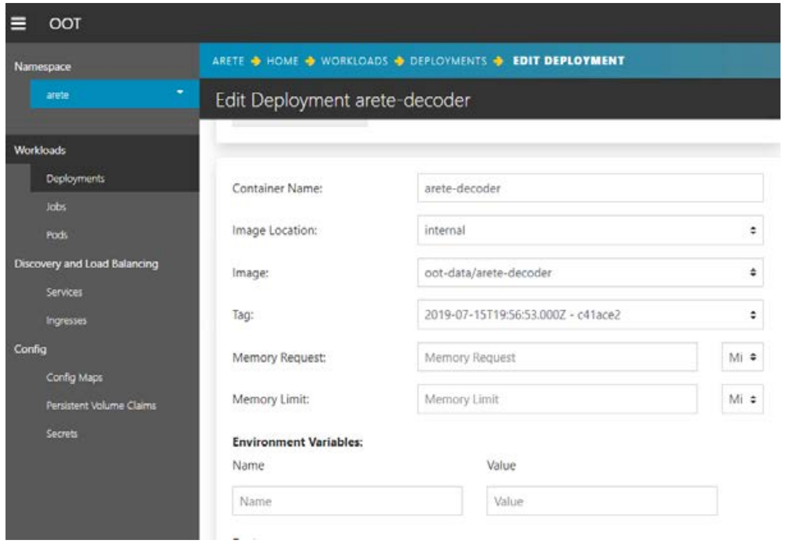
Software Build Process – SUDOE Process

1. Check code into DI2E
2. For new code, set up deployment location/size and ingress
3. For existing code, change git commit hash
4. Deploy/redeploy code, monitor error logs

- Can also provision EC2/VM for state-preserving exploration (e.g. Jupyter Notebook)
- No direct AWS Dashboard login/usage required



Phase 1 Lessons Learned - Inform TA1s

- Work with Gov + TA1 to refine onboard data processing
- Analyze sample raw data from sensors when available
- Analyze past deployments (pierside, SoCal, GoMex)
- Gauge usefulness of health & status reports
  - Float battery level, charge rate, status/error codes, scuttle msgs
- Assess accuracy and fidelity of environmental reports
  - Temperature, Wave height, GPS trajectories
- Determine validity of mission sensor data
  - Evaluate acoustic/radio signal summaries, image analysis
- Exercise any parameters/options/priorities TA1s provide

Phase 1 Lessons Learned

- CAC cards require long lead times
- Kafka: Great for pub/sub, less great for archiving
- Avro: be more proactive about defining, enforcing
- DI2E + SUDOE allows rapid code redeployment
- Shore/Pierside deployments more useful than expected
- TA1s need more feedback, earlier
- Oceanographic models are not always correct

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Summary

- Request CAC + accounts for key personnel
- Utilize NIWC Gov-Cloud as early as possible
- Utilize SUDOE architecture for CI/CD of all software
- Understand OoT data flow and standards used by OoT
- Utilize existing Gov tools for troubleshooting
- Inform TA1s about utility of report contents, timing, etc.
    - Utilize TA1 provided options/configurations
- Deliver novel data ‘products’, analysis,

Phase 2 Focus Areas

Proposals must address all of the following focus areas

- Field Performance and Command and Control
  - Visualization of float location, health, and field capability. Predict field performance resulting from anticipated float movement. Provide commands to floats as needed (e.g., scuttle, activate/deactivate sensors, etc.)
- Track Generation
  - Automation to associate float declarations, initiate a vessel track report, and discriminate between multiple vessels using multi-mode detections
- Data Discovery
  - Understanding of ocean signatures, identification of sensor associations across floats, and generation of many mission products available from the Ocean of Things data set. In addition to recognition of known phenomena, in Phase 2 the performers will identify and categorize new, unknown phenomena

Field Performance Command and Control

- Visualization of float location, health, and field capability
  - Clear reporting of floats position, battery life, duty cycle settings, and any anomalous data
- Predict field performance resulting from anticipated float movement
  - Knowing the current and predicted positions of floats enables the contractor to assess the overall value of the field
- Provide commands to floats as needed (e.g., scuttle, activate/deactivate sensors, etc.)
  - Floats drifting together waste energy by reporting the same information when their duty cycles can be controlled by commands

Float Motion Prediction

Description

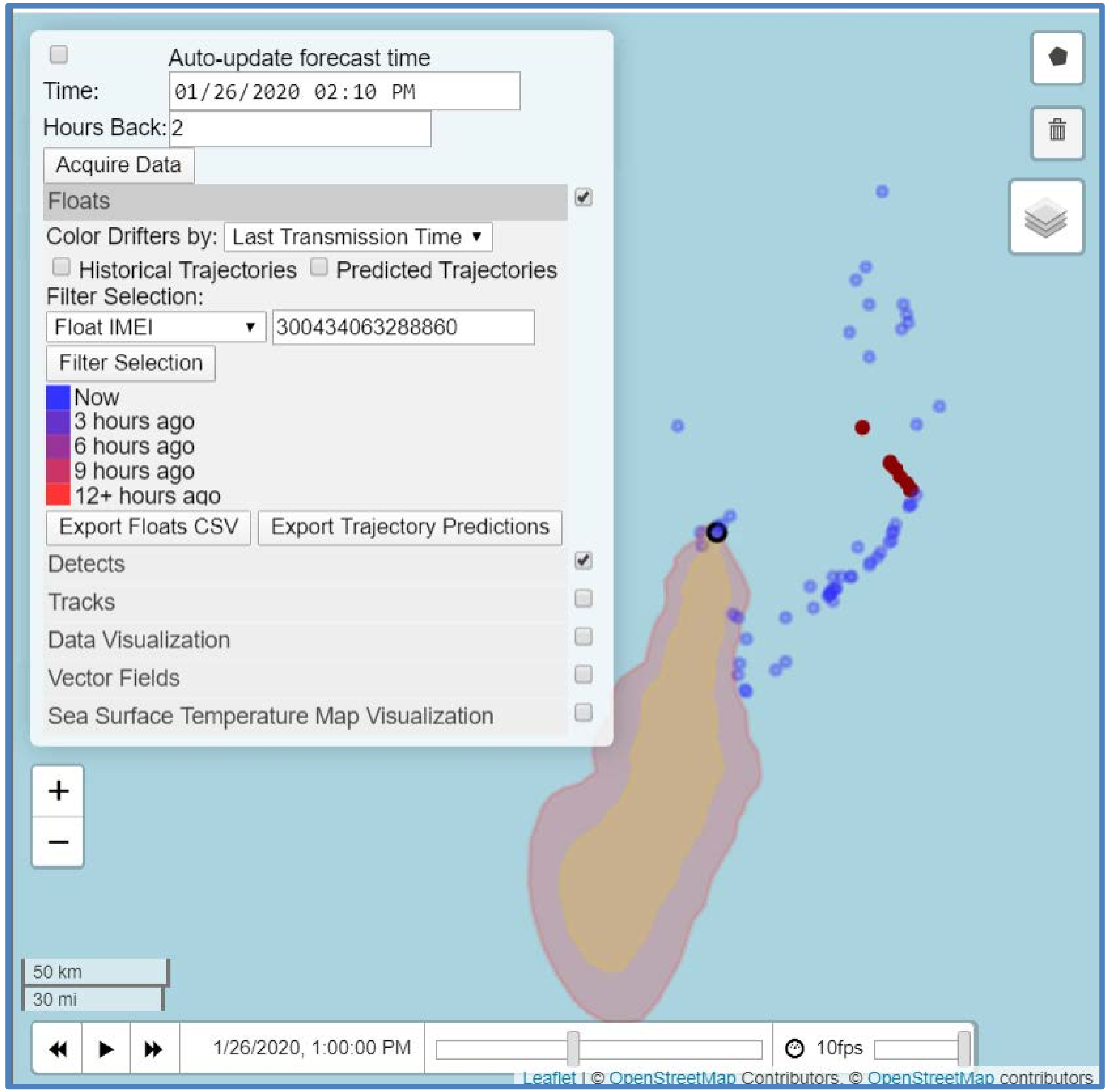
- Predict float motion using publicly available current + wind data
- Learn / Optimize parameters used to derive float motion (e.g. current + wind drag)

Communities of Interest

- Navy / DoD – predict field coverage gaps due to natural motion of floats
- Ocean Modeling – Identify limitations to current modeling techniques
- Machine Learning – baseline algorithm + data for improving float motion modeling

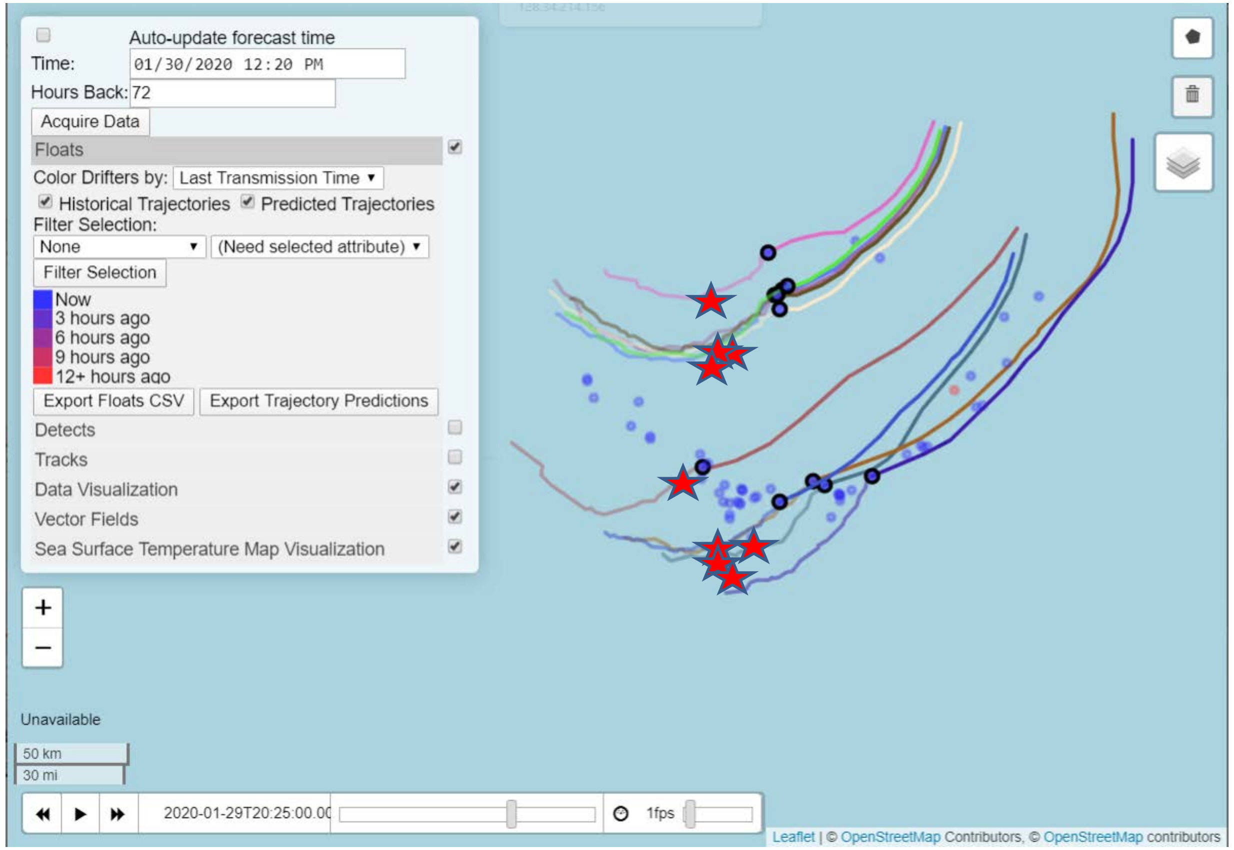
Deliveries to the Consumer

- Generate NetCDF files of observed + predicted data



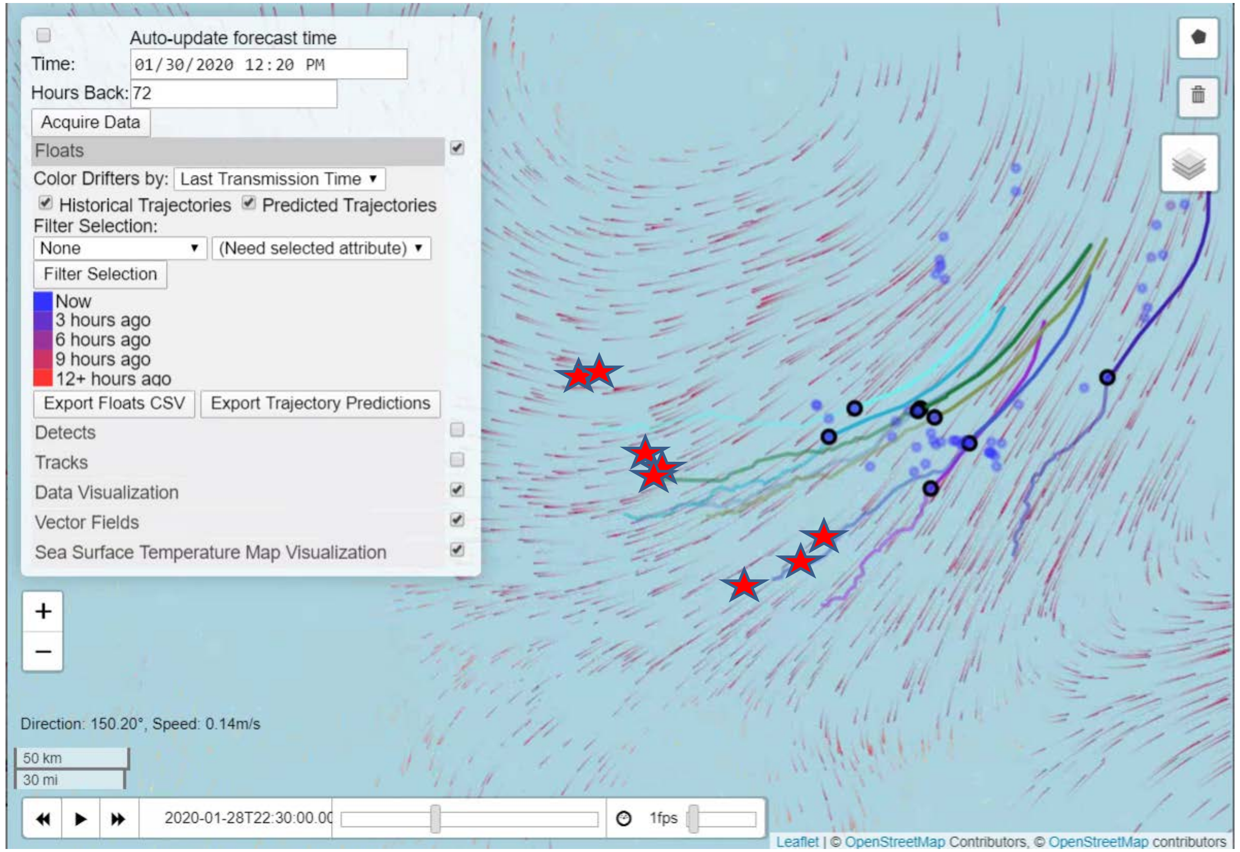
Float Field Predictions

24 Hour Prediction



★ - Real float location after 24 hours

48 Hour Prediction



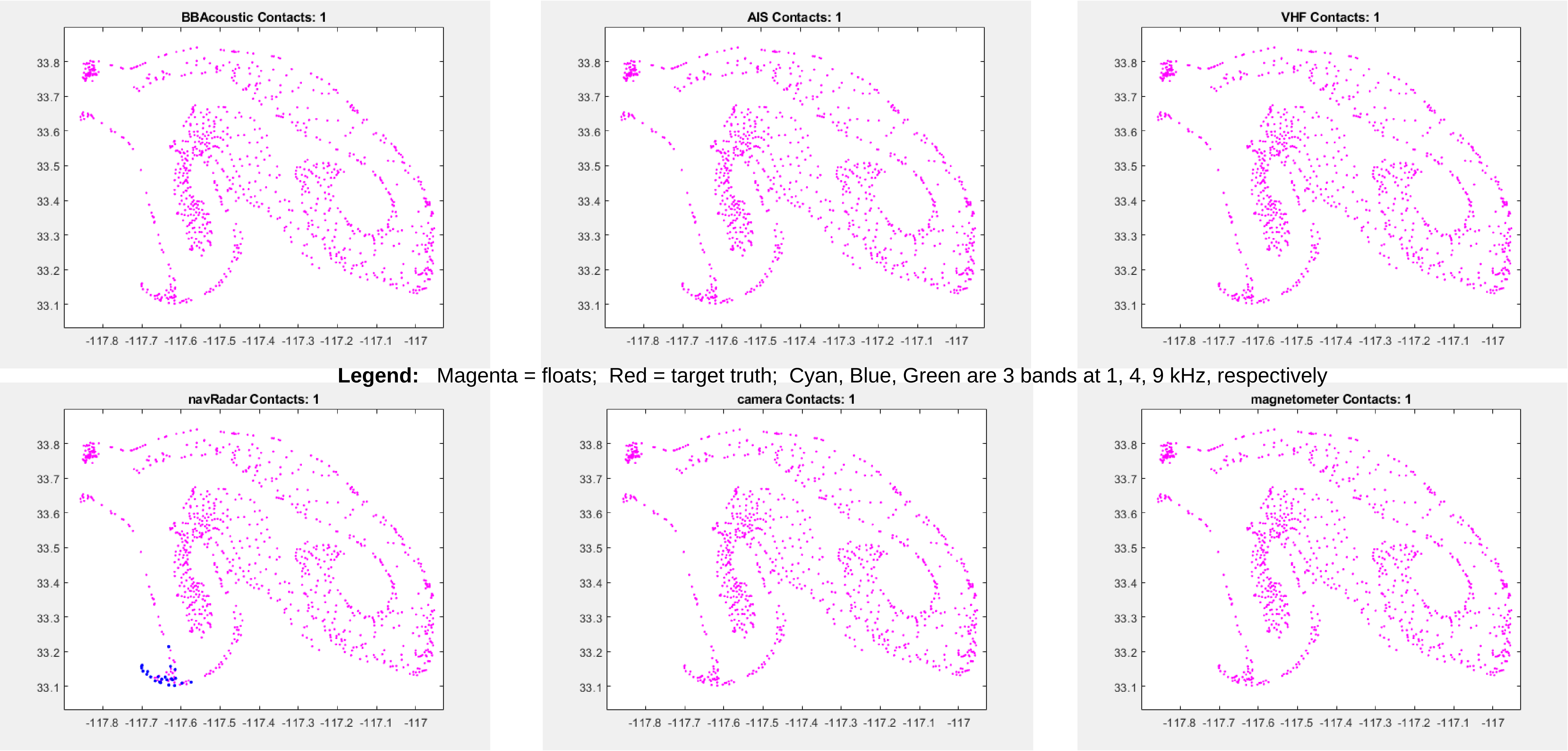
★ - Real float location after 2 days

Track Generation

- Automation to associate float declarations, initiate a vessel track report, and discriminate between multiple vessels using multi-mode detections
- “Tracks” Are not limited to vessels. An automatically generated track can include (but is not limited to)
  - Ships
  - Marine Mammals
  - Weather Fronts
  - Algae populations
  - Eddies

Simulated Multi-Modal Detections for Track Generation

- 6 modes simulated: Broadband acoustic, AIS, VHF, nav radar, camera, magnetometer

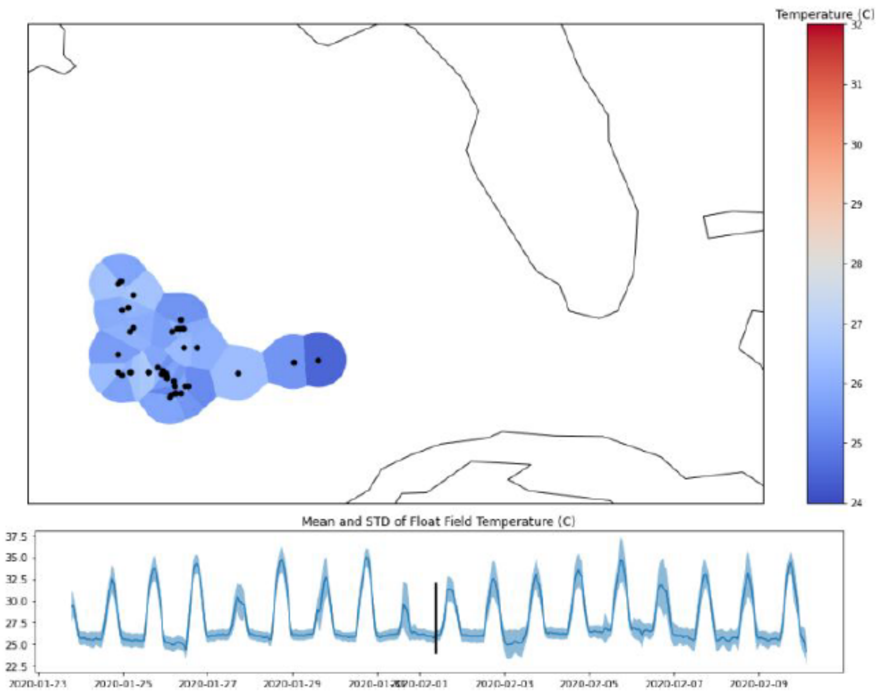


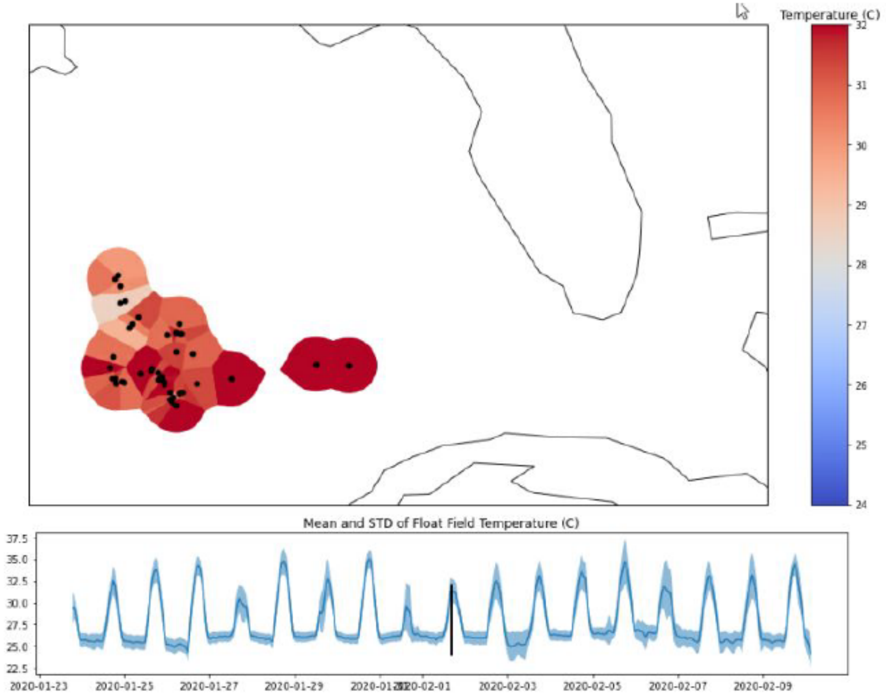
Legend: Magenta = floats; Red = target truth; Cyan, Blue, Green are 3 bands at 1, 4, 9 kHz, respectively

Data Discovery

- Understanding of ocean signatures, identification of sensor associations across floats, and generation of many mission products available from the Ocean of Things data set
- In addition to recognition of known phenomena, in Phase 2 the performers will identify and categorize new, unknown phenomena
- In Phase 2, the contractor should be able to process and display environmental data for oceanographic and meteorological models

Voronoi cells bounded using shapely convex hull and padding routines yield bounded nearest cells.

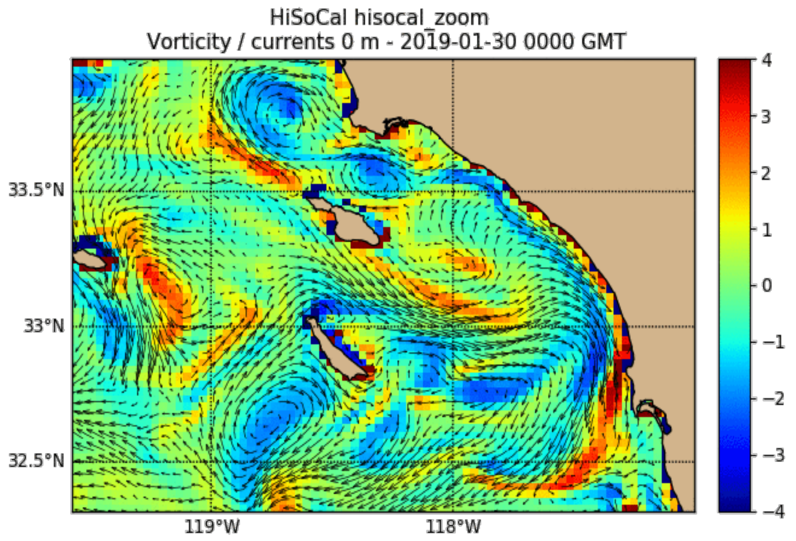




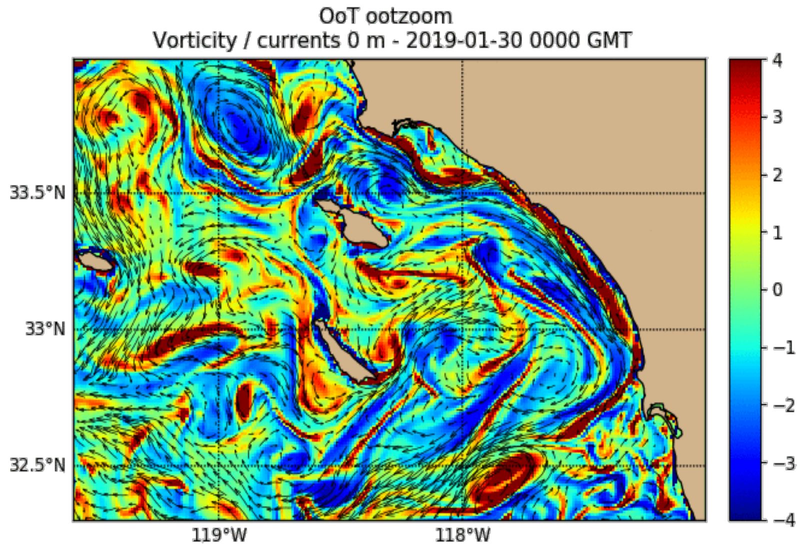
Environmental Data

- Floats include a variety of hotel sensors to support environmental analysis
  - Sea Surface Temperature
  - Inertial Measurement Unit
  - GPS Position
  - Surface pressure
  - Relative Humidity
  - Solar Flux
- Contractors should be able to take advantage of an unprecedented large field of data to identify features in real-time
  - For instance, using IMUs to sense changes in wave height, utilizing hydrophones/microphones to detect an increase in wind velocity, and surface pressure across the field to detect and track storm events

3 km HiSoCal domain zoom-in



1 km OoT domain zoom-in



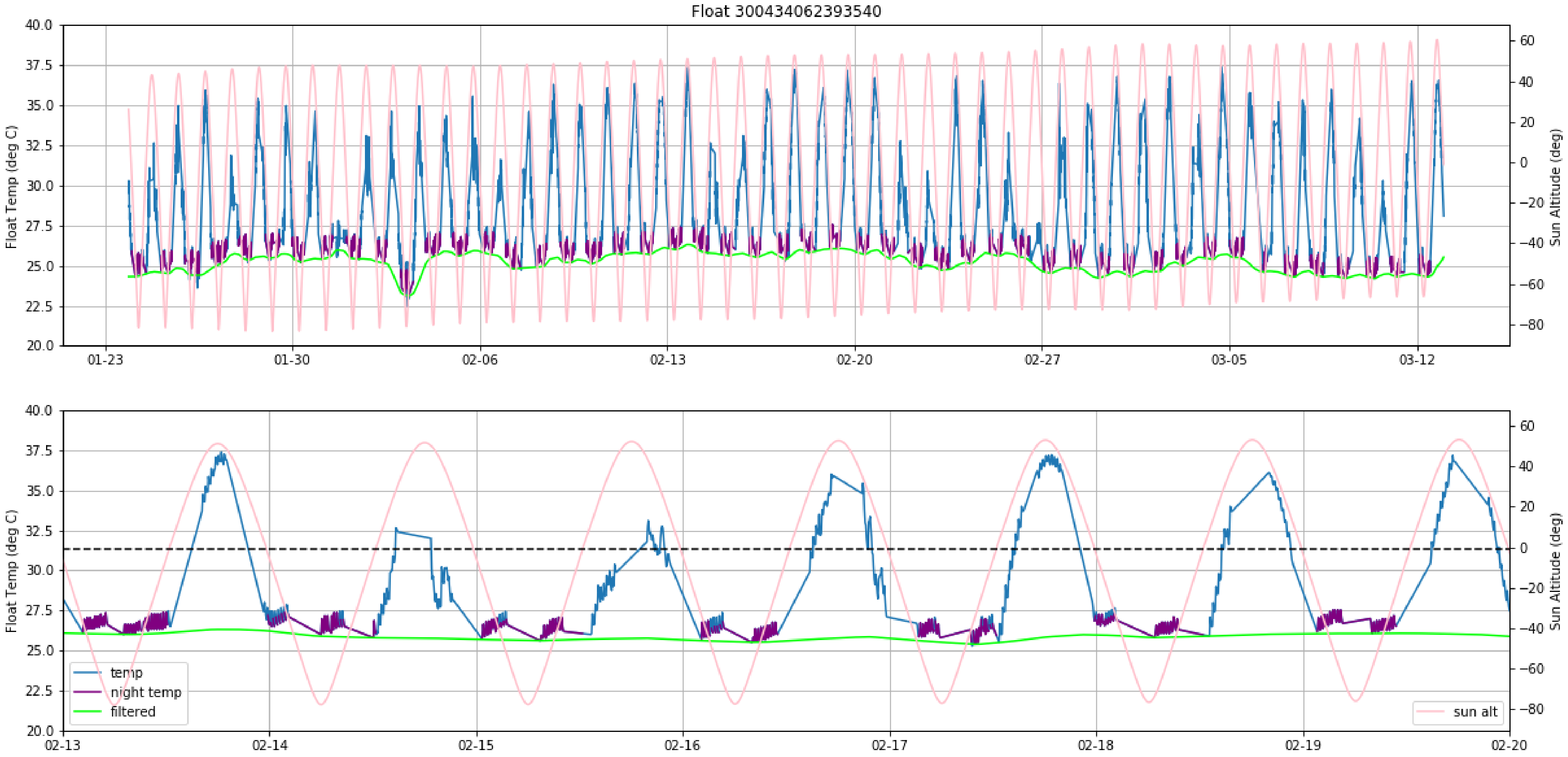
Sea Surface Temperature

- The plot below shows one performer filtering a float's reported sea surface temperature to output a temperature which does not include diurnal surface layer heating

Blue: Reported SST

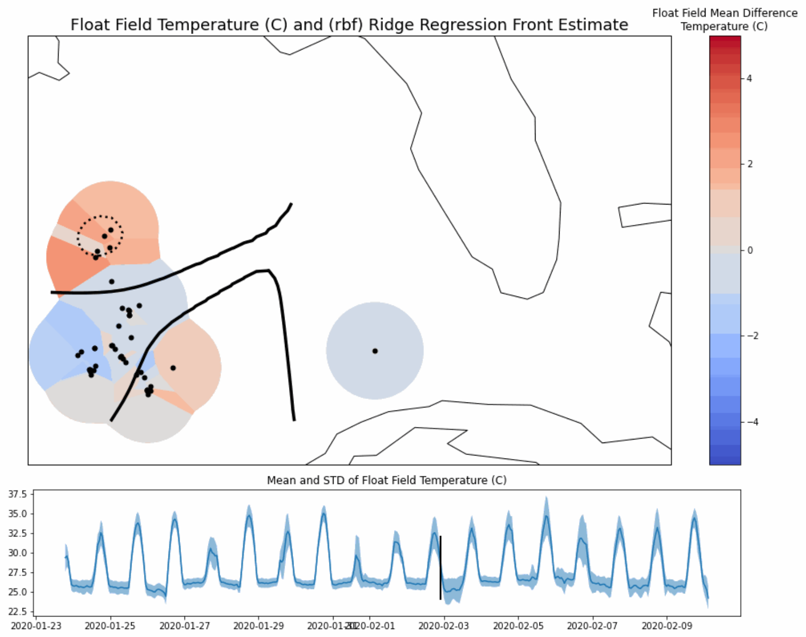
Purple: Reported SST at night (no solar heating)

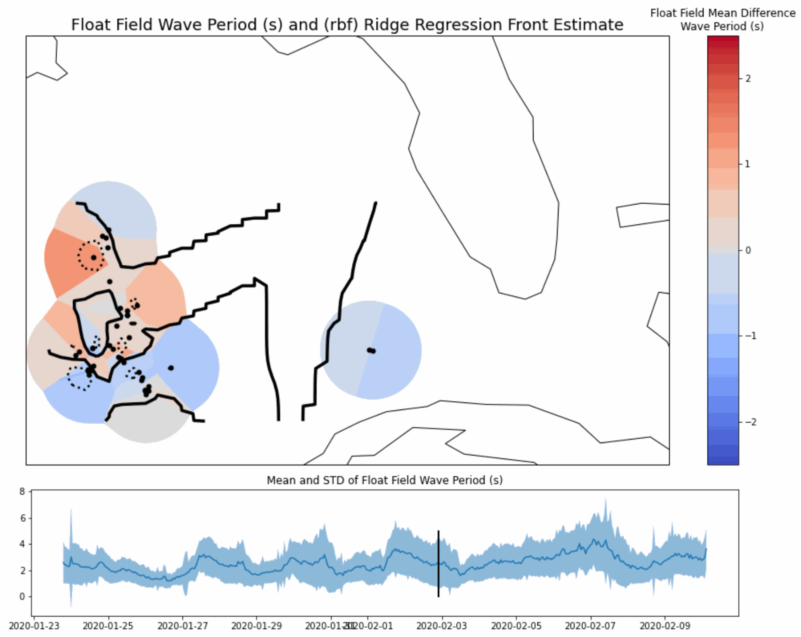
Green: Filtered SST



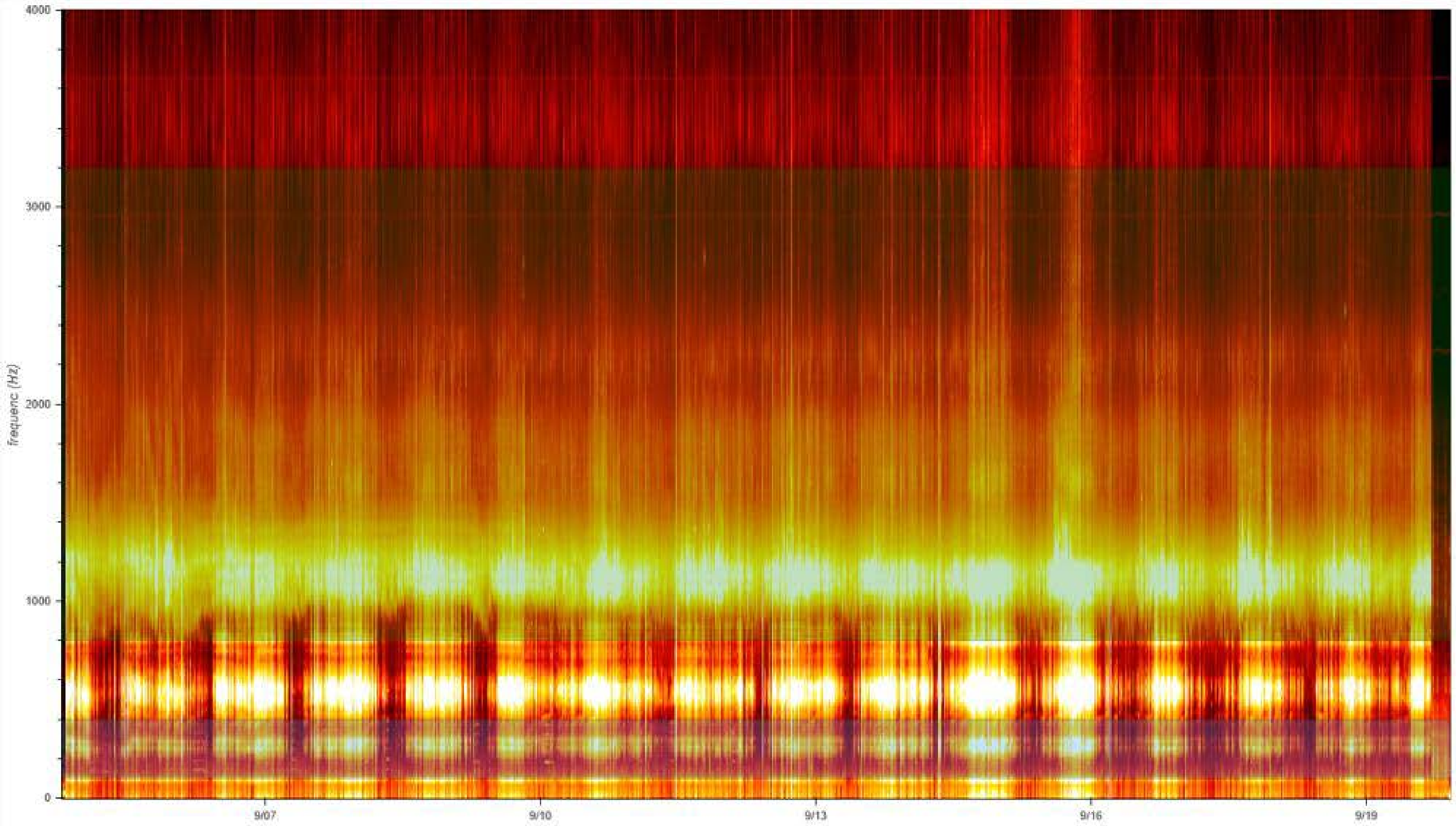
February 3rd Weather Front

- A visual analysis of temperature variability during the night of February 2nd/3rd suggests the presence of a weather front. A north-south gradation of temperature and wave period was obvious in the float field in the early hours of Februay 3rd.
- To better understand the dynamics of this front, we animate the environmental data from the reporting floats in 15 minute increments during this time period. Sensor values are 1 hour averages of reported values, so each animation frame represents a sliding average of reported values. Bounded Voronoi cells are colored according to the closest float's reading as a distance from the float field mean reading.





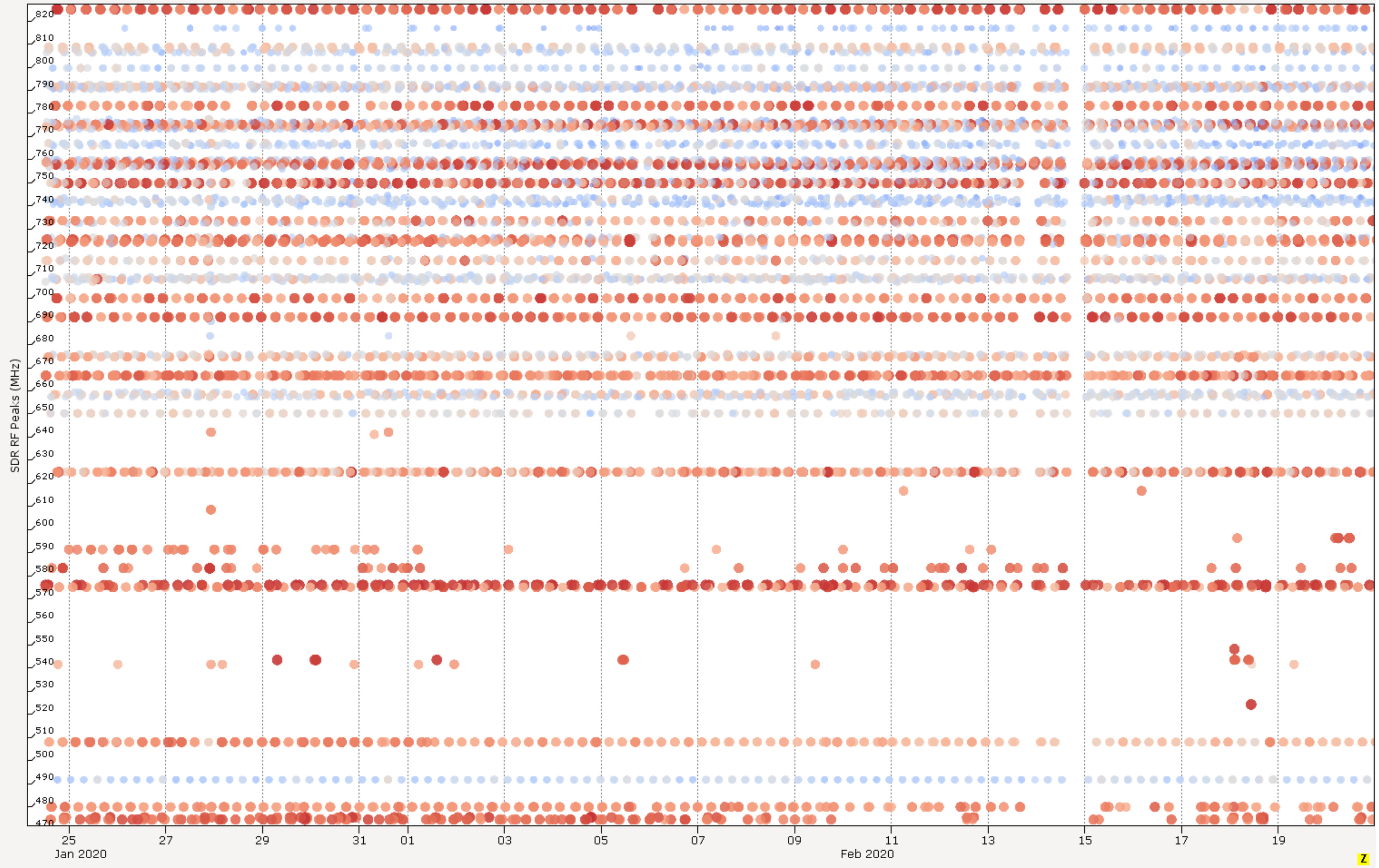
Hydrophone/Microphone: Vessel and Environmental Acoustic Energy



Graph represents a composite of all hydrophone files from a single float pierside in San Diego. The blue-ish band at the bottom (100-400 Hz) represents the “ship” band for onboard analysis, the green-ish band (800-3200 Hz) represents the “wind” band.

Software Defined Radio Analysis

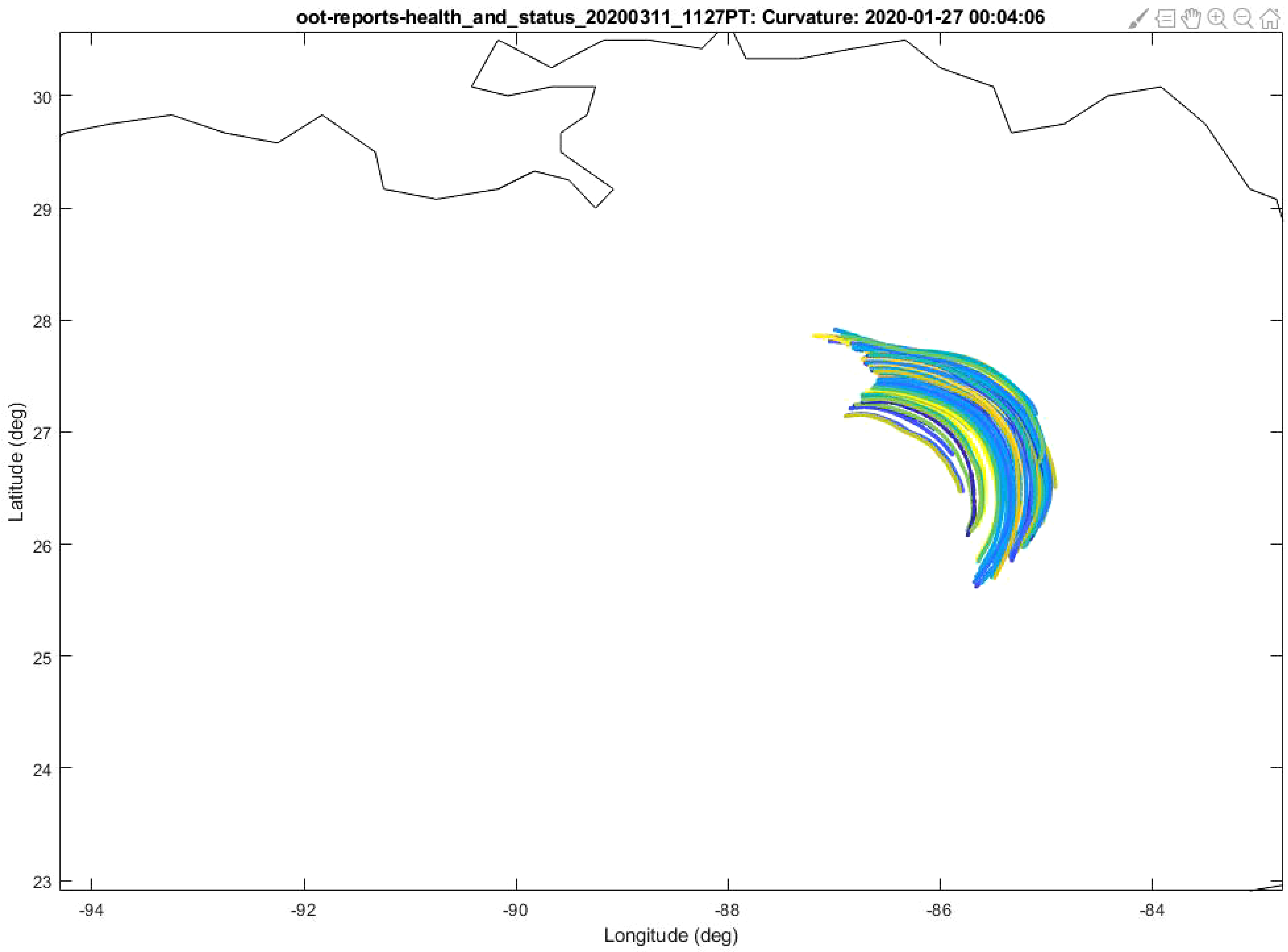
- Show here UHF Band: 470 MHz – 826 MHz
  - Allocated primarily to digital TV
  - Periodic peaks at consistent frequencies
  - 6-hour masking strategy creates “bands” of peaks around certain frequencies- characterizing RF environment
- Possible opportunity:
  - Detecting ship chatter



Anomaly detection

- Automatic detections of pre-defined anomalies is the key to interesting detections and changing today's ocean models. Examples include:
  - Abrupt changes in a float's track inconsistent with predicted track
    - Detects sub-mesoscale features not shown in today's oceanographic models
  - Increased energy outside normal bands of hydrophone data
    - Detects ships, marine mammals, or high wind
  - Abrupt changes in wave height or period
    - Indicate and unpredicted storm event, or the wake of a ship passing by
  - Unexpected change in Sea Surface Temperature
    - Could indicate a float has drifted into an eddy not shown in current models
- Knowing where the anomalies occur enables the contractor to further investigate the data

Detecting Anomalies in Trajectory Curvature



TA 2, Phase 2 metrics

Performance Metrics TA 2 (Data Analytics)

	Phase 1		Phase 2	
Metric	**Threshold**	**Goal**	Threshold	Goal
Field Performance Prediction	Now-cast	24-hour forecast	72-hour forecast	120-hour forecast
Multi-target discrimination	2 targets on orthogonal tracks	2 targets on ~60º divergent tracks	Clustered targets 2 or more	Clustered targets 4 or more
Track initiation	≤ 8 geo-separated reports	≤ 5 geo-separated reports	≤ 4 geo-separated reports	≤ 3 geo-separated reports
	Single sensor	≥ 2 sensor types	≥ 2 sensor types	≥ 3 sensor types
Track continuity	≥ 30% avg. float hold time	≥ 60% avg. float hold time	≥ 50% avg. float hold time	≥ 85% avg. float hold time
Track association	75% if same sensor modality	75% if same sensor modality	75% if same sensor modality	75% if same sensor modality
	-	25% if different sensor modality	25% if different sensor modality	50% if different sensor modality
Data discovery	Automatic recognition of known phenomena		Recognition of new phenomena	
Additional Missions	Technical performance measure for additional missions shall be detailed in proposals (DARPA strongly desires innovation in additional mission capabilities beyond track generation and target behavior characterization. Proposals must detail mission specifications and technical performance measure for each additional mission proposed.)			

Lessons Learned and Phase 2 Direction

Work towards deliverable data products

- Interact with the consumer communities (meteorological, oceanographic, defense, marine biology, commercial shipping, oil and gas, and any others) early to learn what products they value
- Every algorithm developed should support a data product downloaded by an end user

Collaborate with Float Developers early on

- Early and frequent interface fosters an understanding of what data is being delivered by each individual float
- Understand the data offered by the floats before they go in the water, and influence TA-1s with recommendations for the best way to structure and prioritize data

Do not overdevelop the User Interface

- The interface needs to be usable by a trained operator, but is not the final deliverable in this program
- Function and usability take precedence over “sleek” design

Perform work in the SUDOE cloud interface

- Offline development programs (e.g.. Matlab) are not representative of the complexities exhibited working with real-time data in the cloud
- Developing offline does not promote developing a usable interface in the cloud

Refer to the BAA for detailed specifications

Float Deployments and Study Areas

Target Track Development

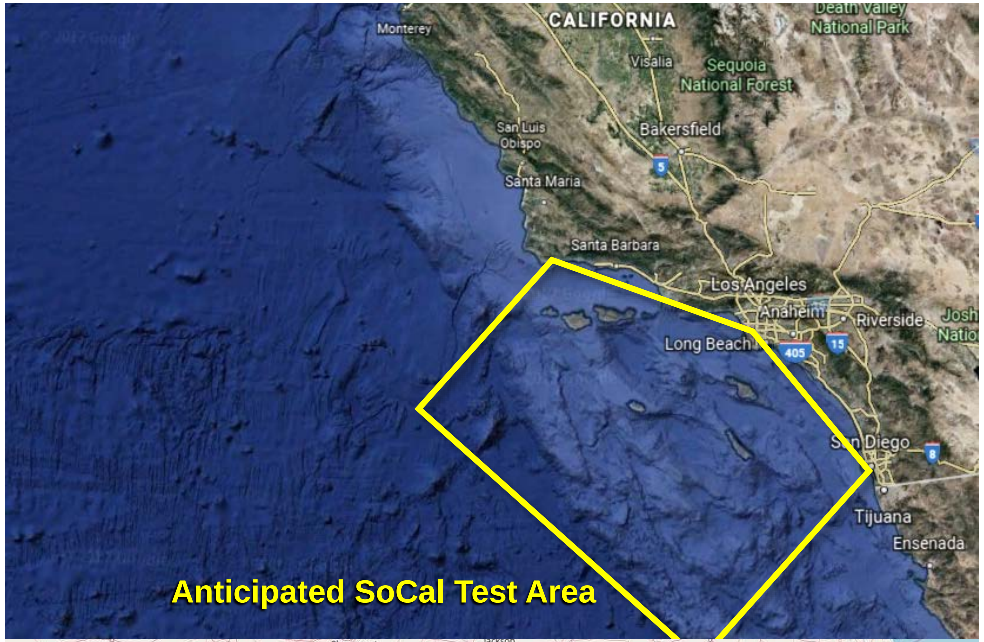
- “Target” in this program is anything that can described with an associated track, including but not limited to:
  - Ships
  - Marine Mammals
  - Weather Fronts
  - Algae populations
  - Eddies

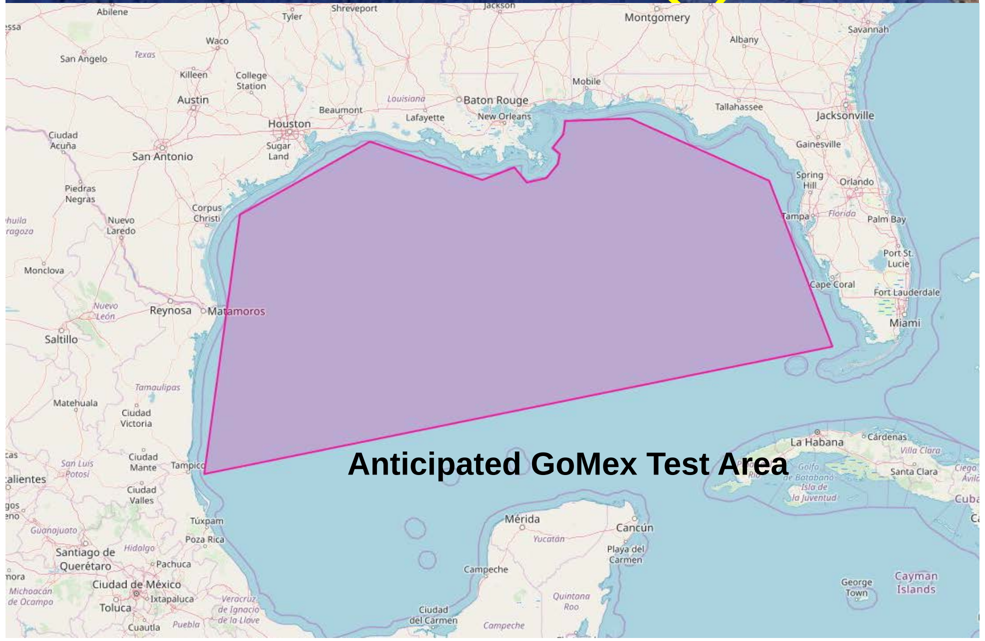
Environmental Analysis of Interesting Local Features

- Large and sub-mesoscale features off the California Bite
- The Loop Current and associated Eddies in the Gulf of Mexico
- Passing weather fronts

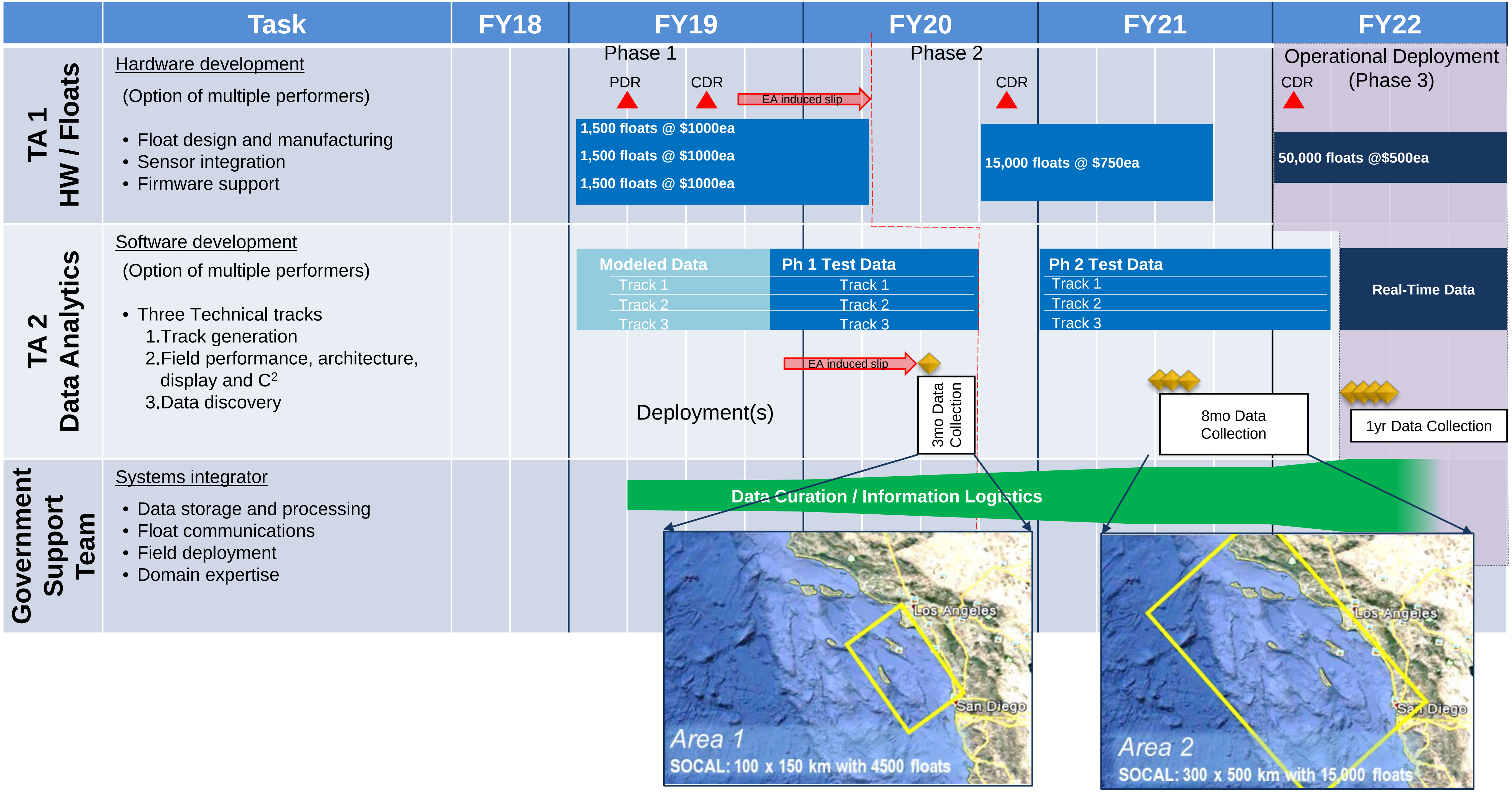
Performers will monitor floats

- Execute float Command and Control
- Analyze float lifecycles
- Support during deployment to address potential issues





Ocean of Things program milestones and schedule



Relevant Links

Ocean of Things website with data files

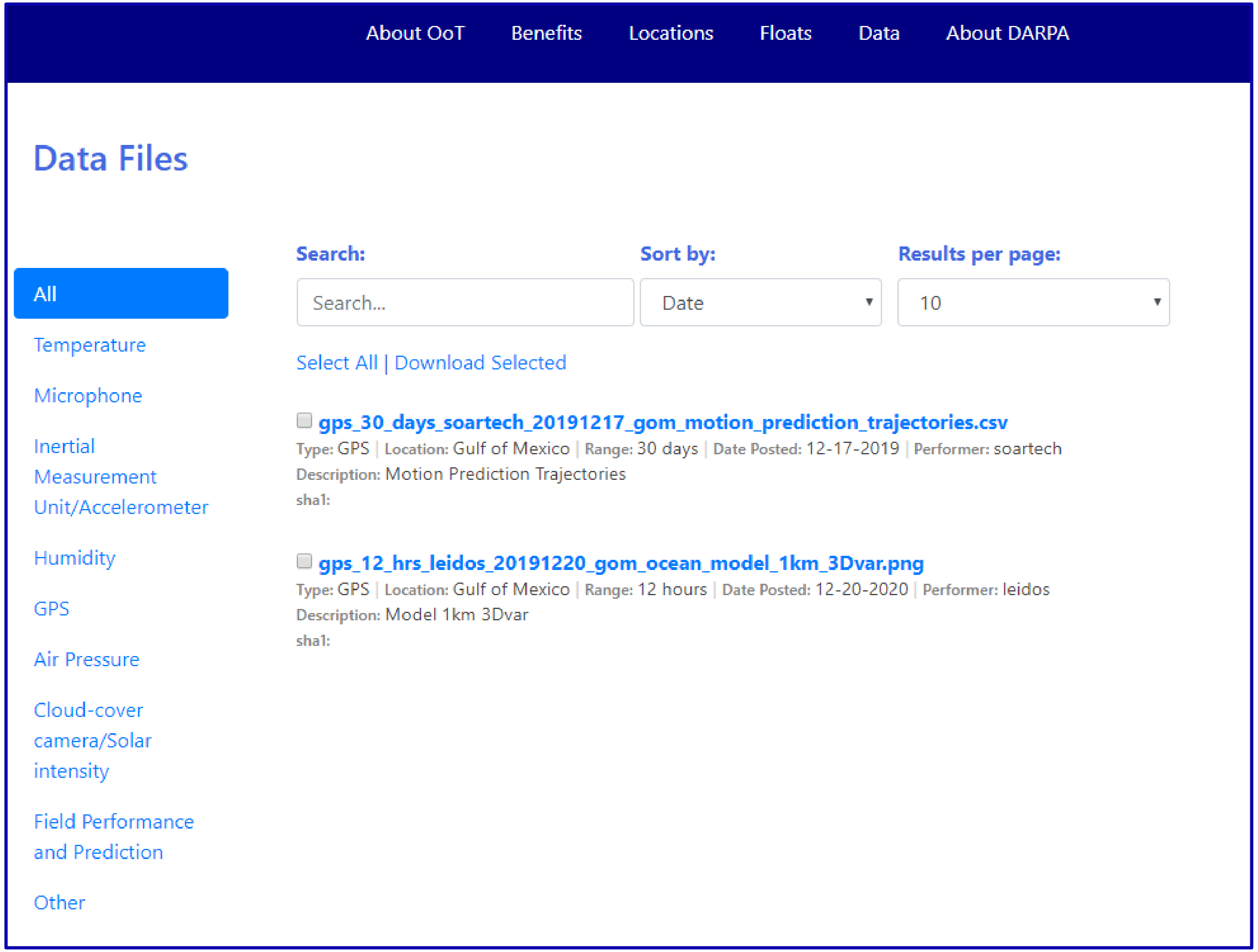
- https://oceanofthings.darpa.mil

Ocean of Things Data Analytics Phase 2 BAA

- https://beta.sam.gov/opp/37991fec08e949db80f9e3185d1a319b/view

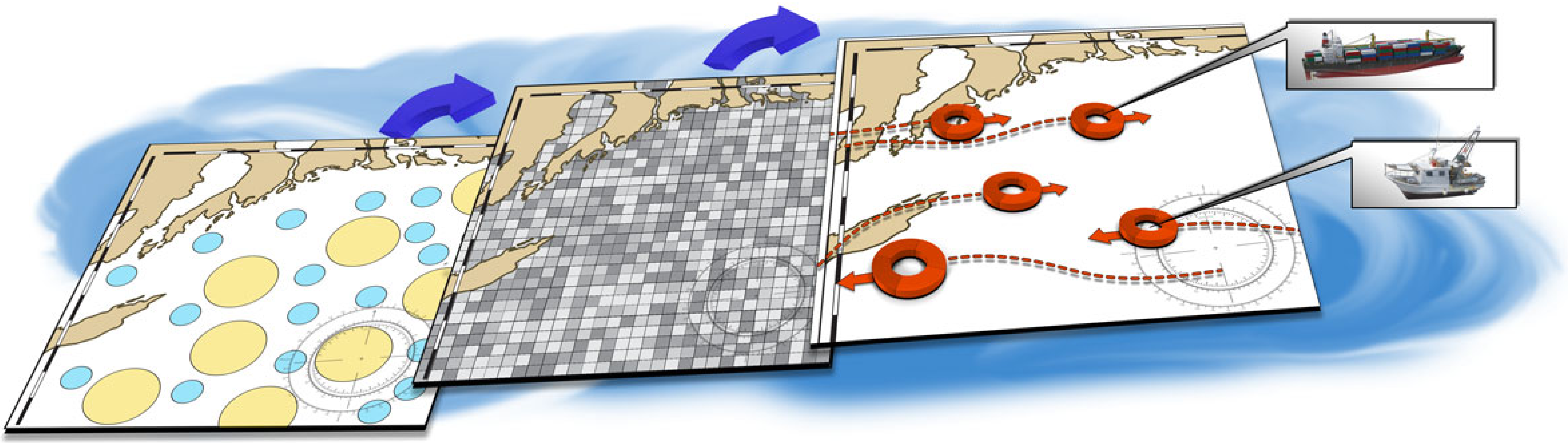
DARPA Opportunities

- https://www.darpa.mil/work-with-us/opportunities



Conclusion

Thank you for your interest in Ocean of Things!



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