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Summary

During cruise RR2107 (November 13 – December 4, 2021; on station November 17 – November 30, 2021), AUV SENTRY, ROV JASON, and a CTD Rosette were used together to map hydrothermal plume surveying, modeling, and tracking in the mid-water (with special focus on 250m altitude from bottom). Buoyant plumes from hydrothermal activity inject significant energy into deep waters and can serve as a mechanism for biogeochemical transport. However, mapping the extent and composition of hydrothermal plumes in the water column is challenging due to their large spatial O(10km) scales and temporal dynamics. This work was aimed at validating and refining scientifically informed probabilistic models of plume phenomenon and using these models to plan trajectories to discover and map plume waters using an autonomous underwater vehicle. Preliminary results indicate that probabilistic, dynamical models are useful for forecasting hydrothermal plume expressions in the water column and can be used effectively to target AUV trajectories. In future work, we will explore how data collected by heterogeneous vehicle teams (AUVs, ROVs, and CTDs) can be used jointly to estimate plume source parameters from mid-water observations and the scientific implications of the resulting models of plume dispersion and nutrient deposition.

Motivation and Scope

To improve expeditionary robotics for science, robots can make use of models of an environment's spatiotemporal dynamics. By explicitly constructing and refining a model the physical environment and using it to inform robotic exploration, we hope to enable more efficient convergence to and sampling of ephemeral, transient targets of interest. For this model-driven approach to be useful for real-time robotic exploration, we need to develop computationally efficient dynamics model of plume phenomena and measures of model uncertainty that can be refined via data-driven inference. In our research, we propose a scientifically-informed probabilistic model that builds a Bayesian inference framework on top of idealized analytical models of plume dynamics. We then optimize sampling trajectories over predictions of plume dynamics from this model to collect scientifically useful observations.

At the hydrothermal vent sites in Guaymas Basin, there is scientific interest in understanding how key compounds, such as methane and ammonium, are distributed and spread throughout the basin ecosystem by plume dynamics. To understand this question, we aim to construct a probabilistic model of hydrothermal plume dynamics in a stratified medium with current-based crossflow. This model can be used to inform sampling strategies of the ROV Jason, CTD casts, and Niskin bottle firings to target chemically diverse observations and samples of plume waters. Additionally, for the autonomous underwater vehicle Sentry, this plume model can be used alongside an optimization-based trajectory planner to produce surveys that target specific portions of the plume phenomena as they evolve due to change currents and ocean conditions. These three sensing modalities have complementary strengths for plume mapping: the ROV JASON enables direct observation of the plume sources; CTD casts and

Niskin bottles enable quantification of the vertical structure of the plume high in the water column; and the AUV Sentry can map the spatial extent and time dynamics of the plume in much higher resolution. By combining the information provided by these platforms, we aim to provide a complete picture of plume evolution, from source parameters to large-scale non-buoyant plume dispersion that can be used to inform scientific models of nutrient cycling and deposition in Guaymas Basin.

Goals

Our goals for the expedition included:

1. Estimate plume source parameters using the JASON ROV and tiltmeter data
2. Use these parameter estimates to form a prior model of plume phenomena and plan surveys over the plume site
3. Update model parameter estimates from Sentry and CTD observations and plan a second, adaptive survey over the plume site.
4. Demonstrate long-distance plume discovery and mapping using standard scientific sensors and experimental methane sensors

Research Activities

Overview of Methodology

To generate sampling trajectories for mid-water plume surveys requires several modules that work together. In this work, we complement a science-informed probabilistic plume modeling technique and trajectory optimization algorithm with several data-processing pipelines. This section provides detailed descriptions of what was tested on RR2107.

Science-Informed Probabilistic Plume Modeling

Morton, Taylor, and Turner's seminal 1956 work demonstrates that hydrothermal plumes can be well described by conservation of momentum, buoyancy, and mass fluxes. Plumes consist of two conceptual parts: a *buoyant stem* and *non-buoyant plume/intrusion layer/neutrally-buoyant intrusion*. The buoyant stem is a positively buoyant structure in the water column that is taller than it is wide (indeed, buoyant stems are well known to only grow a meter for every 10m in height gain as a rule of thumb). The non-buoyant plume forms at the point in which the hydrothermal fluid reaches equal density to the ambient background, and in theory expands infinitely within that uniform density layer.

We use analytical models of idealized plumes in order to ground a probabilistic methodology that allows us to represent uncertainty over our model initial conditions, as well as temporal dynamics. Specifically, we implement three types of model: a *Stationary* plume model based on the work of Speer and Rona (1989) who describe hydrothermal plume models for Atlantic and Pacific basins and assumes no crossflow (i.e., current); a *Crossflow* plume model based on the work of Tohidi and Kaye (2016) who propose a bent-plume model under conditions of crossflow; and a *Multiplume* model, which wraps multiple independent instances of Stationary or Crossflow models and reasons about how those plumes may intersect.

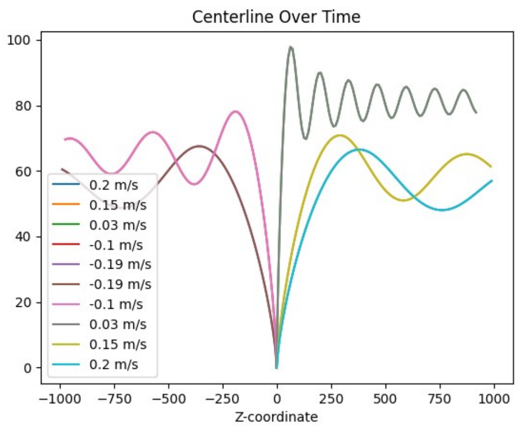


Illustration 1: Crossflow plume centerline under different current magnitude and heading conditions.

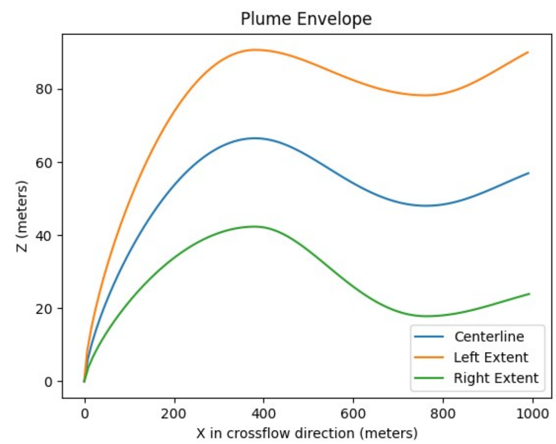


Illustration 2: Vertical cross-section of Crossflow plume model envelope.

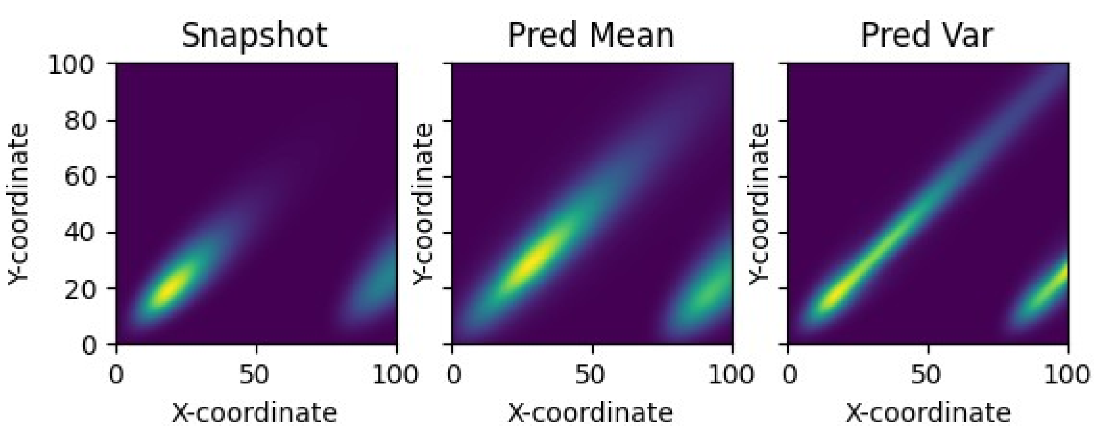


Illustration 3: Example of multiplume model with two crossflow plumes at [0,0] and [75,0]) for some top-down view of a fixed depth. Shows mean and variance from probabilistic samples.

For the purposes of planning in this cruise, we primarily use a Crossflow model, described by a system of coupled ordinary differential equations:

$$E = \alpha \left| \frac{M}{Q} - U\cos(\theta) \right| + \beta \left| U\sin(\theta) \right|$$

$$\frac{dQ}{ds}=Q\sqrt{\frac{2(1-\lambda)}{M\lambda}}E$$

$$\frac{dM}{ds}=U\cos(\theta)\frac{dQ}{dM}+F\frac{Q}{M}\sin(\theta)$$

$$\frac{d\theta}{ds}=\left(F\frac{Q}{M}\cos(\theta)-U\sin(\theta)\frac{dQ}{ds}\right)\frac{1}{M}$$

$$\frac{dF}{ds}=-QN_2\sin(\theta)$$

$$\frac{dx}{ds}=\cos(\theta)$$

$$\frac{dz}{ds}=\sin(\theta)$$

where E is an entrainment coefficient (roughly a mixing value) with coefficients α and β, Q is specific volume flux, M is specific momentum flux, θ is plume centerline angle, F is specific buoyancy, s is a notion of distance along the plume centerline, x and z are planar Cartesian plume centerline coordinates (within the plume crossflow direction frame of reference), U is crossflow magnitude, and N_2 is the Brunt-Viasaala frequency. The latter is computed by comparing plume density and background density profiles.

The initial conditions of buoyancy, momentum, and volume fluxes are set by plume source characteristics of *temperature, salinity, orifice area*, an *exit velocity*. For the purposes of this cruise, we assume source temperature and salinity are effectively known (end members were previous characterized on cruise NA090 in 2017 and directly measured with ROV JASON on this cruise), but we represent orifice area and exit velocity as probabilistic distributions. The prior distributions for these parameters are set to be uninformative uniform priors over the conservative observed bounds for these parameters (exit velocity: 0.1m/s to 1.3m/s; area: 0.15m^2 to 3.14m^2) . Additionally, we are uncertain about the mixing characteristic in the system, and so represent coefficients α and β in the entrainment computation as uninformative uniform priors spanning literature indicated ranges (α: 0.1 to 0.2 and β: 0.1 to 0.8).

Uncertainty over these conditions and parameters is largely driven by the difficulty in directly observing or quantifying them. In order to better estimate these parameters (and therefore better track the plume), we use indirect, in situ plume observations. We employ a Bayesian framework (Metropolis-Hastings) to draw samples of our unknown initial conditions and parameters, push these through our idealized model, and compare the output directly with actual binary detections of plume influenced waters (process described in ***Plume Detection***) in the mid-water, with some probability of accepting or rejecting samples as a function of model-observation agreement and likelihood of a sample.

Uncertainty in temporal evolution of the plume (e.g., advective current magnitude and heading) is not explicitly updated in the system tested on the cruise, however current (and background profiles of temperature and salinity) are mean functions of data-trained probabilistic models as described in ***Current Modeling*** and ***Background Profile Characterization*** which are updated from direct point observations of those quantities in a separate process.

Plume Detection

Our probabilistic plume model uses positive and negative plume water detections at given locations and times to refine the plume parameter estimates used. Water originating from hydrothermal plumes at Guaymas basin is generally hotter, saltier, more turbid, and richer in compounds like methane and ammonia compared to background water. To build a plume detector, we fuse various scientific sensors that can detect and quantify the differences between plume and background water to produce binary plume detections. Our plume detector is based on the method of corroborated anomalies proposed by Jakuba (2007) and uses seven data streams:

- ORP: the oxidative reductive potential, used as the natural log of the time derivative
- PT: potential temperature
- PS: practical salinity
- OBS: the optical backscatter, used as the natural log
- O2: [partial pressure of oxygen], used as the natural log of the time derivative
- NOPP: methane concentration, measured via laser-based spectroscopy
- HCF: methane concentration, measured via hollow core fiber

After a dive, each data stream is subsampled (interpolated) onto the 1 Hz navigational data, so that each timestamp has an associated location and observation from each science sensor. We apply post-processing steps to several data streams (ORP, OBS, O2) to correct for non-stationarity and specific sensor response characteristics, as noted above. Then, for each data stream, we compute the mean and standard deviation over a 200 sample sliding window and classify a point as anomalous if it lies outside of a ± 2 standard deviation interval. Finally, we classify a sample location as being “in” or “out” of a plume by requiring consensus among multiple sensors within a sliding window of 200-samples. For consensus, we “weigh” each sensor based on sensor reliability and relevance to plume detections. Some measurements, such as the value of the ORP probe, exhibit large anomalies in the presence of plume water; others, such as the practical salinity, are less strong indicators and have lower signal to noise ratios. We therefore allow for sensors to be counted with non-uniform weights when evaluating consensus. Our implementation uses the following sensor weights: ORP: 2, PT: 1.5, PS: 1.5, OBS: 2, O2: 2, NOPP: 1, HCF: 1. A “weight” of 6 is used to classify a particular observation as plume water.

Current Modeling

Deep sea currents of magnitude 0.1-0.5m/s have been observed in Guaymas Basin (Scholz et al., 2019) variably from Northwest to Southwest headings and are largely driven by tidal forces. To capture the influence of currents on the mixing and advection of hydrothermal plumes, we include current magnitude and course in our plume model computation. These current models are driven by data collected from two sources: tiltmeters placed at a fixed location on the ocean floor by the ROV JASON and downward facing DVL measurements collected by the AUV SENTRY. During the cruise, tiltmeter data was primarily used; DVL data will be used later to assess and complement this data stream.

Using the tiltmeter data, we applied a data-driven modeling approach to estimate current magnitude and course functions utilizing Gaussian Processes (GPs), a non-parametric Bayesian model. GPs are fully defined by a mean function and a covariance kernel, which describes the way in which data may be inter-related. We trained two GPs with a zero-mean and radial basis function (RBF) kernels individually on subsampled tiltmeter estimates of magnitude and heading (magnitude model: 100 training iterations, learning rate of 0.5; heading model: 200 training iterations, learning rate of 0.1). The mean magnitude and heading function from the trained GPs was then used within our predictive plume framework for the purposes of planning trajectories on this cruise.

Background Profile Characterization

For the purposes of this work, we assume that salinity and temperature most strongly contribute to the density profile of the hydrothermal plumes and background seawater. To compute the background salinity and temperature profiles of our target sites, we train two GPs (zero-mean and RBF kernel) on sub-sampled salinity and temperature data collected by CTD Rosette casts conducted on the cruise. Both GPs are trained with 100 iterations with a learning rate of 0.1. The trained mean function for both temperature and salinity are used within our model and planning framework for this cruise.

Exit Velocity Estimation

The steady-state buoyant plume model we use depends critically on the properties of the hydrothermal vent source, including the total buoyancy and momentum flux. To estimate these source parameters accurately, we require an estimate of the water velocity as it exits the plume source. There are two primary strategies for measuring plume exit velocity: invasive and non-invasive. Invasive measurements use instruments that can be placed directly in the exiting flow and provide a velocity estimate via, i.e., quantifying the rotation rate of a mechanical spinner. Non-invasive measurement strategies use sensors such as RGB cameras or ADCP to estimate fluid velocity without directly interacting with plume fluid. Passive methods have been shown to provide accurate estimates of plume exit velocity, with a slight bias towards underestimation of velocity in experiments (Zhang et al., 2019).

Among passive methods, particle imaging velocimetry (PIV) is often the simplest to implement, requiring only an onboard RGB camera, and is well suited for plume waters that differ visibly from background water, such as in the black smoker sites in at Guaymas Basin. PIV methods track turbulent parcels that have high cross-correlation values between frames. By tracking many specific parcels over several frames, PIV methods can provide a vector field of velocity estimates that can then be averaged to provide mean flow in a specific region. Using the 4K video data collected by a MISO camera, we applied MATLAB's open-source PIVLab software to estimate mean fluid velocity at the orifice of each vent site. The MISO camera was aligned using JASON's manipulator to ensure that the camera face was parallel to the flow exiting the vent source and approximately 5m from the plume. The 10cm-spaced laser points from JASON were used to estimate the scale of features in the camera image.

We additionally collected several opportunistic datasets of the water exiting the plume source with JASON's BlueView multibeam sonar sensor and onboard science cameras. We plan to use these datasets to explore acoustic strategies for passive exit velocity estimation.

Trajectory Optimization

Given a probabilistic plume model, the second key component of our autonomous decision-making stack is the trajectory optimization method, which uses the plume model to select Sentry trajectories that have high probability of intersecting plume water.

The trajectory optimizer consists of three primary components:

- **Parameterized trajectories**: Parameterized trajectories form the basis of the trajectory optimizer. A parameterized trajectory is a function that takes in a set of trajectory parameters, e.g., length, width, location, orientation, and resolution specifying a lawnmower parameter, and produces a set of waypoints that define a Sentry trajectory. In our experiments, we leveraged both lawnmower (e.g., standard boustrophedonic surveying patterns) and spiral-shaped parameterized trajectories.
- **Reward function**: The reward function quantifies which locations are useful for SENTRY to collect observations from. This reward function must encode the scientific objectives of a mission, such as desire to collect observations of locations that have high probability of containing plume waters or desire to collect a diverse set of observations from different concentrations of plume waters. The reward function can query our probabilistic plume model to estimate the probability of detecting plume water at various locations and times along a trajectory. In our experiments, we used a reward function that encouraged SENTRY to spend time in regions with high probability of plume detection.
- **Optimization method**: The optimization method uses both the parameterized trajectories and the reward function to produce a final trajectory to accomplish the scientific objective encoded in the reward function and respects vehicle constraints, such as time budget and safety regions. Starting from an initial guess of trajectory parameters, the optimizer uses numerical gradient-based methods to find parameters that result in maximal reward. We use the Trust Region method with constraints in Python's scipy library and run for 25 iterations or until convergence.

The final output from the trajectory optimizer is a sequence of lawnmower trajectories, each of which have been optimized to maximize the probability of detecting plume water for a given start-time and plume model forecast. This trajectory is loaded into Sentry's mission planning software as a sequence of waypoints and executed over a 14-18 hour mission.

Vehicles, Equipment, and Instrumentation

To complete this work, we primarily made use of the AUV SENTRY and it's typical science instrument suite for mid-water flights over survey targets. Our work was additionally supplemented by excursions with ROV JASON and opportunistic CTD Rosette casts.

UDP Acoustic Communications Monitoring

To listen to USBL location pings during all missions with SENTRY and relevant CTD transects, and monitor AUV SENTRY science instruments during all SENTRY missions, we developed UDP listeners within the SENTRY network architecture that subscribed to various sockets and shunted messages received to sorted files. This allowed us to diagnose progress during missions in terms of plume-intersections, and allowed for opportunistic small changes in missions (or informed decision-making when mission timing needed to change). This also helped to catch instrument errors and send power reset commands to instruments. Acoustic messages for specific queues were received every 40-120seconds, depending on the number of active acoustic queues. Occasional dropout of messages due to distance from ship were also observed.

AUV SENTRY

SENTRY is equipped with an optical backscatter (OBS) unit, optode, oxidation reduction potential (ORP) probe, and CTD which served as our primary sensing targets. Specific to this cruise, we additionally had access to water-tracking acoustic returns from the onboard DVL used for navigation in bottom-lock mode, 2 1L Niskin bottles, 2 experimental instruments (NOPP and HCL, used mutually exclusively), and a downward-looking MISO GoPro camera.

SENTRY was used to fly in both altitude-hold and bottom-lock mode from 30m-120m in (average) altitude. Niskin bottles were fired in both scheduled and opportunistic fashions. The MISO camera was deployed on two dives, once in a snapshot-photo mode, and another in 4k video shooting mode. The relevant configuration for our dives with SENTRY:

- sentry607 (V/G planned) – standard science suite, NOPP
- sentry608 (V/G planned) – standard science suite, NOPP, Niskins
- sentry609 (scrubbed, redive by SENTRY team) – standard science suite, HCF, Niskins, MISO
- sentry610 (V/G planned) – standard science suite, NOPP, water track, Niskins
- sentry611 (V/G planned) – standard science suite, HCF, water track, Niskins, depth-hold mode
- sentry612 (collaboratively planned) – standard science suite, NOPP, water track, Niskins, MISO
- sentry613 (SENTRY team planned) – standard science suite, NOPP, water track

ROV JASON

JASON is equipped with a CTD, optode, and OBS mounted on the chassis, a temperature probe that can be maneuvered using the manipulator, and multiple cameras (including a brow and arm mounted MISO and a 4k science camera). JASON is also equipped with several physical samplers, including two Niskin bottles and high-temperature titanium major samplers.

Our primary objective for JASON was to characterize the plume source properties. The high temperature wand was inserted into the largest plume orifice to measure end member temperature. A peak reading of 340C was observed near the Chimney #1 black smoker site. No salinity end member was directly observed, however previous work has reported slightly elevated salinity (on the order of 0.3 PSU) salinity from Guaymas vents.

Additionally, we were opportunistically able to observe the height of the plume nonbuoyant layer as JASON descended to depth, via a spike in the OBS sensor and visible black smoke in the JASON cameras. Smoke was visible to the human eye starting at 1480m and extending to 1700m. This is largely corroborated by CTD Rosette casts. Relevant dives to our work include:

- JD1388-JD1389 (tiltmeter deployment, MISO Arm camera, MISO Brow camera, temperature probe)
- JD1390 (tiltmeter deployment, MISO Arm camera, MISO Brow camera)
- JD1392 (tiltmeter deployment, MISO Brow camera)
- JD1393 (tiltmeter deployment, MISO Brow camera)
- JD1394 (MISO Brow camera)
- JD1395-JD1396 (tiltmeter recovery, MISO Brow camera, MISO Arm camera)
- JD1398 (MISO Brow camera)
- JD1400 (MISO Brow camera)

CTD Rosette Casts and Transect

CTD Rosettes are equipped with a SBE43 CTD and oxygen sensor, a transmissometer, a florescence sensor (traded with HCF for casts 06, 08, 09, 10, 11), and a bottle carousel. Salinity and temperature profiles were used within our framework to establish background profiles. Cast information:

- CTD01 – (27.40836, -111.38910); within 200m of Chimney 1 at the graben-ridge site
- CTD02 – (27.41014, -111.38818); shallow water transect through the OZM at the graben-ridge
- CTD03 – (27.40964, -111.38232); 600m NE of the graben-ridge site
- CTD04 – (27.50896, -111.68166); Ring vent

- CTD05 – (27.50908, -111.68156); Ring vent
- CTD06 – (27.40796, -111.38834); slow HCF cast SE of graben-ridge site
- CTD07 – (27.40438, -111.37812); 1.2km SE from graben-ridge site
- CTD08 – (27.40834, -111.38924); Repeat of CTD06 cast
- CTD09 – (27.20106, -111.39796); 22km south of graben-ridge site
- CTD10 – NW transect 16km from graben-ridge to within 3km
- CTD11 – NW transect starting from CTD10 stop across the graben-ridge, to about 3-4km past

In the last two CTD casts (CTD10 and CTD11), the CTD Rosette was towed at ~1650m depth. Absolute position of the CTD cast was tracked with a USBL beacon. This transect will be used as part of a future model validation procedure.

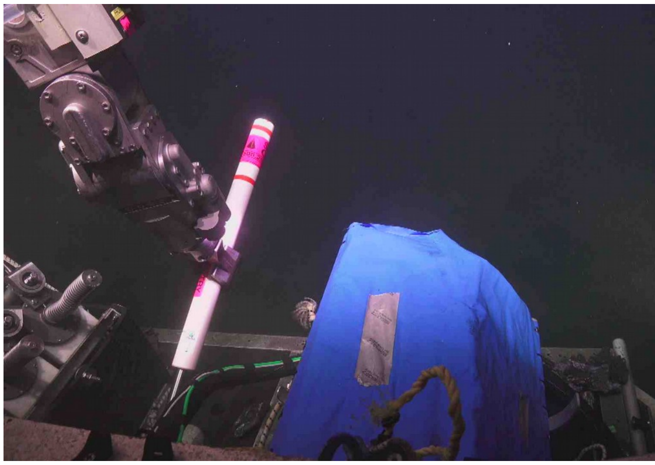
NOPP and HCF

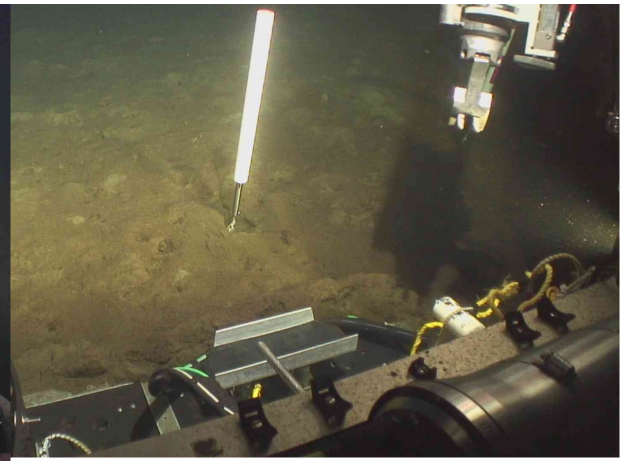
Experimental instruments NOPP and HCF were interchangeably used on AUV SENTRY dives and CTD casts (for HCF); the datastreams of which we have incorporated into our binary plume detection algorithm. Instrument data is interpolated onto the timestamp of the AUV SENTRY or CTD Rosette cast for use in our system.

Tiltmeter

Two TCM-3 tiltmeters from Lowell Instruments were deployed using the ROV JASON. One tiltmeter (tiltmeter A, serial number: 2108300) was placed and recovered over multiple dives, providing dive “snapshots” of current. Another tiltmeter (tiltmeter B, serial number: 2110300) was deployed at a site on the graben-ridge and left over multiple days and recovered at the end of initial operations in N. Guaymas). A lead weight with an eye-bolt was used to anchor the tiltmeters. Deployment locations and durations indicated:

- Tiltmeter A; deployed JD1389; recovered JD1390 total duration 28hrs; (27.4006177, -111.3985321, 1832m initially; moved to 27.4002362, -111.3962494, 1854m); primary dataset used in cruise predictive modeling
- Tiltmeter B; deployed JD1389; recovered JD1396 total duration 6days 15hrs; (27.4006177, -111.3985321, 1832m)
- Tiltmeter A; deployed JD1392; recovered JD1392 total duration 10hrs; (27.4149571, -111.3873036, 1840m)
- Tiltmeter A; deployed JD1393; recovered JD1393 total duration 20hrs; (27.5001163, -111.6832265, 1732m); sunk into the mud at Ring Vent and literally read nothing

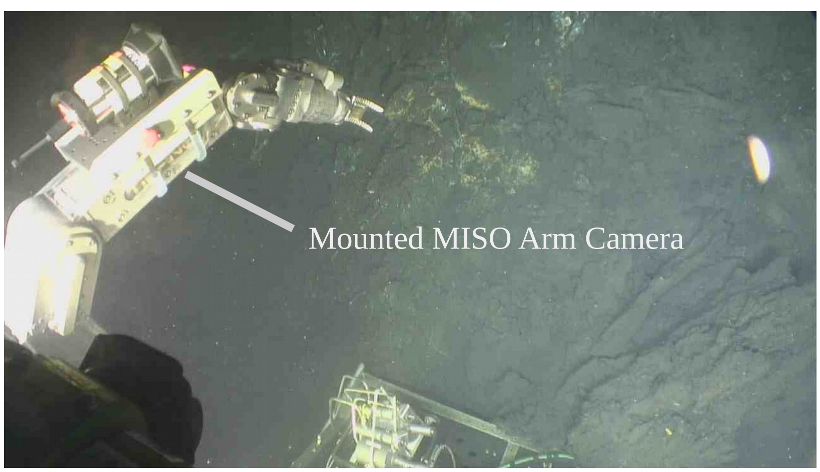




MISO

Two MISO GoPro cameras were used on ROV JASON and AUV SENTRY operations. The “Arm” camera was used on both ROV JASON and AUV SENTRY in order to film black smokers and image seafloor transits (respectively). The “Brow” camera was used primarily to take pictures during ROV JASON dives. Specifically:

- Brow Camera – ROV JASON – All dives except JD1397
  - All modes set to 12MP 1pic/5seconds mode
- Arm Camera – ROV JASON – Dives JD1388, JD1389, JD1390, JD1395, JD1396
  - All modes set to 4k video
- “Arm” Camera – AUV SENTRY – Dives sentry609, sentry612
  - sentry609 – 12MP 1pic/2sec mode; quality poor (no dimmer used)
  - sentry612 – 4k video mode; quality decent (no dimmer used)



Site Descriptions

Dives took place in four locations, the N. Guaymas ridge/graben-ridge, the N. Guaymas Ring Vent, S. Guaymas, and a long-transect from between S. Guaymas back to the N. Guaymas ridge/graben-ridge.

SENTRY flew in all locations; JASON also examined all locations save for the S to N transect.

- **North Guaymas Ridge**: This was the primary site for Jason and Sentry operations. The site consists of a ridge approximately 600m in length. Six separate high-temperature venting sites have been observed along the ridge along features that are ~45-75m high. Of these, Chimney 1 (located on the far southern end of the ridge with coordinates (27.40926223, -111.38931794), orange arrow) and Chimney 2 (located on the far northern end of the ridge with coordinates (27.412645-, 111.386915), red arrow) were well characterized by the JASON ROV. Both chimneys are black smokers and characterized by source fluids of ~350C temperature anomaly and heightened salinity. These two chimneys were the focus of Sentry's missions and adaptive mapping was focused on Chimney 1.
- **North Guaymas Ring Vent**: The ring vent site is a smaller, low-temperature diffuse flow site with several features arranged in a ring shape. AUV SENTRY flew a tight survey over a "blow

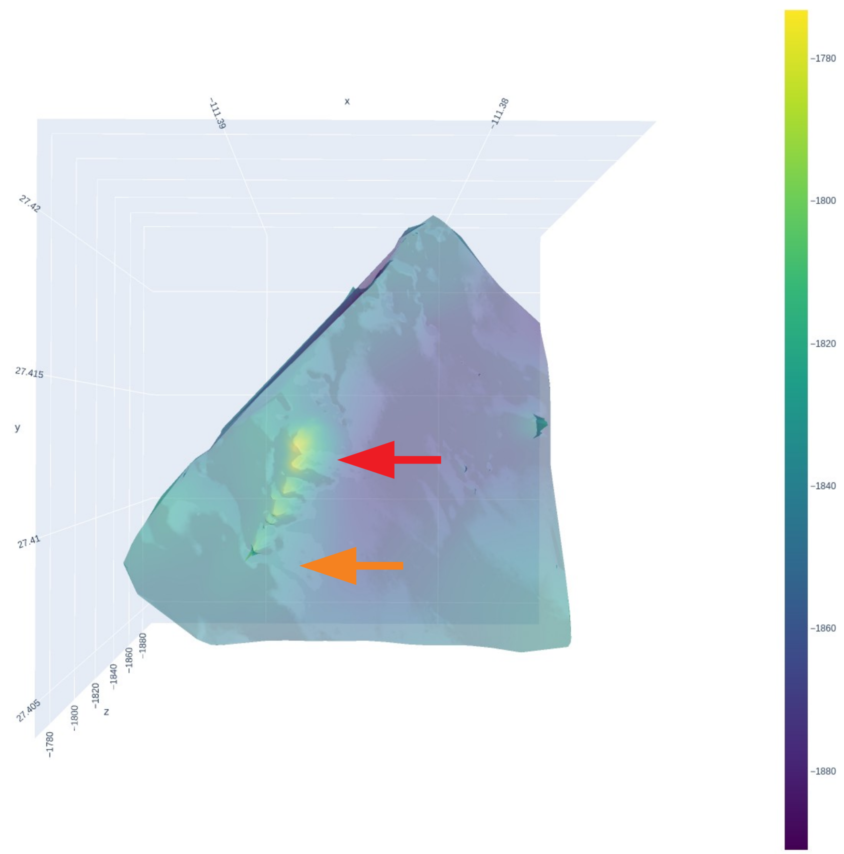


Illustration 4: Overview of graben-ridge bathymetry. Red arrow: Chimney 2; orange arrow: Chimney 1.

hole” observed by ROV JASON as well as a survey over the entire ring vent. ROV JASON performed a slow heat-flow probe survey of ring vent, and examined structure to the SW.

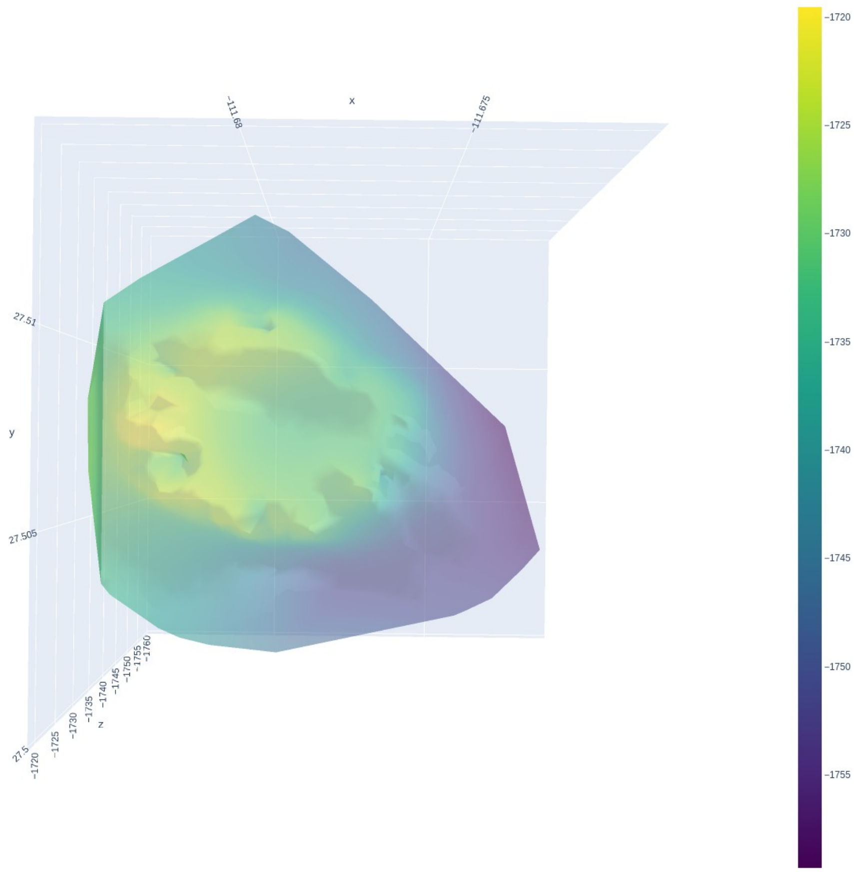


Illustration 5: Overview of Ring Vent bathymetry.

- **South Guaymas Vent Clusters:** S. Guaymas has been previously well studied and marked. SENTRY flew over two clusters of noted vents in the northern part of the site, including a cluster with Rebecca’s Roost, and Cathedral Hill. JASON examined bacterial mats to the South. We did not fly any adaptive trajectories at this site, but will investigate applying multiplume models to the data.
- **South Guaymas to North Guaymas Transect:** The southern and northern Guaymas hydrothermal sites are separated by ~O(50km) of flat basin with little known hydrothermal activity. As a final exploratory mission, Sentry flew a transect from a midway point between the Southern and Northern Guaymas sites (~22km southeast of the Northern Guaymas Chimney 1), ending the trajectory in the graben feature to the northwest of Chimney 1.

Preliminary Results Science-Informed Probabilistic Plume Modeling

As discussed in ***Overview of Methodology: Science-Informed Probabilistic Plume Modeling***, we trained a model on data from sentry607 over Chimney 2 with 625 parameters samples (125 samples used for chain burn-in) to use in planning several of the future sentry dives. The prior and posterior initial condition maximum likelihood expectations were as follows:

- Prior Exit Velocity: 0.699m/s > Posterior Exit Velocity: 0.58m/s
- Prior Source Area: 1.654m^2 > Posterior Source Area: 0.82m^2
- Prior Alpha: 0.148 > Posterior Alpha: 0.15
- Prior Beta: 0.451 > Posterior Beta: 0.19

Notably, in the training process chain mixing is of serious concern. Ideally, more samples would be used to estimate each of these parameters. Due to pushing these samples through the analytical model, the composite distribution of plume detections which maps to initial condition samples is relatively complex, and examining this distribution effectively takes time. Moreover, the only signal to compare a model to real observations is a binary notion of “in” and “out” of a plume (as discussed in ***Overview of Methodology: Plume Detection***), which is helpful, but by no means necessarily “expressive” in the way that continuous-valued observations may be.

Plume Detection

Our binary plume detector using corroborated anomalies was applied the Sentry scientific data for all cruise dives. Initial results for dives sentry607, sentry608, sentry610, and sentry611 are shown below, with plume detections shown in red and non-detections shown in blue. By requiring six sensors to confirm a plume detection, our classifier is quite conservative, detecting plume water only when there was very strong buoyant stem signal near the location of the source (yellow arrow). This is useful when fitting our plume MTT model from observations, as these strong detections help to quickly constrain the entertainment rate and source parameters. In the future, we plan to explore detector performance as a function of the number of corroborations required and anomaly detection algorithm.

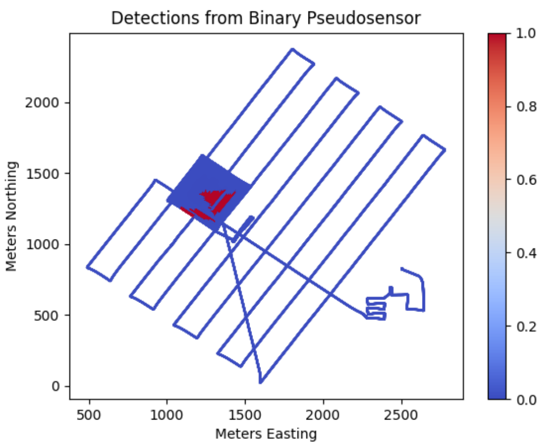


Illustration 6: sentry607

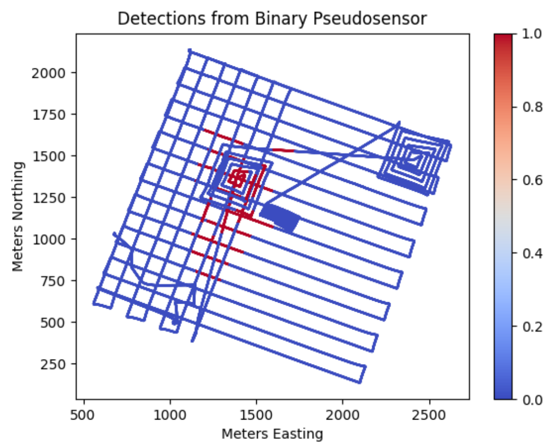


Illustration 7: sentry608

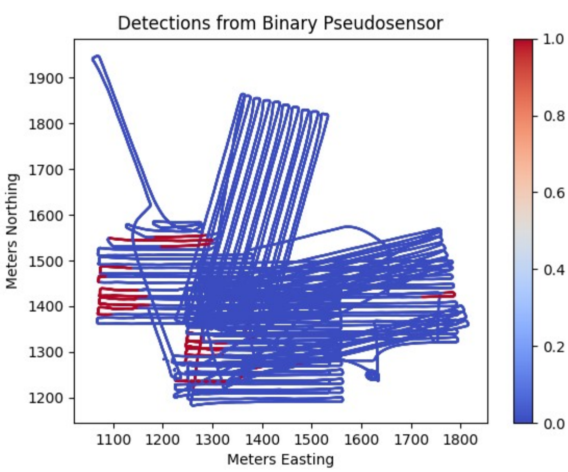


Illustration 8: sentry610

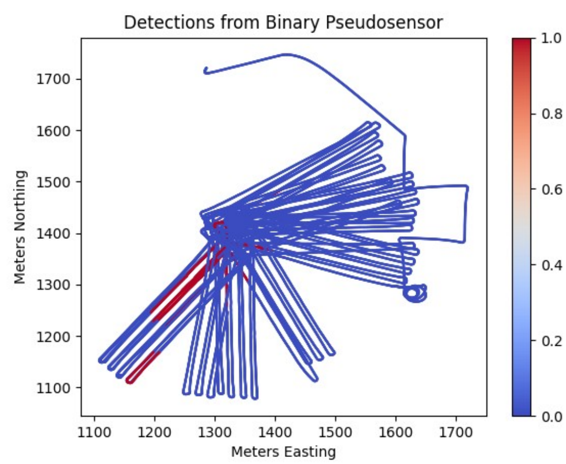


Illustration 9: sentry611

Current Modeling

Current magnitude and course functions trained using the GP method described in ***Overview of Methodology: Current Modeling*** demonstrated a 12hr periodic cycle that tracked with predictive tidal information for the city of Guaymas as computed by CICESE.

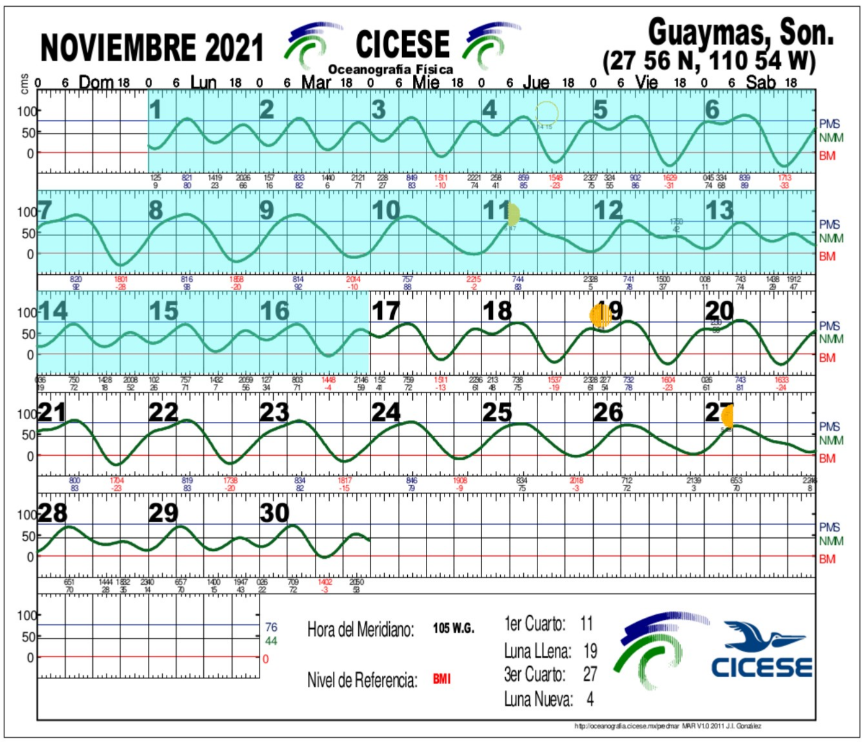


Illustration 10: Reference tidal chart; cruise dates unhighlighted.

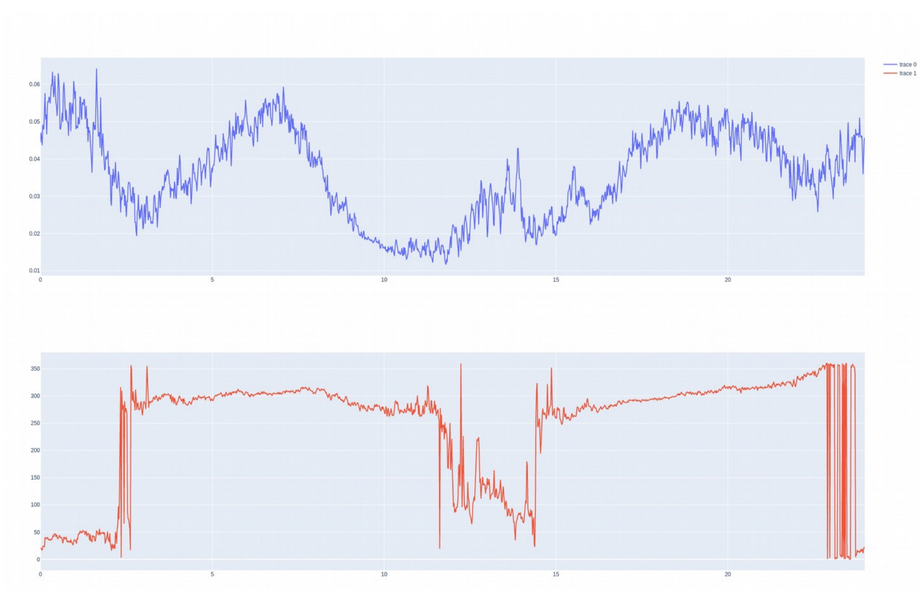


Illustration 11: Magnitude (top) and Heading (bottom) of tiltmeter B data flattened and averaged over a 24 hour span.

Background Profile Characterization

A GP for each of salinity (PSU) and potential temperature (C, ITS90) was trained with a subsample (every 100 samples of spatially ordered data) of all CTD casts (excluding the transect) in order to get a basic profile for use in our system. GPs were trained with learning rate 0.1 and 200 iterations. Agreement between the GP mean and the sampled data was good.

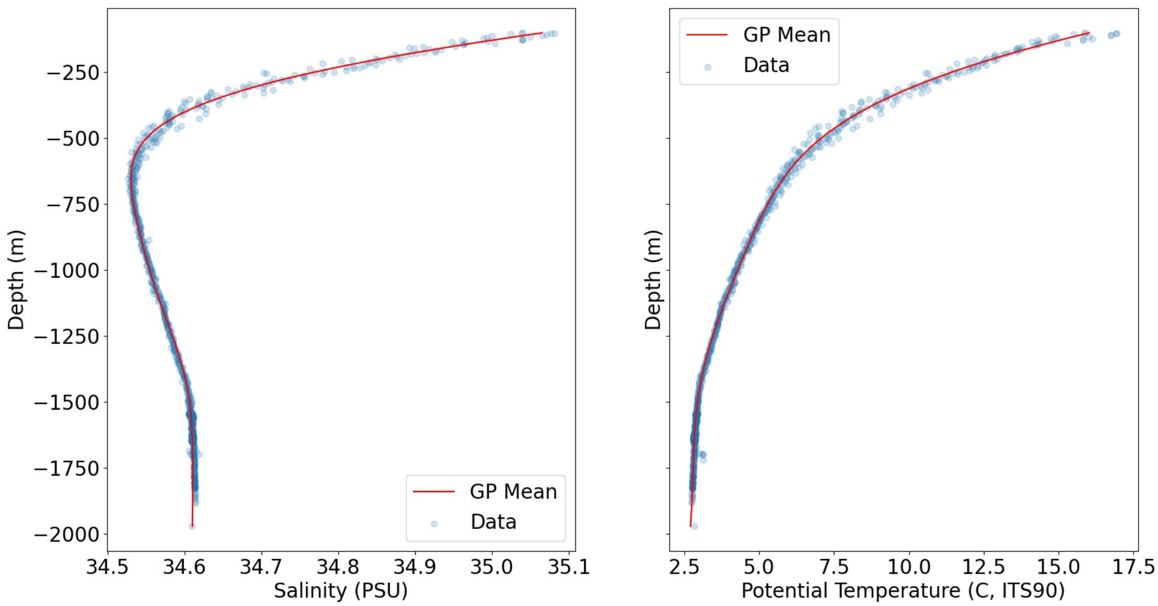


Illustration 12: GP mean of salinity and temperature profiles, with training data plotted.

Exit Velocity Estimation

To ground exit velocity estimates from our model, we have started the process of using a non-invasive PIV technique. Using PIVLab through MatLab, we have analyzed some footage from the Arm MISO camera taken during JD1390 at (27.4018606, -111.3991182, 1809m). Using the JASON 10cm lasers to calibrate the spatial scale in the image, and using auto-calibration in PIVLab to set processing parameters, we found exit velocities estimates well above 0.7m/s (up to 1.33m/s); although over an entire plume region (1-2m wide, 1m tall plume structure visible), the net upward velocity was estimated to be only 0.04m/s.

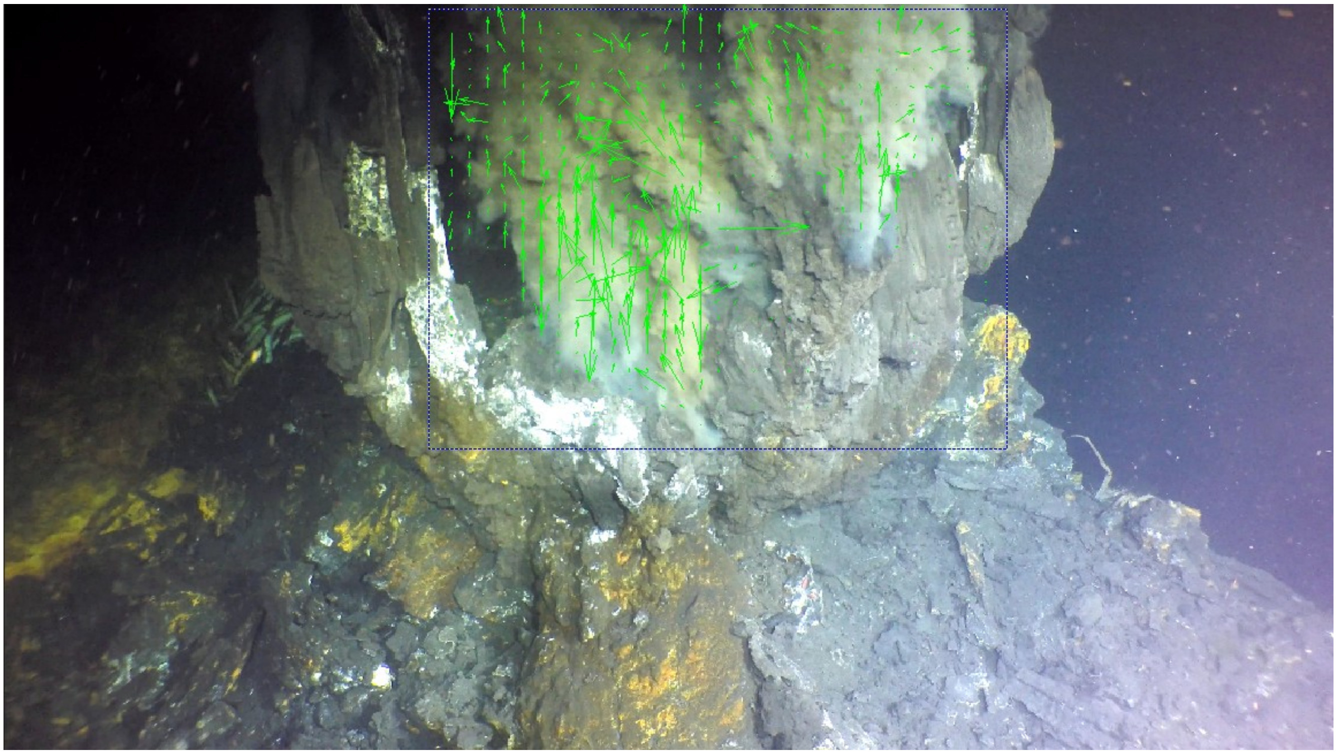


Illustration 13: Example image from MISO Arm Camera of black smoker plume with ROI and PIVLab computed vectors in place.

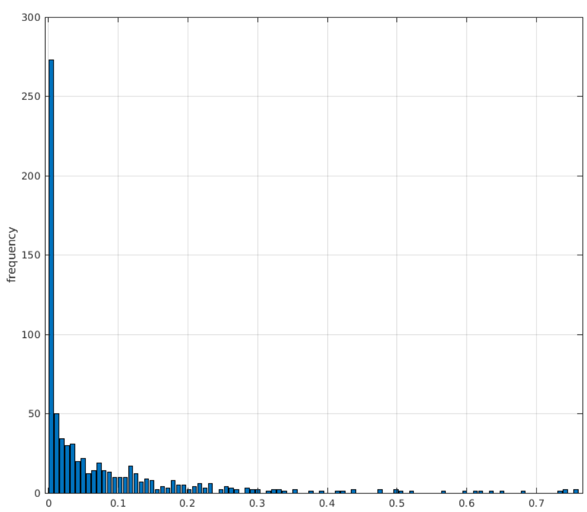


Illustration 14: Histogram of velocity magnitude detected in above frame.

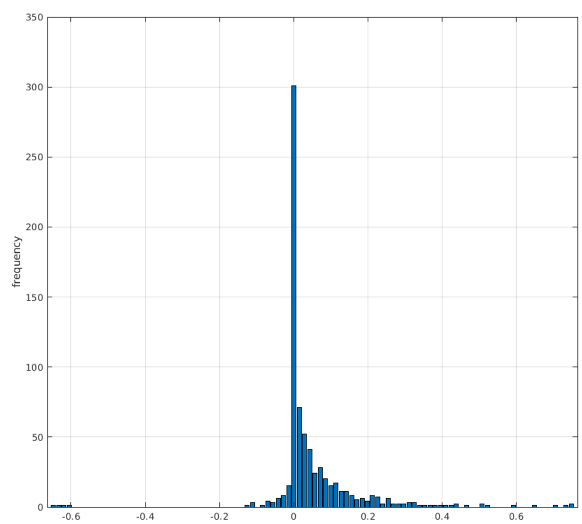


Illustration 15: Histogram of vertical velocities detected in the frame above. Long tail potentially indicates source magnitudes.

Trajectory Optimization

Starting on sentry610, optimized trajectories based on our scientifically-informed probabilistic models were used. A complete list of trajectories optimized by our system is below. Note that all origins are given in meters easting and northing of reference point (27.4, -111.4):

- sentry610
  - lawnmower 1 – origin (1379.1730, 1354.6755); orientation 75.5288
  - lawnmower 3 – origin (1301.266, 1305.1493); orientation 14.5283
  - lawnmower 4 – origin (1275.264, 1319.538); orientation 0.5
  - lawnmower 6 – origin (1389.952, 1403.596); orientation 109.073
- sentry611 (all lawnmowers generated for possible dive window; only subset used)
  - lawnmower 1 – origin (1293.265, 1394.562); h 74.947m; w 315.493m; orientation 31.522
  - lawnmower 2 – origin (1293.420, 1394.695); h 73.370m; w 327.982m; orientation 33.139
  - lawnmower 3 – origin (1291.652, 1395.314); h 75.008; w 300.045; orientation 21.446
  - lawnmower 4 – origin (1292.102, 1396.304); h 74.977; w 327.908; orientation 13.468
  - lawnmower 5 – origin (1298.069, 1378.418); h 74.924; w 300.704; orientation 0.944
  - lawnmower 6 – origin (1292.006, 1399.954); h 74.997; w 299.991; orientation 343.466
  - lawnmower 7 – origin (1295.508, 1403.481); h 74.987; w 299.942; orientation 297.347
  - lawnmower 8 – origin (1298.171, 1404.231); h 75.004; w 309.752; orientation 270.896
  - lawnmower 9 – origin (1302.756, 1402.395); h 75.035; w 299.887; orientation 230.484
  - lawnmower 10 – origin (1303.977, 1403.934); h 74.749; w 299.972; orientation 230.423
  - lawnmower 11 – origin (1299.914, 1406.229); h 75.003; w 299.999; orientation 260.315
  - lawnmower 12 – origin (1300.734, 1405.879); h 75.000; w 300.000; orientation 256.986
  - lawnmower 13 – origin (1301.007, 1403.149); h 74.999; w 299.982; orientation 247.109

Notably, we see that orientation and origin are among the more variable in the optimizer. This is likely because for a given depth, current magnitude and heading have an outsized effect on the plume location, but doesn't necessarily change (at the magnitudes we see) the overall size of the plume.

It is also notable from an operations standpoint that planning these trajectories is sensitive to dive schedules. Working closely with the SENTRY team and Chief Sci was critical for assembling trajectories that were timely and correct. To assist with this in the last optimmized-trajectory dive, we assembled a list of many trajectories, and then selected the relevant subset when the dive schedule became more concrete.

Future Investigation

An incredible amount of data was collected during the cruise relevant to the further development of scientifically-informed probabilistic models for spatiotemporal plume surveying, monitoring, and tracking, as well as sample optimization and decision-making. Our next steps will be to thoroughly assess the techniques used in the cruise from all collected SENTRY dives, and then investigate how well these methods would have performed under other sensing modalities (e.g., if only CTD Rosette casts were available, if only JASON operations data was used, if only two SENTRY dives would be available at a site, etc.). This validation and development pipeline will involved both using there data directly as well as further simulation of plumes for bulk assessment.

Future work that builds on the techniques in this cruise will involve developing a new type of probabilistic science-informed model that rather than takes a hierarchical approach as done here, instead embeds science models more implicitly within a probabilistic representation. Further decision-making work will involve more completely considering multiple levels of operations planning on a ship. For instance, in this work we focused specifically on placing a single vehicle in the right place at the right time, but we could extend this to consider when and where a CTD Rosette cast could be placed relative to a vehicle dive, weigh which type of vehicle or what information is necessary to better place a CTD Rosette or the AUV SENTRY, or increase general adaptability of single vehicle operations.

Several “engineering” tasks are of interest to pursue as well, including further extraction of current information from DVL water track pings and further using PIVLab to analyze both MISO Arm camera and JASON science camera data. Opportunistic Blueview multibeam data of plume flares was also captured at source vents and would similarly be interesting to compare against the visual methods.

While we anticipate a field robotics publication of this cruise work, and that the data will be used to advance algorithmic contributions, we also anticipate scientific contributions with respect to the scientifically-informed probabilistic model development anticipated after the cruise, and in collaboration with several outside scientists. Further, we anticipate assisting with several projects that intersected with our work during the cruise, including ammonia/ammonium and methane mapping in plume structures with A. Michel and S. Wankel. Finally, this data will support several undergraduate research projects advised by Victoria, as well as be components to both Victoria and Genevieve’s PhD thesis work.

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Appendix: Cruise On Station Notes

[20211117] CTD01 0430-0630 ship time; see turbidity spikes with some temp variance from 1800-1600m; site co-located with Chimney #1 in archival information from NA090.

[20211117] Sentry607 0900 ship time in water, multibeam until 1745 ship time, then starts waffles 1815 ship time at 60m in alt hold mode. See ORP dips at UTC 1915, 2015, 2100, 2150, 2330, 20211118 0100, 0215, big excursion at 0303, and so on.

[20211117] JD1388 aborted because of manip ground fault. Dive scrapped until Nov 18, 1000 ship time.

[20211117] Recommended that we talk to Shannon Walker at NOAA about plumes, point-casts with an ORP over diffuse flows, etc.

[20211118] Sentry607 ends 0420 ship time and on deck at 1000 ship time. Data IP is 100.124.34.66 (ship) and 192.168.100.9 (sentry).

[20211118] JD1389 dive aborted after tiltmeters dropped.

[20211118] Sentry608 dive planning handed to Zac at 1800 ship time; request for Niskin fires at (27.40782, -111.3866) and (27.4111, -111.3820)

[20211118] Sentry608 in water at 2300 ship time

[20211118] JD1390 to go in at 0000 20211119

[20211119] JD1390 watch notes: on descent notice at 1520m it's very smoky, at 1440m we are not in the plume. Tiltmeters are already deployed; pick up A at 1050UTC and place it at 1210UTC.

[20211120] Recommended to check out the work of Marv Lilley, Dave Butterfield, Gretchen Ugreen, Shannon Walker, and Tamara Baumgarten who are all "plume people"

[20211121] JD1391 watch notes: smoke seems to be blowing east observed at 0934UTC

[20211121] Current estimation is a challenge; there isn't too much trustworthy current data yet; going to attempt to train current and heading functions as GPs from data that has been collected from tiltmeter A. Will use scipy interpolate function to extract curves from the GP.

[20211121] Planning sentry609 trajectories for 1600 – 2000 potential dive window; want to train model on SENTRY data from last dive.

[20211121] Sentry609 aborted due to servo error.

[20211122] Working in PIVLab on MISO Arm camera data from JD1390. 100 frame snippet grabbed from plume film. Apply PIVLab to restricted region (Load Video > Select ROI > Calibrate > Train PIV Model > Analyze > Statistics). Observe as estimate of 0.33m/s up to 1.277m/s exit velocity estimate, with 0.2m/s mean.

[20211123] Training models from sentry607 data:

- CrossflowModelICU8_sentry607: Bayesian; 200 iters, 1e-15 thresh, 50 burnin, every 10 obs; priors V, A, alph, bet = (0.699, 1.654, 0.148, 0.451); posterior V, A, alph, bet = (0.66, 1.52, 0.154, 0.3). 43 samples accepted. Definitely seems like more samples in the chain are necessary.
- CrossflowModelESTX_sentry607: Bayesian; 500 iters, 1e-15 thresh, 100 burnin, every 10 obs; priors same as previous; posterior V, A, alph, bet = (0.44, 0.692, 0.146, 0.219). 77 samples accepted.

[20211123] Sentry610 dive plan to interleave adaptive and naive lawnmowers together based on current estimates drawn from tiltmeter data.

[20211123] Sentry610 mission looked good, but it was much more behind our timing estimates than expected.

[20211124] Training models from sentry607 data:

- CrossflowModel5WNG_sentry607: Grid; 10 samples/param (10^4 total evaluations); only gets to 5 iterations over many hours; very little movement from initial priors, the means of all of them.

[20211124] Note that sentry610 track needs to be adjusted in the 3rd lawnmower due to drift at 0154UTC

[20211125] JD1395 watch notes: observe the current moving due west at 0755UTC; smoke lens detected at 1510m at (27.410189, -111.388381); smoke layer looks like it exists from 1510m-1620m.

[20211125] Sentry611 mission looking ok, asking Joe to fly the vehicle as high as possible…..some comms errors later and rest of mission flown at 120m.

[20211125] JD1395 watch notes: observe temperature at vent to be 330C at (27.413214, -111.38686, 1790m). At heading 104 see a chimney to the left at 1153UTC.

[20211125] Training models from sentry607 data:

- CrossflowModel071D_sentry607: Grid-Search; 5 samples per parameter (total of 625 combos); prior same as before; posterior V, A, alph, bet = (0.1030, 0.1612, 0.1155, 0.1359).
- CrossflowModelH727_sentry607: Bayesian; 625 samples with 125 burnin; same prior as before; posterior V, A, alph, bet = (0.58, 0.82, 0.15, 0.19) --- electing to use this model moving forward

[20211125] sentry611 things are behind at 0432 ship time; 200m failed so flying at 120m, running out of time so skipping rest of naive lawnmower to get in a few tracklines in the last adaptive path.

[20211126] working on extracting current information from DVL. Prelim results show good agreement on magnitude, but heading is messy, potentially due to the really small magnitude of everything.

[20211126] planned sentry612 survey of S. Guaymas over two venting mounds

[20211127] wrote a haiku: flying through the plume; firing all of the Niskins; the bottles were closed

[20211128] discussing a long transect with SENTRY and CTD through the plume given far-CTD still saw the plume...

[20211129] Suggested to us to look us some of the work of Matthew Albert at Scripps who thinks about the transport and impact of tailings plumes in the deep sea

[20211129] hypothesize that SENTRY should see fallout “rain” before CTD sees the plume top if we start far enough away; unclear if we have

[20211129] see SENTRY obs climb very high then drop; schmutz or real signal?

[20211130] CTD transect recovered

Original Dive Planning Document

SENTRY Dives on Graben Ridge

Dive 1: Wednesday, Nov 17 **– Model Constraining Dives**
Allows for model seeding (current confirmation, initial condition setting)
Hrs 0-7: Multi-beam survey @ 60m
We can use science data from this mission, but specifications to be coordinated by Anna/Zac
Hrs 7-15: Reverse pyramid waffle-spirals (ideally depth hold)
4x lawnmowers over Chimney 2 at 100mx100m, 10m resolution, 30m altitude (2 waffles)
2x lawnmowers over Chimney 2 at 200mx200m, 10m resolution, 60m altitude (1 waffle)
1x spiral over Chimney 2 at 400mx400m, 20m resolution, 90m altitude
Navigate back to center (Chimney 2) and ascend at end of dive

Dive 2: Date TBD **– Model Validation Dives**
Allows for confirmation of current model and initial conditions

- Coordinate with Anna, but time in the dive to fly low and slow over the plumes along the ridge in order to best-test instruments

Hrs 2-14: Medium-resolution extent-constraining spirals

- V&G provide a set of chained spirals with center-offsets that track the heading of the current

Dive 3: Date TBD – **Planning Optimization Dives**
Allows for a trial of the trajectory optimizer with validated model
Hrs 0-2: Super low ridge fly-by

- Coordinate with Anna, but time in the dive to fly low and slow over the plumes along the ridge in order to best-test instruments

Hrs 2-18: High resolution plume tracking

- V&G provide a set of chained lawnmowers at medium resolution potentially at multiple heights (to be determined from previous dives) that attempt to closely track the plume maxima over time
- Navigate back to Chimney 2 and ascend at end of dive

Further dives:

- If further dives on site are available, further validate models (similar to Dive 2 structure) and attempt online adjustments (similar to Dive 3 structure with semi-real time shifts allowed)

SENTRY Dive(s) on Ring Vent or Sonora
Dive A: Date TBD
Have initial data from model confirmation and attempt to transfer model + trajectory training to new environment. Allows opportunity for compelling online planning.
Hrs 0-2:

- 2x lawnmowers over Chimney 2 at 100mx100m, 10m resolution, 20m altitude (1 waffle)
- 2x lawnmowers over Chimney 2 at 100mx100m, 10m resolution, 40m altitude (1 waffle)

Hrs 2-14:

- Medium-plume tracking
  - V&G provide a set of chained lawnmowers at medium to low resolution potentially at multiple heights (to be determined) that attempt to closely track the plume maxima over time
  - Potential for online shifts

  Hrs 15-17:
- 2x lawnmowers over Chimney 2 at 100mx100m, 10m resolution, 20m altitude (1 waffles)
- 2x lawnmowers over Chimney 2 at 100mx100m, 10m resolution, 40m altitude (1 waffle)

JASON at All Sites
Dive 1: Wednesday, Nov 17 (and on first dive at any new site)
Allows us to seed models with good prior on initial conditions

Start of Dive (Hours 0-1): Deploy the 2 tiltmeters at coordinates planned with operations
Initial suggestion: TM A: (27.40246, -111.3835) [plane in front of ridge][deploy after descent], TM B: (27.40757, -111.390) [any location along ridge][deploy during ops]

Hrs 1-2: 10-20 minutes of temperature probe directly (or as close as is safe) in the largest orifice of Chimney #2 ; Align camera and ensure that green lasers are on and visible at the orifice or in the plume (where the temperature probe was deployed). Use lasers to measure orifice diameter. Then, take 10-20 minutes of MISO camera data focused on Chimney #2 (27.41265607, -111.38690875, ~1845m depth)

Hrs 2-8: A ridge survey. For each plume below (or as many as possible), repeat the above process to gather ~10 minutes of video and in plume data.

End of dive (final hour): Recover TM A at coordinates (27.40246, -111.3835)

Chimney Coordinates

Reference	Label	Lat	Lon	Est Depth
NA090-20171022	tall_peak_smoker	27.41030475	-111.38840791	1840
NA090-20171022	black_smoker_chimney	27.41038474	-111.38847751	1840
NA090-20171022	slender_black_smoker	27.40926223	-111.38931794	1840
NA090-20171022	huge_sulfide_wall_chimney	27.40916004	-111.38932667	1840
NA090-20171022	large_diffuse_flow_chimney	27.408978	-111.389397	1850
NA090-20171022	NA090_021, Chimney #1	27.407473	-111.389862	1850
NA090-20171022	NA090_111, Chimney #2	27.41265607	-111.38690875	1845
Herc Track	Southwest Center	27.407739247	-111.390099146	NA
Herc Track	Southwest 2 Center	27.4090877667	-111.389352359	NA
Herc Track	Chimney Field	27.4105224206	-111.388347357	NA
Herc Track	Northeast 2 Center	27.4111370942	-111.388086109	NA
Herc Track	Northeast Center	27.4126149693	-111.387381041	NA

Dive 2-Final:

Allows us to have a continuously updated current model

Start of dive (Hours 0-1): Deploy the new tiltmeter

End of dive (final hours): Recover the second deployed tiltmeter

When possible:

- Station-keeping in the plume waters – *using camera feed and on-board sensors, attempt to keep JASON near the center of plume expression; this allows us to collect a time-series that may be of interest for model validation*
    - Ideally done during slack current (coordinate timing with V & G)
    - Various altitudes between as low as possible (~5m) and 30m
    - As long as possible [ideally 30 minutes minimum]
    - One of V & G should be present during this maneuver
- Short plume profiles – *ascend to ~200m altitude from the plume source at constant location every 1-3 hours; this allows us to collect a profile-time-series that is of interest for model development*
    - Drive ~60m off plume and then ascend to 200m
    - One of V & G should be present during these maneuver

SENTRY Science Dive Plans

Science Dive Description: Sentry 608 – Graben Ridge

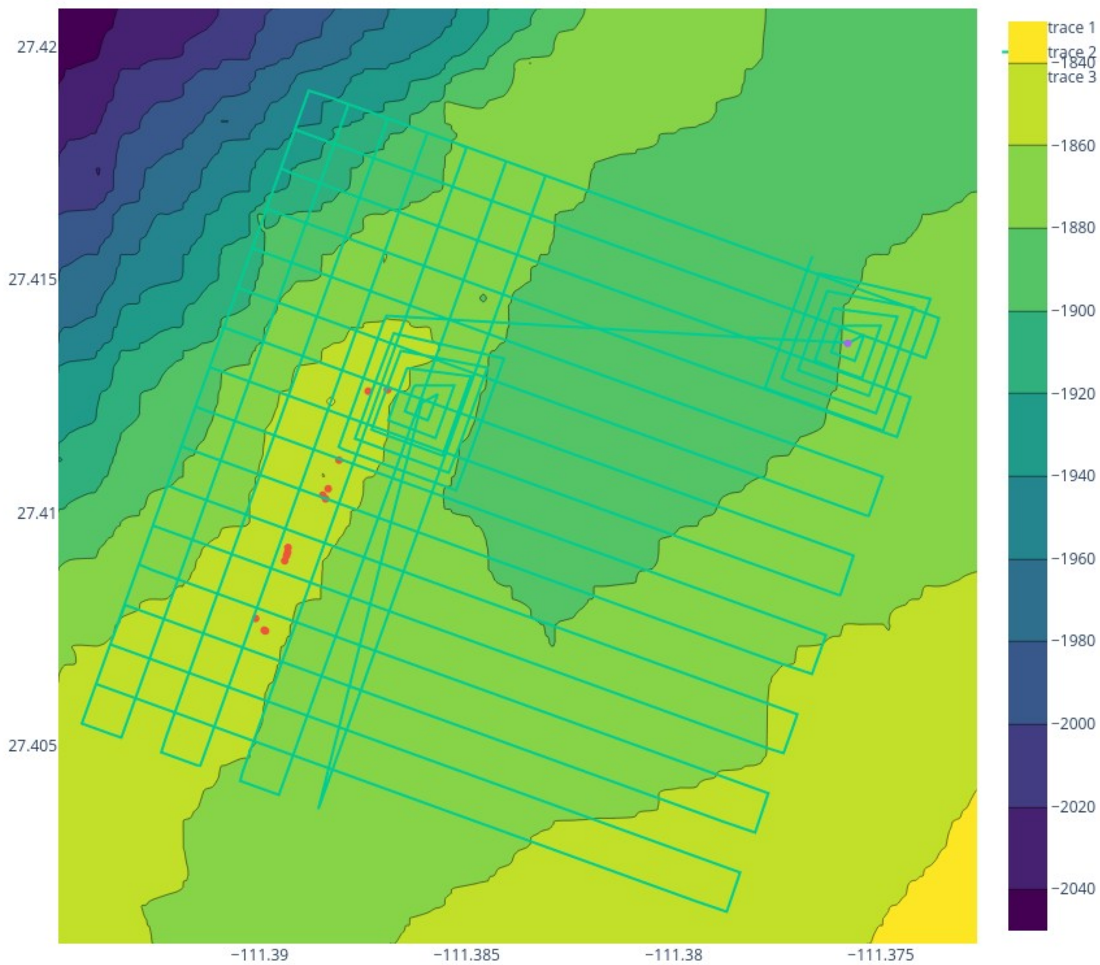
Goal: Constrain the non-buoyant plume height (and bending angle) of advecting plumes in the basin and capture the “current sweep” of plume waters within the basin.

Motivation: Estimating current from observational data alone is an interesting challenge and would add to the robustness of the modeling approach proposed (e.g., if we can do it without tiltmeters or show that we could estimate as well as tiltmeters, that would be of algorithmic and modeling interest). This dive will also allow us to better constrain unknown plume initial conditions by attempting to hit the plume at the non-buoyant layer, which should better reveal aspects of plume buoyancy/momentum and help to contextualize buoyant stem measurements.

Description:

- **Phase 1: Lawnmower over plain**
    - Perform a 1500mx1600m lawnmower starting to the southwest of the ridge at 100m, oriented at the same angle as the ridge/graben at 120m (to be potentially adjusted while in flight)
    - Starting position: 27.40625, -111.394
    - Approximately 10hrs
    - **Note:** Lawnmower designed to cover the entire ridge and plain up to the “Knob” at 27.41364, -111.3758. Some of the graben is also covered. This lawnmower is to be used to capture “current sweep” and non-buoyant layer edges
    - **NISKIN FIRING:** For capturing out of plume water (or lightly plume influenced water) this is likely the time of opportunity for firing the Niskin(s) on Sentry
- **Phase 2: Lawnmower over ridge**
    - Perform a 600mx1600m lawnmower at 100m resolution with long-legs oriented along-ridge at 45m altitude
    - Starting position: 27.41898, -111.3888
    - Approximately 4.5hrs
    - **Note:** Designed to capture contributions from multiple sources along the ridge and capture behind-ridge advection of plume water
    - **NISKIN FIRING:** For highly influenced plume water, this is likely the time of opportunity for firing the Niskin(s) on Sentry
- **Phase 3: Spiral over Chimney 3**
    - Perform a 200mx200m spiral at 100m altitude at 30m resolution just to the southeast of Chimney 2 site.
    - Approximately 1.5hrs
    - **Note:** Designed to capture nonbuoyant advection from a site with a lot of previous Sentry data
- **Phase 4: Spiral over Knob**
    - Transit from Chimney 2 to the Knob and perform a 200mx200m spiral at 30m altitude at 30m resolution centered with the feature

    - Approximately 1.5hrs
    - **Note:** Included for scientific interest over whether there is interesting hydrothermal activity/ pluming at the site
- **<u>Holding Pattern:</u>**
    - A 200mx200m 10m resolution holding pattern at 65m is included at the end of the dive, with potential for opportunistic placement
- **<u>Opportunistic Holding Patterns:</u>**
    - There is some interest in occasionally halting Sentry into a ballast test and adjusting vertical profiles to capture short vertical plume structures as possible. Likely to be done during the holding pattern if time, or opportunistically during the spirals.



Science Dive Description: Sentry 609 – Adaptive Graben Ridge

Note: Mission never executed b/c technical issues

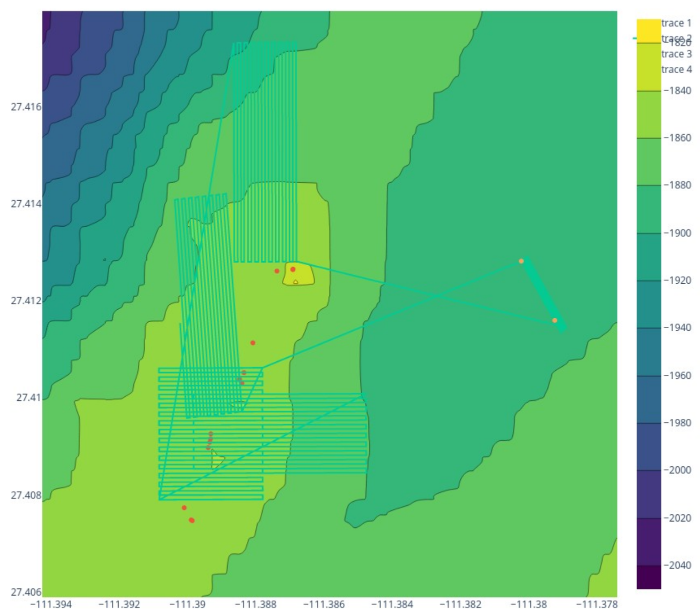
Goal: Using previously collected scientific data (background profiles, tiltmeter data, source measurements), forecast the envelope of the plume and design adaptive lawnmowers that exploit these models to spend more time high in the buoyant plume. "Naively designed" lawnmowers are included as benchmarks.

Motivation: Our measurement informed MTT forward model enables us to forecast plume evolution in space and time. This mission will demonstrate that we can use this model to design adaptive lawnmowers that spend more time in buoyant plume waters, compared to naively designed benchmark lawnmowers. We will additionally use these models to collect bottle samples of buoyant plume water of different ages/distances from the plume source.

Description:

- **<u>Phase 1: Adaptive Lawnmower over Chimney #1</u>**
  - Perform a 180mx500mx10m lawnmower oriented at 0 degrees and offset slightly to the east of Chimney 1, designed to intersect plume water advected by currents at 0 degrees (standard convention).
  - Starting position: 27.40926223, -111.38931794 at 120m
  - Approximately 3.58hrs
  - **Note:** This lawnmower is designed to map plume water current from west to east.
- **<u>Phase 2: Naive Lawnmower over Chimney #1</u>**
  - Perform a 300mx300mx10m "naive" lawnmower oriented at 0 degrees and centered over Chimney 1.
  - Starting position: 27.40926223, -111.38931794 at 120m
  - Approximately 3.55hrs
  - **Note:** This lawnmower is naively designed to map plume water over Chimney #1
- **<u>Phase 3: Video Survey</u>**
  - Transect over to the knobletts and perform a 20x200x5m lawnmower for an exploratory video survey
  - Starting position: 27.41282, -11.38022 at 5m
  - Approximately 0.56hrs
  - **Note:** Exploratory photo mosaic of interesting features in bathy using MISO camera
  - **Note:** Included for scientific interest over whether there is interesting hydrothermal activity/ pluming at the site
- **<u>Phase 4: Adaptive Lawnmower over Chimney #2</u>**
  - Perform a 500mx180mx10m lawnmower oriented at 90 degrees and offset slightly to the north of Chimney 2, designed to intersect plume water advected by currents at 90 degrees (standard convention).
  - Starting position: 27.41236, -111.3861 at 200m
  - Approximately 3.58hrs
  - **Note:** This lawnmower is designed to map plume water with currents from south to north.

    - **NISKIN FIRING:** For capturing out of plume water (or lightly plume influenced water) firing a Niskin at 27.41685, -111.388
- **<u>Phase 5: Naive Lawnmower over Chimney #1 (second time)</u>**
    - Repeat an identical 300mx300mx10m "naive" lawnmower oriented at 0 degrees and centered over Chimney 1.
    - Starting position: 27.40926223, -111.38931794 at 120m
    - Approximately 3.55hrs
    - **Note:** This lawnmower is naively designed to map plume water over Chimney #1.
- **<u>Phase 6: Adaptive Lawnmower over Chimney #1 (second time)</u>**
    - Perform a 500mx180mx10m lawnmower oriented at 96 degrees and offset slightly to the north of Chimney 1, designed to intersect plume water advected by currents at 95 degrees (standard convention).
    - Starting position: 27.40926223, -111.38931794 at 120m
    - Approximately 3.58hrs
    - **Note:** This lawnmower is designed to map plume water current from south to north.
    - **NISKIN FIRING:** For capturing out of plume water (or lightly plume influenced water) firing a Niskin at 27.41391, -11.3901
- **<u>Holding Pattern:</u>**
    - A 200mx200m 10m resolution holding pattern at 65m is included at the end of the dive, with potential for opportunistic placement
- **<u>Opportunistic Holding Patterns:</u>**
    - There is some interest in occasionally halting Sentry into a ballast test and adjusting vertical profiles to capture short vertical plume structures as possible. Likely to be done during the holding pattern if time, or opportunistically.



Science Dive Description: Sentry 610 – Adaptive Graben/Ridge, Chimney 2

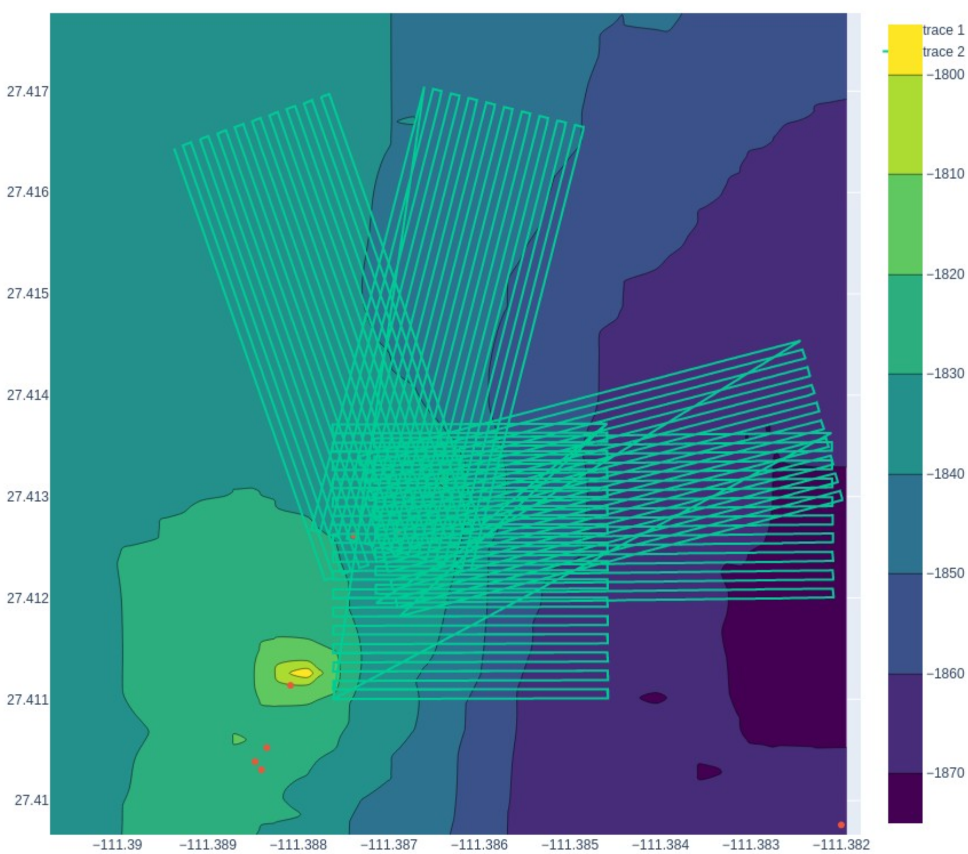
Goal: Using previously collected scientific data (background profiles, tiltmeter data, source measurements), forecast the envelope of the plume and design adaptive lawnmowers that exploit these models to spend more time high in the buoyant plume. "Naively designed" lawnmowers are included as benchmarks.

Motivation: Our measurement informed MTT forward model enables us to forecast plume evolution in space and time. This mission will demonstrate that we can use this model to design adaptive lawnmowers that spend more time in buoyant plume waters, compared to naively designed benchmark lawnmowers. We will additionally use these models to collect bottle samples of buoyant plume water of different ages/distances from the plume source.

Description:

- **Phase 1: Adaptive Lawnmower over Chimney #2**
    - Perform a 180mx500mx10m lawnmower oriented at 75.5288 degrees and offset slightly to the east of Chimney 2, designed to intersect plume water advected by currents.
    - Starting position: 1379.1730m easting, 1354.6755m northing from (27.4, -111.4) at 120m
    - Approximately 3.0hrs
    - **NISKIN FIRING:** A Niskin will be opportunistically fired in order to collect distal plume water
- **Phase 2: Naive Lawnmower over Chimney #2**
    - Perform a 300mx300mx10m "naive" lawnmower placed above Chimney 2
    - Starting position: 150m more west and 150m more south than Chimney 2 locations at 120m
    - Approximately 3.00hrs
    - **Note:** This lawnmower is naively designed to map plume water over Chimney #2
- **Phase 3: Adaptive Lawnmower over Chimney #2**
    - Perform a 180mx500mx10m lawnmower oriented at 14.5283 degrees and offset slightly to the north of Chimney 2, designed to intersect plume water advected by currents.
    - Starting position: 1301.266m E, 1305.1493m N from (27.4, -111.4) at 120m
    - Approximately 3hrs
- **Phase 4: Adaptive Lawnmower over Chimney #2**
    - Perform a 180mx500mx10m lawnmower oriented at 0.5 degrees and offset slightly to the north of Chimney 2, designed to intersect plume water advected by currents.
    - Starting position: 1275.264m E, 1319.538m N from (27.4, -111.4) at 120m
    - Approximately 3hrs
- **Phase 5: Naive Lawnmower over Chimney #2 (second time)**
    - Repeat an identical 300mx300mx10m "naive" lawnmower centered over Chimney 2.
    - Starting position: 150m more west and 150m more south than Chimney 2 locations at 120m
    - Approximately 3.00hrs
    - **Note:** This lawnmower is naively designed to map plume water over Chimney #2
    - **Note:** This was supposed to be flown at 200m, but bottom tracking was difficult, so the track was moved to 120.0m altitude.
    - **Note:** Due to the height of flights, this trajectory was started much later than assumed. To get to the next lawnmower, several waypoints of this trajectory were canceled.

- **<u>Phase 6: Adaptive Lawnmower over Chimney #2</u>**
    - Perform a 500mx180mx10m lawnmower oriented at 109.073 degrees and offset slightly to the north of Chimney 2, designed to intersect plume water advected by currents
    - Starting position: 1389.952m E, 1403.596m N of (27.4, -111.4)
    - Approximately 3hrs
    - **NISKIN FIRING:** A Niskin will be opportunistically fired in order to collect distal plume water
    - **Note:** Only a few tracklines were able to executed in this trajectory due to timing.
- **<u>Holding Pattern:</u>**
    - The last trajectory will be shifted to be used as a holding pattern when necessary.
- **<u>Opportunistic Holding Patterns:</u>**
    - There is some interest in occasionally halting Sentry into a ballast test and adjusting vertical profiles to capture short vertical plume structures as possible. Likely to be done during the holding pattern if time, or opportunistically.



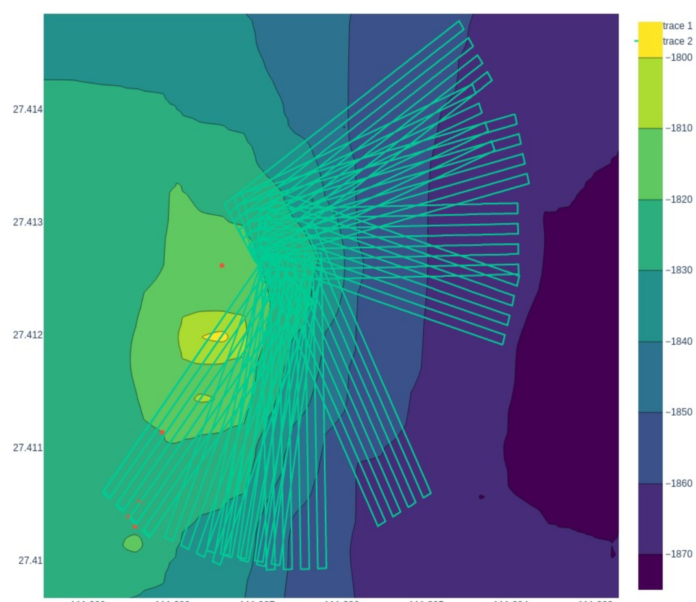
Science Dive Description: Sentry 611 – Data-Informed Adaptive Graben Ridge at Chimney 2

Goal: Using previously collected scientific data (background profiles, tiltmeter data, source measurements), as well as Sentry observations, forecast the envelope of the plume and design adaptive lawnmowers that exploit these models to catch high resolution snapshots of the plume bend.

Motivation: Our measurement informed MTT forward model enables us to forecast plume evolution in space and time. We have updated the *prior* version of this model with *in situ* observations from previous Sentry flights. This mission will demonstrate that we can use this model to design adaptive lawnmowers that spend more time in buoyant plume waters, compared to naively designed benchmark lawnmowers, and that these models can be used within an iterative data-informed regime. We will additionally use these models to collect bottle samples of buoyant plume water of different ages/distances from the plume source.

Description:

- **<u>Radially fanned lawnmowers that track the current</u>**
  - 7-8 1hr long lawnmowers of various lengths will be used to gather near-plume measurements near the Chimney 2 source.
  - **NISKIN FIRING**: will be opportunistically fired
  - **Note:** This trajectory will be done in *depth-hold mode* ranging from 60-140m above the bottom; this is to attempt to hit the plume's nonbuoyant "underlayer" over time.
- **<u>Holding Pattern:</u>**
  - The last trajectory will be shifted to be used as a holding pattern when necessary.
- **<u>Opportunistic Holding Patterns:</u>**
  - There is some interest in occasionally halting Sentry into a ballast test and adjusting vertical profiles to capture short vertical plume structures as possible. Likely to be done during the holding pattern if time, or opportunistically.



Science Dive Description: Sentry 612 – Exploratory Survey of S. Guaymas

Goal: From markers placed by previous science parties at S. Guaymas, this survey is intended to provide a snapshot of multiple-plume expressions possible within the region, specifically concentrated in two areas.

Motivation: As a well-studied site, collecting mid-water chemistry transects of the region offers a unique perspective, scientifically. Algorithmically, as a site with known, clustered large vents, this is an interesting case for studying probabilistic multiplume models.

Description:

- **Video Transect (designed by Sentry team)**
  - A short transect at 5m to be conducted in a flat region in order to test 4k video capabilities of a MISO camera
- **Regional lawnmower**
  - 530m x 1300m at 30m resolution, oriented 145deg from horizontal centered between two clusters of known markers
  - 40m altitude
  - Approx. 8.9hrs
- **Spiral over northern cluster**
  - Centered at (27.01396, -111.4112)
  - 300m x 300m with 30m resolution
  - 100m altitude
  - Approx. 3.9hrs
  - **NISKIN FIRING**: A Niskin will be fired upon arriving to the center of the spiral trajectory
- **Spiral over southern cluster (Rebecca's Roost, Cathedral Hill, etc.)**
  - Centered at (27.0105, -111.4045)
  - 300m x 300m with 30m resolution
  - 100m altitude
  - Approx. 3.9hrs
  - **NISKIN FIRING:** A Niskin will be fired upon arriving to the center of the spiral trajectory