An expansion of Glider Observation STrategies to systematically transmit and analyze preferred waypoints of underwater gliders

Lucy F. Smedstad[1], Charlie N. Barron[1], Rachel N. Bourg[2], Michael W. Brooking[2], Danielle A. Bryant[2], Robert J. Carr[3], Kevin D. Heaney[4], Edward A. Holmberg[5], Andrea C. Mask[2], and Bryan L. Mensi[2]

[1] Naval Research Laboratory (NRL), Stennis Space Center, MS, 39529, USA [2] Naval Oceanographic Office (NAVOCEANO), Stennis Space Center, MS, 39529, USA, [3] University of Washington, Applied Physics Laboratory (APL-UW), Seattle, WA, USA, [4] Ocean Acoustical Services and Instrumentation Systems, Inc. (OASIS), Lexington, MA, 22039, USA, [5] University of New Orleans (UNO), New Orleans, LA, USA

ABSTRACT

The Glider Observation STrategies (GOST) system provides real-time assistance to ocean glider pilots by suggesting preferred ocean glider waypoints based on ocean forecasts and their uncertainties. Restrictions on waterspace, preferred operational areas, and other glider trajectories are also taken into account. Using existing operational regional Navy Coastal Ocean Model (RNCOM) output, demonstrations of glider waypoint calculation are ongoing in Navy operational areas. After the ocean forecast models and GOST components run at the Navy DoD Supercomputing Resource Center (Navy DSRC), GOST-suggested glider paths are transferred to the Glider Operations Center (GOC). The glider pilots at the GOC import this information into their Unmanned Systems Interface (USI), developed at the University of Washington, Applied Physics Laboratory (APL-UW) to evaluate the suggested glider paths, make adjustments, and update waypoints for the gliders. The waypoints being sent are visualized and analyzed using graphic capabilities to convey guidance uncertainty developed under a grant to the University of New Orleans (UNO) and added under the Environmental Measurements Path Planner (EMPath) system within GOST. USI forwards automatic messages from the gliders with recent glider location, speed, and depth to GOST for the next cycle. Over the course of these demonstrations, capabilities were added or modified including use of initial glider bearing, preferred path, refinement of glider turn frequency, correction of glider speed, and introduction of glider rendezvous locations. Automation has been added with help from the modeling group at the Naval Oceanographic Office (NAVOCEANO). GOST supports NAVOCEANO's ongoing efforts to direct and recover gliders, to safely navigate in changing ocean conditions, and to provide feedback to improve ocean model prediction.

Keywords: operational ocean modeling, gliders, autonomous platforms

1. INTRODUCTION

The Navy has identified ocean gliders as an increasingly important source of local observations to guide its ocean forecasts in support of tactical decisions. The various regional Navy Coastal Ocean Models (RNCOM)[1] assimilate a range of available satellite and *in situ* observations before each daily model execution on the Navy DoD Supercomputing Resource Center (Navy DSRC). The Naval Oceanographic Office deploys its Slocum gliders[2] to make additional measurements in areas of interest, which often coincide with RNCOM operational areas. Historically gliders have been used to generally cover an area to provide a generic overview. The Glider Observation STrategies (GOST) system enables more effective use of the gliders by comparing possible combinations of glider measurements, where possible trajectories are determined based on specified glider in-water speed and local forecasts of ocean currents. Glider trajectories are assigned values based on line integrals along the glider trajectories through simple statistical fields quantifying selected mission-relevant properties such as environmental variability or forecast uncertainty. Measurements from multiple gliders may be deemed redundant if the gliders come to close in space or time, leading to a proportionate reduction in the combined valuation. Glider movement may be restricted through both stay out or keep in areas. One of the goals of GOST 2.0, the current version being tested are to accomplish more automated exchange of information between the Glider Operations Center (GOC) and the operational model platform. This report additionally contains results from real time tests performed using GOST 1.3, which relied on a manual exchange of starting glider location and output waypoints.

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2. SYSTEM INFORMATION

The Glider Observation Strategies (GOST) system consists of two main components. The first is the Glider Mission Adaptation Strategies (GMAST) which reads model data in netCDF format and determines constituent cost functions (CCF)s based upon the mission type. The second component of GOST is the Environmental Measurements Path Planner (EMPath)[3,4]. EMPath contains the genetic algorithm[5,6] that weighs the cost functions with the currents and with restrictions on allowed operational areas to select a preferred path for the glider.

There are four mission types:

1. *Feature Investigation/Variability Reduction* is the way Ocean Forecasters are providing glider guidance currently and allows the model to guide the glider to where it predicts the highest variability (uncertainty).
2. *Sustained Coverage* is what the Glider Operations Center (GOC) has historically been doing but looks for more efficient coverage that leverages forecast currents rather than defaulting to a lawnmower pattern of repeated parallel paths.
3. *Tactical Operation* uses specialized cost functions that may, for example, account for observation impact on smaller scales for acoustic applications. This mission type may be supported by ensemble model runs that quantify probabilities of different outcomes.
4. *Rendezvous* may be used at the end of any of the above three to find the best path to get a glider to its recovery location at the proper time.

The main mission type tested for GOST 1.3 and GOST 2.0 is the feature investigation/variability reduction based on the spread of the model forecast. The primary location of the tests is in an operational area in the eastern Pacific. Initial testing of GOST was performed with GOST 1.3 in the Trident Warrior (TW13) [7] are off of the eastern US coast. These tests involved manual sending of glider start locations and waypoints via email. The rendezvous mission has been also tested in both sets of real time exercises.

GMAST provides CCFs representing the criteria for evaluating alternative glider paths through EMPath[8]. The CCFs providing these criteria are derived from the RNCOM forecast fields. GMAST's only function is to produce the CCF file in netCDF format henceforth referred to as the GMAST file. For mission type 1, the CCFs highlight model uncertainty and ocean variability. The longitude and latitude spacing uses RNCOM's model gridding.

The GMAST file has 3 major components:

1. *CCFs* - There are two different types of CCFs: static and dynamic. Static cost functions are time-independent statistics, while dynamic cost functions include a time dimension. To identify ocean variability, the static CCFs are based on the mean and standard deviations from predicted salinity and temperature fields. Other constraint-based dynamic CCFs, such as a rendezvous point, may also be included. Figure 1 contains illustrations of three CCFs.
2. *Water currents* - Water currents are the time-dependent forecast ocean velocity components that are averaged over the glider depth range. These values are in meters per second.
3. *Metadata* – These are additional parameters relating to the netCDF file and the glider mission information. Among those parameters, the most prominent for this project are:
   a. *Start_time* – the assumed time that new instructions are given to the glider
   b. *DeltaTime* – the time increment of the dynamic functions
   c. *TotalTime*- the time from the start of the model run (usually 00Z to the end of the GOST simulation). Because GOST may not be run until many hours after 00Z, this number may be larger than the length of the model forecast
   d. *GliderDepth*, maximum depth for the glider dive pattern in this deployment, in meters
   e. *GliderSpeed*, the average glider horizontal speed through the water, in meters/second

f. *Gl_hr_extrap*- GMAST was equipped with an additional option to extend the forecast length using persistence in order to allow the EMPath to be run for 120 hours. The average RNCOM has a 96 hour forecast.

g. *Cutlat1,cutlat2,cutlon1,cutlon2* – boundaries of a smaller region to make execution of programs speedier. Can be set to match the outer area in EMPath.

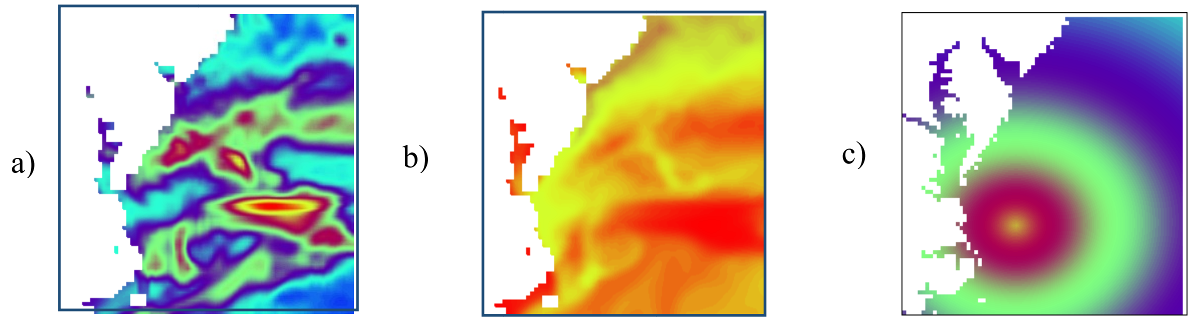

Figure 1. Examples of the CCF during the TW13 exercise illustrate a static CCF (a), a dynamic CCF (b) and a rendezvous cost function (c). The temperature mean spread over time is shown in (a) with the dark areas being the higher variability. The rendezvous CCF is shown on the right. The rendezvous CCF is dynamic and the bull's eye will become smaller and more defined in time as it is technically a dynamic cost function.

EMPath makes use of the environmental information necessary to determine where gliders are able to go in order to quantify the relative value associated with that set of potential glider trajectories. Valuation of possible glider samples are determined by weighted CCFs that quantify the relative importance ascribed to observations at different locations and times (for dynamic CCFs). The CCFs are combined using an array of weights to output a total cost function, represented by a flattened image referred to as a morphology, as shown in the following equation.

$$E(\vec{r}) = \sum_{i=1}^{n} \frac{W_i C_i(\vec{r})}{\sigma(C_i)} + W_b C_b + W_{dp} C_{dp}(\vec{r})$$

EMPath is a self-contained program that runs independently of either RNCOM or GMAST, thereby requiring that the necessary data be passed in as parameters. EMPath allows for many user specified parameters including the keep in areas (OpArea) and keep out areas (waterspace). EMPath requires 6 major inputs:

1. *GMAST file*- generically named gmast.nc - A netCDF file created by GMAST that contains static and dynamic CCF's.
2. *Bathy_file*- generically named bathy.nc - An auxiliary program produces a second netCDF file that contains the water depth values extracted from the RNCOM domain.
3. *Input.prm file* which contains all the necessary parameters for the EMPath executions including the array of weights for the CCF.
4. *Cords_init file* which provides the initial starting position of the gliders.
5. *Rshapes.txt file* which allows the user to input waterspace management (inclusion or exclusion) areas.
6. *OneIndv.txt file* allows the user to specify long range lat/lon points which force EMPath to prioritize a rendezvous.

The GMAST file is soft linked to a standard NetCDF file named gmast.nc, requiring only the filename gmast.nc to be hard coded in the input.prm file. The bathy.nc file is created once per region and soft linked in a scrubbable directory on the NAVO DSRC. Within the input.prm the following should be set:

1. *Glider depth* – maximum depth for the glider dive pattern in this deployment, in meters
2. *Glider speed* – the average glider horizontal speed through the water, in meters/second
3. *Hours allowed before resampling* – minimum time before re-sampling an area (defaults to24)

4. *Glider waterspace flag* (set to 1 if a waterspace area exists)
5. *Total hours* – hours in model time that the EMPath is set to search over
6. *Hours between turns* - time between changes in glider horizontal direction (defaults to 12)
7. *Degrees between gliders* – spacing scale that penalizes gliders (defaults to 0.5)
8. *OpArea*- a polygon describing the boundaries that contain all allowable glider trajectories
9. *Number of gliders* – most tests in this time period involved one, but some deployments had two or three present with the same or different missions
10. *Bounds* - lat_max_bound, lat_min_bound, lon_max_bound, lon_min_bound limits of all data; these are set to the same values as cutlon/cutlat/[12] in GMAST
11. *Weights* –default values of CCF weights exist, but these can be manually altered in the input.prm file. For GOST 1.3 and GOST 2.0 only the rendezvous cost function was increased in weight when required.

Figure 2 is shows the result of an analysis result of an analysis[9] performed during TW13. The starred rendezvous point must be balanced by a long term glider path that does not waste resources trying to get to the rendezvous point (Figure 2a) or miss the rendezvous point (Figure 2b). The desired outcome is that the areas of importance are sampled while still making the rendezvous goal (Figure 2c).

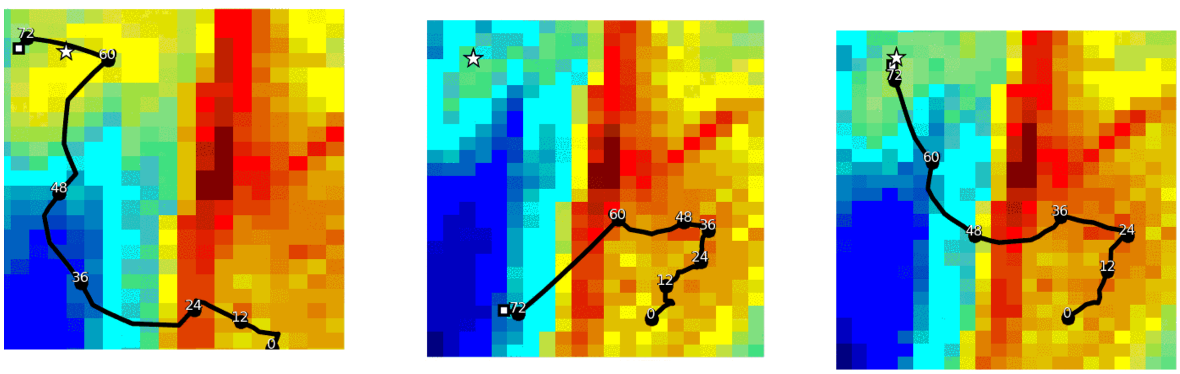

Figure 2. An overemphasis on rendezvous misses important areas (a). Overemphasizing sampling misses the rendezvous location (starred point) and time (b). Mission success occurs when both area achieved (c).

EMPath produces 5 basic outputs:

1. *Morphology.txt* - This text file contains the values for the combined cost function (sometimes referred to as the morphology) for each of the latitude and longitude coordinates at the initial time, (time index=0). This file contains values of each of the CCFs, and the final column is the value of the combined cost function[3].
2. *GA_Run#.csv* - For each of the runs, there is a comma separated variable (csv) file that contains all of the details of the most highly rated set of glider paths. Each run is independent of the others. These details include the lon, lat, and bearing for every glider at every time[3].
3. *GA_BestRun.csv* - GA_BestRun.csv is the GA_Run#.csv that has the highest score[3].
4. *EMPath.log* - EMPath's standard out is piped to a text file. This log file contains the scores for all the runs.
5. *Cost function background graphics* -Graphics of the combined cost function are the output of the EMPath. These images contained the best path overlaid on the morphology. This has been improved in GOST 1.3[9].

Figure 3 illustrates the wiring diagram of GOST. The main model operations components are executed on the NAVO DSRC. The GOC processing is executed within USI on workstations in a separate network. During GOST 1.3 testing a parallel directory for the operational regional NCOM (RNCOM)[1] was set up under a relo_beta directory tree. The GOST scripts sit in the RNCOM directories under GMAST and EMPath subdirectories. A pre_gmast.sh and pre_empath.sh scripts are used to launch each piece. Each component runs on a single processor on the Navy DoD Supercomputing Resource Center (Navy DSRC) in directories associated with a beta version of the applicable RNCOM. The operational setup of GOST 2.0 will be located in a model_apps directory and running subdirectories will be placed under the scratch space of the appropriate regional area. The launching scripts are converted to Perl in GOST 2.0. All relevant inputs and outputs will be archived to mass storage after the exercise for further analysis.

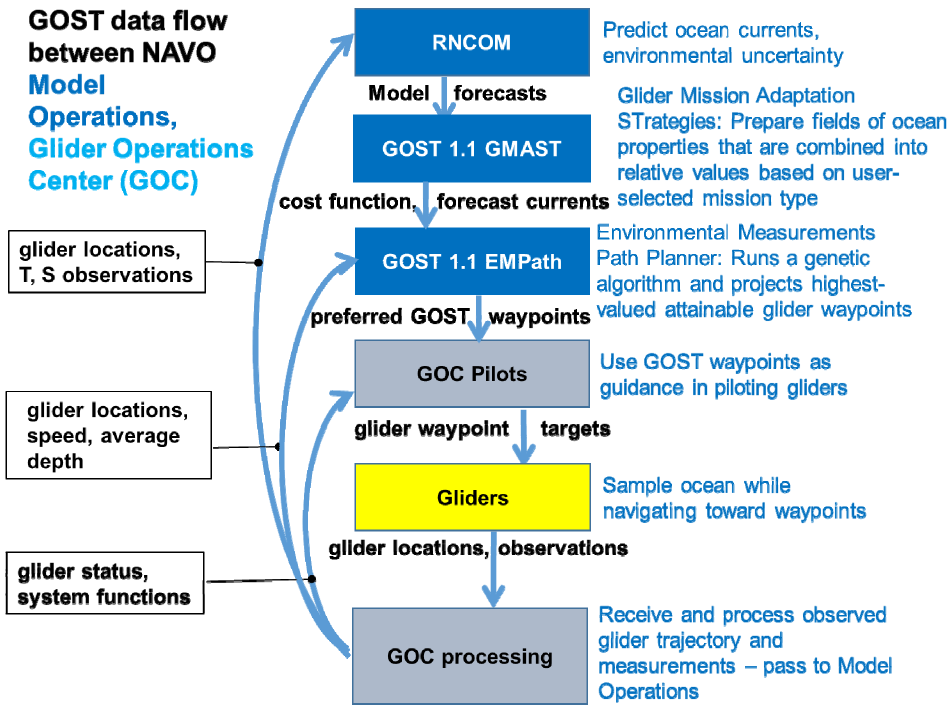

Figure 3. The wiring diagram of the system with function and data exchange illustrated. GOST components, inputs, and outputs are spread between the NAVO DSRC, gliders in the water, and the GOC.

3. APPROACH

With the gliders initially located within an operational region, GOST components were run daily in Trident Warrior 2013 (TW13)[7] in order to send out files containing hourly projections of preferred waypoints. Providing hourly waypoints, however, forced the glider pilots try to chase down too many points. In practice, the glider pilots found it difficult to reconcile the hourly preferred waypoints provided by GOST with the actual glider positions at the time of the update, particularly when there was a time or position offset between the first glider waypoint and the present glider position. Because of the lag in the location of the glider and in the subsequent feedback of the suggested waypoints, the one hour frequency was micromanaging the glider and inconsistent with frequency of updates appropriate for the precision of glider navigation. It was decided that every 12 hours would be sufficient.

Following the short three day test in TW13, it was decided to revisit and test the GOST system involving the systems that are presently operational at the Naval Oceanographic Office (NAVO). All personnel that would be using GOST outputs were included in the testing. Feedback was encouraged from all participants.

The genetic algorithm in EMPath allows glider turns over 360 degrees unless told to do otherwise. Reconfiguring the system to increase the time between waypoints and provide GOST updates only every two to four days provided guidance that was easier for the glider pilots to interpret and follow, better realizing the benefit from the genetic algorithm and model forecast. The model forecast length for the usual high resolution RNCOM nest is 96 hours, so running GOST twice a week usually seems to suffice.

The GMAST is equipped with an additional option to extend the forecast length using persistence in order to allow the EMPath to be run for 120 hours even if the forecast provided is shorter. A typical RNCOM has a 96 hour forecast, and the the GMAST extension allows EMPath to start at any hour, perhaps different from the 00Z forecast start. GOST 1.3

would be manually run between 15Z and 21Z on the NAVO DSRC. Therefore the additional time would be 120 + current time – (96 – current time) with an additional output field added. The frequency of normal RNCOM output is 3 hours.

Operational testing was challenging because a very strict waterspace limitations on the OpArea precluded a straightforward focus on the optimization search (see black polygon areas in Figure 4). Figure 4 shows changes in the glider waypoints for a single glider over a three week period. Waterspace restrictions were set for the areas as a total keep out or avoidance area (see white boxes in Figure 4). Figure 4a illustrates the glider making less eastward progress than expected against strong currents settling into a broad loop covering observable areas of somewhat uniform value. In Figure 4b EMPath identifies an eastward trajectory leading to new areas of greater interest after the cost function has been updated with recent glider data. Figure 4c stands out for showing that a longer path is possible with appropriate conditions from model water current predictions. Figure 4d shows the rendezvous area in the darker box as a target. As the recovery time approaches, the mission switches from emphasis on sampling to emphasis on reaching the rendezvous location by the deadline. The operational area is reconfigured to constrain the acceptable passage between the northern and southern exclusion zones.

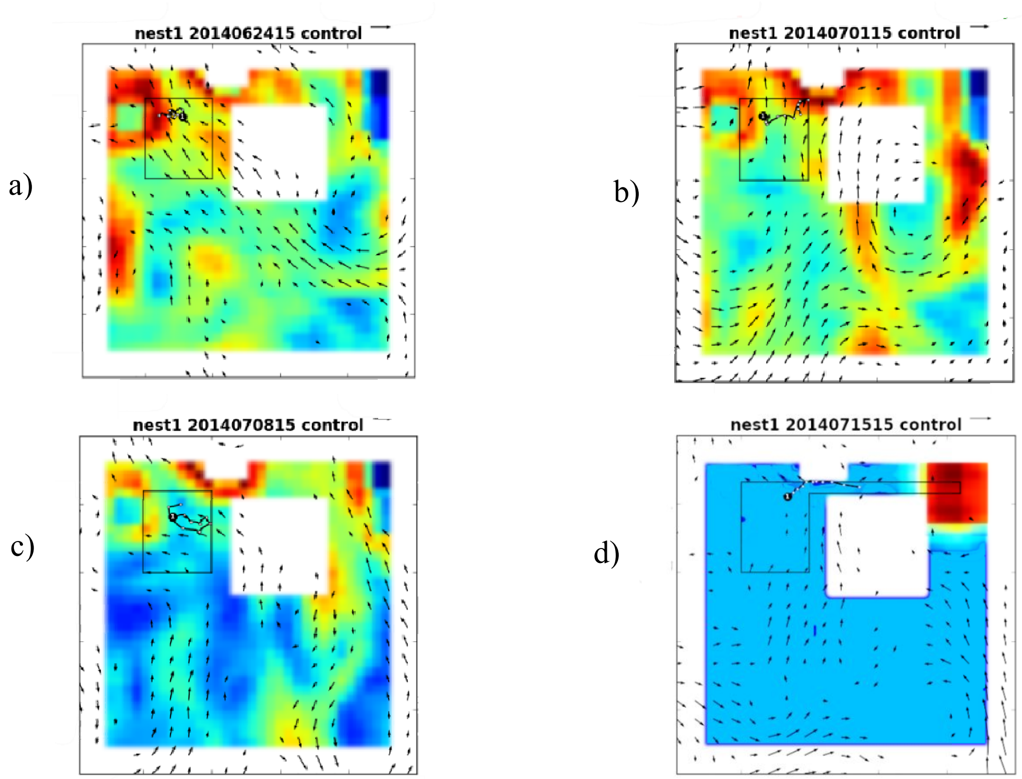

Figure 4 Three weeks of suggested waypoints in an operational area. The white areas are keep out, the green box toward the northwestern corner is a preferred but less strict keep out that tests parameterization using a Gaussian control. The black lined box is the desired OpArea and in d) adds a pathway to constrain the path to the solid boxed rendezvous area.

A three pronged system was added as a post processing to better visualize the EMPath output. This effort was supported by a grant to the University of New Orleans in support of thesis work for a masters in computer science[9]. The visual evaluation toolset has been subdivided into 3 separate packages reflecting different types of analysis that can be performed on the waypoints during the adaptive sampling operations.

1. **Real-time track versus the suggested path:** The goal is to verify that the gliders are actually following the waypoints and to predict the position of the glider for the next cycle's instructions.
2. **Delivery of useful and feasible waypoints:** The goal is to ensure that the delivered waypoints are both useful and feasible. This includes improved graphics.
3. **An evaluation of the quality of the optimal path:** The goal is to provide the confidence levels for the suggested path.

GOST 1.3 was able to use package 2 throughout the real time exercises and an upgraded version is being used in GOST 2.0. Graphics such as those used in Figure 4 made for a much clearer image of the total cost functions, velocity vectors, OpArea and waterspace. Subsequent figures for analysis contain examples of the EMPath output that has been run through package 2. These illustrations helped visualize when the glider was not staying with the OpArea. In the standard EMPath text output contain "Out of Bounds?" category with warning flags thought to help the pilots know that a glider was in an area too shallow for the glider depth, Out of OpArea, or even Out of Bounds of the whole domain. In the case of multiple gliders, the "Too Close" flags would be activated if gliders were less than the allowed degrees between gliders. While the warning flags are helpful, the graphics present a clearer picture of what may have caused the glider to deviate from the OpArea, whether caused by chasing a feature or by strong currents.

Output from EMPath is initially in degrees. The pilots are used to seeing the outputs in whole degrees and decimal minutes. During TW13, there had been much confusion regarding the formats being sent between GOST and the GOC. This was eventually fixed in initial version of the wrapper scripts used in TW13. The degree/decimal minutes corrections were added to package 2. USI allows for multiple formats but he decimal minutes has become the most commonly used in GOST 1.3 Package 2 adds a weighting numeric to represent the relative importance of each glider waypoint from 0 to 1. Glider pilots are given information that could let them choose to skip unimportant points, points with a low weight very close to another point making it almost redundant. Glider pilots could also look at similar weights and decide to operate the glider in patrol with this information. Operating the glider in patrol allows it to hit waypoints out of GOST suggested order and in the order of closest point first.

GOST 2.0 required the initial points and waypoint to be converted back to decimal degrees for automated entry with the degrees west converted to negative values. Glider pilots do not use the temporal waypoint estimate from GOST in their control of the glider; waypoints are simply treated as a sequence of points to follow. More details on this will be discussed in the next section. Furthermore, the interactions among GOST, changing forecasts in ocean currents from one day to the next, and the glider navigation software would at times take the points out of order or otherwise produce erratic reverses in the trajectories.

4. RESULTS

The designated OpArea does not always control the locations of waypoints from the EMPath output. Figure 5a shows success as the EMPath output ideally moving into and remaining in the OpArea (the black box) containing most of the GOST output path. This occurred in Figure 5a even though the initial point was outside of the OpArea. Overall the rule of the OpArea was followed, but not always (Figure 5b). Figure 5b shows 2 gliders being managed by GOST in which glider #1 cuts across the whole area and glider #2 looks for the high value area outside of the box. Conversely, Out of OpArea messages would sometimes appear in EMPath output even when the glider was indeed inside of the OpArea, but very close to the boundaries. Examples in Figure 5b represented occurrences when user imposed bearings sent to the initial coordinates which backfired and others were victims of multiple gliders being required to space too far apart.

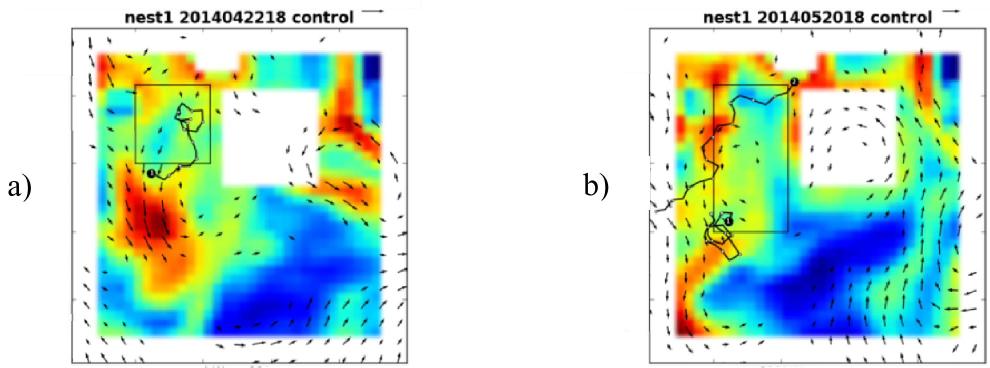

Figure 5 A success (a) and failure (b) of glider waypoints to remain in the OpArea seeking out areas of interest.

Despite the example in Figure 5b, most glider guidance from GOST obeyed the OpArea restrictions. Out of 63 similar graphics brought down from the NAVO DSRC, 43 graphics showed the glider in the OpArea as exemplified in Figures 6a-6d. Therefore 68% of these tests show the glider following the OpArea rule. Figure 6a and Figure 6b show gliders remaining in a box and gravitating to the areas of interest (warm ore red) areas. Figure 6c and Figure 6d show gliders remaining inside of the OpArea even when a very small warm area exists and working toward that small area of interest.

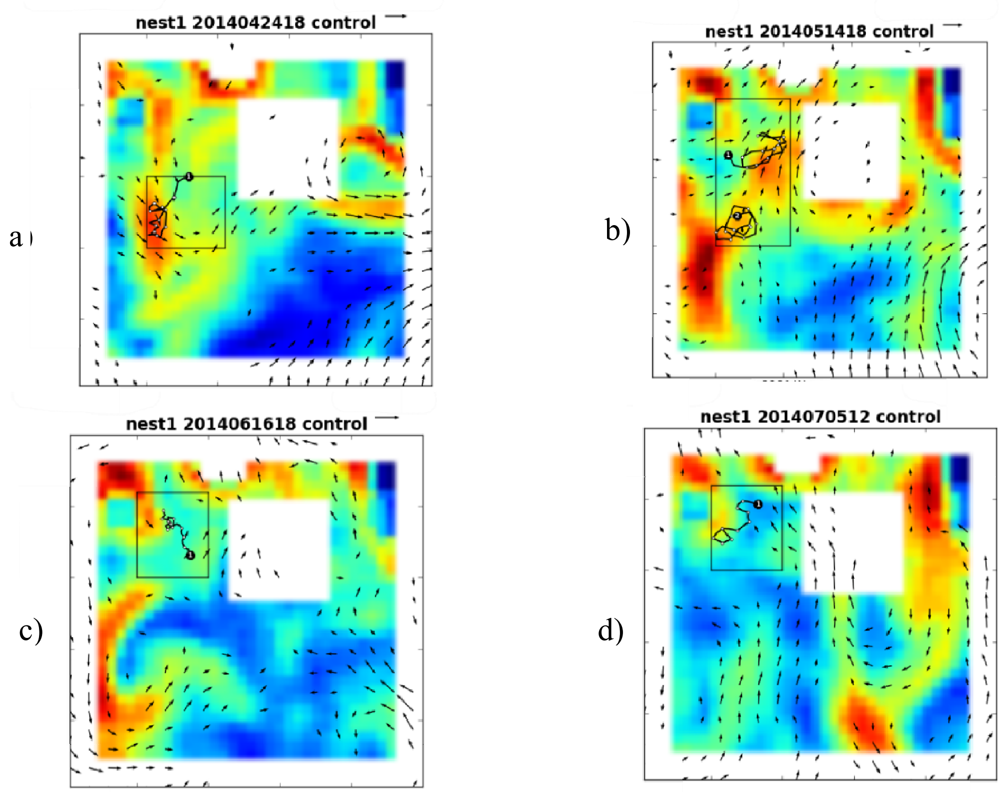

Figure 6 Examples of glider waypoints developing a path that will seek out the area of interest and remain in the OpArea.

In order to quantify the success of the waypoints during the manual exchange phase feedback was requested from the GOC glider pilots. As visible from Figures 3-5 the paths could sometimes look a bit squirrelly. Points visible to the naked eye without the background graphics could appear to not provide waypoints that might not need to be continually adjusted throughout a mission. Background graphics of the morphology can illustrate the areas of interest that the glider should sample. However, Figure 7 illustrates a set of waypoints that follow cost function output (yellow) that is more discernible to the naked eye with the help of the background graphics. The lighter yellow area is sandwiched between darker blue areas and delivers a series of almost straight paths.

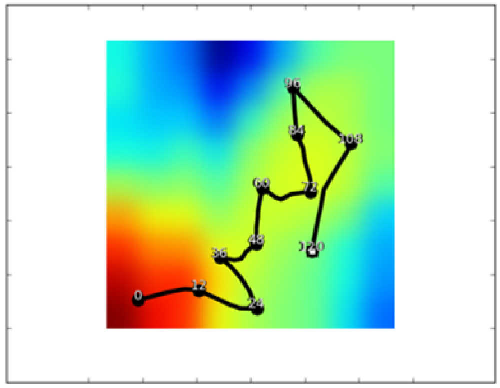

Figure 7. Examples of glider waypoints following a feature.

Quantifying the usability of GOST suggested waypoints is achieved by categorizing them. Table 1 contains the categories: Points Good as is, Adjusted (multiple reasons), and multiple reasons for not using points at all. The glider pilots were encouraged to adjust the points as needed to utilize fully both a person experienced with glider maneuverability and control and the automated interpretation of the model output. An adjustment of glider waypoints by the glider pilots was still considered to be a successful performance of GOST.

Points going outside of the OpArea were placed under the Adjusted slightly for Boundary category. Points that had a time lag in delivery or were best suited to a patrol command where they might hit out or order were placed in the Adjusted due to Timing or changing Order of points category. Setup issues involved some of the earlier confusion over degrees minutes and decimal degrees and accompanying errors in conversion by shell scripts. Most of these types of errors sent waypoints to the glider pilots that were kilometers away from a current location. The remainder of the setup issue involve confusion over OpArea and changes to the rendezvous dates and mission length. Points going into an area not desired either involved waypoints being so far outside of the OPArea or in the waterspace restrictions that they were unusable. Some sets of points were just bunched up in a circle which was also not desirable. Rendezvous issues involved points not going directly toward rendezvous in a timely manner or overshooting the rendezvous. In the case of the latter the pilots only needed to cut off the extra points. Hardware issues resulted in the occasional abandoning of GOST influence and the glider pilots had to manually get the glider to recovery as soon as possible.

Table 1. Feedback from glider pilots tallied over 93 sets of GOST waypoints sent between December 2013 and October 2014

Date	Used	Adjusted	Not Used	Total
Points Good as is	39			Used 41.9%
Adjusted Slightly for Boundary		14		
Adjusted due to timing or changing order of points		11		Adjusted 39.8%
Setup issues		7	4	Not Used 18.3%
Points going in pattern /area not desired			7	
Rendezvous issues		5	2	
Hardware/Battery			4	

As was suggested by the glider pilots approaching points at different times the points suggested by GOST were not always achievable by the predicted time. Figure 8 illustrates an analysis capability that has shown a known problem, but has not been analyzed to sufficiently recommend a solution or to decide if one is needed. The timing of the GOST suggested outputs did not match up with the glider speed. Gliders would get to points more slowly or more quickly than anticipated. This is the result of several causes. The model outputs may not be perfectly accurate in such a small area over such a long forecast. The glider speed as transmitted by the Slocum itself is an average measurement which could significantly change over a 120 hour timeframe. The same is true for the glider's average depth, it may not have the same value throughout the analysis. The glider pilots and the USI software do not interpret the glider points in terms of hourly intervals, but only in terms of order. By disregarding the suggested time the pilots were able to make use of the suggested sampling pattern.

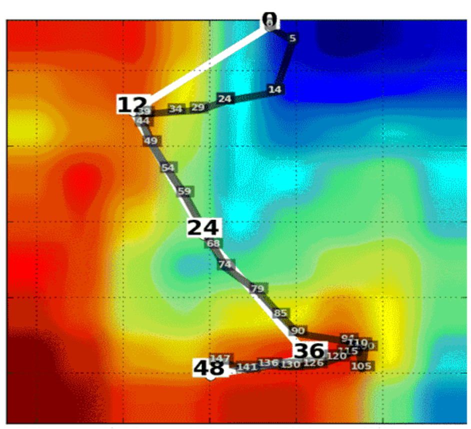

Figure 8 An example of real glider locations (grey) vs the suggested path (white). The glider in this case was much slower than anticipated but still was able to hit the waypoints.

Work is ongoing with GOST 2.0. Files to pull out the glider's location, mission area, speed, depth, and name have been designed within USI. These files are called greq (GOST request) files and are delivered using a series of automated programs that exchange information to and from the NAVO DSRC. Files are usually delivered within 20 minutes of creation. GOST scripts have been moved to a central location and adjusted to make specific version for different operational areas. Work continues on automating the USI acceptance of GOST output, the initial launch of GOST routines when a new glider or region is introduced, and the addition of OpArea, waterspace, and rendezvous information into the request file.

5. CONCLUSIONS

Automation of the system will prevent manual lat/lon errors on the future, such as confusion over degree minutes vs decimal degrees. Limitations in model data resolution and imperfect bathymetry are acknowledged as long term limitations. A time lag in automated transfer of points to actual glider locations has shown improvement in early tests of GOST 2.0 where the transfer of GOST-suggested waypoints to the Glider Operations Center (GOC) takes less than 20 minutes. Moving to this automated transfer will avoid any problem that existed with connections to the NRLSSC server.

Areas that should receive more immediate improvement include genetic algorithm emphasis on allowed operational areas, balance of rendezvous, irregularly shaped areas, automated transfer of glider locations to the modeling group and in turn. Rendezvous points almost always need careful tweaking when forcing the glider through a narrow area and the declaration of a preferred path during recovery. Future testing of ways to avoid the occasional glider transfer of surface depth (not allowing the software to work over a 3D water column) and extremely slow or fast speeds will need to be added to GOST 2.0. Errors in predicting the speed of the glider, especially the speed of multiple gliders in different area of a domain are the most challenging to fix. The glider pilots' interpretation of points as only sequential instead of temporal will eliminate this as a hindrance to the system's use.

Further automation between USI and the Navy DSRC under GOST 2.0 will eventually make the system outputs easier to ingest for the glider pilots and allow for multiple areas to run GOST at once. Better use of the additional capabilities present in the packages available for analysis of the waypoints is planned for the future. The system has been redesigned to execute from an application directory and will not need to be individually tuned to a specific RNCOM.

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