Spray Underwater Glider Operations

DANIEL L. RUDNICK, RUSS E. DAVIS, AND JEFFREY T. SHERMAN

Scripps Institution of Oceanography, La Jolla, California

(Manuscript received 17 December 2015, in final form 25 March 2016)

ABSTRACT

Operational statistics for the Spray underwater glider are presented to demonstrate capabilities for sustained observations. An underwater glider is an autonomous device that profiles vertically by changing buoyancy and flies horizontally on wings. The focus has been on sustained observations of boundary currents to take advantage of the glider's small size, which allows it to be deployed and recovered from small vessels close to land, and the fine horizontal resolution delivered by the glider, which is scientifically desirable in boundary regions. Since 2004, Spray underwater gliders have been deployed for over 28 000 days, traveling over 560 000 km, and delivering over 190 000 profiles. More than 10 gliders, on average, have been in the water since 2012. Statistics are given in the form of histograms for 297 completed glider missions of longer than 5 days. The statistics include mission duration, number of dives, distance over ground, and horizontal and vertical distance through water. A discussion of problems, losses, and short missions includes a survival analysis. The most extensive work was conducted in the California Current system, where observations on three across-shorelines have been sustained, with 97% coverage since 2009. While the authors have certain advantages as developers and builders of the Spray underwater glider and Spray may have design and construction advantages, they believe these statistics are a sound basis for optimism about the widespread future of gliders in oceanographic observing.

1. Introduction

Since the seminal article by Stommel (1989)—if not earlier—autonomous underwater gliders (Davis et al. 2003; Rudnick et al. 2004; Rudnick 2016) have offered the promise of sustained ocean observation. Here we define underwater gliders as autonomous underwater vehicles that change buoyancy in order to profile vertically and that glide horizontally on wings. Underwater gliders communicate to shore and collect navigational data by satellite while at the surface. The value of gliders as scientific platforms lies in their ability to carry small, low-power sensors to measure such quantities as temperature, salinity, pressure, velocity, chlorophyll fluorescence, dissolved oxygen, nitrate, acoustic backscatter, and many other variables for long durations and distances. Usual deployment durations are anywhere from 1 to 6 months, and at horizontal speeds of 0.25 m s^{-1}, ranges of over 3000 km can be achieved. A typical glider dive will go from the surface to 1000 m and back in 6 h, covering 6 km horizontally in that time. Stommel's enticing description of possible capabilities seemed almost too good to be true, and a worldwide community of users adopted gliders remarkably rapidly. The question 25 years after Stommel's paper is whether the promise of underwater gliders has been fulfilled. We address this question by summarizing our ongoing operations of the Spray underwater glider (Sherman et al. 2001).

A recent paper by Brito et al. (2014) calls the promise of gliders into question by examining data from a community of European glider users. The sobering conclusion of Brito et al. is that ''the probability of a deep underwater glider surviving a 90-day mission without premature mission end is approximately 0.5'' (p. 2858). This conclusion was reached using data from users who bought commercial off-the-shelf gliders starting in the early, heady days of glider availability. As developers and operators of Spray, we have used our deep understanding of our glider's function to mitigate problems and to improve the design as we learned Spray's operational deficiencies. Our experience is

Corresponding author address: Daniel L. Rudnick, Scripps Institution of Oceanography, 9500 Gilman Drive, Mail Code 0213, La Jolla, CA 92093-0213.
E-mail: drudnick@ucsd.edu

DOI: 10.1175/JTECH-D-15-0252.1

more representative of the possibilities for gliders operated by a dedicated group than are the scenarios presented in Brito et al. (2014).

The presentation begins with a discussion of Spray operations, where the elements of our approach are outlined (section 2). Section 3 has a presentation of a number of operational statistics, such as mission duration, number of dives, and distance covered. While each of these statistics can be useful as a measure of performance, the more relevant issue is whether the scientific objective of glider operations is achieved. Problems, losses, and short missions are addressed in section 4, including a survival analysis. In section 5, Spray glider operations in the California Current system are presented as a project whose scientific objectives require a sustained sequence of missions. We close in section 6 with a brief discussion of what our experience suggests for the future of gliders in observing systems.

2. The elements of Spray operation

This first operational Spray was similar in design and function to the other two gliders developed in parallel through an Office of Naval Research initiative, Seaglider (Eriksen et al. 2001) and Slocum (Webb et al. 2001). Papers comparing the three gliders have been published (Davis et al. 2003; Rudnick et al. 2004), and the basic designs persist. Spray does have a few features we believe to be unique and to have contributed to operational advantages. Spray profiles by changing buoyancy using a small reciprocating pump to move hydraulic oil between bladders inside the pressure case and in the flooded bay in the tail. An air vent provides a way to purge air that may get into the hydraulic system during long missions. Antennas for Iridium satellite communication are embedded in each of Spray's wings. These two antennas provide redundancy without extra drag, but it also means that the glider must roll in order to communicate. Backup emergency communication is accomplished through the Argos satellite system with an antenna in the tail fin. Navigation is aided using a dead reckoning calculation in which the glider's speed through the water is estimated using pressure, heading, and pitch, along with GPS fixes at the beginning and end of each dive. As do the profiling floats in the Argo array, Spray uses a pumped Sea-Bird CTD to measure temperature and salinity. Pumping water through the sensors is necessary for accurate measurement, but it does require energy. This brief summary of Spray design is intended to help in evaluating the operational statistics discussed below.

We have focused our effort on sustained observation of boundary currents to take advantage of two fundamental properties of underwater gliders. First, Spray's small size (2-m length, 50-kg mass) allows it to be deployed from vessels as small as rigid-hulled inflatable boats. So, Spray operations do not require relatively expensive research vessels. A reliance on small boats leads to economy, but it also ties glider operations to land. Second, underwater gliders may be usefully considered floats whose position is controllable. But the position is controllable only while actively profiling, so underwater gliders naturally produce a high density of profiles in the region of operation. This has led to our focus on boundary currents, where land is close by and scientific objectives require fine resolution in space and time.

A sensible measure of sustained glider operation is the glider-year, that is, a year of continuous glider operation. To achieve a glider-year of operations takes a series of missions each typically lasting 3–5 months. We usually aim to deploy a freshly refurbished glider at the same time we recover a glider at mission's end. So, we need a minimum of two gliders to achieve one glider-year, with one in the water and a second being refurbished in the laboratory. Refurbishment involves replacement of batteries and an extensive checkout, including ballasting, compass calibration, and sensor checks. Almost all field operations are done from small boats launched from shore. The gliders send data through Iridium to our servers for subsequent distribution. We pilot through a web-based interface that queues commands to be delivered when Spray surfaces, typically once every 3–6 h. Much of our piloting is done using an onboard algorithm to navigate using waypoints, where Spray's dead reckoning calculation allows an estimation of set by the current. In swift currents, faster than the $0.25\,\mathrm{m\,s^{-1}}$ horizontal speed of Spray, we sometimes navigate by maintaining a constant heading relative to the current. In strong western boundary currents, the glider crosses as rapidly as possible as it is set downstream. Remote operations have the additional complications of travel, shipping, and indoor space for glider preparation. Having reliable local contacts in remote locations is essential for success. This brief summary describes the elements of operation through which we have achieved many glider-years of observations in several locations.

3. Operational statistics

The beginnings of Spray operational use, as opposed to purely developmental missions, date to September 2004. Since that time, Spray gliders have completed missions for over 28 091 days (77 years), covering 561 184 km over ground, 564 278 km horizontally through water, 209 739 km vertically, and have done 193 143 dives. Deployments have been all over the world (Fig. 1), with

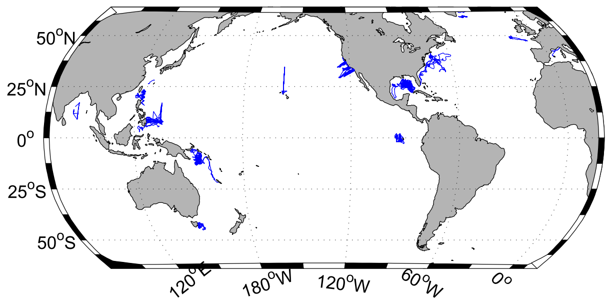

FIG. 1. Trajectories of completed missions by Spray underwater gliders since September 2004.

special emphasis on boundary regions near the United States, including the California Current system and the Gulf of Mexico, and the western tropical Pacific, including the Solomon Sea and Philippine Sea. We include all missions that have been run through our servers at Scripps Institution of Oceanography. Colleagues at Woods Hole Oceanographic Institution, Monterey Bay Aquarium Research Institute, and L'Institut Français de Recherche pour l'Exploitation de la Mer (Ifremer) operated a few of these missions, 7% of the total duration. These colleagues are expert in Spray operations, having been involved from the early stages of development and/or having received training in our laboratory. In the following, we first discuss statistics of 297 missions lasting at least 5 days, to exclude short engineering tests and missions that were aborted soon after deployment to address immediate issues. Missions shorter than 5 days are addressed in section 4.

Spray operational activity has increased steadily since the first deployments. Our preferred metric of the magnitude of operations is glider-days day^{-1}, calculated by summing the total number of days each glider is in the water during each year and dividing by the number of days in that year (Fig. 2). This metric is understood as the average number of gliders in the water during each year. Our operations have grown to the point that we have averaged over 10 gliders in the water since 2012. The steady growth has been due to a number of sustained operations, particularly off California and in the Solomon Sea. We believe ours to be the most active research glider fleet in the world by the metric of glider-days day^{-1}.

We present several statistics that might be used to assess the value of a glider mission. The word *value* is used loosely to refer to some of the virtues of gliders as autonomous profile-generating machines. For example if all else were equal, a longer mission is better than a shorter mission, more dives are better than fewer dives, and it is better to survey over more ground or through more water than less. The statistics to follow are specific about the metric used for value, although the particular

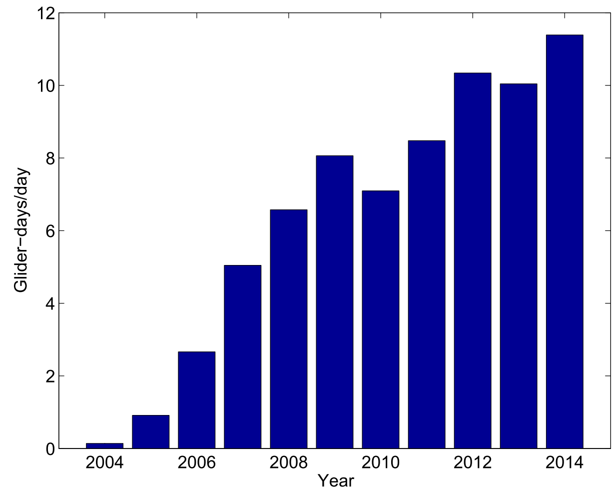

FIG. 2. Spray operations measured in glider-days day^{-1} for each year from 2004 through 2014.

measure of value that is most appropriate depends on the scientific or technical objectives of any individual glider mission.

A metric often used to quantify the value of a glider mission is duration (Fig. 3). This is reasonable because each mission has fixed costs, such as batteries, labor, expendable supplies, and the costs of deploying a glider in the field. All else being equal, a longer mission might be considered better. Our most typical missions involve continuous profiling from the surface to 500–1000 m, during which we often aim for durations of 100–130 days. The broad mode of the distribution of duration is in the range of 95–135 days, constituting 54% of the missions. The histogram is relatively flat at shorter durations except for peaks at 10 days and 60 days. The

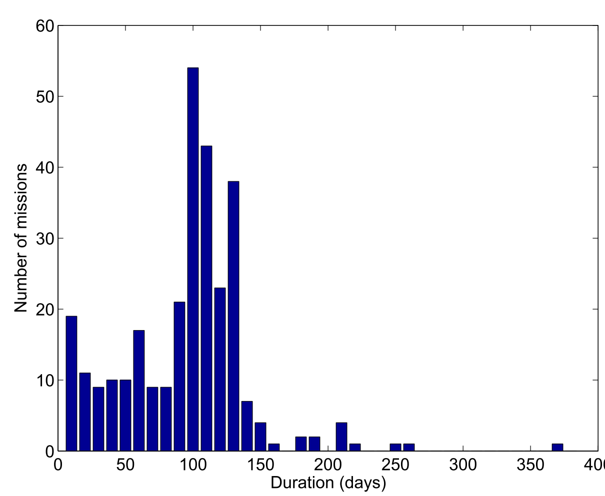

FIG. 3. Histogram of duration of Spray glider missions in bins every 10 days, with the first bin centered at 10 days.

TABLE 1. Spray underwater glider operational statistics for missions longer than 5 days.

Number of missions	297
Total duration (days)	28 091
Median duration (days)	100
Upper quartile (days)	119
Maximum duration (days)	375
Number of missions ending with problems (status ID ≥ 1)	84
Number of missions ending with critical problems (status ID ≥ 5)	49
Mean hazard rate, critical problems (per year)	0.64
Number of losses	9
Loss rate (per year)	0.12

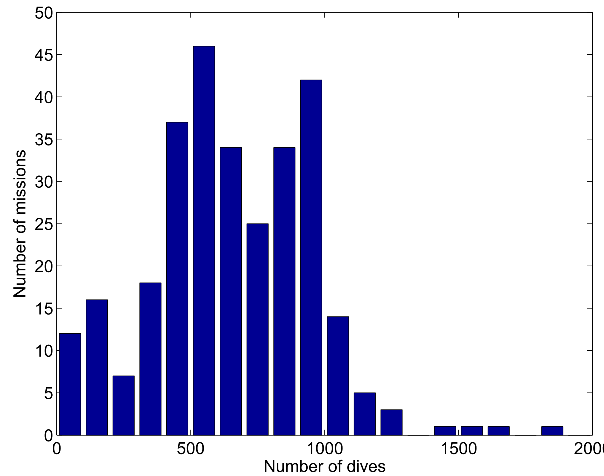

FIG. 4. Histogram of number of dives during Spray glider missions, in bins of 100 dives, with the first bin centered at 50 dives.

10-day spike includes a number of extended engineering tests and also some missions that were cut short for operational reasons. The 60-day spike is caused by a number of deployments that were split in two, often to repair a broken sensor. The longest missions were achieved by drifting at depth as an Argo float does, to profile less often than usual. A summary of duration statistics is given in Table 1 analogous to Brito et al.'s (2014) Table 2. The median and upper-quartile durations of 100 and 119 days are worthy of note in comparison to Brito et al.'s 64 and 80 days, respectively, for a similar glider type.

The mission that lasted 375 days was the longest underwater glider mission ever done, to our knowledge. This is not necessarily a point of pride, as the profiling frequency was reduced in order to lengthen the life until recovery was possible. The glider's tail fin was completely dislodged, likely by fishing gear judging by the marks observed upon recovery. The glider's position was no longer controllable, and the glider functioned as a profiling float until recovery by the R/V *Revelle* when it happened to be in the area. The other long deployments of roughly 180 days and longer were also achieved by drifting at depth periodically. These gliders were equipped with acoustic transceivers to communicate with subsurface moorings (Send et al. 2013), and since the purpose of the missions was to act as a data ferry rather than as a profiler, there was clear value in extending the missions.

What does this examination of mission duration have to do with the likelihood of completing a mission planned for a given length? The most obvious calculation is to divide the number of missions longer than, say, 90 days by the total number of missions to get 0.67. But it would be incorrect to conclude that 0.67 is the probability of a glider completing a mission longer than 90 days. Many missions shorter than 90 days were intended to be shorter or were cut short for reasons unrelated to the vehicle, like fixing a broken sensor. Mission duration, by itself, is not an adequate measure of value, as the scientific or engineering purpose of the mission must be considered. The survival analysis in section 4 below yields the probability of achieving a mission of a given duration.

Another sensible measure of value is the number of dives per mission, as gliders are essentially profile-generating machines, and a profile is something of a unit of measure for oceanographic data. The histogram of profiles for Spray missions has two modes, near 500 and 1000 dives (Fig. 4). These modes are directly related to the dive depths during the mission. We often pilot the gliders to dive either to 500 or to 1000 m, depending on scientific objectives. Much of our work off California was designed to match California Cooperative Oceanic Fisheries Investigations (CalCOFI) sampling, which has traditionally been to 500 m. In other parts of the world, gliders are usually sent to 1000 m to measure deeper water, to reach weaker currents at depth to make navigation easier, and to discourage biofouling. The longest mission by this measure, as with duration, is not a special achievement. Failure of an electronic circuit during this mission prompted us to limit dive depth, so there were many more dives. Other missions with many dives were in shallower water on the continental shelf. In summary, the number of dives during a mission is mostly a measure of the depth to which a glider dove to address scientific objectives.

A measure of value for any survey is distance covered over ground. The histogram of distance over ground for Spray missions, calculated using GPS fixes at the beginning and end of each dive, has a broad mode between 1600 and 2800 km (Fig. 5). The longest glider tracks were

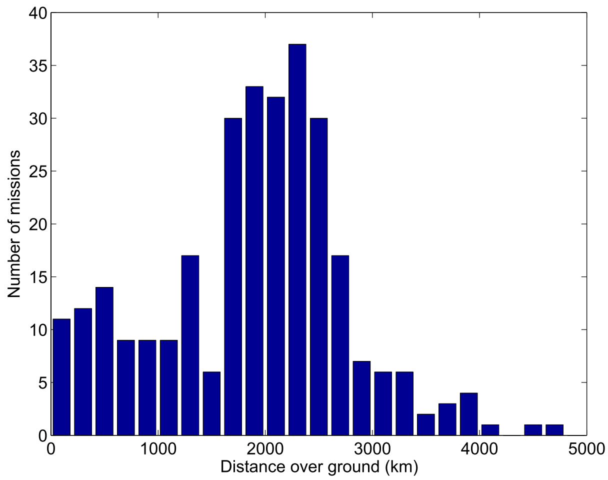

FIG. 5. Histogram of distance covered over ground during Spray glider missions, in bins every 200 km, with the first bin centered at 100 km.

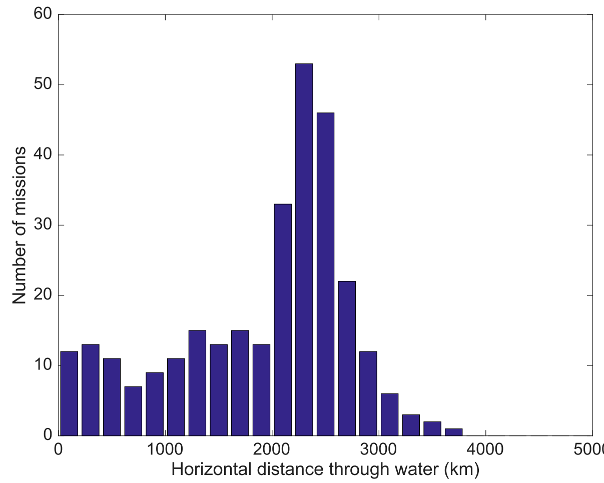

FIG. 6. Histogram of horizontal distance through water during Spray glider missions, in bins every 200 km, with the first bin centered at 100 km.

over 3500 km and were exclusively in fast western boundary currents in the Gulf of Mexico and in the Gulf Stream. Piloting in these strong currents, often much swifter than the 0.25 m s^{-1} speed of the glider, requires riding the current. Because strong currents make it challenging to navigate between waypoints, we often pilot to make repeated crossings of the current while the glider is advected downstream. The piloting algorithm of maintaining a constant heading relative to the current is advantageous. In slower currents, less than the speed of the glider, we usually navigate between waypoints, requiring the glider to head into the current to maintain a line. This explains the lower end of the mode at 1600 km, which is made up of many of our missions off California where we repeat lines. Because the distance over ground is so strongly affected by currents, it is an ambiguous measure of the value of a glider mission.

Spray underwater gliders calculate the horizontal distance traveled through water using an algorithm based on measurements of pressure, heading, and pitch. Assuming a constant value of angle of attack of 3°, consistent with hydrodynamic modeling of Spray (Sherman et al. 2001), the calculation is straightforward trigonometry. The horizontal displacement through water is used in a dead reckoning calculation of the water velocity averaged over a glider's path by differencing with GPS positions at the beginning and end of each dive. Because we pilot Spray to maintain a constant pitch, the path through water is quite symmetrical between ascent and descent (Rudnick and Cole 2011), the average vertical velocity is held approximately uniform with depth, and the average over the path is very nearly a depth average. This depth-average horizontal velocity is used to estimate set in real-time glider navigation. The depth-average horizontal velocity has proven to be accurate to within about 0.01 m s^{-1}, by comparing the implied current before and after turns by the glider (Todd et al. 2011b). The assumption of a constant angle of attack is certainly open to question, especially when the glider is fouled, and sideslip may also be an issue (Davis et al. 2012). As Spray's speed through water is typically about 0.25 m s^{-1}, we can calculate the horizontal displacement through water with about 4% accuracy.

The histogram of horizontal distance through water for Spray missions has a well-defined mode between 2000 and 3000 km (Fig. 6). The mode is consistent with the glider's speed through water of 0.25 m s^{-1} and the mode of duration of 95 days (2052 km) to 135 days (2916 km). The majority, 56%, of missions cover 2000–3000 km. Dive depth, ocean currents, and frequency of profiling minimally influence horizontal distance through water during a mission. So, horizontal distance through water does not have the extreme values as do number of dives, distance over ground, and mission duration. Of all the metrics discussed so far, horizontal distance through water is perhaps the best measure of value when used in isolation.

A simpler measure is the vertical distance through water, or simply the sum of twice the depth of each dive (Fig. 7). A mode is apparent in the range of 700–1050 km. The ratio of these distances to the range defining the mode for horizontal distance through water is consistent with the Spray path through water at an angle to the horizontal of 20° (pitch ~17° plus angle of attack ~3°)

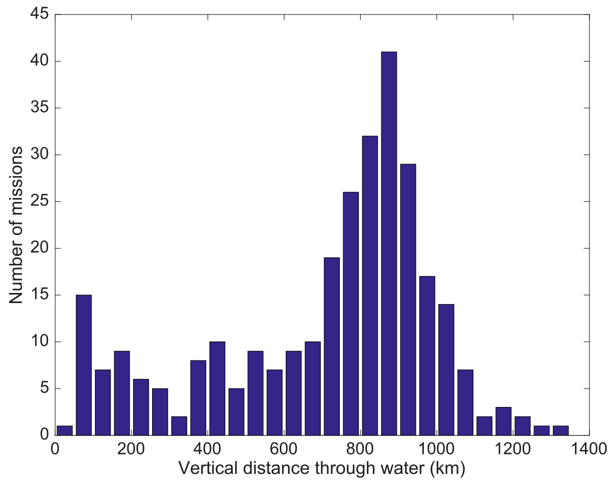

FIG. 7. Histogram of vertical distance through water during Spray glider missions, in bins every 50 km, with the first bin centered at 25 km.

Vertical distance has the advantage that it does not require knowledge of vehicle hydrodynamics as expressed in the angle of attack. But it has the disadvantage that vertical profiles count even if the glider is not traveling through the water in the horizontal.

4. Problems, losses, and short missions

Upon recovery, we assign a status identifier (status ID; Table 2) classifying each mission on a range from normal (status ID 0) to having some sort of problem (status IDs 1–8) to the worst outcome of loss (status ID 9). We are sensitive to problems, primarily to make sure issues are addressed in refurbishing the glider. Many problems are relatively minor, as with sensor problems that do not affect glider flight (status IDs 1–3). Other problems can be quite severe, jeopardizing the glider, such as a failed hydraulic pump (status ID 8).

Out of 297 missions longer than 5 days, 84 have ended with problems (status ID $\geq$ 1), 28% of the total. Counting only critical problems that affect glider flight (status ID $\geq$ 5), the number is 49, 16% of the total (Table 1). The mean hazard rate is 0.64 yr^{-1}, calculated by dividing the total number of critical problems and dividing by the total duration. A categorization of a problem does not necessarily mean that immediate recovery was required. For example, the longest mission of 375 days had a problem, as did many successful missions. The success of a mission has to do with whether its objectives were addressed rather than the glider's condition upon recovery.

A total of nine missions longer than 5 days ended with lost gliders (Table 1). This loss rate is 0.12 yr^{-1}, or one loss for every 8.6 years of operation. Six of these losses happened during the first half of operations as measured by duration, with three losses during the second half (since October 2011). Thus, the loss rate has improved to 0.08 yr^{-1} during the last 38.7 years of operation. In two of these three cases, we were either trying new sensors or new code, and in one case the glider was on its maiden voyage. In other words, these were risky missions in the sense that there was something previously untested. There is an inherent risk in putting autonomous instrumentation into the ocean.

The reliability of glider operations is assessed through survival analysis (Liu 2012). In addition to status IDs, the relevant data include the day a problem first occurred during a mission. Taking the probability that a glider survives to time t without problem to be $S(t)$, the hazard rate $h(t)$ is defined as

$$h(t) = -\frac{1}{S}\frac{dS}{dt}. \quad (1)$$

The hazard rate is calculated for discrete time bins by summing over all problems that occurred during that

TABLE 2. Status identifiers for Spray underwater glider missions.

Status ID	Meaning	Number of missions
0	Normal	213
1	Non-CTD sensor problem	14
2	CTD minor problem (sensor drift, etc.)	1
3	CTD major problem (may affect scientific objectives)	12
4	Biofouling that severely compromises flight	8
5	External physical damage that affects flight	13
6	Minor mechanical/electrical/software (MES) problem (does not endanger flight, but early recovery to fix)	5
7	Significant MES problem (affects ability to address scientific objectives, but glider is still controllable)	15
8	Major MES problem (glider not controllable)	7
9	Lost	9

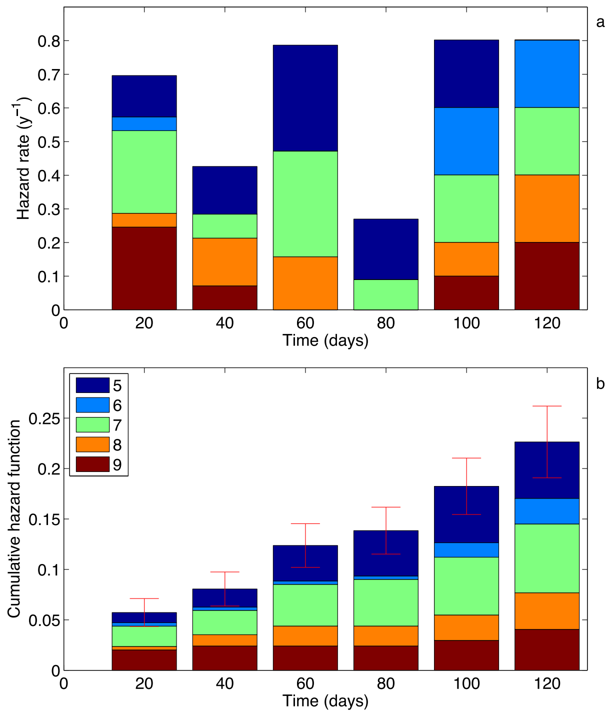

FIG. 8. (a) The hazard rate of having a critical problem (status ID ≥ 5) for missions lasting longer than 5 days. The first bin is the hazard rate for the first 30 days of a mission, and subsequent bins are every 20 days centered at 40, 60, . . . , 120 days. (b) The cumulative hazard function was calculated by integrating the hazard rate. The bars' colors indicate the status ID according to the legend in (b). Error bars (red) indicate a range of twice the standard error.

time bin, dividing by the width of the time bin, and dividing by the number of gliders that survived to the beginning of the time bin without problem (Fig. 8a), where critical problems only are considered (excluding sensor problems and biofouling, status ID ≥ 5). The hazard rate fluctuates around the mean value of $0.64\,\mathrm{yr}^{-1}$. The relatively small number of problems in each bin contributes to these fluctuations; for example, the hazard rate at 80 days is the result of three problems. The decreasing number of missions surviving without problems at a long duration of time means that each problem contributes more to the hazard rate. The four problems at 120 days result in a much larger hazard rate than the three problems at 80 days. The cumulative hazard function $H(t)$ is defined to be the integral of the hazard rate,

$$H(t) = \int_0^t h(u)\,du\,. \tag{2}$$

The cumulative hazard function is calculated by a discrete sum of the hazard rate to get a monotonically increasing function (Fig. 8b). As H is calculated by a sum, the contribution of each problem to the cumulative hazard can be identified. Since H is an integral of h, it is more statistically reliable, and the standard error of the estimate of H is calculated using Eq. (2.15) in Liu (2012).

The relationship between survival and the cumulative hazard function is determined from Eqs. (1) and (2) to be

$$S(t) = e^{-H(t)}\,. \tag{3}$$

The values in Fig. 8b can be used to estimate the probability of survival relative to any critical problem. For example, the cumulative hazard function at 100 days is 0.18 for all critical problems, yielding a survival probability of 0.83. The most severe problems that cause a loss of control over buoyancy or loss of the glider itself (status ID ≥ 8) have H equal to 0.05 at 100 days and 0.08 at 120 days, leading to survival probabilities of 0.95 and 0.92. The reliability has improved over time, and H calculated for data since October 2011 is 0.14 at 100 days for critical problems, yielding a survival probability of 0.87. Thus, the probability that four such missions can be completed to cover a year without a critical problem is 0.57. This manageable survivability is essential to sustained operations.

The categorization of problems by discrete status IDs is somewhat subjective, as is our cutoff for "critical" problems (status ID ≥ 5). Our status IDs are pragmatic, as the main purpose is to identify problems that we can fix. For example, problems with a status ID of 6 are relatively minor, mostly having little to no effect on the scientific objectives. The worst problems caused by external damage (status ID = 5) can result in a loss of control over horizontal position, but we give these a lower status ID, as there is little we can do to prevent the problem. Including all missions with status ID ≥ 5 in our definition of critical is thus conservative, as it includes several missions that were scientifically successful but ended with minor problems.

We exclude from our statistics 66 missions shorter than 5 days. Intentionally short local tests account for 38 of these missions. We always do these tests when trying new sensors. We also often do full-scale ocean tests before shipping to remote locations, as we would prefer to find problems at home rather than in the field. The remaining 28 short missions constitute the infant mortality of Spray operations. During the first few days of a mission, we have a low tolerance for problems. If a glider shows any sign of a problem, we recover, deal with the problem, and typically quickly redeploy. Of the short missions 12 were local, and all were redeployed within days. The remaining 16 short missions were at remote sites. In several cases these gliders were recovered, fixed, and redeployed soon. Six of these short remote missions were since October 2011. In two of these cases, the glider carried a unique sensor package performing intentionally short test missions. A third deployment of this same glider resulted in the only immediate loss within the last 6 years, underlining the point that trying new things in a remote location is inherently risky. In summary, we think it is fair to exclude missions shorter than 5 days from our operational statistics, as they reflect tests or problems that were quickly fixed and redeployed, thus only causing minor disruptions to the scientific objectives.

5. A sustained sequence of missions

The first step toward determining the success of a glider mission, or more realistically a sustained sequence of missions, is to define operational goals. To make this determination concrete, we take a specific example. Suppose the goal is to make repeated sections along a set of lines, as CalCOFI has done for several decades off the California coast (McClatchie 2014) using quarterly ship surveys. We sustain glider observations on three CalCOFI lines: 66.7 off Monterey Bay, 80.0 off Point Conception, and 90.0 off Dana Point. Our efforts started in 2005, and gliders have occupied all lines continuously since 2009 (Fig. 9). This operational California Underwater Glider Network (CUGN) distributes data in real time to public servers, to forecast and hindcast models, and has resulted in many publications (Davis et al. 2008; Todd et al. 2009; Todd et al. 2011a,b, 2012; McClatchie et al. 2012; Ohman et al. 2013; Johnston and Rudnick 2015; Jacox et al. 2015; Powell and Ohman 2015). A particular focus has been to observe the local effects of climate variability as caused by El Niño (http://www.sccoos.org/data/el-nino/). By any reasonable operational or scientific measure, the CUGN should be considered established and mature.

Our straightforward operational goal in the CUGN is to keep one glider on each of our three lines at all times. We quantify performance using the metric of duration in glider-days day^{-1} averaged over calendar years on the three lines (Fig. 9). Perfect performance would be 1 glider-days day^{-1} on each line for a total of 3 glider-days day^{-1} (or equivalently 3 glider-years yr^{-1}). Since 2009, we have operated at 97% of our ideal. During 2009–14, we have averaged 26 dives per day typically to 500 m, 59 km over ground per day, and 65 km through water per day. This results in dives every 2.7 h with an average spacing of 2.2 km over ground. All operations are relatively local, and we have established contacts along the coast for space to prepare, boats for operations, and personnel to help. In short, we have many advantages that allow us to succeed.

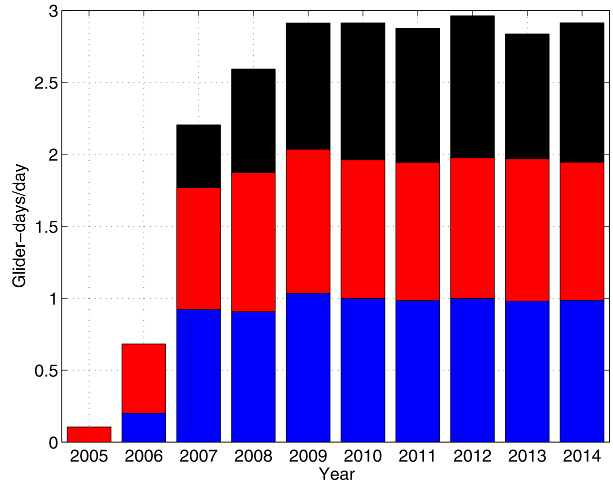

FIG. 9. Glider-days day^{-1} averaged over calendar years on each of the three CalCOFI lines: 66.7 (black), 80.0 (red), and 90.0 (blue). Perfect performance would be a value of 1 glider-day day^{-1} on each line for a total of 3 glider-days day^{-1}.

The cumulative hazard function is less in the CUGN than for our other missions. For a 100-day CUGN mission since 2005, $H = 0.13$. Since October 2011, the cumulative hazard for the CUGN has improved to 0.09. Because of the control over the success of missions locally, gliders in the CUGN have been the most heavily instrumented. The gliders have routinely carried acoustic Doppler profilers (ADPs) and chlorophyll fluorometers, and have occasionally included dissolved oxygen sensors. The relative ease of replacing gliders has led to a low tolerance for misbehavior of the conductivity and temperature sensors. Including these sensor failures, $H = 0.30$ in a 100-day mission, with most of the problems in sensors other than the CTD, which does not necessarily prompt an early recovery. The CUGN hazard statistics are relevant to the potential for glider operations performed locally by expert personnel.

To complete this discussion of sustained glider operations, here are a few of our guiding principles. The duration of each mission, or even the loss of a glider, is less relevant than the overall efficiency of the operations. As Argo has demonstrated with its transformational observing system (Roemmich et al. 2009), the individual elements can be disposable, as long as enough value is realized from each single use. We achieve an acceptable level of economy with missions that typically last 100 days, where biofouling is the ultimate limiter rather than battery life. We sometimes split missions in two, by having two 50-day missions, when there is operational economy in doing so. An intention in starting this work was to prove the possibilities of sustained glider observations, and we believe we have completed the proof.

6. Conclusions

We were motivated by the rather grim analysis of Brito et al. (2014) to write this paper, as we believe that experienced glider operators do achieve their scientific objectives. Besides ours, other examples of sustained glider operations include those off Washington (Pelland et al. 2013) and Oregon (Mazzini et al. 2014). We hope that scientists interested in beginning to use underwater gliders will appreciate the capabilities as demonstrated by experienced operators and will be willing to make the investments needed to achieve the same level of success. Our intention is to provide justifiable optimism toward the future of gliders in sustained observation.

We present conservative estimates of the survival statistics, as we include problems that do not necessarily require the glider to be recovered. Considering our definition of critical to include all problems except faulty sensors and biofouling, the probability of completing a 100-day mission without a problem is 0.83. If only the problems that stop the glider from profiling are included, then the probability of surviving a 100-day mission is 0.95. These numbers can be compared to Brito et al.'s finding of a 0.5 probability of surviving a 90-day mission.

The CUGN offers the best example of what is possible in a sustained sequence of missions. For these CUGN missions, roughly one-third of the total for all missions as measured by duration, the cumulative hazard function $H = 0.13$. For all missions $H = 0.18$, so the missions that are not CUGN had more problems. Other sustained operations in the Solomon Sea ($H = 0.17$) and off Palau ($H = 0.16$) were marginally more reliable than the average over all, even though these missions were risky in that these locations were remote and the gliders were operated far from shore. In general, our sustained operations have tended to be successful, and the greatest risk has come from the one-off missions.

The best conceivable outcome for a sustained network of glider observations is to be to regional oceanography what Argo is to global oceanography. An underwater glider network could be the dominant source of profiles in the boundary regions of the world's oceans, providing baseline observations of climatically important western boundary currents and biologically productive eastern boundaries. An approach to such a network may be to rely on centers of excellence, where gliders are serviced in a few places, but deployed and recovered in the field by many people with local knowledge. We expect the next generation of gliders to be more robust, requiring less technical expertise to operate in the field. There are grounds for confidence about a positive future of gliders in oceanography.

Acknowledgments. The Instrument Development Group at Scripps Institution of Oceanography is responsible for Spray operations, including Ben Reineman, Evan Randall-Goodwin, Derek Vana, Kyle Grindley, and Nicolas Delfino. We have been fortunate to receive support from the Office of Naval Research (ONR), the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF), the Gordon and Betty Moore Foundation, and BP, among others. During the preparation of this article we were supported by ONR through N00014-13-1-0483, N00014-13-1-0481, and N00014-13-1-0455; by NOAA Climate Observation Division through NA10OAR4320156 and NA15OAR4320071; and by NSF through OCE1232971.

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