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A Wave Glider Approach to Fisheries Acoustics

Transforming How We Monitor the Nation's Commercial Fisheries in the 21st Century

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ABSTRACT. Possessing the world's largest Exclusive Economic Zone (EEZ), the United States enjoys the benefits of a multi-billion dollar commercial fishing industry. Along with these benefits comes the enormous task of assessing the status of the nation's commercial fish stocks. At present, many of the most valuable commercial fish stocks are assessed using acoustic surveys conducted from manned survey vessels. The expense and limited availability of ship time often compromise the quantity and quality of the acoustic stock assessment data being collected.

Here, we describe our vision for how an unmanned mobile platform, the Liquid Robotics Wave Glider, can be used in large numbers to supplement manned survey vessels and transform fisheries acoustics into a science more consistent with the new ocean-observing paradigm. Wave Gliders harness wave energy for propulsion and solar energy to power their communications, control, navigation, and environmental-sensing systems. This unique utilization of wave and solar energy allows Wave Gliders to collect ocean environmental data sets for extended periods of time.

Recently, we developed new technology for Wave Gliders that enable them to collect multifrequency, split-beam acoustic data sets comparable to those collected with manned survey vessels. A fleet of Wave Gliders collecting such data would dramatically improve the synoptic nature as well as the spatial and temporal coverage of acoustic stock assessment surveys. With improved stock assessments, fisheries managers would have better information to set quotas that maximize yields to fishermen and reduce the likelihood of overfishing. Improved observational capabilities also would enable fisheries scientists and oceanographers to more closely monitor the responses of different fish stocks to climate variability and change as well as ocean acidification.

INTRODUCTION

Commercial marine fisheries in the United States Exclusive Economic Zone (US EEZ) produce annual landings valued at $5 billion (NOAA NMFS, 2012). In addition, they directly or indirectly support more than one million jobs, yielding an additional $32 billion to the US economy. Since the middle of the twentieth century, ship-based acoustic surveys have been adopted by fisheries agencies throughout the world as a standard method for assessing the status of many commercial fish stocks (Fernandes et al., 2002; Simmonds and MacLennan, 2006). In the United States, responsibility for acoustically assessing and managing the nation's commercial fish stocks resides with the National Marine Fisheries Service (NMFS) regional science centers (NOAA Fisheries Science Centers, 2004).

While there have been many significant advances in fisheries acoustics over the past 50 years (Fernandes et al., 2002; Simmonds and MacLennan, 2006; Chu, 2011; Alaska Fisheries Science Center, 2013), one major impediment has prevented the field from achieving even greater success—the amount of available ship time. As currently practiced, acoustic stock assessments are conducted from manned survey vessels, ships that are expensive to both build and operate. Therefore, even as the demand for acoustic stock assessment data has steadily increased, budgetary constraints have often limited the ability of fisheries scientists to keep up with this demand. Such budgetary constraints typically manifest themselves through the reduced availability of ship time. The high cost of building and operating a fleet of ships has resulted in fewer federally funded vessels being built and a steady decline in the numbers of operational days available for stock assessment surveys (National Ocean Council, 2013). Because these budgetary constraints will likely continue to limit the availability of ship time into the foreseeable future, fisheries scientists must find a new way to stretch their budgets without compromising the quantity and quality of the stock assessment data being collected.

Currently, many stock assessment surveys are conducted only on a yearly or biennial basis due to the expense and limited availability of ship time. In addition, such surveys often are conducted by a single ship over a time span of one or two months with no repetition of spatial coverage. Thus, the data cannot be assumed as synoptic in any realistic sense, and there is no way to determine if the results are repeatable. These operational compromises have become standard practice in many stock assessments, but such data-collection methods greatly limit the accuracy and precision of abundance estimates, blur our understanding of temporal changes in spatial distribution patterns, and diminish our ability to detect ecosystem regime shifts, overfishing, and other factors influencing the abundances and distributions of commercially important fish stocks.

Given the importance of commercial fisheries to the US economy and the challenges society faces in monitoring and managing them properly, now is the time to reassess our strategy for fisheries acoustics in the future. Fortunately, we find ourselves contemplating this strategic reassessment right in the middle of what has been described as an "ocean-observing revolution" (Perry and Rudnick, 2003). Since the beginning of the twenty-first century, marine scientists have witnessed a large increase in the variety of unmanned mobile platforms (e.g., autonomous underwater vehicles, drifters, floats, and gliders) available for observing the ocean environment and its processes. These unmanned mobile platforms are rapidly advancing the abilities of oceanographers to quantify ocean circulation and biogeochemical dynamics (Perry and Rudnick, 2003; Rudnick et al., 2004; Davis et al., 2008). They also have the potential to transform the way fisheries scientists and oceanographers study marine population and ecosystem dynamics (Fernandes et al., 2003; Ohman et al., 2013). Here, we describe our vision for how one of these unmanned mobile platforms, the Liquid Robotics Wave Glider, can be used in large numbers to transform fisheries acoustics from a

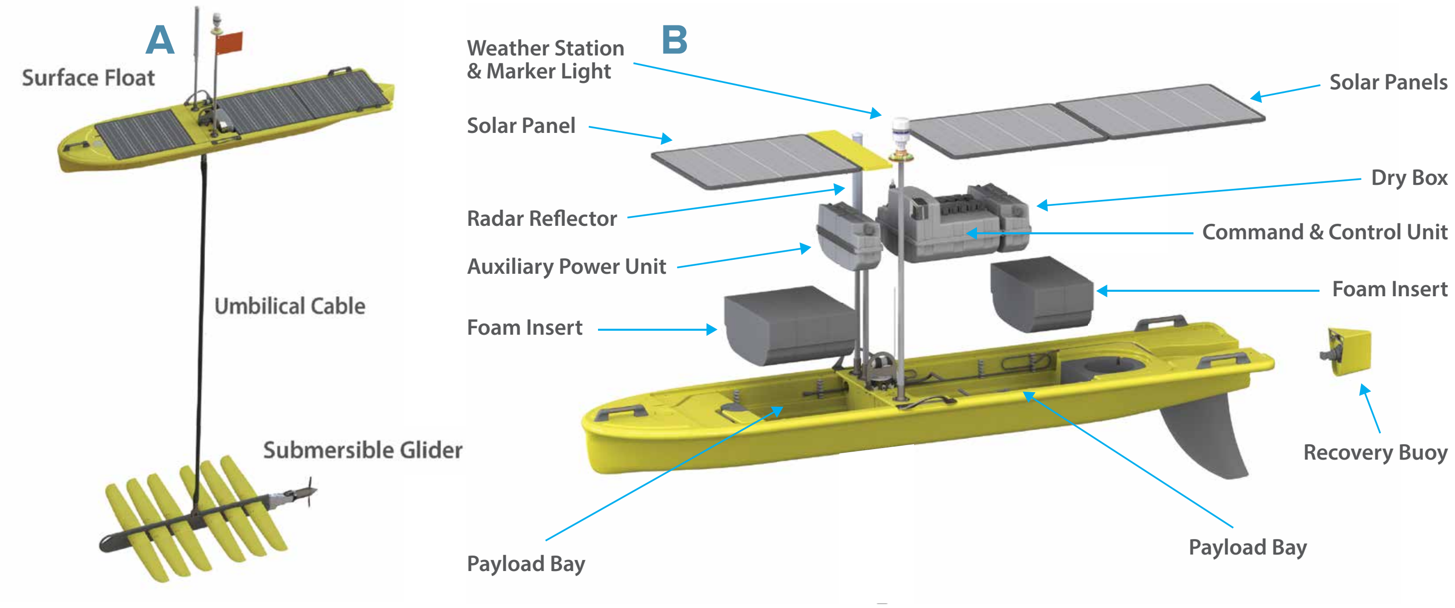

FIGURE 1. (A) The Wave Glider SV3. (B) Components of the Wave Glider SV3's surface float.

science severely constrained by the limited availability of ship time to a science consistent with the new ocean-observing paradigm, one based on near-synoptic, continuous monitoring of the nation's commercial fisheries.

THE WAVE GLIDER APPROACH

The Liquid Robotics Wave Glider is a self-propelled, unmanned mobile platform designed for long-term deployments to collect oceanographic and other environmental data (Manley et al., 2009; Willcox et al., 2009). It consists of a surface float tethered with an umbilical cable to a submersible glider (Figure 1A). The surface float houses a command and control unit for communications, navigation, and power systems, and a modular payload unit for user-specified environmental-sensing systems (Figure 1B). The submersible glider has a series of paired wings that generate propulsive forces and a rudder to provide steering. The key innovation of the Wave Glider is its ability to harness wave energy for propulsion. It does this with each passing wave by taking advantage of the differential motion between the surface float and the submersible glider (Figure 2). Solar panels on the deck of the surface float recharge a lithium ion battery pack inside the Wave Glider's hold. This battery pack supplies power to systems inside the Wave Glider's command and control unit and modular payload unit. A simple, Web-based interface transmits control system and sensor data from the Wave Glider to shore and commands back from shore to the Wave Glider during a mission. Two-way transmission via cellular network or Iridium satellite provides real-time navigational, operational, and sensor control as well as real- or near-real-time data reporting.

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The Wave Glider's performance and versatility at sea make it a consistent and reliable platform for collecting ocean environmental data. Its speed through water is proportional to sea state, with higher waves increasing the differential motion between the surface float and submersible glider and thus propelling the glider more rapidly. During rigorous testing, the Wave Glider has been found to cruise at speeds between 0.5 and 1.5 knots in Beaufort Sea State 1 conditions and at speeds greater than 1.5 knots in Beaufort Sea State 3 conditions or higher. Over longer-duration missions, speeds tend to average ~ 1.5 knots or higher, even while weathering storms with sustained winds of 30 knots, gusts up to 80 knots, and wave heights exceeding 8 m (Manley et al., 2009; Willcox et al., 2009). In terms of endurance, the Wave Glider's unique utilization of wave and solar energy for propulsion and systems power, respectively, enables it to collect data for extended periods of time. The effects of biological fouling on Wave Glider performance after months at sea typically set the limits on mission duration.

For applications in fisheries acoustics, several technologies were developed for deploying a multifrequency, split-beam acoustic system from the Wave Glider (Munday et al., 2014; **Online Supplement**). The acoustic system itself is a modified version of the commercially available BioSonics DT-X Submersible (SUB) echosounder (Munday et al., 2014). This version of the DT-X SUB echosounder can operate at all four frequencies typically used by the NMFS for its acoustic stock assessment surveys: 38 kHz, 70 kHz, 120 kHz, and 200 kHz. It is fully programmable, allowing the user to set a variety of system and data-processing parameters either prior to deployment or during the mission via cellular network or satellite-relayed commands. Raw multifrequency, split-beam data are stored internally for post-mission processing, while real-time processing for echo integration is conducted, with reports transmitted to shore at regular intervals, typically 10 minutes.

This version of the DT-X SUB echosounder was modified for packaging in the pressure case of a custom-built tow body (Figure 3A). Constructed of acetal plastic (Delrin^{TM}) and polyvinyl chloride, the neutrally buoyant tow body is deployed directly behind the submersible glider with a sinusoidal-shaped tow cable (Figure 3B). The shape of the tow cable is the result of adding slack-tensioning elements, which greatly reduce pitch, roll, and yaw of the tow body relative to its performance with a conventional tow cable (Figure 3B; **Online Supplement Videos S1 and S2**).

No description of a new platform for fisheries acoustics, manned or unmanned, would be complete without some discussion of noise considerations. The fisheries research community has worked diligently to reduce the noise of vessels used for acoustic stock assessment surveys (Mitson, 1995). Although dramatic noise reductions have been achieved, no ship powered by diesel engines can match the quiet operations of a Wave Glider. In a study assessing performance during both passive and active acoustics research, Bingham et al. (2012) demonstrated that the Wave Glider operates at low noise levels, especially when data are collected from near the submersible glider.

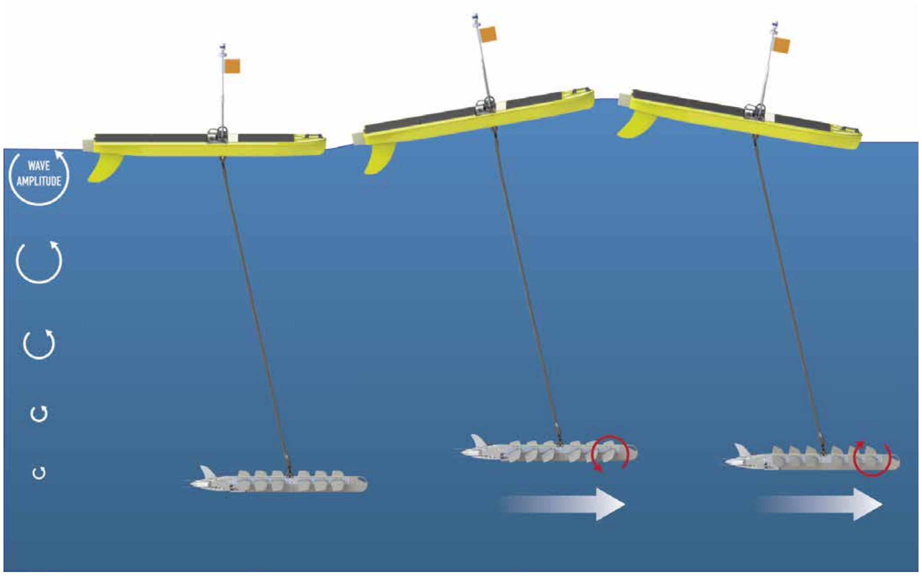

FIGURE 2. Wave Glider propulsion from the differential motion of the surface float and the submersible glider. With the passing of a wave crest, the larger wave amplitude at the surface relative to that at depth causes the surface float to pull upward on the submersible glider, placing the umbilical cable under tension. Specially designed wings on the submersible glider shift their angles of attack (as shown by the small red curved arrows) to convert this upward tension into a forward directed propulsive force (as shown by large white straight arrows). With the passing of a wave trough, the umbilical cable slackens, and the submersible glider begins to descend in response to gravity. The wings on the submersible glider shift their angles of attack by 90° to convert this gravity-driven downward force once again into a forward directed propulsive force. Equipped with a rudder, the submersible glider acts like a tug for the surface float, propelling and steering the Wave Glider in accordance with commands relayed to the vehicle.

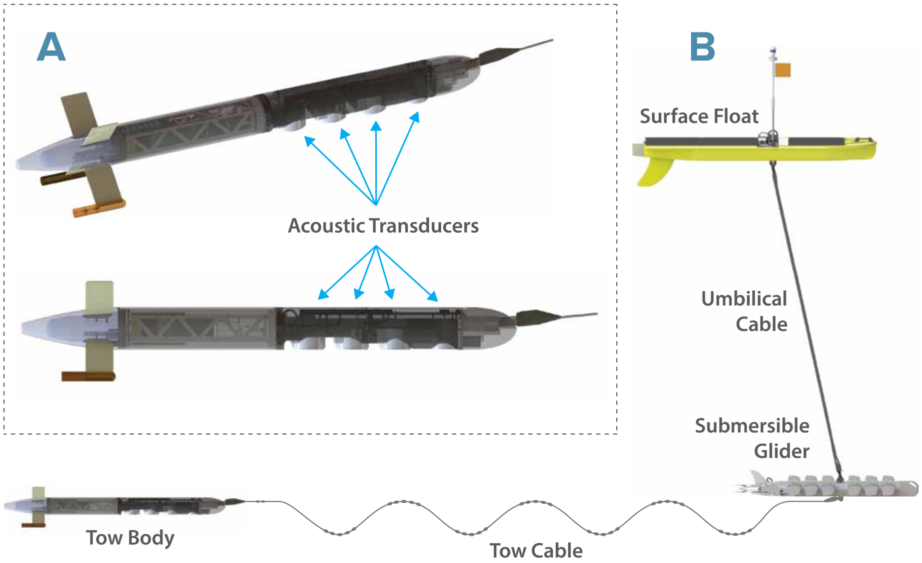

FIGURE 3. (A) Four-frequency version of the BioSonics DT-X SUB echosounder packaged in the pressure case of a custom-built tow body. Isometric and side views of the tow body are shown, with the four transducers of the echosounder labeled. (B) Side view of the tow body deployed from the Wave Glider's submersible glider with a sinusoidal-shaped tow cable.

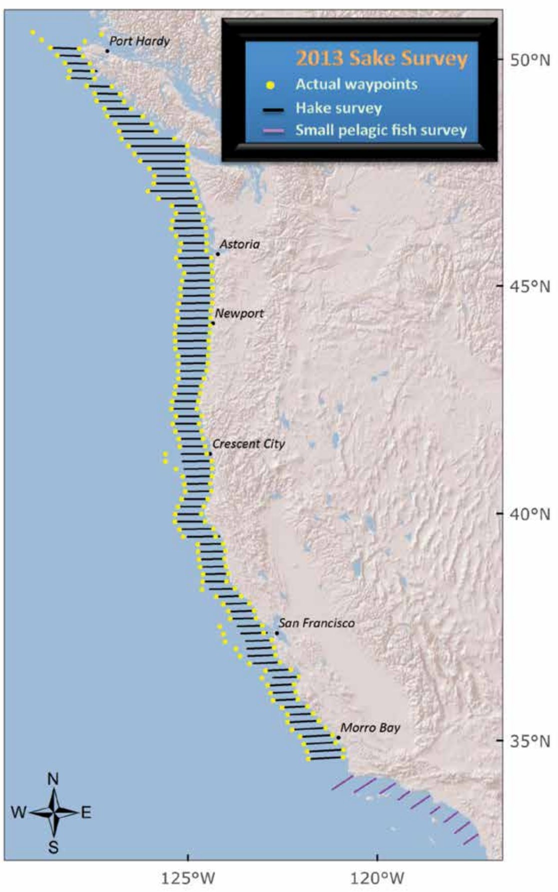

FIGURE 4. Transect lines from the 2012 SaKe Joint-Pacific Hake and Sardine Survey. Survey lines were spaced 10 nautical miles apart and run by FSV *Belle M. Shimada* and R/V *Ricker* from central California to northern British Columbia.

THE WAVE GLIDER FLEET: POWER IN NUMBERS

With the recent commissioning of its newest fishery survey vessel (FSV) *Reuben Lasker*, the National Oceanic and Atmospheric Administration (NOAA) has upgraded its fleet to include five state-of-the-art, low-noise ships designed for conducting fisheries acoustics studies. These five FSVs—*Reuben Lasker*, *Belle M. Shimada*, *Oscar Dyson*, *Henry B. Bigelow*, and *Pisces*—are the only ships operated on behalf of the NMFS regional science centers that comply with the International Council for the Exploration of the Sea (ICES)-recommended standards for noise reduction in ships used for fisheries acoustics research and surveys (Mitson, 1995; Alaska Fisheries Science Center, 2013). Construction to meet the ICES standards is expensive, but ships compliant with these standards have been demonstrated to reduce fish avoidance and potentially improve the accuracy of acoustic stock assessment surveys (DeRobertis et al., 2008). In addition to their low-noise characteristics, these five FSVs are capable of collecting acoustic data while simultaneously trawling for biological samples. These samples are critical for ground truthing the acoustic data and determining other important information about the age and size structure, health, and reproductive condition of the fish stocks being assessed. In a period of tightened science budgets, acquisition of these highly capable FSVs represents a valuable investment by the federal government in enhancing NMFS's ability to assess and manage the nation's commercial fisheries.

Valuable as they are, however, these low-noise FSVs are too few and too expensive to meet the full scientific needs of the NMFS by themselves. With the world's largest EEZ, at 11,351,000 km^2, the United States faces an enormous task in monitoring the health of its marine ecosystems and the status of its living marine resources, including its commercial fisheries. While satellites provide synoptic coverage on large scales, which can be useful for some applications, unmanned mobile platforms operating on or below the ocean's surface will be essential for filling in the huge gaps in coverage that cannot be monitored by a relatively small fleet of FSVs.

To illustrate the potential of Wave Gliders for filling in this coverage gap, we will look at an example from the west coast of continental North America. During 2012, the Northwest and Southwest Fisheries Science Centers (NWFSC and SWFSC) cooperated with the Canadian Department of Fisheries and Oceans to conduct the SaKe integrated acoustic and trawl survey of sardine and hake stocks along the US West Coast EEZ and into Canadian waters (Figure 4) (CalCOFI, 2013). With this stock assessment survey requiring over two months to complete, the expense of ship time alone exceeded $1 million. These surveys are conducted during the summer months when hake behavior (viz. reduced migration and the presence of feeding aggregations) and weather conditions are more favorable for improving the accuracy and precision of stock assessments.

For comparison, we explore the potential for conducting an acoustic stock assessment of the US West Coast EEZ, with approximately the same spatial resolution as the SaKe survey, using a fleet of Wave Gliders running the same survey lines (Figure 5, **Videos 1 and 2**). The NMFS low-noise FSVs have an operational cruising speed between 10 and 12 knots in calm seas, but that speed can be reduced by half when encountering rougher sea states, like those more common during other seasons. For illustration purposes, we will assume an average operational cruising speed of 7.5 knots. The cruising speed of a Wave Glider is wave-height dependent and actually increases asymptotically with increasing sea state conditions. We will assume an average cruising speed of 1.5 knots, a value consistent with many sea trials under a variety of conditions (Willcox et al., 2009). Cruising at 7.5 knots, an FSV can complete one survey line five times faster than a Wave Glider cruising at 1.5 knots, and it can complete approximately five lines in the time it would take a Wave Glider to complete just one line (Figure 5A,B; **Video 1**).

However, the power of the Wave Glider approach to fisheries acoustics comes in numbers. With a fleet of Wave Gliders, each one running a survey line, an acoustic stock assessment of the West Coast EEZ could be completed in one week, the same time that an FSV would complete just ~ 12.5% of the survey (Figure 5C; **Video 2**). During the eight weeks that it would take an FSV to complete an acoustic stock assessment survey of the West Coast EEZ, a fleet of Wave Gliders would complete the equivalent of eight near-synoptic surveys (Figure 5D; **Video 2**).

For the purpose of stock assessment, acoustic data derived from a Wave Glider fleet would offer significant advantages over those derived from conventional ship-based surveys. Most importantly, spatial and temporal coverage would be improved dramatically, with each realization of fish stock distribution more closely achieving the synoptic ideal. In comparison to the eight weeks required to complete one conventional, ship-based survey, the one week required to achieve full spatial coverage with a Wave Glider fleet makes concerns about replication and repeatability largely disappear. Full spatial coverage in a week also reduces concerns about aliasing and other sampling issues that are especially relevant when the assessed fish stocks are highly migratory and/or sparsely distributed in schools.

Remarkably, these significant improvements in the quality of acoustic stock assessment data need not come at great expense, especially when the costs are spread over a sufficiently long time period. While it is true that the capital expense associated with acquiring a fleet of fully equipped Wave Gliders to monitor the West Coast EEZ would be comparable to the expense of adding another FSV, the ongoing operational and maintenance costs would be reduced considerably. Currently, the SWFSC's *Reuben Lasker* and NWFSC's *Belle M. Shimada* are capable of fulfilling the ship-time demand for a combined annual acoustic and trawl survey of the West Coast EEZ's hake and small pelagic fish stocks. However, fulfilling this demand comes at the expense of ship time that could otherwise be used for additional efforts to sample the ecosystem, operations also critical to ecosystem-based fisheries management (Rose, 2014). A techno-economic analysis, which takes into consideration data-quality issues and costs per unit area surveyed, would be valuable in determining the most effective mix of assets and protocols necessary for the NMFS regional science centers to meet their scientific objectives at present and in the future. With ship-time costs between $25 thousand and $30 thousand per day, including fuel, FSVs like *Reuben Lasker* and *Belle M. Shimada* are too valuable to be used for collecting only acoustic survey data, an activity often referred to by fisheries scientists as *mowing the*

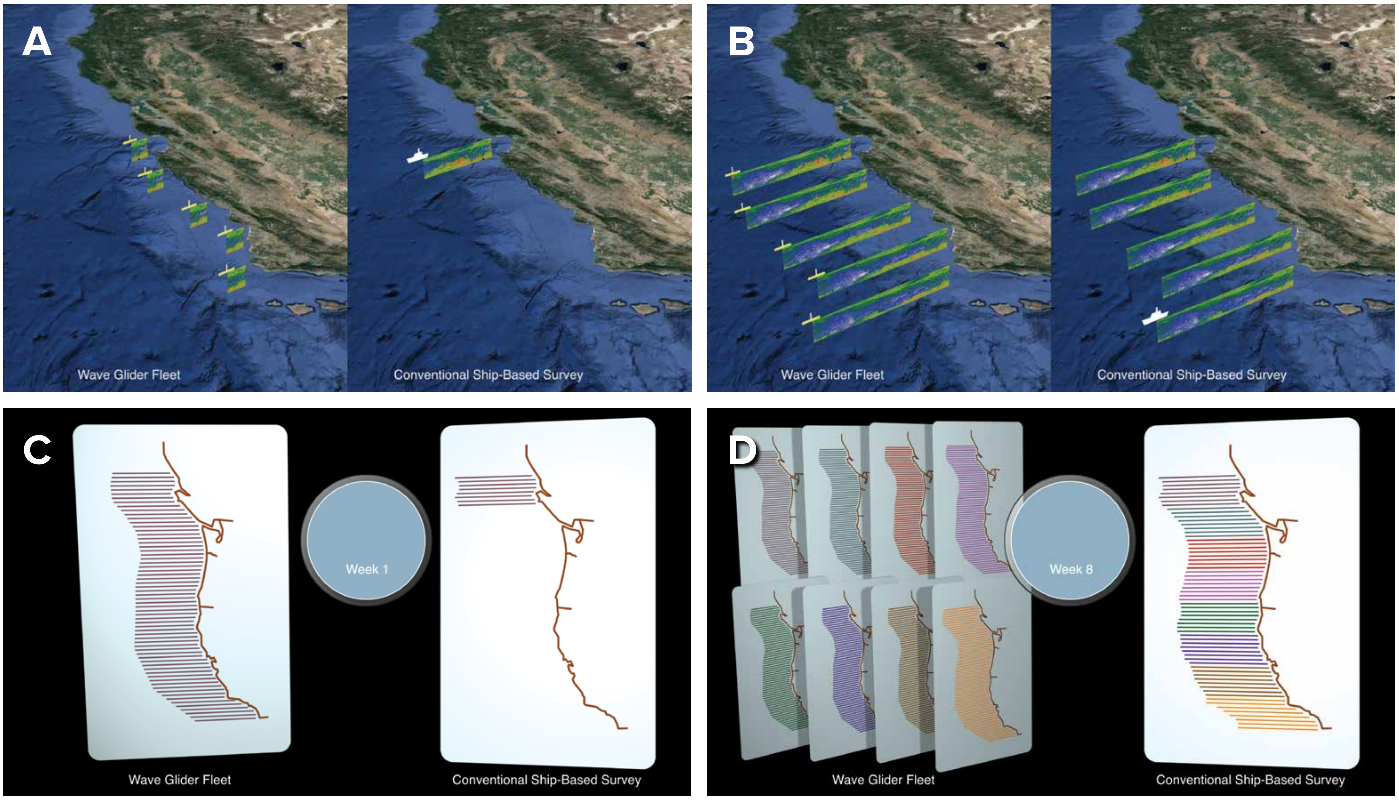

FIGURE 5. (A) Assuming an average cruising speed of 7.5 knots, an FSV covers five times the distance along a single survey line as a Wave Glider cruising at 1.5 knots for the same length of time. (B) Five Wave Gliders, each running its survey line at 1.5 knots, can complete five lines in the same amount of time that a single FSV completes the same five lines (**Video 1**). (C) With a fleet of Wave Gliders, each one running a survey line, a full acoustic stock assessment of the West Coast Exclusive Economic Zone (EEZ) can be completed in one week, the same amount of time that an FSV would need to complete ~ 12.5% of the survey. (D) A fleet of Wave Gliders can complete the equivalent of eight near-synoptic surveys of the West Coast EEZ during the eight weeks that it takes an FSV to complete one full acoustic stock assessment survey of the West Coast EEZ (**Video 2**). Each color corresponds to the survey lines completed during a given week.

lawn. Such routine tasks should be left to unmanned mobile platforms, while FSVs conduct integrated acoustic and trawling operations as well as other sampling activities that are only possible at present using ships.

CONCLUDING REMARKS

Viewing the Wave Glider approach to fisheries acoustics as only an incremental improvement to the way we collect stock assessment data fails to appreciate its full potential. This approach offers an opportunity to transform fisheries science and management in a truly fundamental way. At present, ship-based assessment surveys provide fisheries scientists and managers with what can be thought of as static snapshots of fish stocks, often collected at relatively infrequent intervals of a year or more. In addition, because these surveys take so long to complete, the corresponding assessments are in fact highly blurred snapshots, far from the synoptic ideal typically assumed when the data are analyzed.

In contrast, because of much lower operational costs, a fleet of Wave Gliders would not face the same logistical constraints that compromise the stock assessment data collected by FSVs. Beyond generating data sets that are more synoptic, such a fleet would make continuous and even year-round monitoring of fish stocks conceivable. The resulting large volume of spatially and temporally indexed observational data would then offer the unprecedented potential for more dynamic and sophisticated analytical approaches, including data-assimilation modeling. With better observational and analytical capabilities, fisheries science could enter a new era of greatly improved forecasting skill. From a societal perspective, such improved forecasting skill would be a valuable achievement, enabling fisheries managers to set quotas that maximize the yields to fisherman while simultaneously reducing the likelihood of overfishing. At the same time, the improved observational and analytical capabilities would enable fisheries scientists and oceanographers to more closely monitor the responses of different fish stocks to climate variability and change as well as ocean acidification. The global demand for food from a rapidly changing ocean will be staggering when the world population reaches 9 billion in 2050. Fisheries science and management will need the best observational and analytical tools available to help society meet this demand. By supplementing its relatively small fleet of FSVs with a large fleet of Wave Gliders, the NMFS can begin to position itself for the challenges ahead.

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ONLINE SUPPLEMENTARY MATERIALS.

Videos 1 and 2 and the supplemental materials, *Field Performance of a Prototype System* and Videos S1 and S2, are available online at: **http://www.tos.org/oceanography/archive/27-4_greene.html**.

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