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Microsats and Moby Dick: Microsatellite Support to Whale Science and Conservation

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ABSTRACT

Scientists who study the 92 species of whales and dolphins (aka cetaceans) know that many populations are endangered. There may be only 12 vaquita porpoises left, and the ~450 North Atlantic Right whales are being decimated by ship collisions and fishing gear. Conservation efforts rely on implanted radio tags and satellite transponders to track cetaceans in 1.3 billion cubic kilometers of ocean. These efforts, however, are handicapped by technology and the limits of available satellite support. Leading cetologists surveyed in Booz Allen Hamilton's Project WHALES (Whale/Habitat and Location/Environment Smallsats) agreed there are simply not enough tracking assets in space. The existing U.S.-led ARGOS radio tracking system needs to be supplemented with more satellites, especially in the tropical regions where ARGOS transceivers on polar-orbiting satellites leave gaps of up to two hours. A constellation of small satellites appears to be the most cost-effective way to achieve this objective. Cetologists can also benefit from partnerships with the increasing number of commercial Earth-observing microsatellite constellations. Imaging satellites with one-meter resolution can spot whales directly, while lower-resolution systems can track relevant phenomena like pollution plumes. Additionally, big-data analysis of tracking information and projecting tracks in a 3D environment with software like Booz Allen's OceanLens™ can multiply the utility of satellite tracking to scientists studying cetaceans and to naval forces trying to avoid injuring cetaceans. Small satellites may well be key to saving the largest animals on Earth.

INTRODUCTION

"…the moot point is, whether Leviathan can long endure so wide a chase, and so remorseless a havoc; whether he must not at last be exterminated from the waters."

– Herman Melville, *Moby Dick*

Project WHALES (Whale/Habitat Advanced Location and Exploration Smallsats) was initiated to explore using the study team's expertise in satellites, especially microsatellites, to improve connectivity and provide increased data transfer during contacts with tagged cetaceans (whales, dolphins, and porpoises) and otherwise improve space support to the study and conservation of cetaceans, many species and populations of which are endangered.

The study team almost immediately discovered two key facts. First, the international ARGOS system supported by the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Organization (NOAA) and used to track cetaceans, while very useful, still has limitations, and cetologists we talked to unanimously expressed the need for more space assets to provide more continuous tracking. The other is that, outside the ARGOS community, there's been too little dialogue between the cetacean and space communities. Of over 121,000 papers published in the 55 years 1960-2015 by the largest aerospace professional organization, the American Institute of Aeronautics and Astronautics (AIAA), only two concerned cetacean research.[1]

Conserving and understanding cetaceans for the long run requires opening a broad, continuing dialogue between the community of cetacean scientists and conservation officials in government, academia, and non-governmental organizations (NGOs) and the space community (defined here to include commercial firms, U.S. government agencies, academia, NGOs, and international organizations). There are important ways in which the space community in general and the smallsat community in particular can provide increased capabilities to cetacean science. While some details await follow-on studies, the Project WHALES team identified requirements and several options to give scientists and policymakers additional data and, secondarily but also important, better tools to analyze and display that data. Small satellites, microsatellites (defined here as under 100 kilograms (kg)), and even nanosatellites (most based on the familiar CubeSats) will be part of any comprehensive solution.

Discussions with leading cetacean scientists[2] indicate the most significant requirement is for more frequent contact and increased data transmission from tags affixed to cetaceans. The preliminary solution set includes some combination of these actions:

- Orbiting additional ARGOS transceivers using the smallest, lowest-cost satellites practical
- Shrinking the ARGOS equipment for smaller satellites like the new commercial microsat constellations.
- Redesigning the tags to use (as a primary or a secondary channel) the Nationwide Automatic Identification System (NAIS) as a partial solution in U.S. waters
- Redesigning tags to use a commercial system like Orbcomm Generation 2 (OG2)
- Redesigning tags to use new microsatellites.

A final point is that cetacean science is not conducted in a vacuum. Tags, transmitters, and other hardware or techniques applicable to one type of marine life, such as turtles, may overlap with that used to study cetaceans, so an improvement in cetacean studies is an improvement in many other aspects of marine science/conservation.

THE VIEW FROM SEA LEVEL

The cetaceans today

The cetaceans, members of the infraorder Cetacea, are sometimes spoken of separately from the dolphins and porpoises, but the smaller animals are included for the purposes of this paper. Together they add up to 92 currently recognized species.[3]

Human activity has placed cetaceans of all size in danger. China's baiji dolphin (*Lipotes vexillifer*) went extinct in 2006 due to hunting and pollution. The vaquita porpoise (*Phocoena sinus*) of the Gulf of California may be down to 12 animals due to being netted during illegal fishing. The Western Pacific population of the gray whale (*Eschrichtius robustus*) was devastated by Soviet whaling and still numbers only some 150 animals. The ~450 North Atlantic right whales (*Eubalaena glacialis*) are threatened by fishing gear (including drifting "ghost gear") and ship collisions. In 2017, there were 17 known fatalities and zero surviving calves. Ship strikes continue off the Northeast and California coasts, partly because large whales have a limited repertoire of behavior to avoid collisions. The United States lists 14 cetacean species or populations as Endangered.[4] (The Marine Mammal Protection Act (MMPA) protects all marine mammals, including cetaceans, in U.S.–controlled waters.) The International Union for the Conservation of Nature (IUCN)'s Red List of endangered species includes a dozen cetaceans.

Cetaceans remain in danger despite the moratorium on commercial whaling enacted by the International Whaling Commission (IWC) in 1986. Japan takes hundreds of whales per year via a loophole allowing "research whaling," and Norway and Iceland have resumed commercial whaling.

The World Wildlife Fund (WWF) lists the following threats to whales today:

- Renewed or illegal whaling
- entanglement in fishing gear
- climate change
- ship strikes
- toxic contamination
- oil and gas development
- habitat degradation. [5]

Efforts to mitigate these threats require more information on the environment and the whales themselves.

Figure 1. Whale entanglement by fishing gear (NOAA)

The United States funds major efforts on cetacean science through NOAA's National Marine Fisheries Service (NMFS) and other offices. In one year, U.S. Fiscal Year (FY) 2016, NOAA spent $146M on programs supporting marine mammals, not counting related efforts such as Sustained Ocean Observation ($42M) and Environmental Satellite Systems ($132M).[6] NOAA and NASA participate in the U.S./European ARGOS consortium. The U.S. Navy, required by the MMPA to deconflict its training and exercise activities/areas from cetacean activity as much as possible, funds much whale research through academic organizations and NGOs. The Naval Research Laboratory is currently working on the problem of reducing ship strikes off the Northeast coast.[7]

NGOs supporting whale research range from large organizations such as the Pew Charitable Trust and the Alfred P. Sloan Foundation as well as groups focused on cetaceans, such as the American Cetacean Society (ACS) and the Cascadia Research Collective. The Society for Marine Mammology (SMM) is the largest professional organization for cetologists.

Despite scientific study and centuries of whaling, cetaceans retain mysterious. The large baleen (filter feeding) whale known as Bryde's whale (*Balaenoptera edeni*) was in 2015 determined to consist of two species, and Omura's whale (*Balaenoptera omurai*), a unique species 20 meters (m) long, was only differentiated from the similar-looking Bryde's whale in 2003. These are not merely academic distinctions: they are critical to regulating and preserving the subject species. Scientists who thought they understood one species' movements well must start over if they learn they've lumped two distinct species together. Five species of the deep-diving group called beaked whales were confirmed or discovered in the present century, the latest being completely unknown until a specimen was beached in Alaska in 2016.

There are many other uncertainties. There is no agreement yet on how damaging human activities like seismic searches for oil and sonar exercises may be. While recorded whale strandings date to 1577, some modern researchers believe specific strandings, as well as disturbances to activities such as feeding, may be linked to human-caused (anthropogenic) noise produced by sonar and other sources: more data is needed both to confirm/refute linkages and to deconflict activities more accurately if required. Just to mention a few recent examples of puzzling events: Thirty whales from three species stranded in Alaska in the summer of 2015: an algal bloom (a toxin-producing spike in cyanobacteria or dinoflagellates, a phenomenon studied by examining ocean color from satellites) may have been to blame. A mass stranding due to unknown causes in Chile that same year killed 337 sei whales (*Balaenoptera borealis*).[8] The annual migration of thousands of humpback whales to Hawaii was months later than usual in 2015-16: while satellite tags helped determine the extent of this phenomenon, scientists remain puzzled about why it happened.

WHALE SCIENCE FROM SPACE

The use of satellites to monitor one threat, ocean pollution, goes back at least to the Nimbus-7 satellite of 1978, whose Coastal Zone Color Scanner (CZCS) "observed ocean color and temperature."[9]

Satellite tracking of tagged whales was pioneered by Dr. Bruce Mate in 1979.[10] Today the ARGOS system uses transponders on six large meteorological/scientific satellites (the European METOP-A/B, NOAA 15, 18 & 19 and the Indian/French SARAL) to receive transmissions from tags secured with fasteners or darts in a whale's dorsal fin or blubber layer. The ARGOS-equipped constellation provides overflight at the poles at 850 km on average every 10 minutes (a revisit time that drops as latitude decreases). ARGOS, now approaching its fourth generation (ARGOS-4) is a consortium including two European and one Indian partner(s). Some ARGOS satellites can downlink in real time, but they mainly store data and downlink it to stations in the U.S. and France.

The use of satellite-monitored radio tags on whales has yielded an enormous amount of information for the conservation and management of whales large and small. These tags provide detail on whale location, movement, and habitat use than direct observation efforts could yield, although acoustic detection and visual observation (greatly assisted by tags' role in telling the searchers what areas to search) also contribute to the full picture of whale activity – one that would be even more enhanced if satellite contacts were more frequent and included more data. Only a small fraction of any whale population can be tagged, which makes it all the more important to get the most out of those that are.

Currently only a few types of tags are being used in tagging whales. Some examples made by the largest company involved, Wildlife Computers, include Low Impact Minimally Percutaneous Electronic Transmitter (LIMPET) tags that monitor temperature and depth, depth-transmitting Mk10-A tags, and the location-only SPOT5 tags. The tags providing more data are larger and require longer contacts, higher data rates, or physical recovery of a data log after it's detached from the whale via a corrosive link. Location-only tags are the mainstay of tracking, and depth-recording transmitting tags have so far been used in only two trials. Tag transmitters have power levels of 1w or less, so satellites in low Earth orbit (LEO) must be used. The low orbits allow for tags to be made smaller as technology advances: ARGOS engineers are aiming to produce transmitters needing only 100-200 milliwatts, greatly extending battery life.[11] There are more complex tags which log several types of data, but these must be physically retrieved after separation from the whale.

ARGOS tags (also called Platform Transmitter Terminals (PTTs)) currently work exclusively with ARGOS transponders. Existing tags transmit 32-byte messages using an uplink frequency of 401.65 MHz. The transmission from the tag to the overhead satellite lasts less than one second and is repeated every 45 to 200 seconds for as long as the contact lasts. ARGOS can handle larger messages (up to 30 kilobits for the ARGOS-3 and -4 series transponders) but the small tags on marine mammals can't support that yet.[12] Tags can transmit for months, but there are many variables, and some last only weeks.

The ARGOS/tags infrastructure is limited by coverage as well as data rate. By the nature of polar orbits, the ARGOS system has gaps of over two hours in the tropics. Since 85 percent of whale species live in, visit, or transit this belt, scientists already constrained by short messages and the whales' habits (varying with species) of limiting their time on the surface face a frustrating lack of connectivity.

Allowing the tags to transmit more data in a brief contact (a satellite at 750km with a fixed antenna is likely to have about 5-7 minutes contact with a low-power tag) can be done by redesigning the tag but will likely also need software and/or hardware upgrades for the satellite equipment, as the designs are tightly coupled.

As mentioned above, low-power tag transmissions normally include only GPS location. Current ARGOS transmit/receive units, which collectively weigh over 20kg, are not suitable as a secondary instrument for most microsatellites: they cannot piggyback on the exploding number of commercial smallsat communications and imaging spacecraft. However, smallsats may help solve the problem by carrying ARGOS-compatible equipment on more affordable, more frequently launched satellites dedicated to the ARGOS mission. Modeling the current ARGOS constellation and a notional microsatellite constellation found that an equatorially-focused constellation with a notional inclination of at least one degree per microsatellite could reduce the gaps in the ARGOS coverage in the tropics to approximately 30 minutes.

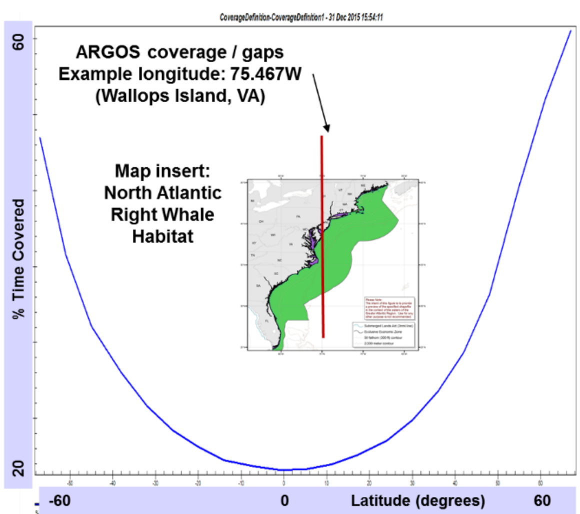

Figure 2. ARGOS coverage variation by latitude (inset map NOAA)

Satellites vs. Other Tools

Whales are difficult to track via satellites, but often impossible by any other means. Ships and buoys must be in line-of-sight range (the horizon on a quiet sea is, for an antenna 9m above the waterline, only 10.8km). Hydrophones, such as the Navy SOSUS array, can hear whales' varied calls but leave large areas of the oceans uncovered and may not give much information beyond frequency and direction. For the vast open seas, the satellite is the tool of choice. To save battery life, tags have salt water-activated switches so they cease transmitting when submerged. So the satellite has to be, not only in the right orbit, but visible at the right time.

Microsatellites today perform missions including communications, weather monitoring, space weather monitoring, navigation, tracking of ground vehicles and ships, and a multitude of scientific endeavors. Of interest to cetacean science are imaging, ocean studies, communications, climate, and weather, all of which interface in the complex business of studying and protecting millions of individual cetaceans in 1.33 billion cubic kilometers (km) of ocean with a surface area of 360 million square km.

Spotting Whales Directly – Space Imaging

Following whales visually is a difficult concept, requiring almost continual observation, but selecting a "box" astride a major migration route or calving ground and visiting it at regular intervals may be a valuable tool. The potential was demonstrated in 2014, when scientists used a single commercial image from the WorldView2 satellite to examine a swath of ocean covering 104 square km off Argentina with a panchromatic imager offering .5m resolution and a multispectral imager offering 2m. After processing the image, they spotted 55 definite and 23 probable whales at the surface. Moreover, one band of the multispectral imager (measuring violet/indigo light at 400 to 450 nanometers) indicated 13 possible whales just below the surface.[13] There are few civilian satellites with this kind of resolution, but large advances will be made by the Planet and Black Sky constellations now being emplaced, and Earth-I offers video of a 5km-square footprint at 1m and still images at .6m.[14] While resolution is not the only factor in whether satellites can detect whales – some spectral bands will pick them out better than others, and image processing capabilities are very important – a large whale stands a very good change of being detectable at 2m or smaller (all resolutions are at nadir, when the satellite is directly over the target.)

The U.S. military is also making advances, and military capabilities have in the past been offered on an as-available basis to civilian agencies. The Army Space and Missile Defense Command (SMDC)'s Kestrel Eye 1 weighs 50kg and provides a resolution of 1.5m. Black Sky Global will image the planet at 1m, with emphasis on mid-latitude coverage. The company projects that some areas in the tropical belt will be examined 40 times or more per day when the whole 60-satellite constellation is in place.[15] Planet (formerly Planet Labs) is already blanketing the Earth with its 5-kg 3-5m imagers. The Finnish firm ICEYE is bringing synthetic aperture radar (SAR) to microsatellites, with its 80kg X2 satellites offering resolution under 3m.[16] Satellites not capable of identifying whales directly can monitor pollution plumes, weather systems, ice cover, algal blooms, legal and illegal whaling vessels, and ship traffic that might pose a collision hazard. Several of these companies are planning ground and processing systems to provide imagery to clients much faster than legacy systems can, another point of importance for cetology and conservation.[17]

Microsatellites are increasingly contributing to our knowledge of the ocean environment. Late in 2016, for example, NASA's eight-microsat Cyclone Global Navigation Satellite System (CYGNSS) launched to measure ocean surface winds, with special focus on the beginnings and growth of hurricanes. NOAA is developing microsatellites to supplement their costly 2,200-kg class polar-orbiting environmental satellites.

Further contributions lie ahead. A U.S. government Space Studies Board study released in 2016, "Achieving Science with CubeSats: Thinking Inside the Box," reported, "A LEO constellation comprising several or dozens of individual small spacecraft could provide both global spatial and high temporal resolution. The understanding of many Earth processes benefit from this kind of observation, including severe weather, cloud formation and evolutionary processes, aerosols or air quality related measurements, atmospheric photochemistry, vegetation, ocean color, and Earth outgoing radiation."[18]

Several of these applications are promised by commercial microsat constellations. One example is Spire Global, which offers global weather data with 3U CubeSat-based spacecraft (over 70 of the planned 100 are on orbit) using the GPS radio occultation technique to analyze the atmosphere, and ship tracking using the Automatic Identification System (AIS) beacons required on large vessels. The company advertises its utility in, among other things, tracking extreme weather (which affects whales and those trying to observe them) and illegal fishing, which often includes killing smaller cetaceans as "bycatch."[19]

Tyvak is building the GeoOptics, Inc. CICERO constellation using the same weather sensing technique. This technique is a well-proven one, demonstrated by a microsat (MicroLab-1) in 1995.

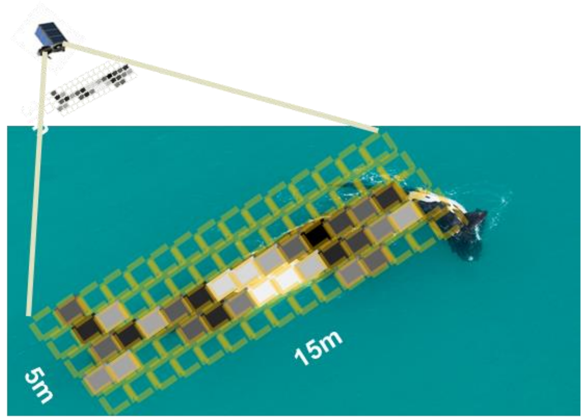

Figure 3. Right whale with calf imaged at 1m resolution by microsatellite (15 pixels by 5)

Making Use of a Worldwide Phenomenon

Microsats have become a gateway to broad international participation in space. Much of the credit goes to the CubeSat wave: well over 100 organizations, many educational, in dozens of nations have participated in CubeSat development. Most whale science cannot be done by CubeSats, at least not by single CubeSats, although formation techniques now in development offer promise of better imaging and communications capabilities via "virtual apertures." However, the global boom in nations participating in space will facilitate international cooperation in any microsat-based cetacean solution. The SSTL-built Disaster Monitoring Constellation (DMC) is an example of a working coalition, providing imagery since 2002 through microsats operated by the space agencies of Algeria, Nigeria, China, Turkey, and the U.K. The survey firm SpaceWorks, in January 2018, reported known projects were developing 936 microsatellites (including all from 1-50kg) and projected 2,600 such satellites might launch through 2022.[20]

Microsatellites offer more affordable refreshment of technology on orbit and the opportunity to replace satellites lost to malfunctions or launch accidents, as demonstrated by NASA's NanoSail-D2, a solar sail experiment built on a three-unit (3U) CubeSat platform and launched in 2010 to replace an original destroyed on launch in 2008.

CubeSat-based platforms are growing in size as well as popularity: from a beginning as a modular 10cm cube, 3U satellites weighing about 5kg are now popular for science and imaging, while 6U and 12U CubeSats (like the 6U craft being built by Blue Canyon Technologies for PlanetIQ's GPS occultation weather constellation) are under construction.[21]

The costs of launching a CubeSat can be as low as $100,000,[22] although satellites needing placement in a particular orbit benefit from launching in groups as primary or secondary payloads. Rideshare arrangements can be facilitated by NASA's CubeSat Launch Initiative[23] and DoD's Space Test Program (STP), and companies like NanoRacks have made steady businesses out of arranging secondary flights.

Efforts are underway by NASA and private industry to lower the cost of dedicated microsatellite launch vehicles. To give only some examples, Generation Orbit Launch Services has NASA support for technology development for its air-launched GOLauncher 2[24], to carry 40kg to LEO.[25] Other companies like Vector Space Systems (45 kg for $2-3M) and Interorbital Systems (6.3kg), are trying for the same market,[26] as is Rocket Lab, which has a NASA Venture Class Launch Services contract for its Electron launcher (which flew successfully in January 2018).[27] Larger launchers like Virgin Galactic's LauncherOne (300kg payload to a sun-synchronous orbit at 500km) and the Firefly Aerospace Alpha (1,000kg to LEO, first flight 2020) could launch larger microsats or constellations.[28] There won't be enough market for the many small launchers in development, but there are enough competitors and business to be confident a few such launchers will become established.

OPTIONS FOR CETACEAN SCIENCE

Tracking

One option to improve tracking is to build microsatellites optimized to receive transmissions from tags.

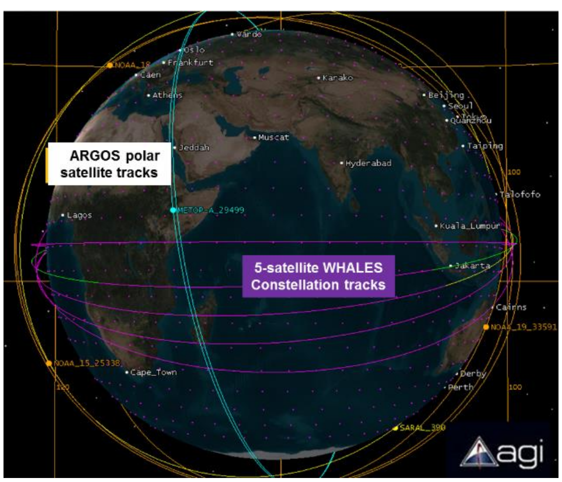

Figure 4: Polar ARGOS orbits and a possible WHALES microsatellite constellation (image used by permission of AGI)

Such smallsats could be a supplement to ARGOS polar satellites or a wholesale replacement system. Figure 4 above, created using System Tool Kit™, shows a notional combined system.

ARGOS units today (ARGOS-3) are made by Thales and include a 16-kg Receiver Processing Unit approximately 25x28x36 cm and an 8-kg Transmitter Unit 10x36x30 cm. The UHF antenna (using the example of an ARGOS-2 system) adds another 4kg.[29]

Using ARGOS components on microsatellites appears practical, but only if a satellite roughly the size of the commercial Orbcomm Generation 2 (OG2) or Planet's 100-kg SkySat carries it as a primary payload. Redesigning the payload to fit smaller satellites is an attractive option, since it could make for cheaper dedicated microsats or more options for piggyback systems, but has not yet been explored or costed. There is nothing inherently difficult in making a small satellite to use the ARGOS frequencies, although depending on size it might need an extendable mesh antenna (a technology advancing rapidly in the microsat world).

Putting the ARGOS-4 equipment on more satellites offers at least a partial solution, and four candidate satellites due for launch in 2018-2029 may carry it.[30] Old satellites, though, may go out of service in this time (NOAA-K was launched in 1988), so the number will increase slowly at best. Space/weight on these satellites is at a premium, and many more instruments are proposed than can be carried. An ARGOS system lost out in the fierce competition to be on Joint Polar Satellite System (JPSS)-1, aka NOAA-20, launched in 2017. (JPSS is the successor to the America's canceled National Polar-orbiting Operational Environmental Satellite System (NPOESS)). Three more JPSS satellites are in the pipeline, but it's unknown whether any will host ARGOS equipment.

Giving tags a higher data rate and other increased capabilities to uplink more data on each pass is another option that appears practical, but this only ameliorates the limited message size problem and not the connectivity problem. A combined project to create better tags that work with smaller ARGOS-type transponders is attractive, although it requires international cooperation along with increased funding to confirm the plausibility and then do the work. A bit of good news is that such cooperation in the ARGOS system has gone quite well, with the French space agency Centre national d'études spatiales (CNES) the most important overseas partner.

Figure 5: Scientist Russ Andrews tags a killer whale (aka orca) using a gas-powered darting gun (NOAA)

A list of possible options is shown in Table 1. It is critical to understand 1) these are preliminary, without detailed engineering or costing studies, and 2) the solution may lie in a combination of these approaches.

Table 1: Preliminary Solution Set

Approach	Advantages	Challenges
Existing tags: More transceivers on ARGOS-type polar satellites	Works with existing tags	Costly: few satellites are launched; competition for payload space
Existing tags: Dedicated microsatellites for tropical coverage where ARGOS has biggest gaps	Specialized for cetacean science needs; puts coverage where most needed	Cost: Unclear whether commercial bus would work without further study
Redesigned tags to use US National Automatic Identification System (NAIS)	Could feed in real-time to USCG database of ship information to reduce collisions	Mainly U.S. water, limited in open ocean; practicality of tag design uncertain; means two types of tags in the field
Resigned tags to use commercial system like Orbcomm-2	Offers global coverage	Means two types of tags in the field; practicality of tag design uncertain
Redesigned tags for adapted or new-design WHALES microsatellites	May be able to use smaller, cheaper satellites than (2); puts coverage where it's needed most	Cost: many engineering uncertainties to be examined; requires two types of tags in the field

Other Space Support

It appears the new commercial remote sensing constellations will add a great deal of capability if we can facilitate close cooperation with cetologists and their organizations. Weather and other sensors for atmospheric data (even if the GPS radio occultation technique does not quite reach to the ocean surface) will tell us more about weather patterns, ocean temperatures, and changing climate that affect whales and their food supplies.

Likewise, direct observation of whales at or near the surface will be enabled on a much greater scale than today. The commercial constellations, along with military and civilian government assets, offer the possibility of revisiting key areas often enough to keep a count on numbers and movements of the larger species at least. Again, it'll be a matter of dialogue and agreement on tasking, funding, and other matters.

MAKING USE OF THE DATA

Obtaining better data is key, but making the most of that data requires skills in data analytics and visualizations that make data easy to grasp, manipulate, and use.

Enhanced satellite tracking will add to data from current tag tracking, buoys, direct observations, pop-up tags, mortality events, hydrophone arrays, satellite-based environmental observations and ship tracking, and more. The correlations, associations, and links between each source's digital footprint and all other sources' digital footprints correspond to an exponential explosion in possible data products.

Increased usability of the data by diverse participants can be achieved by creating shareable data packets (such as standardized time series path data on a per-whale basis; or map files that can be imported into different tools such KML Keyhole Markup Language map files). Such interoperable data types both enable and encourage greater data-sharing and hence greater scientific community involvement in cetacean protection and conservation programs.

Once a broader community is accessing and using these data, then a wide variety of analytics tools can be developed and applied (depending on the different skills and expertise of the participating audiences). These analytics approaches can include predictive modeling (of whale movements, individually or in groups); visual analytics (for discovery of interesting patterns, anomalies, or trends and for decision support through visual displays); prescriptive modeling (identifying conditions or actions that can applied in order to avert a negative predicted outcome, and thus deliver more optimal outcomes, based on causal factor analysis from multiple data types, data sources, and contextual data); and data assimilation (which uses sparse incomplete data to update comprehensive dynamic models that have full global coverage but are dependent on real-time updates from live data sources in order to make the model as realistic and as timely as possible).

Upgrades in spatial-temporal global data coverage (through one or more of the Smallsat and tagging solutions listed in Table 1) will benefit these analytics efforts immensely, by providing stronger evidencebased validation of analytics-based models, by providing new insights to a wide audience of participants of current activities in the whale environment and specifically at the human-whale interface, and by delivering accurate and timely actionable data to decision-makers.

NOAA is already pursuing increased data integration, as shown by the WhaleWatch diagram in Figure 6. Increased data from whale tags and the increasing data from smallsat constellations will greatly enhance this capability. For example, if increasing the number of satellites with ARGOS equipment can cut gaps in the tropics from 2.5 hours to .5, that will multiply the tagged data inputs from this zone, increasing the information available to the data analytics systems and thus the comprehensiveness and utility of the results.

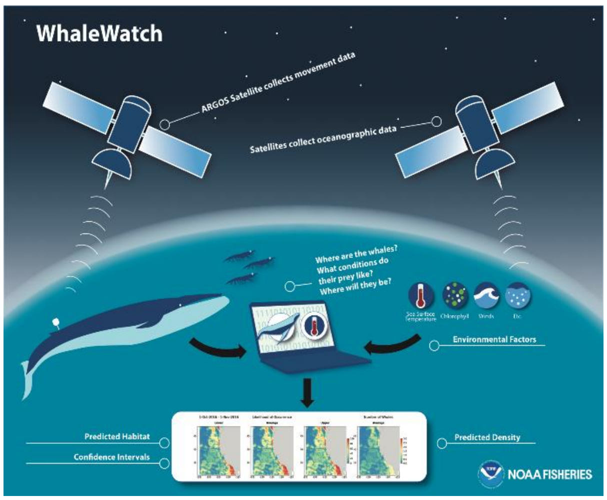

Figure 6: NOAA Fisheries West Coast Region's vision of combined data and analytics (NOAA)

An example of 3D visualization software which can help in several ways is Booz Allen's OceanLens™. This visualizes, in 3D with full motion, tracks, human-produced and (where data is available) whale-produced sound clouds, and seafloor terrain. Taking advantage of data from recovered tags and from experimental new tags that transmit depth data, it provides a view the leading U.S. cetologists we talked to thought would be highly useful.

The example shown in two images below is a record of one humpback whale's travels in the Antarctic, showing the maximum depth reached in each segment of the tracked journey. The whale data, from a field test of a new tag type, was provided by Drs. Ari Friedlaender and Ben Weinstein of the University of California – Santa Cruz (UC SC).

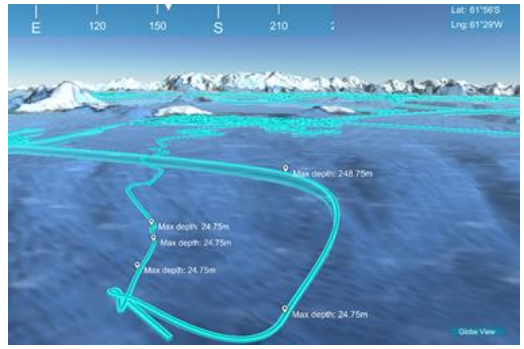

Figure 7. OceanLens™ snapshot. Copyright 2018 Booz Allen Hamilton.

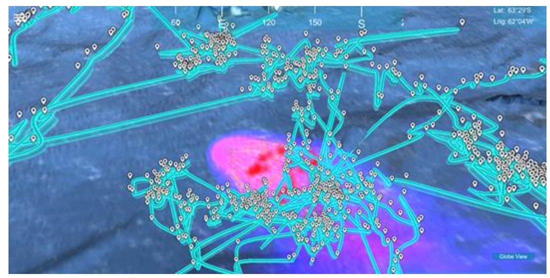

Figure 8. Same whale, surface movements, with sound cloud from a research ship (130dB at 2KHz). Copyright 2018 Booz Allen Hamilton.

ORGANIZATION AND EDUCATION

There are other aspects of a long-term solution which are not amenable to purely technical approaches. One is connecting the space and cetology communities. One starting point could be a workshop to which all sectors are invited. An important offshoot of such collaboration is increased science, technology, engineering, and math (STEM) outreach. The Project WHALES team has already presented its work through the USA Science & Engineering Festival and other forums. We are actively seeking partners among both the space and cetacean communities to put this work to use in the field.

CONCLUSIONS

Comparing the humped herds of whales with the humped herds of buffalo… the hunted whale cannot now escape speedy extinction.

– Herman Melville, *Moby Dick*

The status of cetaceans today is uncertain, with some populations and species still on the brink. A key reason why cetaceans are not more effectively understood and protected is the data gaps which still plague cetologists and policymakers. Environmental satellites and the ARGOS system have improved enormously on old methods of study and enforcement, but such basic data as where some species live and what threats they face eludes us. More satellites receiving better data from tagged whales will be an enormous step forward. When we have that data, we have to make the most of it by analysis and visualization available to all parties. The Project WHALES team at Booz Allen is proud of its groundbreaking work in this area, and we hope our study will be a catalyst for a new combined space-enabled approach to protect the planet's largest animals.

LATE ADDED NOTES

1) NASA Ames has a small project under Andres Martinez looking at better tracking via adapting a ground receiving station for launch by high-altitude balloon. 2) A French project is examining shrinking the ARGOS payload for a microsatellite called ANGELS: An orbital test may take place late in 2019. 3) Developments in software defined radio (SDR) may offer another path to investigate in shrinking payloads.

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Disclaimer

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