An Evaluation of Passive Acoustic Monitoring Using Satellite Communication Technology for Near Real-Time Detection of Tagged Animals in a Marine Setting

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Abstract: Passive acoustic monitoring has become a common tool for monitoring tagged marine animals. Recent improvements in acoustic technology have addressed some of the limitations of the system; specifically, the need to manually download data and the time delay between detection and data analysis. Coupling a robust passive acoustic receiver with a satellite communications modem has allowed for remote download of detection log files on a time scale of the user's choice from real-time onwards. This coupling has also allowed the user to maintain a watch on the receiver's status and thus affect timely repair to avoid loss of data. Using satellite communication is a cost effective means of monitoring acoustic receiver hardware in remote or difficult to access areas. Because this system requires a surface buoy for the satellite modem, mooring design is critical and will require careful consideration of the local environmental conditions. It is recommended that future deployments of this system include a sentinel tag to aid system diagnostics when tagged animals are absent.

Keywords: Acoustic monitoring, telemetry, Iridium, white shark, *Carcharodon carcharias*.

INTRODUCTION

The marine environment remains a challenging environment for studying animal movements. Simple mark and recapture techniques were reportedly first used in 1653 [1] to demonstrate that juvenile Atlantic salmon return to their natal river following a marine phase. Tag and recapture methods progressed little for the next 340 years, providing limited information on when and where an animal was tagged and recaptured. The early 1990s saw a dramatic change in tag and recapture studies with the introduction of archival tags [2-4] capable of gathering data on the environments their host passed through and could also be used to calculate the route taken from the initial tagging to their ultimate recapture.

The next great leap in tag and recapture studies occurred in the late 1990s when the archival tag was coupled with a satellite transmitter [3-6]. These tags would both detach from their host at a predetermined time and transmit a summary of their archived data, or they would transmit a summary of their archived data every time their aerial was clear of the water. These tags eliminated the need for recapture of the tagged animal. The main drawbacks to satellite-based tags were their cost, relatively short battery life, short retention times on their host, and their reliance on the ARGOS satellite array for the delivery of archival data which is constrained by limited bandwidth and, until recently, only one-way communication was possible.

Prior to the development of satellite-based tags, low cost acoustic technology was being developed to assist with tracking animals. Close to 300 years after the first tagging studies on Atlantic salmon, acoustic technology was first applied in an aquatic setting to study the movements of Chinook salmon [7, 8]. These first acoustic tags were large (~6.4 cm long and 2.3 cm diam.), the tracking equipment was cumbersome, and its use was labour-intensive [8]. Advances in electronics and miniaturisation of components increased the utility of acoustic technology such that the current generation of acoustic tags are less than ¼ of the size of the original tags, more powerful, have a longer life, and can accommodate a range of sensors. Furthermore, with the introduction of autonomous, or passive, acoustic monitoring systems reductions have been made in the labour required to monitor tagged fish, and increased the number of fish able to be monitored at one time from 10s of animals to thousands [9, 10].

As a result of the advances made in acoustic technology over the past 50 years, acoustic tags have become a common tool in fisheries science (see for example, [10-14]). In Australia, and around the world, several large national and inter-

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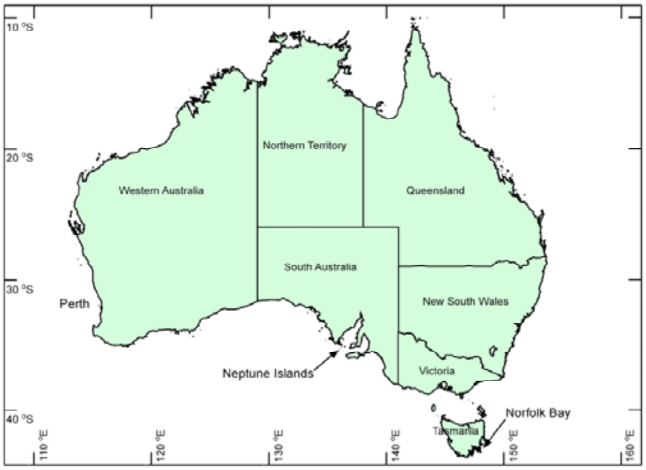

Fig. (1). Location of VR4-Global acoustic receiver deployments in Australia.

national initiatives are installing acoustic infrastructure with the intent of establishing a collaborative community of users (e.g. Ocean Tracking Network (OTN), Integrated Marine Observing System (IMOS), Australian Acoustic Tagging and Monitoring System (AATAMS), Pacific Ocean Shelf Tracking (POST)). In addition to facilitating a collaborative approach, these initiatives are encouraging researchers to allow access and share data recorded on individual project-based acoustic receivers that are not directly aligned with these major initiatives.

Despite the relatively wide acceptance of acoustic technology today, initial uptake has been hampered by several limitations. 1) Active tracking was, and remains, labour intensive [15], 2) passive acoustic monitoring required a physical download of a receiver's memory [16], 3) passive acoustic monitoring involved a delay period in data recovery dependent on the frequency of downloads, 4) an inability to remotely assess moored receivers on a regular basis to ensure receiver integrity, and 5) the often considerable investment (both financially and in time) associated with downloading moored receivers.

Receiver technology has been constantly evolving to help address some of these issues. 'Remote' transmission of data was developed using systems which used radio signals to relay detections from acoustic receivers *via* a surface buoy to a base station [17]. This system alleviated the need to physically download a receiver's memory file and allowed more sophisticated information on detailed three-dimensional movements of tagged animals within the array of receivers. However, the system required the use of at least three receivers in a triangular array each with a surface buoy unit and a base station within 'line of sight range' of the buoys, and was designed for short-term studies (days) of detailed movements [18]. The limitation of line of sight meant that data transmission was limited to within a few kilometres of range.

The ability to remotely transmit detections of tagged animals and collected data over global distances enabled researchers to more easily monitor receivers in remote locations without physically visiting the site. Such systems integrated an acoustic receiver with an Argos satellite transmitter to relay detections and data over global distances [19, 20]. However, due to its reliance on the ARGOS satellite array, such systems have been constrained by some of the same bandwidth limitations for the transfer of data as satellite-based tags.

Recent years have seen the establishment of various regional and international ocean observing systems that incorporated technologies to remotely log and transmit data on a variety of physical and biological parameters in the marine environment (see for example [21]). They were designed to collect sustained (long-term) multidisciplinary observations across multiple scales from global and local ecosystems [22] and link environmental observations to scientifically sound management of ecosystems and natural resources [23, 24]. These programs are providing data that enhance our ability to understand and predict system dynamics in coastal seas and open oceans, and in particular provide high quality, cost-effective, real-time data streams. The core strength of such programs has primarily been focussed in physical observations (e.g., temperature, salinity, oxygen, currents, and altimetry). Biological data, specifically the movement of marine species as monitored by broad-scale acoustic receiver arrays, has been more challenging to incorporate into such automated data collection and transfer systems due to the limitations involved in remotely accessing and uploading data. This means that despite the incorporation of acoustic receiver arrays into coastal/ocean observing programs (e.g. IMOS), access to their data is limited by costly physical retrieval and the utility provided by real-time data streams has not been realised.

This paper describes the first deployments of a new acoustic receiver that incorporates an Iridium (www.iridium.com) satellite modem. The Iridium satellite network provides for two-way communication, high bandwidth throughput relative to the ARGOS satellite system (i.e. ability to transfer large amounts of data with little compression), provision of data in real-time, and the ability to monitor the status of various components of the receiver system to detect faults that if left undetected may lead to the likelihood of losing data. We report on the first units installed, discuss the advantages and disadvantages of this technology in the context of the current proposed uses with an aim to promote further discussion on potential uses of the technology, and present sample data using the white shark (*Carcharodon carcharias*) as a case study.

METHODS

Study Sites

VR4-Global (VR4G) acoustic receivers (Vemco, a division of AMIRIX Systems Inc., Halifax, Canada) were deployed at three sites around Australia (Fig. **1**): VR4G-TAS in Norfolk Bay, Tasmania (43° 00.3' S and 147° 45.8' E); VR4G-SA at the North Neptune Islands, South Australia (35° 13.9' S and 136° 4.3' E); VR4G-WA off Perth, Western Australia (31° 47.9' S and 115° 41.8' E).

Norfolk Bay is a relatively sheltered bay in south eastern Tasmania (Fig. **2**) with gently sloping bottom topography to a maximum depth of around 20 m. The VR4G-TAS mooring was placed in about 15 m of water with the hydrophone

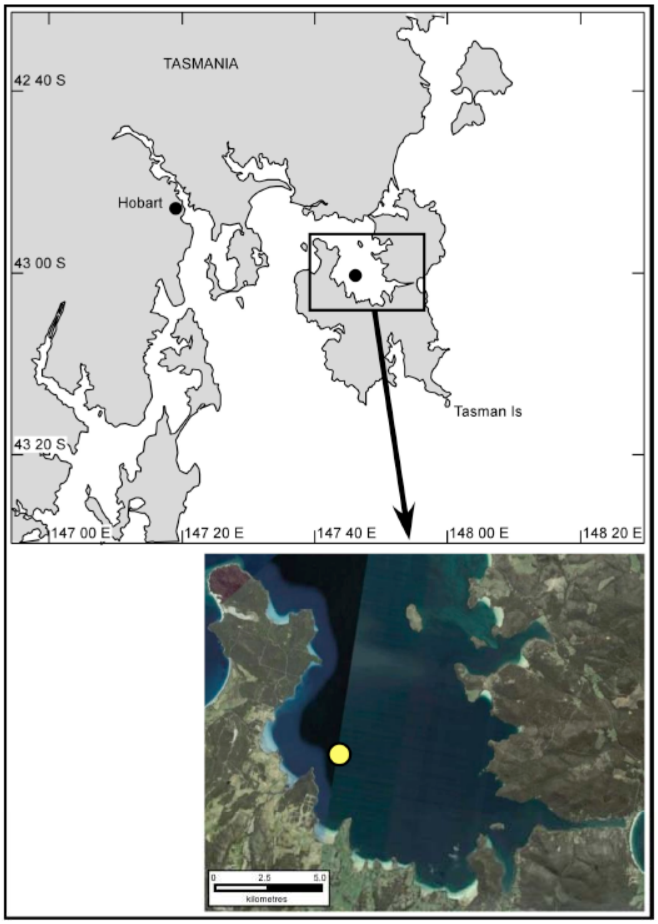

Fig. (2). Location of VR4-Global acoustic receiver at Norfolk Bay, Tasmania. Yellow = VR4G-TAS.

about 5 m below the water surface. Norfolk Bay is protected from southern, eastern and largely northern winds; the mouth of the bay provides the longest fetch for winds from the north western sector.

The North Neptune Islands are located on the shelf in the Great Australian Bight about 60 km south of Port Lincoln, South Australia (Fig. **3**). It consists of two islands, the smaller of which protects a small bay from north westerly swells and winds while the larger island protects the bay from north easterly swells and winds. The bay is relatively shallow, reaching a maximum depth of about 18 m. The VR4G-SA mooring was placed in about 15 m of water with the hydrophone about 5 m below the water surface.

Perth is located on the north-south orientated coastline of Western Australia in a high energy area exposed to the Indian Ocean. The initial mooring was positioned in 8 m of water with the hydrophone at about 2 m below the water surface. This initial deployment suffered from some mooring design issues and is included here only to aid in discussion of mooring designs.

VR4G Technical Specifications

The VR4G, expands upon the VR2W technology released in 2006, by linking a submersible hydrophone to a surface mounted electronics package that includes an Iridium satellite modem. The dual frequency hydrophone operates at 69 kHz and 180 kHz, is rated to 100 m, and power is supplied through the connecting cable. The surface unit consists of a power supply (9-volt alkaline battery pack), acoustic receiver, and an Iridium satellite modem. Together the hydrophone and surface unit weigh approximately 9 kg.

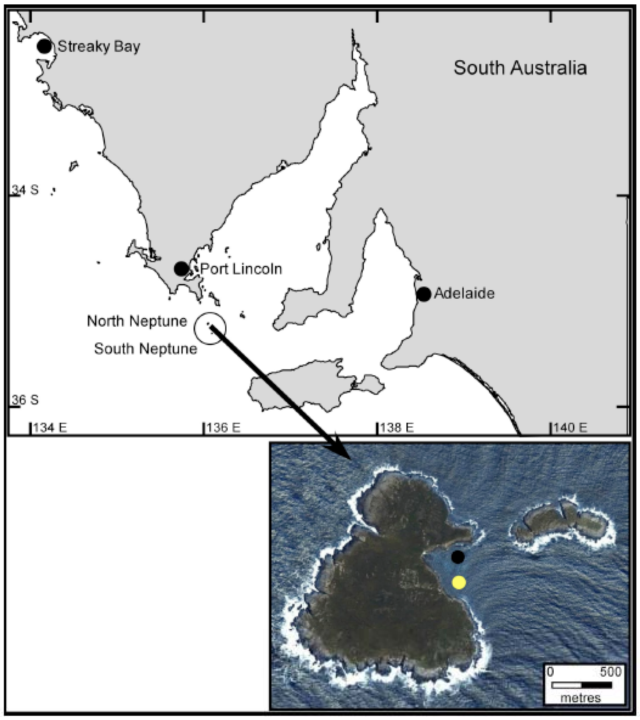

Fig. (3). Location of VR4-Global acoustic receiver and VR2W acoustic receiver at North Neptune Island, South Australia. Yellow = VR4G-SA; black = VR2W 101915.

The Iridium satellite modem provides access to key features in addition to those provided by the standard VR2W technology. Specifically, by providing bi-directional communication (at data rates up to 2400 bps) between the acoustic receiver and the researcher, detection logs can be downloaded remotely. Downloads can be scheduled or provided on request. In addition, all of the VR4G's parameters can be programmed remotely, including remote upgrades of the VR4G's firmware. Information on the status of the VR4G (battery voltage and usage, detection and ping statistics, operating mode, receiver and hydrophone health) can also be requested on a user-defined schedule. Further, the researcher is able to define a watch list – a list of tag ID codes – that the receiver can monitor and provide email notification of detections on a real-time basis.

Power is supplied by a 9-volt alkaline battery pack with an expected lifespan of 12-18 months. Power is conserved by operating the Iridium satellite modem in one of two modes depending on the required data load. The low power consumption mode, mode 1, is used for messaging such as near real-time detection notifications, status updates, and minor configuration changes. Higher power consumption, mode 2, is used to establish a dedicated connection for the upload of detection logs, major configuration changes and remote firmware upgrades.

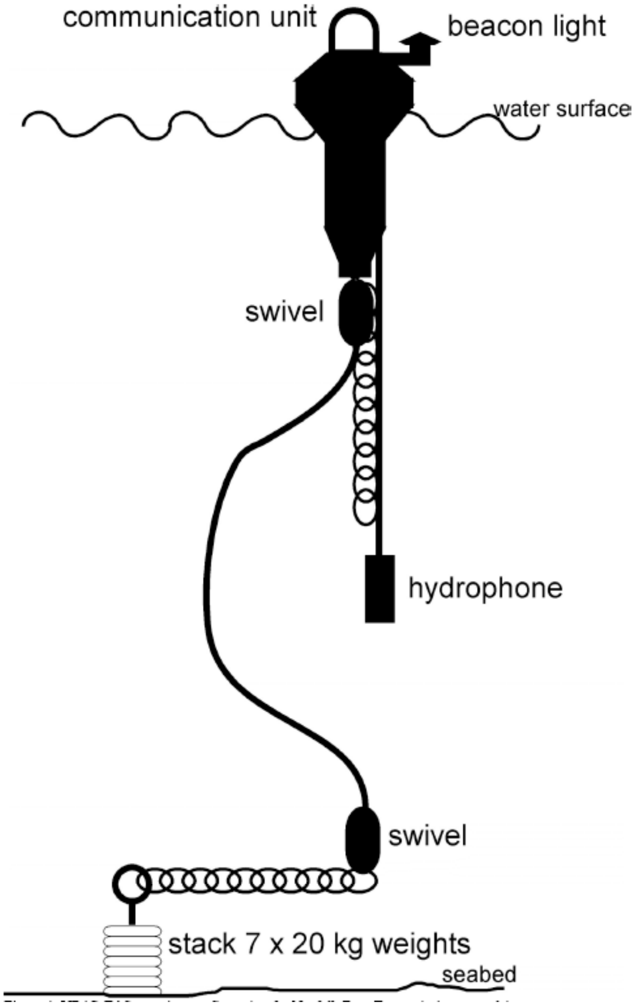

Fig. (4). VR4G-TAS mooring configuration for Norfolk Bay, Tasmania (not to scale).

Mooring Designs

The VR4G- TAS mooring (Fig. **4**) consisted of 140 kg of steel weights; 25 m of 18 mm braided mooring rope (swivels at both ends); foam-filled aluminium buoy counter balanced by 20 m of chain wrapped in PVC layflat hose. The VR4G communication unit was mounted on top with a beacon light to one side. The hydrophone cable was protected and supported by a heavy duty PVC hose with a reinforced PVC inner tube.

The VR4G-SA mooring (Fig. **5**) consisted of a light truck tyre filled with concrete (approx weight 140 kg); 20 m of 14 mm braided mooring rope (no swivels); 800 mm hard chined V-bottomed buoy with plastic covering for the VR4G communication unit (provided both a weather shield and some protection from vandalism) on top of which was mounted a beacon light. The hydrophone cable was protected and supported by an industrial, reinforced EDPM synthetic rubber hose.

The VR4G-WA mooring (Fig. **6**) consisted of light truck tyre filled with concrete (approx weight 130 kg); 15 m of mooring rope with swivels attached to a flat circular 800 mm buoy. The hydrophone cable passed through the centre of the buoy and wrapped around the central post; with the hydrophone hard-fixed to the post about 2 m below the water's surface.

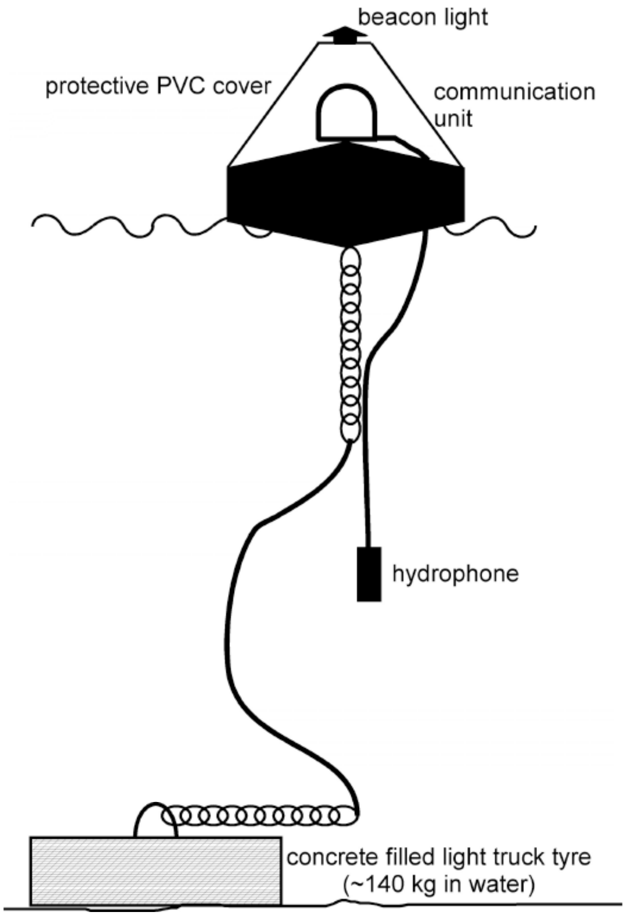

Fig. (5). VR4G-SA mooring configuration for North Neptune Island, South Australia (not to scale).

Sentinel & Range Test Tags

Both the VR4G-TAS and VR4G-SA units were deployed with at least one sentinel tag (Amirix-Vemco V16 R64K coded acoustic tag). A further three range test tags were, on one occasion, deployed at North Neptune Island. Table **1** details the locations of the various tags and their factory programmed specifications. The sentinel tags were embedded in small individual floats; those sentinel tags attached to the mooring line were about 2 m below the water's surface. Sentinel tags deployed at some distance from the VR4G mooring line were situated about 0.3 m above the seabed. The range test tags deployed at North Neptune Island were suspended on a weighted line with the tags positioned about 15 m above the seabed.

Weather Data

Data on wind speed, direction, and atmospheric pressure were obtained from the Australian Bureau of Meteorology (http://www.bom.gov.au/climate/dwo/) records for the weather stations located at Tasman Island, Tasmania (station number 094155) and at South Neptune Island, South Australia (station number 018115). The Tasman Island station is located at 43° 24.00' S and 148° 0.00' E, 240 m above mean

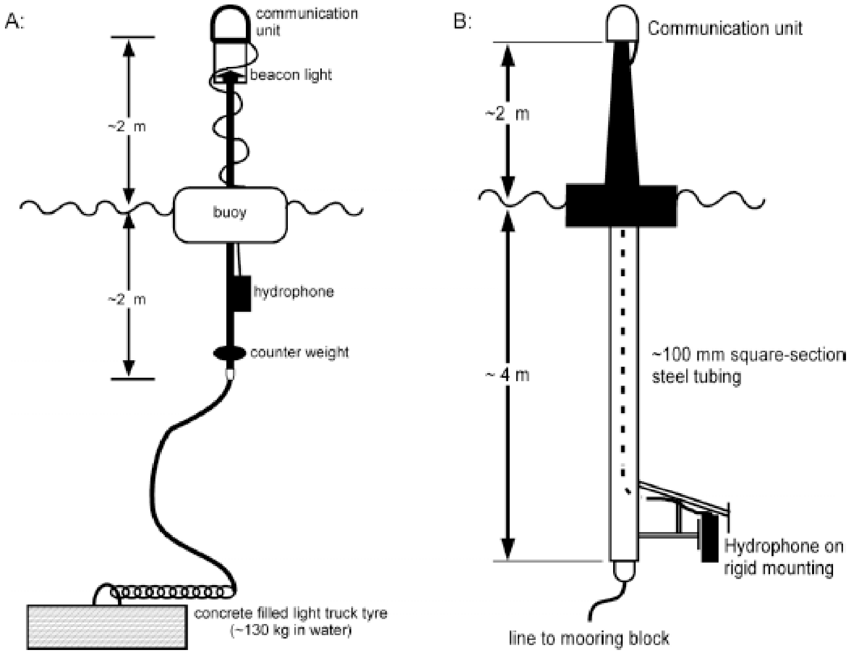

Fig. (6). VR4G-WA mooring configurations for Perth, Western Australia (not to scale). **A**: original design; **B** revised design.

Table 1. Placement and Factory Specifications for Sentinel and Range Test Tags Deployed in Conjunction with the VR4G Units at North Neptune Island, South Australia and Norfolk Bay, Tasmania

Tag Type	VR4G Unit	Distance from VR4G (m)	Transmission Interval (s)	No. Expected Transmissions (Assuming 100% Detection Rate)	
				per hour	per day
Sentinel	VR4G-SA	0	540-660	5-7	131-160
Sentinel	VR4G-SA	150	540-660	5-7	131-160
Sentinel	VR4G-SA	300	540-660	5-7	131-160
Sentinel	VR4G-TAS	0	540-660	5-7	131-160
Range	VR4G-SA	100	50-130	28-72	672-1728
Range	VR4G-SA	300	50-130	28-72	672-1728
Range	VR4G-SA	500	50-130	28-72	672-1728

sea level, and approximately 33 km distant from the VR4G-TAS mooring. The South Neptune Island station is located at 35° 20.19’ S and 136° 7.04’ E, 32 m above mean sea level, and was approximately 12 km distant from the VR4G-SA mooring.

Reporting Schedules

Within the present study VR4G detection data were downloaded through the Iridium satellite system on a weekly basis. Log files (as comma separated value (.csv) files) of tag detections were sent to an email list shortly after being downloaded. The detection log file was then imported into an existing database using custom scripts developed in Access Visual Basic (VB). A second system, which is being developed at the request of the authors, will allow for tag detections to bypass the email notification route; instead, notifications will be directly passed to a local server over a TCP/IP socket. This will provide for the fastest broadcast rate of a tag’s detection. Diagnostic files were not included in the weekly log file distributed to researchers, but were available on request.

Tagging

The majority of white sharks were fitted with an externally attached acoustic tag (Amirix-Vemco V16 6H R64K: transmit interval 50-130 seconds; expected battery life of 5-7 years). These tags were first embedded in a 35 x 55 mm float coated in antifouling paint. A short tether (10 cm), of either braided stainless steel or LIROS D-Pro coated Dyneema (LIROS Rosenberger Tauwerk GmbH: www.liros.com), ending in a stainless steel dart (8 x 32 mm) was used to secure the tag into the dorsal musculature of the shark. External tags were applied to free swimming white sharks using a hand pole. In 2008, acoustic tags (without floats) were surgically implanted into seven juvenile (1.75-3.0 m) white sharks

Table 2. Comparison of the Detection Rates Logged on a VR4-Global and VR2W Acoustic Listening Station Located on the Same Mooring Line for Three Sentinel Tags Deployed at North Neptune Island, SA

Tag ID	Range (m)	No. Active Days	No. Days Detected		No. Detections	
			VR2W	VR4G	VR2W	VR4G
7971	150	172	114	122	6424	8010
7972	350	348	127	196	828	1238
7973	0	182	151	140	10823	10522

(see [25] for details). Tagging of sub-adult (3.0-3.6 m) and adult (>3.6 m) white sharks remains external.

RESULTS

Deployments/Moorings

Moorings were successfully deployed at the three locations: however, during the period of this study several extreme weather events occurred, which highlighted some design issues. During these weather events there were some slight shifts in the location of the VR4G-SA unit. Maximum wind gusts at South Neptune Island during one of these extreme events exceeded 100 km h^{-1} over three successive days (13-15 September 2008). The high swell that accompanied the high wind period (A. Wright, Calypso Star Charters, pers comm.) is believed to have exceeded the length of the mooring rope, thereby lifting the mooring and affecting a slight shift of about 50 m to the north. Reported here are the results from a 12-month deployment of VR4G-SA totalling 348 days (accounting for 15 days of downtime).

In April 2008 the Perth unit (VR4G-WA) broke free of it mooring and was later recovered from a beach on the 22nd April. This was not believed to be as a direct result of weather conditions at the time, rather the high-energy nature of the environment caused fatigue in one component of the mooring system. A second deployment of this mooring design was made in May 2008. Again, the mooring broke free and the unit later recovered from a beach. A new mooring design (Fig. **6B**) was deployed in January 2009; to date there have been no further problems.

Although not a direct result of weather conditions, on approximately 7 April 2009 VR4G-SA broke free of its mooring. The cause of this failure was fatigue on the lower shackle/mooring rope attachment point resulting in the mooring rope breaking. The prototype VR4G did not include support for GPS positioning. However, the general location of the unit could be monitored through the Iridium network. Locations are determined by the Doppler shift method with accuracy of location quoted as a CEP (circular error probability) radius in km. According to the theory of the CEP, there is a 50% probability of the actual location being within n km of the Doppler estimate, 93% probability of being within 2n km of the Doppler estimate, and effectively 100% probability of being within 3n km of the Doppler estimated position. VR4G-SA was found on 15 April 2009 at 35° 13.73’ S and 136° 4.00’ E, within the 93% probability ellipses of the most accurate Doppler estimates for the previous two days, about 500 m from the mooring site.

During the test phase for the VR4G, failure in the hydrophone cable occurred on two occasions. Both failures were attributed to excessive strain having been placed on the hydrophone cable. Each of the current deployments had a single anchor point mooring. The initial deployment of VR4G-SA had the hydrophone cable passing through a protective hose, with hose and cable loosely secured to the mooring line. The hydrophone cable could move within the protective hose. Vertical movements of the buoy caused fatigue in the conductors of the hydrophone cable at the base of the hydrophone where it routinely butted against the protective hose. The solution (hard fixing the support hose to the buoy and loosely fixing the support hose to the mooring line while allowing for some movement of the hydrophone cable within the supporting hose, and hard fixing the hydrophone to the support hose outlet) resulted in fault-free performance of the hydrophone until VR4G-SA broke free of its mooring.

In Norfolk Bay the lessons from the North Neptune deployment were implemented. However, the buoy design was different and a fault in the hydrophone was detected in April 2009. In this case the hydrophone failure appears to have been due to the support hose becoming wrapped around the mooring line and pinching the hydrophone cable. The VR4G-TAS deployment covers a period of 125 days. For the VR4G-WA deployment, the hydrophone cable was wrapped around the central support post and through the buoy. The hydrophone was then hard-fixed to the support post about 2 m below the water’s surface. For all WA VR4G deployments there have been no failures in hydrophone cable despite two VR4G units breaking free of their mooring and drifting ashore.

Sentinel Tags

The longest VR4G deployment was at North Neptune Island. Between 01 April 2008 and 31 March 2009 there were almost 20,000 sentinel tag detections on VR4G-SA, the majority (10,522) from sentinel tag 7973, which was attached to the VR4G mooring line on 29 September 2008 (182 active days).

A VR2W receiver was located on the same mooring line as the VR4G-SA unit and was used here to compare detection rates between the VR4G and VR2W units. Table **2** compares the total number of detections for each sentinel tag and the total number of days on which detections were made. Detection rates for the sentinel tags on the mooring line and 150 m distant were similar for both the VR4G-SA and VR2W receivers. At 350 m the detection rate on the VR4G-SA receiver was noticeably better than that of the VR2W.

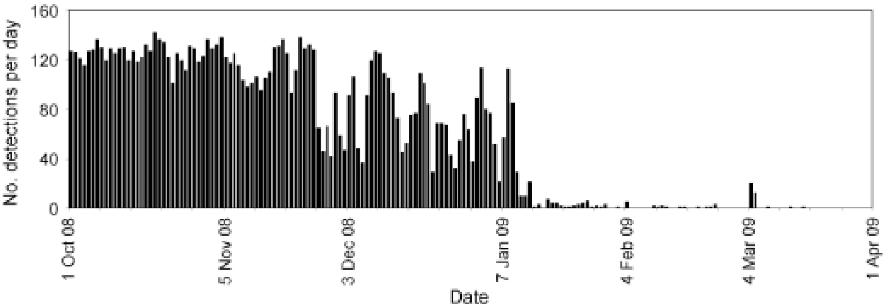

Fig. (7). Total daily detections by VR4G-SA of sentinel tag 7973, attached to the VR4-G-SA mooring line at North Neptune Island, South Australia.

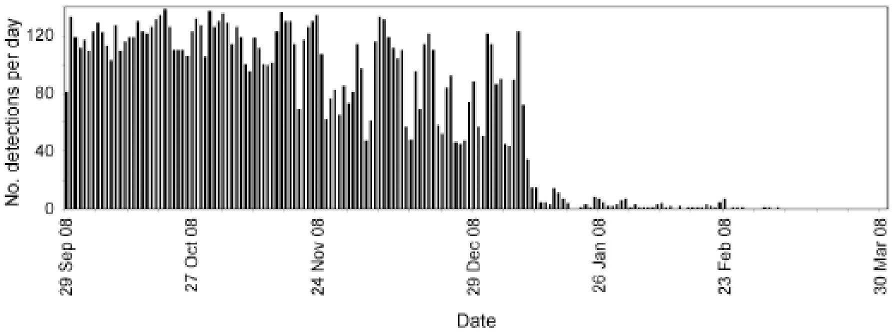

Fig. (8). Total daily detections by VR2W 101915 of sentinel tag 7973, attached to the VR4G-SA mooring line at North Neptune Island, South Australia.

Between 29 September 2008 and 31 March 2009, the VR4G-SA unit detected sentinel tag 7973 on 140 of a possible 182 days (76.9%). Of the 140 days recording detections, the rate of detection varied from a low of 1 to a high of 142 detections per day. Only on 14 (7.7%) days did the rate of detections fall within the theoretical range of the maximum number of detections expected per day.

The rate of detections on the VR4G-SA unit also varied by month (Fig. **7**): in October 19.4% of days recorded daily detections > 130 per day; in November 23.3% of days recorded daily detections > 130 per day; from December 2008 through March 2009 no days recorded daily detections > 130 per day.

Over the same period, the VR2W acoustic receiver on the VR4G-SA mooring line showed a similar pattern in the detection rate of sentinel tag 7973 (Fig. **8**).

Detection rates of sentinel tag 7973 showed a dramatic decline starting in late November 2008 on both the VR4G-SA and VR2W units. A catastrophic decline occurred in mid January 2009. The similarity in pattern between both VR4G-SA and VR2W suggested the problem lay with the sentinel tag and not with the actual detection efficiency of either acoustic receiver. The most likely explanation being the sentinel tag broke free of the mooring line and drifted to the edge of the detection range.

From 10 December 2008 to 28 February 2009 VR4G-TAS recorded 11,431 detections of sentinel tag 7974, which was attached to the VR4G mooring line. The detection rate was within the theoretical range of the maximum number of detections on all days except the first when two high repetition rate tags resulted in a very high collision rate.

The results from the Neptune Islands consistently showed a lower detection rate than in Norfolk Bay, even for the sentinel tag attached to the mooring line. This suggested that the ambient noise level was considerably higher at the Neptune Islands; most likely due to the proximity of the VR4G-SA unit to the active shoreline of North Neptune Island.

Range Test Tags

Logistical constraints reduced the length of time for which the range tags were deployed at North Neptune Island to 19 hours between 1540 on 24 April 2008 and 0940 on 25 April 2008. Due to a rapid drop off in the detections of the range test tag at 300 m distance from the VR4G-SA unit, we included the results of detections of sentinel tag 7971, which was 150 m distant from the VR4G-SA unit.

Table **3** provides a comparison of hourly detections of range test tags for the VR4G-SA and VR2W acoustic receivers. Both acoustic receivers routinely detected range test tags out to 150 m followed by a rapid drop off to 300 m. At 100 m distant the VR4G-SA receiver detected the range test tag more in each hour block than the VR2W receiver. At 150 m the detection rate of the VR4G-SA unit was better 63.2% of the time, and 85.7% of the time at 300 m distance.

Tagging

In total 55 white sharks from across southern Australia, ranging in size from 1.75 to 4.8 m, have been tagged with acoustic tags; thirty of which have been detected at North Neptune Island. All tags were placed on the watch list prior to release. Notification of tag detection by a VR4G was emailed directly to the authors, and in the first instance was

Table 3. Comparison Between VR4-Global and VR2W Hourly Detection Rates for Range Test Tags Deployed at North Neptune Island, South Australia

Acoustic Receiver	Number of Hour Blocks with Detections (% within Range of Max Detections – see Table 1)			
	100 m	150 m	300 m	500 m
VR4G -SA	19 (42.1)	18 (50.0)	6 (0)	0 (0)
VR2W	18 (5.6)	17 (11.8)	2 (0)	0 (0)

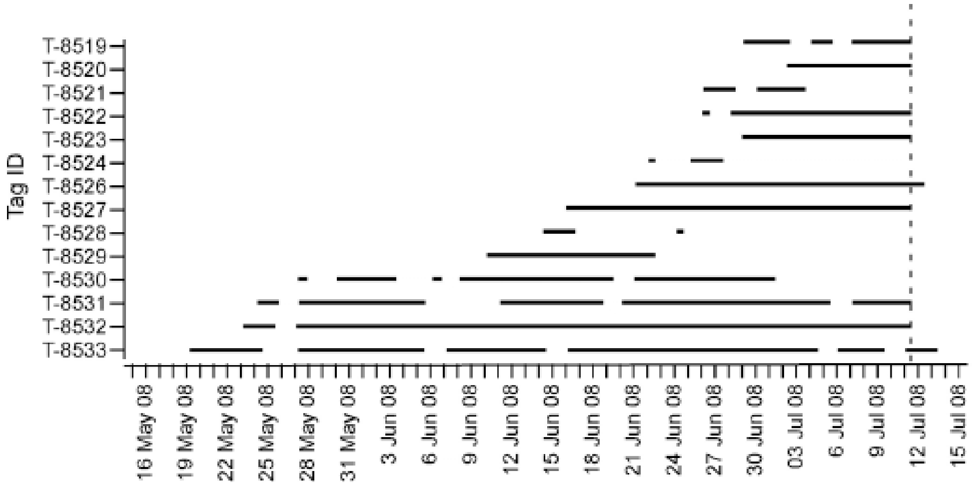

Fig. (9). Acoustic tag detection pattern before and after an extreme weather event at the Neptune Islands Marine Reserve, South Australia in July 2008.

on a near real-time basis. As the number of tags deployed increased the number of notifications became unmanageable and frequency of notification was scaled back. Shark cage dive operators were alerted to the presence of a tagged shark as early as possible by creating an email rule to forward emails of detections.

Just prior to 11 July 2008, nine tagged sharks were being routinely detected on the VR4G-SA unit (Fig. **9**). On 11 July 2008 all nine tagged sharks departed North Neptune Island. The tour operators confirmed that there were no tagged (or untagged) sharks at the site for the next five weeks, after which there were only sporadic and brief appearances until September 17 when sightings returned to a daily basis. Examination of the weather data from the South Neptune meteorological station indicated that a strong front passed through between 9 am and 3 pm, with winds showing a 180° change in direction and atmospheric pressure dropping by 13 hPa over the same period.

DISCUSSION

The VR4Global acoustic receiver represents the latest advancement in passive acoustic monitoring technology. Using the Iridium satellite network to transmit data has overcome the range limitations imposed by radio (VHF) communications [26] as well as the bandwidth limitations of the ARGOS satellite array. Through the provision of two-way remote communication the user is now able to maintain a closer watch on the status of their acoustic monitoring hardware, analyse data on a more frequent basis, and, if required, obtain real time notification of tag detections.

The detection performance, based on sentinel and range test tags, of the VR4G was similar to that of the VR2W acoustic receiver. The similarity in detection patterns for the two models suggested that differences in detection rate were not related to environmental variables, but rather to the configuration of the sentinel tag and hydrophone.

The detection envelope is one of the most variable factors involved in acoustic studies [10] and can vary within and between sites even when using the same hardware. At North Neptune Island the tag detection envelope was smaller than has been reported elsewhere for acoustic technology [27-29]. However, detection rates on the VR4G-SA and VR2W-SA units were similar, suggesting that the smaller detection envelope was due to environmental factors. A short test on range was performed in the quiet conditions of Norfolk Bay resulting in a maximum detection envelope for a VR2W of 380 m (Bradford, pers com). Lembo *et al.* [30] reported an average detection envelope of about 230 m for a wireless acoustic system deployed in an environment subject to high ambient noise levels. Within this context, the VR4G technology appeared to perform as well as other available technologies.

The Australian Shark Monitoring Network (SMN) was developed in part to improve our understanding of the spatial dynamics of white sharks in Australian waters. Acoustic listening stations have been used at the Neptune Islands since 1999 to examine the presence-absence of white sharks. The installation of a VR4G unit in 2008 allowed us to expand the utility of the listening station approach to include real-time notification of shark presence-absence at North

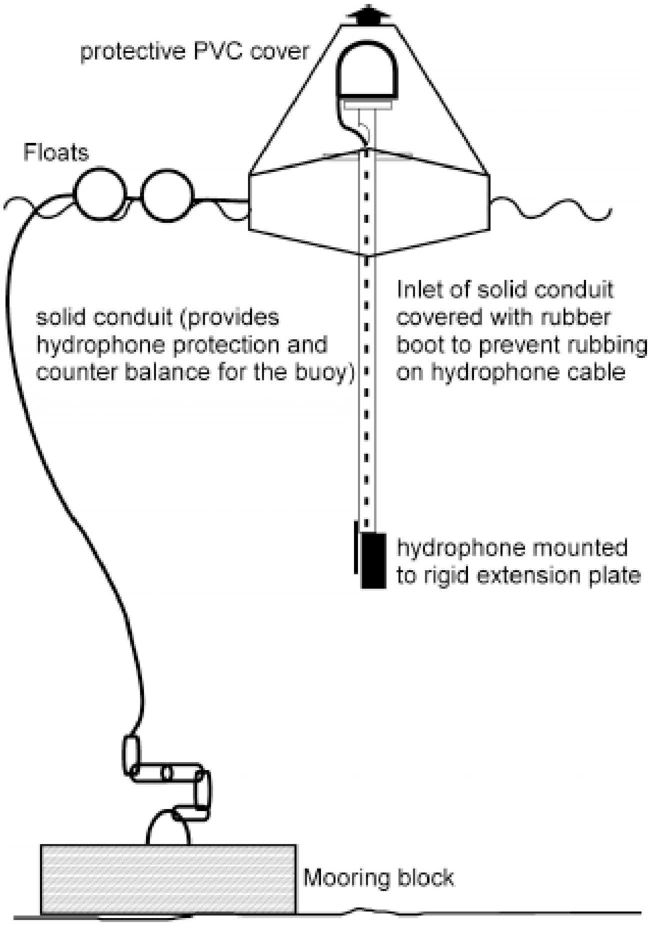

Fig. (10). Suggested configuration for a low profile mooring system for the VR4-Global acoustic receiver (not to scale).

Neptune Island to the tourism operators, to examine linkages between presence-absence and weather parameters, and most importantly evaluate the performance of the VR4G in actual field conditions.

Tag detections are provided in two formats: 1) real-time notification of tag detection if the tag ID is placed on a watch list; 2) complete log file with all detections delivered *via* email on a user defined frequency. Prior to the end of the period covered in the study there were 55 active acoustic tags on white sharks, 35 of which had been deployed within the Neptune Islands Marine Reserve. Examination of the time between tag detection by the VR4G-SA unit and email notification indicated that on average the lag time was less than two minutes (mean = 1.7 minutes; SD = 1.2 minutes). The majority of the lag was due to factors outside the control of the VR4G system, such as the frequency of message checking. Bypassing the email system for real-time notification of tag detection, through the use of a direct TCP/IP socket connection could result in some improvement in efficiency. Using this method, the notification would be independent of the email system and avoid the external factors inherent in email to ensure the smallest possible delay between detection and notification.

The real-time notification of tag detection could be used to best effect in managing interactions with threatened or endangered species. White sharks can occasionally pose a threat to users of the marine environment. In Australia a range of measures are in place to alert authorities to the presence of a shark; these include regular aerial patrols over popular beaches, shark meshing at sites off eastern Australia, and tracks from a small number of satellite tagged sharks. All of these measures are relatively expensive to establish and maintain and generally do not provide uninterrupted coverage. A cheaper and potentially longer lasting option may be to acoustically tag white sharks and use the real-time notification capability of the VR4G to alert authorities to the presence of a tagged shark.

Real-time notification of a tagged animal's presence could also be used in other time critical events to elicit a management response. For example, if sufficient numbers of animals were tagged, notification of the arrival of a threatened/endangered species could be used to limit access to a fishery or region until the threatened/endangered species has passed through.

The application of acoustic monitoring has the potential to result in the collection of vast amounts of data. Data management has become an important consideration for all acoustic monitoring studies [10]. The detection log file (as opposed to the real-time notification of detections) from the prototype VR4G units was received as a CSV file attached to an email. The advantage of this form of data delivery is that relatively simple computer code can be written that will import the CSV file directly into an existing relational database. Where hardware from several manufacturers is being used this would be the most efficient means of storing and querying data.

Deploying equipment in remote and/or difficult to access locations raises its own set of challenges. Remote locations generally equate to less frequent access; they are often located in areas exposed to environmental extremes; and they are often less secure leading to potential tampering with equipment and/or vandalism. Through the ability to schedule status messages on a regular basis the VR4G allows for a remote "eye" on the equipment. Although regular contact with the VR4G will not prevent any of the above from happening, it will allow the researcher to put in place procedures that may reduce the negative challenges of placing equipment in remote locations. For example, during the present study a faulty hydrophone was replaced within 15 days of first notification. Without regular communication with the unit (and associated sentinel tag) this problem would not have been noticed until the next service trip (~ every 10 months), and would have compromised the results of the study.

Mooring design was critical to the successful operation of the VR4G and required slightly different approaches to account for local environmental conditions. Teething problems with the design of the mooring block arrangement (the common link between the various designs and loss of the surface unit) were associated more with a lack of operator experience than hardware fault. However, the design of the surface component was critical to long-term performance of the VR4G. From our experience it is essential that the hydrophone cable be securely attached to the surface float. This would have prevented the damage due to repeated stretching experienced by the hydrophone cable. Fig. (**10**) illustrates design changes that will prevent hydrophone damage and improve long-term performance.

The VR4G represents a larger investment in both purchase price and communication costs over the traditional passive acoustic technology. In addition to the higher purchase price for a VR4G, the cost for a suitable mooring will add a further financial burden on the research budget. However, for longer-term studies when data need to be downloaded on a regular basis, the ability to remotely download the log file may lead to substantial savings. For example, at the Neptune Islands, a remote and difficult to access site, traditional passive acoustic stations have been collecting data since 1999. A typical service trip to download a receiver and replace the battery would be ~ AUS $10,000. Although prices will vary, based on about 10,000 detections per month, the cost in 2009 for 12 months of downloads from a VR4G was about a tenth of a single service trip to the Neptune Islands Marine Reserve. This cost saving alone makes the VR4G an attractive alternative to traditional passive acoustic technology when deployment is in a remote location. The opportunity to access the log files on a regular basis and progressively analyse the data would further reduce the effective running costs of the VR4G relative to traditional passive acoustic technology. Further cost savings may be possible with the introduction of a GSM modem communicating across a local cellular network (currently in test phase).

The key feature of the VR4G is the incorporation of an Iridium satellite communication modem, allowing for two-way communication with the receiver and the transfer of large packets of data. The Iridium network currently allows data transfer rates of 2.4Kbps in either direction on all of the 66 satellites in the network. This key feature has resolved several of the main limitations of current acoustic technology. These include the following: 1) Communication is ensured with global, 24 hour coverage provided by the satellite network; 2) The receiver's memory (log file and diagnostics) can be downloaded remotely on a schedule best suited to the study at hand; 3) The status and security of the receiver can be monitored remotely.

The VR4Global acoustic listening receiver has proven its design under a range of conditions from a relatively calm embayment to a highly dynamic open water environment. However, these initial trials highlighted the importance of designing and using mooring systems suitable to each study site. Further developmental work to expand the capabilities of the VR4G may lead to an integrated oceanographic and biological observation platform.

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