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Tracking cryptic animals using acoustic multilateration: A system for long-range wolf detection

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The study of animal behavior in the wild requires the ability to locate and observe animals with the minimum disturbance to their natural behavior. This can be challenging for animals that avoid humans, are difficult to detect, or range widely between sightings. Global Positioning System (GPS) collars provide one solution but limited battery life, and the disturbance to the animal caused by capture and collaring can make this impractical in many applications. Wild wolves *Canis lupus* are an example of a species that is difficult to study in the wild, yet are of considerable conservation and management importance. This manuscript presents a system for accurately locating wolves using differences in the time of arrival of howl vocalizations at multiple recorders (multilateration), synchronized via GPS. This system has been deployed in Yellowstone National Park for two years and has recorded over 1200 instances of howling behavior. As most instances of howling occur at night, or when human observers are not physically present, the system provides location information that would otherwise be unavailable to researchers. The location of a vocalizing animal can, under some circumstances, be determined to within an error of approximately 20 m and at ranges up to 7 km. © *2019 Acoustical Society of America*. https://doi.org/10.1121/1.5092973

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I. INTRODUCTION

The ability to locate and follow wild animals is essential for the study of behavior of animals in their natural environment. However, many species are difficult to locate in the wild or to follow as they go about their normal activities. This may be because the animals themselves are cryptic or avoid humans, active at night, or range over very large distances (Boitani, 2003). Difficulties in locating these animals can lead to a poor understanding of their social behavior, habitat use, and population dynamics, all of which are important for making conservation and management decisions (Boitani, 2003). Technological solutions have been available for many years to follow wild animals based on various radio tagging technologies (Ropert-Coudert and Wilson, 2005; Boitani and Powell, 2012). These include simple low-power beacons for use with direction finding antennae, data-logging Global Positioning System (GPS) devices, and data download via cellular telephone technology. However, all of these solutions require instrumenting the animal with some kind of electronic device. This approach has a number of drawbacks.

First, the animal must be captured without injury, and a device suitably attached to the animal, such as a collar (Schemnitz *et al.*, 2009). While many species may be easy to trap and release, the very species that avoid human contact may be wary of approaching traps or react adversely to having a collar attached (Wilson and McMahon, 2006). The process of capture, instrumentation, and release, as well as the presence of the device itself, may affect the behavior of the animal in the future (Wilson and McMahon, 2006). Also, while collaring animals can provide large amounts of accurate position data, only those animals wearing collars are recorded. Unless an entire group can be instrumented, information on social behavior may be difficult to achieve.

Second, the device requires a power supply that almost inevitably has a finite lifespan. While very high frequency (VHF) beacons may last for years, GPS receivers, and particularly devices with wireless data download, may be limited to months of operation, or even weeks (Johnson *et al.*, 2002). Although larger animals are capable of carrying large batteries, those that range over longer distances may require more powerful transmitters, thereby reducing the battery life even further (Cagnacci *et al.*, 2010).

Third, the cost of the equipment and capture-release can be considerable. Instrumenting a large number of animals may be prohibitive purely in terms of capital outlay, and those animals that must be darted, rather than live-trapped, incur considerable extra cost simply for the procedure of instrumentation (Boitani, 2003).

All of these considerations notably come together in the study of wild canids. Few large predators are the subject of such widespread conservation and management challenges as the grey wolf *Canis lupus* (Fritts *et al.*, 2003; Mech and

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Boitani, 2010). The most widespread terrestrial mammalian predator in the world, the wolf was indigenous to the entire Holoarctic region until population numbers were severely reduced by human activity (Nowak, 2003). In many parts of the world, notably North America and Europe, rising wolf populations have frequently come into conflict with human activity, particularly ranching and the rearing of livestock (Sillero-Zubiri and Laurenson, 2001). Thus, the conservation efforts to re-establish wolf populations as an essential element of the native ecosystems (Beschta and Ripple, 2009; Fortin *et al.*, 2005) is in conflict with the management efforts to minimize livestock losses and maintain a positive perception of these wild animals among sympatric human populations (Fritts *et al.*, 2003). For these reasons, the detailed and quantitative study of wolf movement behavior, social behavior, and population dynamics is particularly challenging. In most locations, wild wolves avoid humans and can be difficult to survey (Boitani and Powell, 2012). In North America, in particular, wolves range over very large and inaccessible areas, meaning that following the animals on foot or in vehicles is almost impossible. In the largest study of wild wolves, in Yellowstone National Park (YNP), a small number of animals are darted from helicopters, collared with radio beacons, and used to find the approximate location of packs (Smith, 2005). If the pack can be found in an accessible location, researchers then make behavioral observations from a static site.

The idea of using animal vocalizations to census and locate populations has been widely used for birds (Lambert and McDonald, 2014), anurans (Jones and Ratnam, 2009), elephants (Zeppelzauer *et al.*, 2015), and primates (Spillmann *et al.*, 2015), as well as canids such as jackals (Debnath and Choudhury, 2013) and wolves (Blanco and Cortés, 2011; Suter *et al.*, 2017). Wolf howling is a long-range communication signal and so lends itself well to the detection of animals at a distance (Harrington *et al.*, 2003), and has long been used as an alternative method for surveying wolf presence and population size (Harrington and Mech, 1982; Passilongo *et al.*, 2015; Fuller and Sampson, 1988; Suter *et al.*, 2017; Llaneza *et al.*, 2005). Howling is a narrow band frequency modulated signal used to advertise pack territories, maintain group cohesion, and by dispersing animals to locate potential mates (Mech and Boitani, 2010).

Wolf howls can be heard at a range of several kilometers, and can often be elicited by imitated howling or playback of howling or similar sounds (Harrington and Mech, 1983; Harrington, 1986). However, other than a general impression of the direction of the howling source, merely listening to howls does not provide quantitative location information. Fortunately, the technology to pinpoint a distant sound source, known as acoustic multilateration, has existed for many years, and has been widely applied and is well proven, both in tracking marine mammals (Gillespie *et al.*, 2009) and in non-biological applications such as sniper detection (Carapezza *et al.*, 1997). Multilateration relies on the finite speed of sound, and identifies the most probable location of the sound source, based on the relative time differences of sound arrival at multiple widely spaced detectors. Using passive acoustic localization can provide accurate sound source location, in principle, allow the tracking of animal movements, and also lead to inferential conclusions about the use of vocal communication to mediate social behavior in the wild (Campbell and Francis, 2012; Fitzsimmons *et al.*, 2008; Blumstein *et al.*, 2011).

Passive acoustic localization has been a well-established technique in marine mammal research for many years (Clark *et al.*, 1996; Zimmer, 2011), and the low attenuation of sound underwater allows for accurate measurements to be made over long distances. Many commercial and non-commercial systems are available for tracking whales, in particular, using this technology (Gillespie *et al.*, 2009). However, terrestrial applications are much more challenging. Few terrestrial animals make calls audible over long distances, and so existing work on acoustic localization in terrestrial environments has focused on short-range calls and birdsong, in particular (Mennill *et al.*, 2012b; Mennill *et al.*, 2012a; Frommolt and Tauchert, 2014). Accurate localization at short ranges is complicated by the small time delays involved, and so care must be taken to measure the locations of the recorders and the time differences very accurately, for the latter, usually by means of spectrogram correlation (Frommolt and Tauchert, 2014; Harlow *et al.*, 2013). In addition, synchronization between detectors must be particularly precise, and this, as well as cost considerations, may give hard-wired systems an advantage over GPS synchronization, although hard-wired detectors severely limit the area of deployment (Piel, 2014; Kalan *et al.*, 2016). There have been some successful implementations of such systems (Campbell and Francis, 2012; Mennill *et al.*, 2012a; Harlow *et al.*, 2013), but such systems can only be used for behavioral and movement tracking while the focal species is within the acoustic range of the detectors.

We present here a complimentary system for studying wolves in the wild based on passive acoustic localization. The possibility of using passive acoustic localization for wolf tracking was investigated recently using simulated wolf howls (Papin *et al.*, 2018), but ours is the first study to test this possibility with field recordings of animal vocalizations. We deployed multiple acoustic detectors in YNP over a period of two years and analyzed wolf howls and those of the related coyote *Canis latrans* to locate the source of the sound. We assess the accuracy and precision of this technique, and propose its utility both for assisting survey and research goals, as well as providing a monitoring and management tool and, potentially, also its use for specific behavioral studies.

II. MATERIALS AND METHODS

A. Data collection

The study took place in YNP, USA, under permit numbers YELL-2015-SCI-6062 and YELL-2016-SCI-6062. The equipment used consisted of five Wildlife Acoustics SM3 autonomous recording devices (Wildlife Acoustics Inc., Concord, MA) with GPS option. Recordings were made with omnidirectional microphones at 24 000 Hz sample rate, 16 bit resolution, Waveform Audio File (WAV) format, and with two channels operating at different gain levels: −35 dB and −45 dB, to allow flexibility in the case of variable ambient noise levels. The SM3 GPS option allows recordings to be synchronized to a GPS clock with millisecond accuracy. In that way, all five devices recorded audio that was pre-aligned so that the time difference of arrival of a sound at each device could be easily measured. The latitude and longitude of each device was also recorded automatically by the GPS unit. Although the altitude was not recorded on the devices, the study took place on a relatively flat topographic plateau within YNP, and by estimating the altitude from digital elevation model data (United States Geological Survey SRTM 1 Arc-Second Global), we determined that the error in path length due to unknown altitude would be no more than 1.2%. The recording devices were deployed during the winter seasons, November–April, 2014–2015 and 2015–2016. National Park Service researchers report that at this site, wolf howling activity is considerably higher during the winter, and declines to very low levels in the spring when pups are born (National Park Service, 2014). The deployment of recorders was coordinated with the wolf monitoring activities of the YNP Park Service so that recorders could be deployed opportunistically in areas with a high probability of wolf activity (Fig. 1). We relocated the recorders as necessary in response to Park Service reports of the movements and locations of wolf packs to maximize the chances of recording howls on each particular day. We attempted to deploy the recorders in the pattern of a regular polygon with recorders ~1–3 km apart (consistent with the typical range for detection of howls as determined by pilot studies using this equipment), but this was not always possible within the constraints of the terrain and research permit, which allowed deployment only on marked trails. The recorders ran almost continuously over the study period (excepting equipment and battery failure) with batteries and memory cards changed approximately every three days.

B. Howl extraction and multilateration

In total, approximately 4300 h of recordings were made between all five SM3 units. We then scanned the audio files for instances of wolf or coyote howling. Due to the similarity between wolf and coyote howling, no attempt was made in this study to distinguish between the two, but casual inspection suggested that approximately half of the recordings were wolves and half coyotes. Although many automated algorithms have been proposed for detecting bioacoustics signals in long-term recordings (Mellinger and Clark, 2000; Stowell *et al.*, 2016; Swiston and Mennill, 2009), we found in pilot studies that the performance of automated algorithms

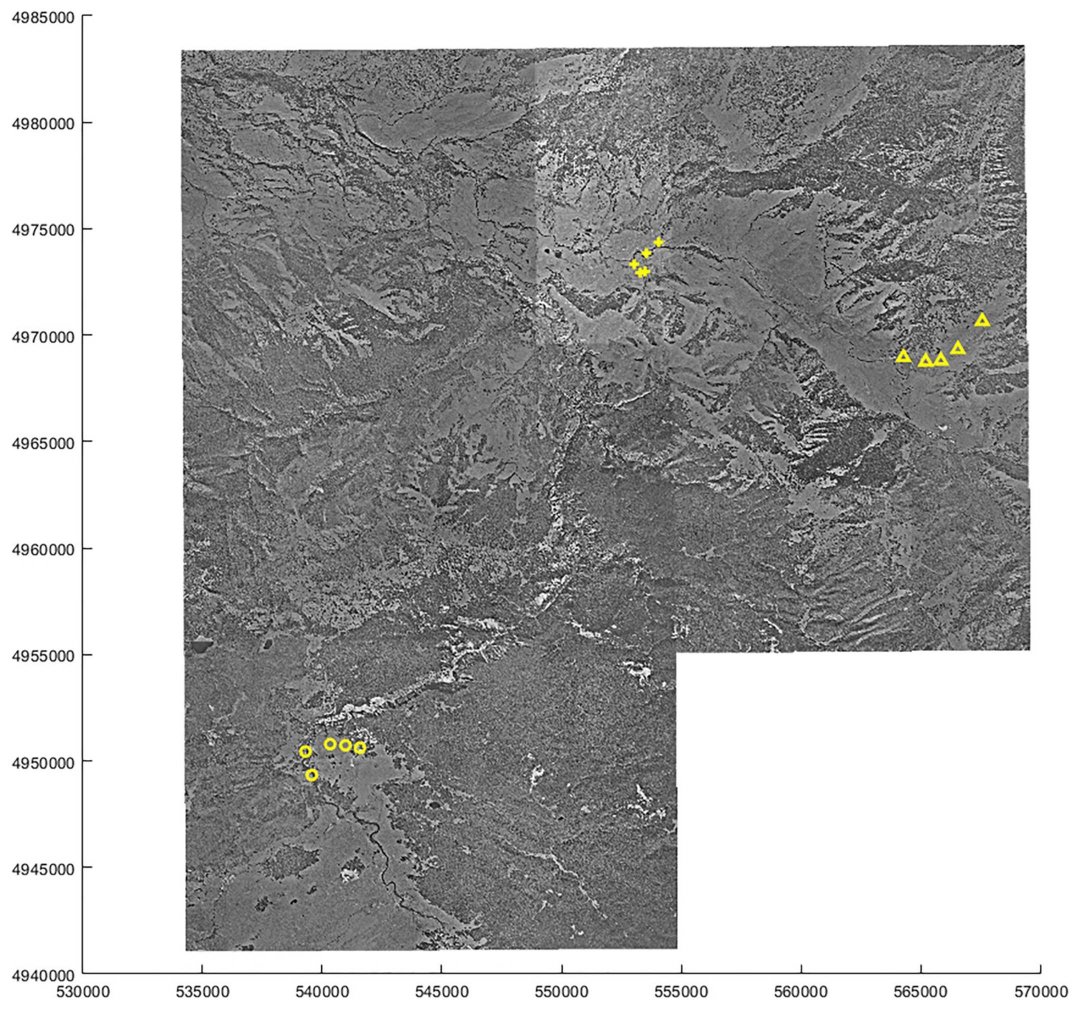

FIG. 1. (Color online) Location of detector deployments (circles) within YNP. Map axes show Universal Transverse Mercator coordinates in meters. Between four and five detectors were deployed at any one time, so the map represents multiple deployments during the study period, and each deployment shows as a separate symbol.

was hampered by the low amplitude of the signals, and so manual inspection was faster and more reliable. Howls were often faint and difficult to hear but nonetheless visible on spectrographic representation. We used Raven 1.4 (Cornell Lab of Ornithology, Ithaca, NY) to scan each recording and marked the approximate positions of any howls using the selection table feature (Fig. 2). We generated the spectrograms using a Hann window of 2560 samples, 50% overlap, 3 dB filter bandwidth of 13.5 Hz, and frequencies displayed between 0 and 2 kHz. As multilateration requires the signal to be detected on at least three devices, we only needed to scan n - 2 of the n operating SM3 units to ensure that any workable detection was recorded. For example, if only three SM3 units were operational, only one needed to be scanned because if a howl was not detected on one particular unit, multilateration could not be performed.

Having marked the approximate location of howls, we used a custom MATLAB (R2016a, The MathWorks, Inc., Natick, MA) script to create a series of five-track audio files containing the synchronized data from each of the SM3 units, one data file for each detection, although adjacent detections were merged into a single file (Fig. 3; see footnote 1). Viewing these files in Raven, we marked salient points on each of the channels, labeling them so that features corresponding to the same howl from different SM3 units received the same label. We then ran a custom MATLAB script to calculate the time differences between the channels for each labeled howl. Although other researchers have used spectrogram cross correlation to improve the accuracy of the time difference measurement (Simard *et al.*, 2004; Harlow *et al.*, 2013; Frommolt and Tauchert, 2014), we found that manual labeling was more reliable due to the low signal-to-noise ratio of many of the howls, and also because of the relatively large time differences between channels (corresponding to a large distance between deployed SM3 units) compared to other applications.

Given the time difference of arrival of each howl at each SM3 unit and the known locations of the units, we calculated the likely location of the howl source using the MATLAB function *fmincon* to find the minimum of a constrained nonlinear multivariable function (Appendix A). Variation in the speed of sound with temperature was not taken into account as the differences over or under the conditions of study amounted to no more than approximately 5%. Optimization approaches have been shown to outperform hyperbolic solutions to multilateration problems in many cases (Urazghildiiev and Clark, 2013).

C. Assignment of single source cases

As we had no knowledge of the actual location of the vocalizing animal, we used a subjective approach to identify howls that appeared to originate from a single source. Howls that occurred during a single bout, were localized close together, and appeared similar spectrographically, we considered a "single source," and from this we could make measurements of precision if not accuracy. The precision and accuracy of multilateration falls sharply when the sound source is far from the center of the detector polygon as small differences in actual location led to negligible differences in path lengths to the detectors. Therefore, in our subjective analysis we treated sources within the detector deployment polygon differently

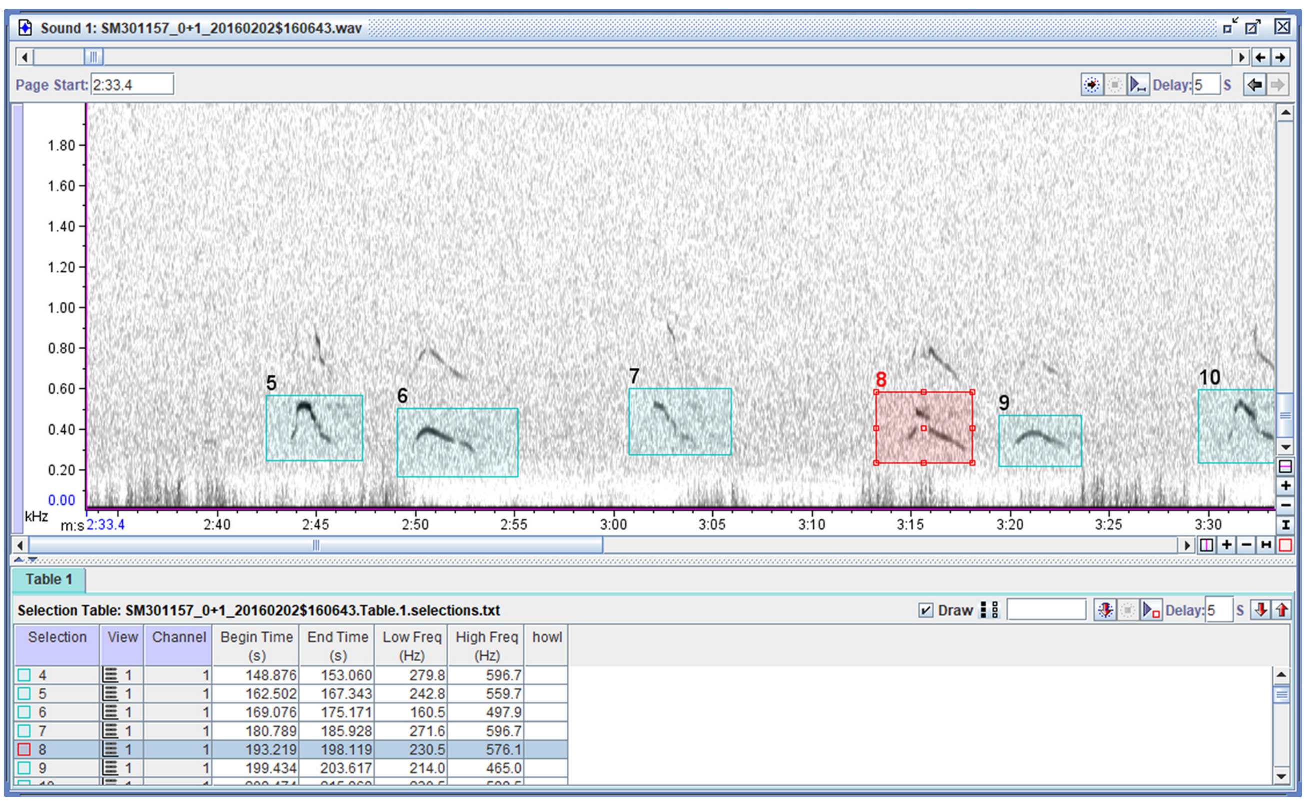

FIG. 2. (Color online) Selection of howl events in the Raven window.

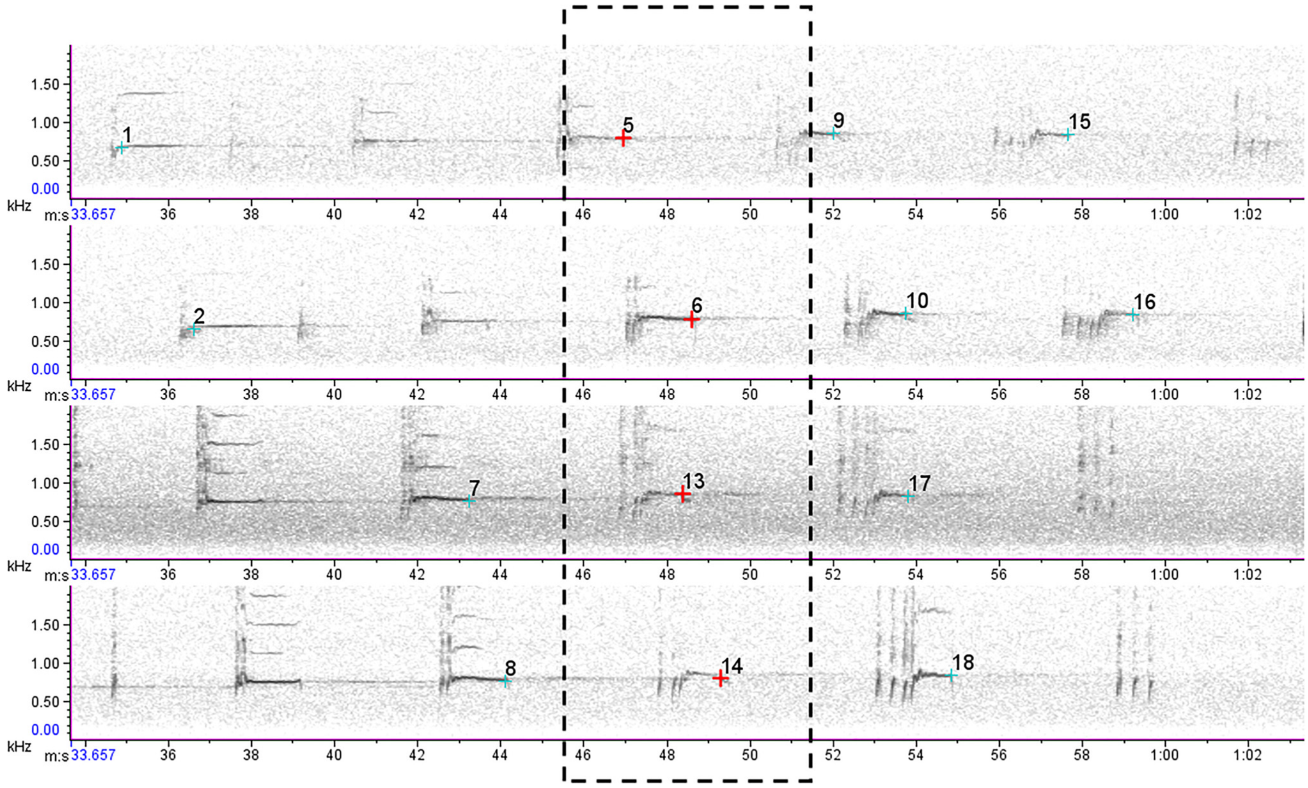

FIG. 3. (Color online) Multi-channel file, each channel representing a different SM3 unit, with start timings synchronized using GPS. A salient point is marked for the same howl (boxed with a dashed line) on each of the four channels. Note the difference in time of arrival of the signal is on the order of four seconds.

from those outside of the polygon (Fig. 4). Sources within the polygon were grouped together more conservatively (i.e., widely separated localizations would be considered separate sources), whereas those outside the polygon were grouped together even if they showed a large difference in range (but not bearing). The grouping analysis was performed separately by two of the investigators and the results compared for inter-observer reliability using normalized mutual information, which provides a measure of classification agreement when classes are not shared between raters (Zhong and Ghosh, 2005; Kershenbaum and Roch, 2013).

D. Validation using known signals

Given that no absolute estimate of accuracy was possible for wolf howls, we also attempted to validate our accuracy using artificial sound sources. Generating a sound source similar in frequency, intensity, and range to a wolf howl is largely impractical, particularly in inhabited areas. Therefore, we deployed the SM3 units in the town of West Yellowstone (44° 39′ 19″ N, 111° 05′ 56″ W), and recorded the siren of a West Yellowstone Police Department patrol car. The sirens were processed as described above for wolf howls to provide the likely location of the sound source. We then measured the localization error as the distance to the known location of the police car. Sirens possess many of the acoustic characteristics of wolf howls as they are narrow band frequency modulated signals of high intensity, and known to elicit howling in canids of various species (Wenger and Cringan, 1978).

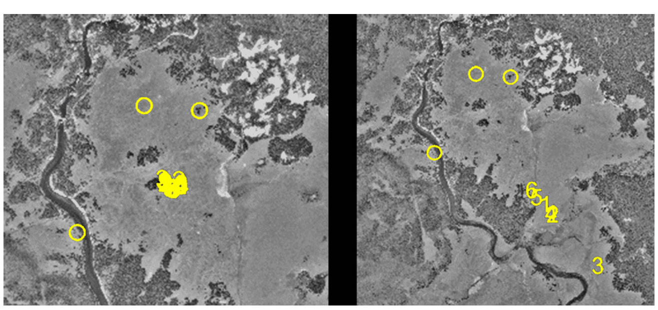

FIG. 4. (Color online) Detections (numbers) near the center of the polygon comprising the SM3 units (circles) are well clustered (left), but detections outside of the polygon (right) have good precision of bearing but poor range precision.

III. RESULTS

We performed successful multilateration on 1247 howls that occurred between 7 November 2015 and 2 March 2016 (Fig. 5). Of these, 51 were within the polygon of detector units, 882 were outside of the polygon, but within 2 km, 306 were localized as being more than 2 km from the detectors, and 8 were determined to be over 10 km, implying a probable failure of the multilateration algorithm.

To calculate an estimate of precision, we then analyzed a subset of 1128 howls that occurred in bouts of 2 or more (maximum 67, mean 51.4). Inter-rater reliability for assignment of howls to putative single sources was 89.6%. We grouped the howls into 169 sources and of these, 60 howls (11 sources) were within the detector polygon and 1068 howls (158 sources) were outside. As a measure of precision,

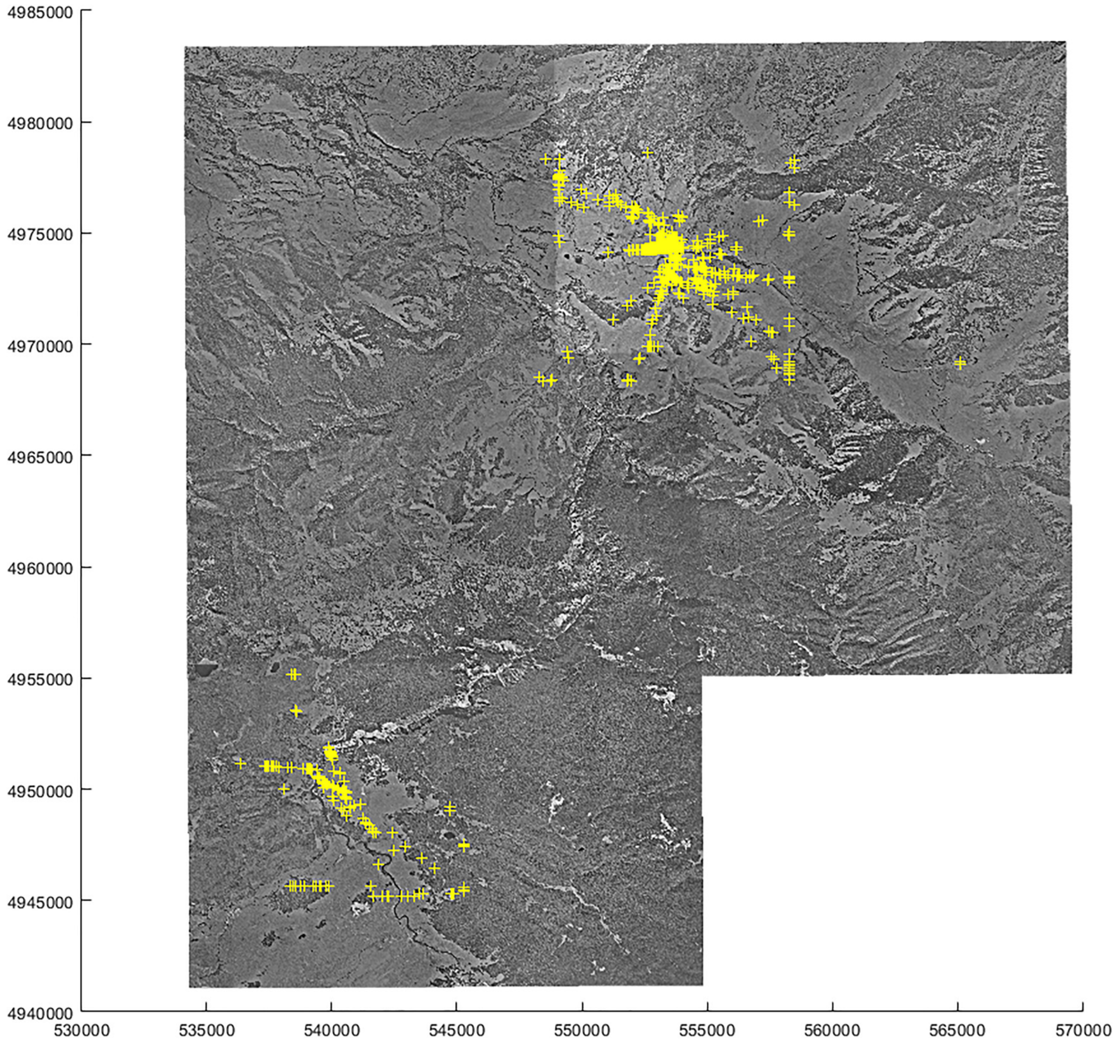

FIG. 5. (Color online) Locations of all detections made by the multilateration system.

we used the standard error of the distance of calculated howl locations from the mean calculated location of all the howls in a source for those sources with at least three howls. For those sources within the detector polygon, the median standard error of the spread of detections judged to be from a single source was 9.7 m with a maximum of 67.6 m (Table I). Of those sources outside of the polygon, the median standard error was 23.3 m, and 59% of sources had a standard error of spread less than 50 m [Fig. 6(a)]. For those howls outside of the detector polygon, accurate measurement of the range to the sound source is problematic. The standard error of location along an axis passing through the center of the detector polygon increased sharply with distance from the detectors [Fig. 6(b)], Pearson correlation coefficient $R = 0.475$, $p < 0.001$, $N = 128$. However, the error of bearing (angle to this axis) remained small with 97% of sources having a standard error of bearing less than 5 deg [Fig. 6(c)].

Using police sirens to validate accuracy, we analyzed a total of eight sirens. The location of the siren source was inside the detector polygon (Fig. 7). The mean distance of the detection to the sound source was 83 m (range 9–127 m). The standard error of spread of detections was 9.2 m, close to the median spread for howl detections within the detector polygon (9.7 m, Table I).

IV. DISCUSSION

We have demonstrated one of the few systems for passive acoustic localization of terrestrial animals at long ranges. Wolf howls can be heard over many kilometers, but

TABLE I. Standard error of spread of detections for sources at different ranges from the detectors.

	Standard error of detections (m)					
	Minimum	Median	Mean	Maximum	Number of howls	Number of sources
Within detector polygon	1.9	9.7	17.9	67.6	52	7
Outside detector polygon, <2 km	1.2	12.5	27.7	231.9	701	76
Outside detector polygon, >2 km	3.7	188.8	197.2	495.5	307	52

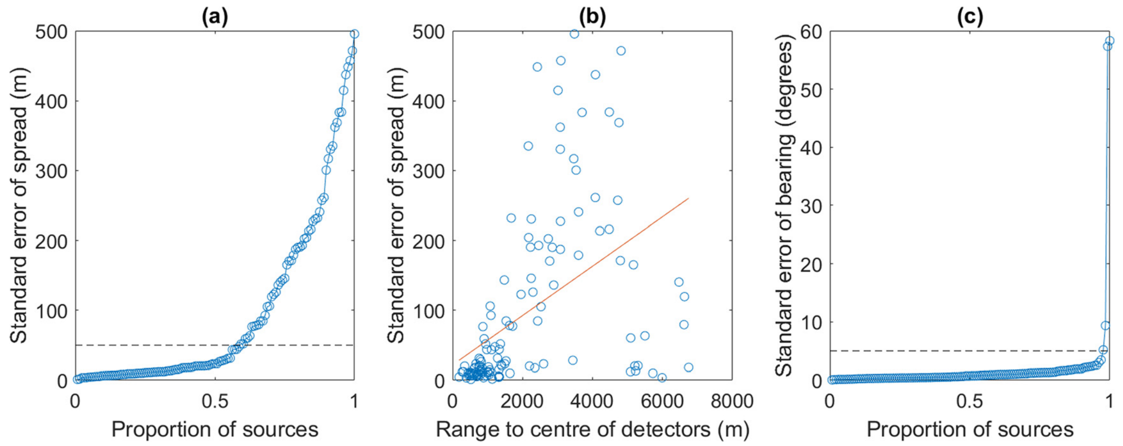

FIG. 6. (Color online) (a) Distribution of errors for sources localized outside of the detector polygon. The standard error of spread is mostly below 50 m but increases steadily above that value. (b) Correlation between range to the detectors and error of spread. Red line indicates linear regression. (c) shows that the standard error in bearing is less than 5 degrees for the large majority of localizations.

even when not audible to the human ear, sensitive detectors such as the SM3 are capable of recording the calls at over 7 km and under a variety of wind and rain conditions. This provides a potential for monitoring and tracking wolf movements at scales previously only realized in marine environments. When close to the center of the polygon of detector units, localization is extremely accurate, possibly as accurate as ∼3 m. Comparing the wolf detections to siren

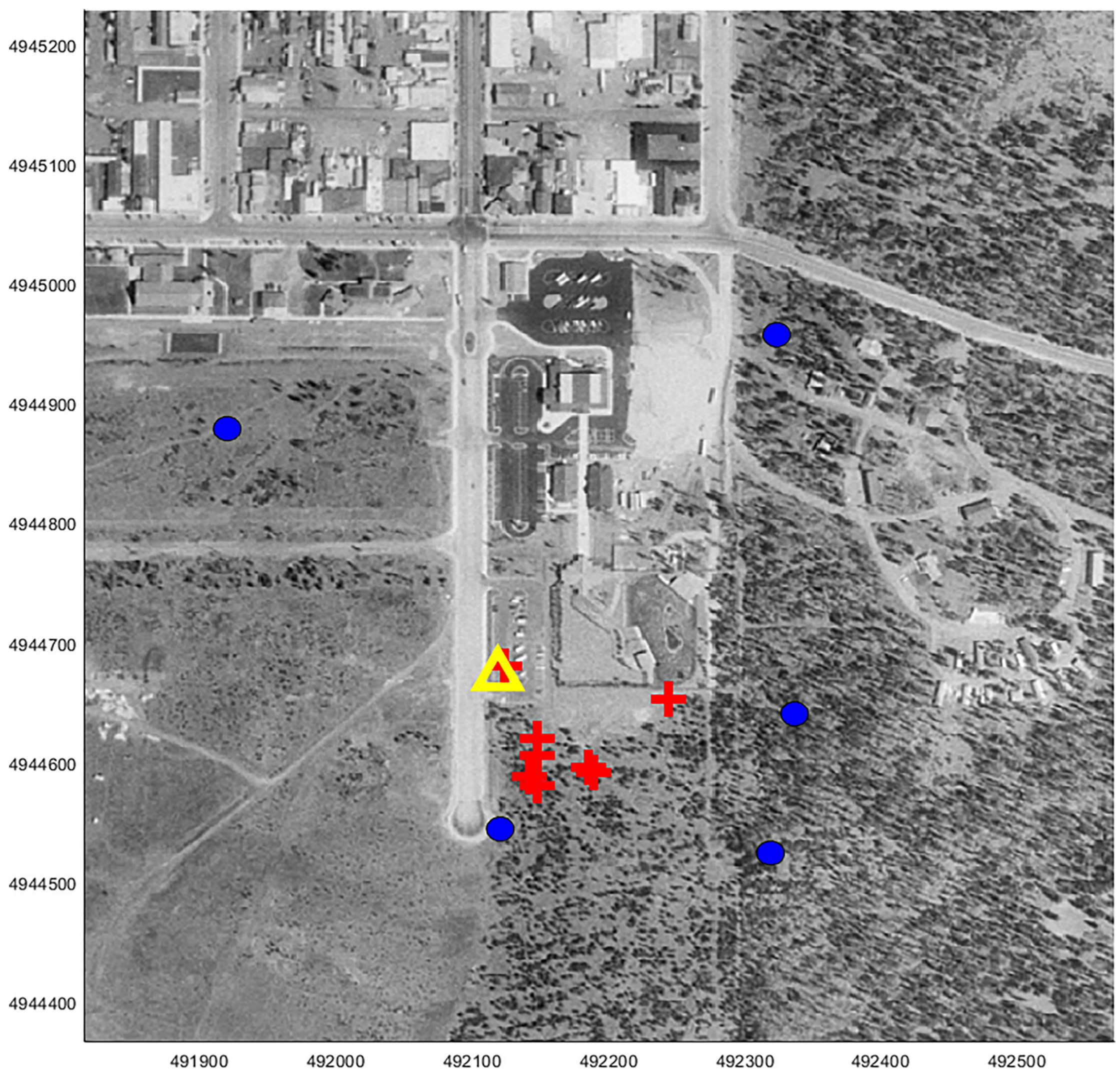

FIG. 7. (Color online) Map showing the locations of the detectors (circles), siren detections (crosses), and actual police car location (triangle). Axes are in meters.

detections, the spread of locations was similar, but the mean error on siren detection was over 80 m. This could reflect the true accuracy of the system at localizing wolf howls or reflect the greater range and fidelity of howls compared to artificial sirens. At longer ranges, and when well outside the polygon formed by the deployment of detector units, range accuracy drops dramatically, and it is not possible to identify the range to a distant animal with confidence. However, the bearing to the animal remains precise to within 5 deg, which translates to a lateral error of ~85 m at a range of 1 km. Overall, the system shows good localization of distant sound sources and has potential as a practical solution for tracking animals with long-range vocalizations. The long range of wolf howls means that widely spaced detectors can be synchronized more approximately using GPS clocks, and a broad deployment over the territory of a single pack should be able to record their movement behavior based on their howling activity.

Using simulated howls to estimate the accuracy of a localization system has previously had mixed results (Papin *et al.*, 2018) with mean position errors of 315 m. One possible explanation for the improved precision and accuracy in our study is the use of frequency modulated simulated signals (police sirens), which not only more closely match the characteristics of wolf howls, but also allow for more precise measurement of the time differences between recorders than using flat single-frequency signals. For example, identifying the start of the howl as the common event between multiple recording channels can be inaccurate if more distant detectors do not pick up early low intensity howl onset. Mid-howl changes in frequency are more likely to be detected on all channels, and also open the possibility of performing spectrogram cross correlation to improve accuracy.

The primary limitation of our study is that we have no information on the actual location of the howling animals, and so our estimates of system accuracy are not authoritative. Such a limitation is almost inevitable with species that are by their nature cryptic. In our continuing work in YNP, we are examining the possibility of correlating acoustic localization with manual observations, however, the very large majority of our recorded howls occurred either at night, or when no observation teams were near the focal animals. We believe that our analysis methods suitably compensate for this lack of a ground truth by being conservative in our calculations. Similarly, our subjective method for assigning groups of detections to single source locations is lacking in objective validation. However, the possibility of artificially inflating the localization precision by excluding detections that, in fact, originated from the same source is partially balanced by the possibility of including multiple sources in a single cluster.

The relative positions of the detectors affect the overall precision of the localization. Detectors arranged in a regular polygon should be more precise as this configuration maximizes the time differences of arrival of the signal. However, in this study, National Park Service regulations required detectors to be placed only on marked trails, and so the placement configuration was sometimes suboptimal. We expect a greater precision in deployments where the relative positions of the detectors are not constrained in such a way.

We also made efforts to perform some objective validation of accuracy using artificial sound sources, however, generating howl-like calls that are detectable at realistic ranges is highly problematic, and there was no artificial sound source available that met these requirements. Sirens are known to evoke strong responses in domestic dogs and can be heard over several kilometers, and this was the basis for choosing police sirens as artificial stimuli. Although the number of sirens localized was small, it is clear from the results in Fig. 7 that the placement of the sound source is, in general, reasonable.

Using passive acoustic localization is clearly only a realistic option for species that are highly vocal and where deployment of detector devices is feasible. To achieve accurate localization, detectors are best placed around the probable animal locations, and for wide ranging species, this can mean using many detectors and deploying them in remote locations. We are currently working on a solar-powered system with remote data download and online processing and sound source localization, which will facilitate the use of this technology in mainstream animal behavior research. However, broadening the use of new technologies to solve long-standing problems in the study of wild animals is an essential step forward. In particular, wolves and other wild canids have considerable significance in terms of their impact on human activity, their ecological and conservation importance, and their role in the public perception of wildlife and rewilding. Large scale monitoring of wild canid activity has an important role to play in balancing these often conflicting concerns, and we believe that the technology proposed here can be usefully applied by researchers and wildlife managers to provide the information necessary to strike such a balance.

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APPENDIX A

MATLAB code for multilateration by optimization:

```
% Find the most likely location of a sound source (x) given a
% series of time differences of arrival (dt) between detectors
% at different locations (loc). The maximum distance of sound
% source is defined by MAX_RANGE
s = optimset('Display','off');
% Initial estimated position is at the centre of the detectors
x0 = mean(loc);
x = fmincon(@(x)errfunc(x,dt,loc),x0,[],[],[],[],x0-MAX_RANGE,x0+MAX_RANGE,[],s);
```

```
% Error function to be minimised
function er = errfunc(x,dt,loc)
SSOUND = 343; % Speed of sound
% Calculate expected time differences between detectors
et = sqrt((loc(:,1)-x(1)).^2+(loc(:,2)-x(2)).^2)/SSOUND;
et = et-min(et);
% Build matrix of pairwise expected time differences
[a,b] = meshgrid(et);
edt=a-b;
% Calculate the error in the observed and expected pair-
wise time
% differences
er = sum((edt(:)-dt(:)).^2);
```

[1]See supplementary material at https://figshare.com/s/aca2f82ec91886641b13 for data accessibility. Data on howl source locations as well as five-track audio files can be found. Raw recordings are available on request as they are too large for most data repositories (∼5 Tb).

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