PROCEDURAL OPTIMIZATION AND MEASUREMENT OF PASSIVE ACOUSTIC SENSOR NETWORKS FOR ANIMAL OBSERVATION IN MARINE ENVIRONMENTS

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To myself,

Perry H. Disdainful,

the only person worthy of my company.

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I want to “thank” my committee, without whose ridiculous demands, I would have graduated so, so, very much faster.

ABSTRACT

Static Observation Networks (SONs) are often used in the biological sciences to study animal migration and habitat. These networks are comprised of self-contained, stationary sensors that continuously listen for acoustic transmissions released by sonic tags carried by individual animals. The transmissions released by these tags carry serial identification numbers that can be used to verify that a particular individual was near a given sensor. Sensors in these networks are stationary; therefore, sensor placement is critical to maximizing data recovery. Currently, no open-source automated mechanism exists to facilitate the design of optimal sensor networks. SON design is often governed by loose "rules of thumb" and "by eye" readings of low resolution bathymetric maps. Moreover, there is no standardized method for evaluating the efficacy of a SON. In this paper, we present a system which takes advantage of high-resolution bathymetric data and advanced animal modeling to provide optimal network designs. Our system also allows for statistical analysis of existing network configurations in order to create efficacy-metrics that can be used to evaluate arbitrary network configurations.

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CHAPTER 1
INTRODUCTION

Static Acoustic Observation Networks (SAONs) are often used in the biological sciences to study aquatic animal migration and habitat. These networks are comprised of self-contained, stationary sensors (hydrophones) that continuously listen for acoustic transmissions released by sonic tags carried by individual animals. The transmissions released by these tags carry serial identification numbers that can be used to verify that a particular individual was within detection range of a specific sensor at a given time. Acoustic networks are relatively inexpensive (compared to GPS/VHF Radio/Satellite tags). The primary goal of any tracking study is to obtain a high number of high quality data points (relating individual animals to space and time) in order to gain some insight into animal behavior. SAONs provide a way to generate a large volume of data points at low cost, resulting in cost-efficient data points. However, unless these data points are captured, the cost efficiency of SAONs is lost. Within SAONs, data capture rates are highly dependent upon the chosen locations for sensors within the study area. The malplacement of sensors (in locations that interfere with the reception of data or where no tagged individuals are present) leads to low data returns, wasted resources, and diminished cost-efficiency. We present an application that takes advantage of high resolution bathymetry, flexible behavioral modeling, and simplified acoustic propagation models to maximize the data recovery of a SAON. Our application provides a reproducible, customizable, and distributable method for generating optimal sensor placements and analytical network metrics.

1.1 Static Acoustic Observation Networks

1.1.1 Sensor Assembly

[Diagram of rigging] SAONs are composed of stationary rigs that are responsible for maintaining the chosen location for a sensor. Because positional data is interpolated from the position of nearby sensors, it is important that sensors are deployed accurately and maintain their position throughout the entire experiment[11]. This is best accomplished by attaching sensors to permanent emplacements (such as a rigid metal frame driven into a rocky substrate) that will resist substantial amounts of force (such as strong currents and curious animals). However, when it is not always possible to create such permanent emplacements (perhaps due to regulation or extreme depth), more creative approaches are called for. A popular rigging consists of an acoustic sensor attached to a length of wire/rope with a strong float on one end, and a substantial ballast with an acoustic quick release on the other[11]. Such a rig can be dropped in the ocean and allowed to sink to its desired location. Obviously, various situations will require different rig designs and may contribute significantly to network costs (acoustic releases cost approximately $2700 per piece).

1.1.2 Sensor Deployment & Recovery

The labor required for sensor deployment and recovery depends on the design of the sensor assembly. Creating a permanent, rigid emplacement for a sensor can require multiple divers, special equipment, and hours of underwater elbow grease. Recovery of a permanent, rigid emplacement will most likely require a diver to physically remove the sensor from its emplacement. Deployment of ballast/float assemblies can be as simple as dropping the assembly overboard. Recovering a ballast/float assembly simply requires signaling the acoustic release with a hydrophone and allowing the buoy to carry the sensor assembly to the surface.

1.1.3 Tag Deployment

The most challenging and time consuming task in animal tracking is the physical deposition/implantation of tags on/into the individuals to be tracked. In the case of marine tracking, this can be particularly challenging as animals must be located, captured, tagged, and released relatively quickly to avoid over-stressing the animals. Improper handling/release of an animal can result in its death and the loss of a tag. All telemetry technologies will eventually require interaction with the individual to be tracked, and acoustic tracking is no different.

1.1.4 Comparison of Technologies

1.1.4.1 Very High Frequency Radio

Very High Frequency radio (VHF) tracking involves attaching a VHF transmitter to an animal, and then using a VHF antenna and receiver to receive transmissions. VHF transmissions have effective ranges on the order of tens of kilometers. Transmissions from VHS devices do not generally contain positional data, but instead serve as a means to estimate the distance and direction of a VHS device. Positional data is derived by noting the direction and strength of a signal from several different observational positions, and estimating the transmitter's position by triangulation[8]. In a marine setting, VHF observation is generally performed from a plane or boat[1].

1.1.4.1.0.1 Sateallite/GPS Satellite and GPS tracking are distinct but related technologies that rely on a network of satellites (either ARGOS or GPS, respectively) to compute the positional data of a tag. GPS tags rely on the GPS network of satellites to triangulate a tag's three dimensional position. GPS telemetry may be stored on-board a tag (requiring later retrieval), or transmitted via satellite to a remote server[8]. Satellite tags operate by transmitting messages to the ARGOS satellite system, which computes a tag's position by observing the Doppler effect on a tag's transmission[2]. Because the telemetry from satellite tags is transmitted back to remote servers, data recovery is automatic. Both technologies have fairly poor penetration into the ocean, and so GPS/Satellite transmissions generally occur only when an animal is near the surface of the ocean. This can lead to data sets with large spatial/temporal gaps between detections. Additionally, neither technology is desirable for observing animals that reside at significant depths. Due to the high cost of Satellite/GPS technology, studies using this technology generally have very small sample sizes.

1.1.5 Advantages of Acoustic Networks

After initial deployment, SAONs require no maintenance and incur no operating costs (unlike satellite and VHF radio technologies). This means that SAONs can operate around the clock, and in conditions that would otherwise make it unsafe/impossible for field researchers to track animals (e.g. in a storm)[11]. However, it is necessary to retrieve the acoustic sensors at the end of the study in order to recover data[11]. Finally, SAONs allow for passive animal monitoring, removing the potential disruption of natural behavior caused by active tracking (e.g. aircraft/boat noise/shadow scaring animals)[11]. SAONs also function at greater depths than satellite/VHF-based systems. Because the reception of acoustic transmissions (by acoustic sensors) occurs at the resident depth of the target species, an acoustic tag's transmission need not penetrate to the surface to be detected (unlike Satellite and GPS based systems).

1.2 The Cost of Data

1.2.1 Cost of Alternative Technologies

SAONs are relatively cheap, with acoustic sensors costing $1300, and acoustic tags costing $330 each. Moorings for acoustic receivers can be significantly more expensive, with acoustic releases costing slightly more than twice the cost of a receiver. However, these costs are still significantly more affordable than satellite-based tags and collars, which cost upwards of $5000 each[5]. Additionally, recurring service fees and per-transmission charges may apply to data transferred over the satellite network. VHS radio tags are a seemingly cheaper alternative at $223 per unit, but require active monitoring to obtain each data point. The cost of paying for vehicles(boats/planes) and crews to periodically collect telemetry from these tags will significantly outweigh any initial cost savings.

Technology	Tag Cost	Receiver Cost	Operating Cost
VHF Radio Tag	$223[4]	$2940[3]	Agents & Transport
Satellite Tag	$3000-$5000[5]	$0	Service fees
Acoustic Network	$330	$1300	$0

Table 1.1: Cost Summary of Alternative Technologies

1.2.2 Operating Costs

While SAONs require no maintenance to operate, both Satellite and VHF based systems can incur operating costs while deployed. Satellite tags will require very little maintenance (precluding animal mortality), but satellite network operators may charge for access to and transmission over their network[5]. VHF systems require little maintenance, but do require active field work in order to obtain positional information. Because a tag's location is interpolated from observations of its VHS signal from multiple locations, it is necessary for a field agent to routinely collect these observations to obtain telemetry data. VHF networks have perhaps the highest operating cost, requiring a salary for one or more field agent(s) and transportation costs (renting a boat/plane). The operating costs for each technology should be included in the total cost of data collection, and subsequently the cost effectiveness of each solution.

[http://www.wildlifetracking.org/faq.shtml] [http://www.lionconservation.org/lion-collars.html] [http://www.africat.org/projects/radio-collars-for-lions]

VR2's cost $1.5k each, tags cost $350 each. http://www.gulfcounty-fl.gov/pdf/882532513025603.pdf

1.2.3 Cost Efficiency

Technology	Tag Model	Transmit Period	Expected Lifespan	Expected Transmissions
VHF Radio Tag	Telonics FIS-040	1s	0.7 days	60,480
Satellite Tag	Telonics ST-18	60s	117 days	168,480
Acoustic Tag	Vemco VR-13	90s	1,135 days	1,089,600

Table 1.2: Lifespan & Total Expected Transmissions

Technology	Tag Model	Tag Price	Expected Transmissions	Price Per Transmission
VHF Radio Tag	Telonics FIS-040	\$199	60,480	\$3.29e^{-3}
Satellite Tag	Telonics ST-18	\$3000	168,480	\$1.78e^{-2}
Acoustic Tag	Vemco VR-13	\$330	1,089,600	\$3.03e^{-4}

Table 1.3: Price per Transmissions

http://vemco.com/products/v7-to-v16-69khz/ http://www.wildlifetracking.org/faq.shtml http://www.telonics 18/ http://www.mrcmekong.org/assets/Publications/Catch-and-Culture/catchmar02vol7.3.pdf

1.3 State of the Art

1.3.1 Rules of Thumb for Sensor Placement

While animal tracking studies draw upon hard data to draw conclusions, the methodology for collecting this data is based upon loose rules of thumb driven by anecdotal evidence. Heupel et al's highly cited 2006 paper distills their prior experience with animal tracking into "rules of thumb" for designing a SAON. These rules focus on generalized considerations such as avoiding areas of high noise, bathymetric obstruction, and acoustic echoing[11].

While Heupel et al's publication gives sound advice on design issues that warrant warrant consideration, the discussion of analytical methods for measuring these issues falls out of the publication's scope.

1.3.2 Metrics

1.3.2.1 Data Recovery Rate

The most common metric used in analyzing the success of animal tracking studies is the Data Recovery Rate (DRR): $(\frac{pings\_emitted}{pings\_recovered})$. While it may seem intuitive to understand data recovery rates as an indicator of the quality of the dataset, one must bear in mind the objective of the study. As illustrated in section 1.3.3, the objective of the study defines how useful a particular dataset is in addressing a research question. Therefore, Data Recovery Rate should be treated simply as a measure of how complete a particular dataset is, and how strongly it can support a claim.

1.3.2.1.1 Unique Absoloute Data Recovery Rates When discussing recovery rates, the Absoloute Data Recovery Rate (ADRR) and Unique Data Recovery Rate (UDRR) can give insight into the qualities of a particular network design. ADRR is computed as the total number of pings that were received by all sensors in the network, divided by the total number of emitted pings. This means, that data recovery rates of more than 100% are possible.

1.3.2.2 Network Sparsity

Network Sparsity (δ) is a unit-less measure of the observational qualities of an acoustic network. This metric is useful in quickly expressing the density and intent of an acoustic network. For a list of n receivers within a SAON r_1, r_2, r_3, ... r_n, let a_i $(1 \leq i \leq n)$ be the distance to receiver r_i's nearest neighbor. Then, a is the median over all a_i. d_r is given as the detection range of a sensor. Network sparsity is defined as $\frac{a}{2d_r}$.

A δ of 0 describes an array of receivers that are virtually stacked on top each other. A *delta* between 0 and 1 indicates that receivers are placed such that their detection ranges overlap (a smaller δ indicates more overlap). A δ of 1 signifies that receivers in the array are positioned such that their detection ranges are just touching but not overlapping. A δ greater than 1 indicates that the receivers are farther apart, and that there are gaps between receiver coverage areas. With this definition, it becomes obvious that Network Sparsity is a positive indicator for data fusion (section 1.3.3.1), and data resolution(section 1.3.3.1).

1.3.2.3 Sample Size

Another important factor to consider is the number of tagged individuals within a dataset. A dataset for a single tagged individual, no matter how complete, will not offer very much support to any conclusions drawn. At the same time, a dataset for a large number of individuals, with very low data recovery rates may not provide enough individual telemetry to draw a conclusion at all.

1.3.3 Data Quality

1.3.3.1 Data Resolution

Acoustic receivers like the Vemco VR2 log detections of acoustic transmissions as a tuple of time, tag number, and transmission strength. The strength of the received transmission can be used to approximate the distance between the tag and receiver. Data from a single receiver has a fairly low certainty of the exact position (low resolution) of the transmitting tag because only a single distance can be observed. If multiple receivers are in close enough proximity to receive the same transmission, the strength of the transmission observed from several different known, fixed positions can be used to triangulate a more precise position (higher resolution). This process of combining multiple observations into a more accurate observation, known as **Data Fusion**, is useful for increasing the resolution of tagged individuals and allows for the tracking of fine movements within a three-dimensional space. This increase in resolution does however have a price. Detection of a tag by more than one receiver requires that those receivers have overlapping detection ranges. Assuming a fixed number of receivers, placing receivers closer together reduces the actual coverage area of the array. Thus, the coverage area of the array is inversely correlated with the resolution of the array. Alternatively, purchasing more receivers will achieve a higher resolution, but increases the cost of the array.

1.3.3.2 Meaningful Data

Obviously the number of sensors and the size of the research area determine Data Resolution. However, high-resolution data, while desirable, is not always critical to the study. First consider a number of receivers placed in a tight cluster.

If the target species were highly sedentary, and the receiver cluster was placed around the area where a large number of individuals were captured and tagged, then the study would very likely yield a high Data Recovery Rate, but that dataset would be of little use in determining the spatial distribution of that species, as the data would be limited to the small area in which the receiver cluster was placed. On the other hand, this dataset would be highly useful in confirming the sedentary nature of the species and defining a small home range. Additionally, data from multiple receivers could be combined to provide high-resolution telemetry for the location of an animal over time (see section 1.3.3.1). This high-resolution telemetry could be used to infer fine-scale co-location of two individuals, giving insight into social movement behaviors such as schooling and mating.

If the target species tended to roam over a large home range, then it is likely the cluster would receive only a few pings. In this case, little data will be gathered in regards to the extent of the specie's home range, but high resolution telemetry can be gathered for a short time if the animal passes through the cluster. This might be useful in identifying particular corridors that individuals prefer.

Now consider a number of receivers placed in an array very far apart from each other over a very large spatial area. If the target species were highly sedentary, then individuals might show up on one or two receivers. If many individuals were tagged, then the dataset could describe the spatial distribution of the species over a large area. The data on particular individuals would likely be very low resolution, as detection by a single receiver only tracks proximity.

If the target species tended to roam over a large home range, then it is likely the receiver array would pick up an individual animal over a number of distant sensors. This data could be used to detect potential corridors for animal movement, establish individual home ranges, and to identify the spatial distribution of the species over a large area. Again, the telemetry for individual animals would be very low, but the detection of many individuals by a single receiver could indicate areas of interest for future research.

1.3.4 Scale of Experiments

1.3.5 Oversights

CHAPTER 2
RELATED WORK

2.1 Yuan et al - Fast Sensor Placement Algorithms for Fusion-based Target Detection

Using data fusion for enhanced range and accuracy Constrained Simulated Annealing and Optimal Placement

2.2 Poduri et al Constrained Coverage for Mobile Sensor Networks Constrained Coverage (K-Neighbor Networks vs Maximum Coverage)

Density of Deployment Influencing global network properties via local restrictions Force dispersion algorithm

2.3 Pedersen and Weng - Estimating Individual Animal Movement from Observation Networks

Movement models Observation models Network Sparsity Home Range Investigation Assumptions when simulating fish movement in state-space models Fish speed and sensor area Observable space and total study area ?Environmental factors affecting fish behavior?

2.4 Howard et al - Mobile Sensor Network Deployment using Potential Fields Potential Field Algorithm

Static Equilibrium: Optimal placement vs Run time Runtime and Results

2.5 Akbarzadeh et al - Probabilistic Sensing Model for Sensor Placement Optimization Based Signal Simulation and Attenuation (Omni Directional Sensors)

Line of Sight modeling Weighted Coverage L-BFGS, Simulated Annealing, and Covariance Matrix algorithms Here is where you discuss the related work. Use BibTex to reference related work.

CHAPTER 3
DESIGN

3.1 Program Requirements

3.1.1 Motivation

While the detriments to SAON technologies are well-known [6], [11], [12], [13], [17] there few tools/services to analytically design SAONs around them. Further, none of these tools/services are free and open-source.

3.1.1.0.1 Cost Efficiency In section 1.2.1, we discuss the costs of marine telemetry systems, noting that acoustic telemetry systems produce data at a significantly lower ($\geq$10x cheaper) cost than VHF or GPS/Satellite based technologies. In order to maintain the cost-efficiency of acoustic technology, at least 10% of the produced transmissions must be captured by the SAON's receiver array. Given the numerous (but avoidable) impediments to reception of these acoustic signals (1.3.1), the array-design process becomes critical to maintaining the cost-efficiency of SAON technologies. A free network design tool would help to maintain the cost-efficiency of SAONs by eliminating costs surrounding their design and evaluation.

3.1.1.0.2 Metrics The computation of network metrics (Absoloute Recovery Rate, Unique Recovery Rate, Network Sparsity) is very labor intensive at large scale. Additionally, the process of computation may vary from experiment to experiment. An automated tool would solve both issues by providing a fast, simple, repeatable, and well-documented method for computation. Metrics from such a tool would be useful in directly comparing different network deigns.

3.1.1.0.3 Transparency An open-sourced tool/service would make the design process more transparent, permitting peer-review and modification. This would provide increased confidence in the process, and increased adoption of the tool. This in turn would allow for increased efficiency in SAON design, leading to higher data recovery rates, better data quality, increased return-on-investment, and the ability to better address scientific-research questions.

3.1.2 Supported Workflows

3.1.2.0.4 Static Analysis As mentioned in section 3.1.1.0.2, a primary motive for this tool was the ability to create a repeatable means of measuring the performance of a SAON. To this end, the ability to measure an existing network design is important. Users should be presented with network metrics after specifying bathymetry, receiver locations, network properties, and an animal model for a given study site.

3.1.2.0.5 Optimal Design The primary motive for this tool is the ability to design optimal SAONs. Users should be presented with a network design (optimal receiver locations), and network metrics after specifying bathymetry, the number of receivers in the network, network properties, and an animal model for a given study site.

3.1.2.0.6 Optimal Addition Similar to the problem of optimal design, is the problem of optimal addition: the augmentation of an already existing SAON. Users should be presented with a network design (optimal augmenting receiver locations), and network metrics after specifying bathymetry, the number of receivers to add to the network, network properties, existing receiver locations, and an animal model for a given study site.

3.1.3 Bathymetric File Support

3.1.4 Evaluation of Sensor Emplacements

3.1.5 Selection of Optimal Emplacements

3.1.6 Bathymetric Shadowing

3.2 Animal Modeling

Animals exhibit many different movement models and habitat preferences (both of which can vary in three-dimensional space). This greatly affects their distribution and thus the network configuration that should be deployed to capture their movement. Our program models account for both the habitat and movement preferences of the target species by allowing for various optional parameters and functions.

3.2.1 Animal Movement Models

To simulate animal movement across a two dimensional x/y space (as one would expect to see on a map), we provide two basic probabilistic movement models: Random Walk, and Ornstein-Uhlenbeck(OU).

3.2.1.0.7 Random Walk Model The Random Walk model assumes that animals move randomly through the environment. As a result, over the entire study period, each valid grid cell (as defined by vertical habitat range) will see roughly the same amount of animal traffic. The result is that every valid cell in the grid will have the same chance of capturing an animal's sonic tag. We assume that animals will be willing to very briefly (in probabilistically negligible time frames) pass through invalid cells to get to valid cells. This means that disjoint sections of habitat are still capable of seeing animal movement.

3.2.1.0.8 Ornstein-Uhlenbeck Model The Ornstein-Uhlenbeck(OU) model assumes that over time, animals will prefer to gather near certain points of interest. This concept models an animal's desire to seek out and remain near a physically significant structure, a region of high food availability, breeding grounds, shelter, etc. Users must provide the x and y coordinates for this point (as grid indicies), the strength of attraction in the separate x and y directions, and the correlation between the x and y attraction as parameters to the program. http://en.wikipedia.org/wiki/Ornstein

3.2.2 Simulated Animal Depth Preference

Some animals exhibit the preference to reside within a specific section of the water column; for example, prey animals may prefer hiding in reef heads at the bottom of the water column, while predators will prefer to hover several meters off the bottom. This preference can be incorporated into the behavioral model by specifying mean (Preferred Depth) and standard deviation(SD of Preferred Depth) values. These values are given as a measure of the distance (in meters) from the bottom. For example, specifying a depth of '0' for "Preferred Depth" indicates that the animal prefers to live on the sea floor, while a value of '5' indicates that the animal prefers to live 5m off the sea floor. Allowing a standard deviation value allows for the modeling of animals that tend to be sedentary within the water column (a small deviation), and those that migrate through the water column (a large deviation).

3.2.3 Restricted Vertical Habitat Range

Some animals will live only in a specific depth range. For example, a deep sea fish may live only in depths of 300-400 meters. To incorporate this into the behavioral model, users can specify a minimum and maximum vertical habitat range for their animal. If this option is selected, the program will only simulate animals in cells whose depths are between the minimum and maximum depths.

3.3 Sensor Projection

Normally users have a set number of sensors to place in the water. However, the question of How much better could my results be if I had had just a few more sensors? often arises. The program allows for the projection of additional sensor placements, and graphs how much more data collection would have been possible.

3.4 Network Model Ingestion

3.4.1 Customizable Network Models

The program supports three distinct ways to define sensors in a network: user specification, program-placed sensors, and projected sensors. User placed sensors represent sensors that already exist, and are being integrated into a new network. Program placed sensors are sensors that are optimally placed by the program, and take into account any user placed sensors. Projected sensors are Add new sensors (with optimal placement) to an already existing network Analyze the data recovery rate for a sensor network Create an optimal sensor network

3.5 Goodness Algorithms

3.5.1 Selectable Goodness Algorithms (Bias)

The Goodness algorithm is the driving force behind the selection of sensor placements. While users are able to write their own Goodness algorithms, three basic algorithms are provided:

3.5.1.0.9 Animal Only (Option 1) This option prefers to place sensors in areas of high animal activity, completely oblivious to the surrounding topography.

3.5.1.0.10 Topography Only (Option 2) This option places sensors in areas that have the best visibility of the surrounding area. This is useful for experiments where animal habitat is unknown or to be determined.

3.5.1.0.11 Visible Fish (Option 3) This option chooses sensor locations that have the best view of areas of high animal activity. Both animal presence and visibility due to topography are considered.

CHAPTER 4
RESULTS

Here is where you discuss the results from your evaluation.

CHAPTER 5
CONCLUSIONS

Here is where you discuss your conclusions and future directions.

APPENDIX A
SOME ANCILLARY STUFF

Ancillary material should be put in appendices, which appear before the bibliography.

APPENDIX B
MORE ANCILLARY STUFF

Subsequent chapters are labeled with letters of the alphabet.

BIBLIOGRAPHY

[1] Animal migration tracking. <https://en.wikipedia.org/wiki/Animal_migration_tracking#Radio_tracking>.

[2] How argos works. <http://www.argos-system.org/web/en/337-how-argos-works.php>.

[3] Innovative technology/lab support proposal online form. <https://www.uaf.edu/tab/past-proposals/proposalDetails.xml?id=667>.

[4] Vhf systems for fish (fis). <http://www.telonics.com/products/vhfImplants/vhfFish.php>.

[5] Wildlife tracking. <http://www.wildlifetracking.org/faq.shtml>.

[6] Vahab Akbarzadeh, Christian Gagné, Marc Parizeau, Meysam Argany, and Mir Abolfazl Mostafavi. Probabilistic sensing model for sensor placement optimization based on line-of-sight coverage. *IEEE Transactions on Instrumentation and Measurement*, 62(2):293–303, 2013.

[7] Paul C Etter. *Professional Development Short Course On: Underwater Acoustic Modeling and Simulation*. 2004.

[8] Rey Farve. Technology and development at the usda forest service, satellite/gps telemetry for monitoring lesser prairie chickens. http://www.fs.fed.us/t-d/programs/im/satellite_gps_telemetry/wildlifetrackingtelementry.htm.

[9] Alan Frieze, Jon Kleinber, R Ravi, and Warren Debany. Line of Sight Networks. *Proceedings of the eighteenth annual ACM-SIAM symposium on Discrete algorithmsProceedings of the eighteenth annual ACM-SIAM symposium on Discrete algorithms, 968-977*, pages 968—-977, 2007.

[10] J Hansen and Michael Jones. perSpeCtIve : FISHERIES MANAGEMENT the value of Information in Fishery Management. 33(7), 2008.

[11] M. R. Heupel, J. M. Semmens, and a. J. Hobday. Automated acoustic tracking of aquatic animals: Scales, design and deployment of listening station arrays. 57(1):113, 2006.

[12] Andrew Howard, M.J. Mataric, and G.S. Sukhatme. Mobile sensor network deployment using potential fields: A distributed, scalable solution to the area coverage problem. *Proceedings of the 6th International Symposium on Distributed Autonomous Robotics Systems (DARS02)*, 5:299–308, 2002.

[13] Steven Thomas Kessel, Nigel Edward Hussey, Dale Mitchell Webber, Samuel Harvey Gruber, Joy Michelle Young, Malcolm John Smale, and Aaron Thomas Fisk. Close proximity detection interference with acoustic telemetry: the importance of considering tag power output in low ambient noise environments. *Animal Biotelemetry*, 3(1):1–14, 2015.

[14] William D Pearse, Andy Purvis, Life Sciences, and Silwood Park Campus. Generation Tool for Ecologists. *Methods in Ecology and Evolution*, 4(10):920–929, 2013.

[15] Martin W. Pedersen and Kevin C. Weng. Estimating individual animal movement from observation networks. *Methods in Ecology and Evolution*, 4(10):920–929, 2013.

[16] S. Poduri and G.S. Sukhatme. Constrained coverage for mobile sensor networks. *IEEE International Conference on Robotics and Automation, 2004. Proceedings. ICRA '04. 2004*, 1, 2004.

[17] Anna E Steel, Julia H Coates, Alex R Hearn, and a Peter Klimley. Performance of an ultrasonic telemetry positioning system under varied environmental conditions. *Animal Biotelemetry*, 2(1):15, 2014.

[18] Acoustic Telemetry. Technical white paper understanding the performance of vemco 69 khz single frequency acoustic telemetry. 2008.

[19] Yuan Zhaohui, Tan Rui, Xing Guoliang, Lu Chenyang, Chen Yixin, and Wang Jianping. Fast sensor placement algorithms for fusion-based target detection. *Proceedings - Real-Time Systems Symposium*, pages 103–112, 2008.