



An Amplitude-Based Estimation Method for International Space Station (ISS) Leak Detection and Localization Using Acoustic Sensor Networks

Jialin Tian and Eric I. Madaras
Langley Research Center, Hampton, Virginia

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Report Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers, but having less stringent limitations on manuscript length and extent of graphic presentations.
 - **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
 - **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.
 - **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.
 - **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
 - **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.
- Specialized services also include creating custom thesauri, building customized databases, and organizing and publishing research results.
- For more information about the NASA STI program, see the following:
- Access the NASA STI program home page at <http://www.sti.nasa.gov>
 - E-mail your question via the Internet to help@sti.nasa.gov
 - Fax your question to the NASA STI Help Desk at 443-757-5803
 - Phone the NASA STI Help Desk at 443-757-5802
 - Write to:
NASA STI Help Desk
NASA Center for AeroSpace Information
7115 Standard Drive
Hanover, MD 21076-1320

NASA/TM-2009-215948



An Amplitude-Based Estimation Method for International Space Station (ISS) Leak Detection and Localization Using Acoustic Sensor Networks

Jialin Tian and Eric I. Madaras
Langley Research Center, Hampton, Virginia

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

November 2009

Available from:

NASA Center for AeroSpace Information
7115 Standard Drive
Hanover, MD 21076-1320
443-757-5802

Acronym List

FEM	Finite Element Method
FMM	Fast Marching Method
ODE	Ordinary Differential Equation
ISS	International Space Station
RMS	Root Mean Square

Table of Contents

Abstract	7
1. Introduction	8
2. ISS Surface Mesh Distance Computation	9
3. Amplitude-Based Leak Detection and Localization Algorithm	12
3.1 Amplitude-Distance Decaying Function Model	13
3.2 Acoustic Sensor Network Placement Strategy	14
3.3 Leak Detection and Localization Method	18
4. Conclusions and Future Work	21
References	22

Abstract

The development of a robust and efficient leak detection and localization system within a space station environment presents a unique challenge. A plausible approach includes the implementation of an acoustic sensor network system that can successfully detect the presence of a leak and determine the location of the leak source. Traditional acoustic detection and localization schemes rely on the phase and amplitude information collected by the sensor array system. Furthermore, the acoustic source signals are assumed to be airborne and far-field. Likewise, there are similar applications in sonar. In solids, there are specialized methods for locating events that are used in geology and in acoustic emission testing that involve sensor arrays and depend on a discernable phase front to the received signal. These methods are ineffective if applied to a sensor detection system within the space station environment. In the case of acoustic signal location, there are significant baffling and structural impediments to the sound path and the source could be in the near-field of a sensor in this particular setting. In the case of structural methods, the signal that we receive from a structure-borne sensor has no discernable phase front to detect. We propose a solution that is able to overcome these challenges by utilizing the structural uniqueness of the space station node module. This method emphasizes the amplitude decaying properties of the acoustic signals and the surface mesh system of the module. These two underlying components are employed to solve the leak localization problem. In the amplitude-based estimation method, a discrete mesh system is constructed for the International Space Station Node Module; a distance matrix that contains the shortest paths (geodesic paths) on the station surface is then generated using the discrete mesh. The sensors are characterized by the amplitude-distance decaying function using experimental data sets. The pre-defined components are applied to the detection and localization algorithm during real-time operation. This approach is especially effective when computational and physical resources are limited since the most required algorithmic elements are pre-determined and stored in the memory.

1. Introduction

The development of a robust and efficient leak detection and localization system within a space station environment presents a unique challenge. A plausible approach includes the implementation of an acoustic sensor network system that can successfully detect the presence of a leak and determine the location of the leak source. Traditionally, acoustic target detection and localization schemes involve methods such as maximum likelihood estimation, sensor-array beamforming, least-square filtering, and other types of stochastic estimation techniques [1-5]. Most of those systems are designed specifically for far-field detection scenarios in which the acoustic signals travel within an airborne environment. The distances between the sensors and the source are extracted based on a Cartesian coordinate system. These localization algorithms are usually designed using the phase and amplitude information received at the sensor array. For our particular problem, the location of the leak cannot be easily derived using the conventional acoustic detection solutions because the space station node module features a near-field and structure-borne setting that presents two unique challenges to the leak localization problem. First of all, the measured relative phase information among sensors is inadequate in a near-field situation. Furthermore, there are significant baffling and structural impediments to the sound path in this particular setting. Secondly, the acoustic signal travels within a structure-borne environment, which implies that the sensor-to-leak distances cannot be estimated based on a Cartesian coordinate system as is typically used in airborne acoustics. Instead, the signal travels along a geodesic path in a curved space; in other words, the signal travels along the shortest path between points on the station module surface.

Likewise, there are similar applications in sonar [7-9]. These methods follow acoustic methods using advanced signal processing techniques and have been well developed for naval applications. In the case of leak localization, these methods are of interest, but obviously, the medium of transmission is distinctive and not relevant. In solids, there are specialized methods for locating events that are used in geology and in acoustic emission testing that involve sensor arrays and depend on a discernable phase front being detected by the receiving sensor [10-13]. In our case, the structure-borne signal generated by a leak has no discernable phase front to detect. Therefore, these methods are ineffective if applied to a sensor detection system within the space station environment. Signal processing methods that involve cross correlating signals from an array of sensors can derive relative phase information that can be used to indicate relative directions from groups of sensor [14]. That technology is another possible method that is being investigated for this purpose.

We propose a solution that is able to overcome many of the challenges of structure-borne sound detection of leak noise by utilizing the structural uniqueness of the space station node module. This method emphasizes the amplitude decaying properties of the acoustic signals and the surface mesh system of the module. These two underlying components are employed to solve the leak localization problem. This approach is especially effective when computational and physical resources are limited since the most required algorithmic elements are pre-determined and stored in the memory. The algorithm can be summarized in the following steps: (1) construct a discrete mesh representation for the station module (for illustration purposes, we have generated a two-dimensional flattened map of a module); (2) design a sensor network system that optimizes the number of sensors and their placements subject to a set of constraints; (3) at each node in the mesh, compute the acoustic field amplitudes generated by a leak, for demonstration purposes, we can simulate this step with the following two sub-steps: (A) compute the geodesic distances from the sensors to every location on the mesh and (B) characterize the amplitude-distance decaying function with an approximated $1/\text{distance}$ ($1/r$) relation, which is justified from

experimental data measurements; (4) detect the presence of a leak signal based on an amplitude threshold; (5) localize the leak signal using the amplitude measurements, the pre-computed distances, and the amplitude-distance decaying function. The first three procedures are pre-determined; therefore they do not consume any real-time computational resources on-board. The last two steps are performed during the real-time detection and localization process.

In Section 2, we discuss the techniques of constructing a mesh model for an ISS NODE Module (Figure 1) and generating the geodesic distance matrix using the fast marching method. In Section 3, we present the characterization of the amplitude-distance decaying function, the sensor network placement strategy, and the proposed leak detection and localization algorithm.

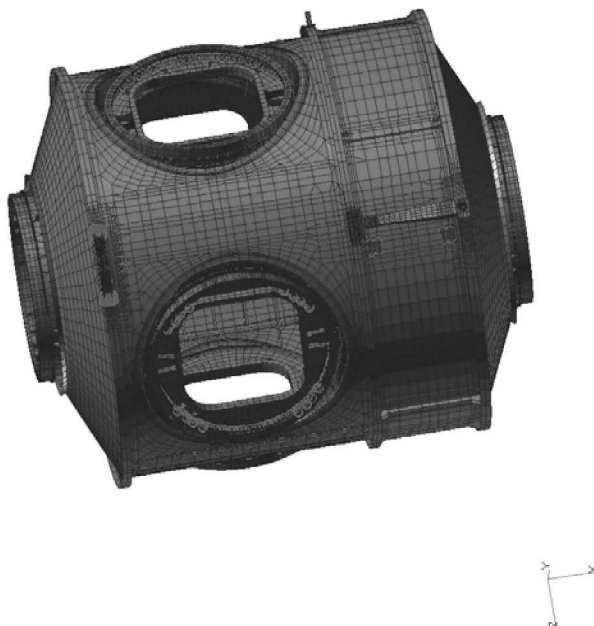


Figure 1. A high-resolution mesh for the ISS NODE Module.

2. ISS Surface Mesh Distance Computation

This section describes the techniques for creating a distance matrix that contains the shortest surface (geodesic) paths between points on a discretized ISS mesh model. The distance information is stored and can be retrieved during the real-time leak localization process. Figure 2 depicts the necessary steps for generating a distance table of an ISS module based on a pre-defined discrete mesh system. In the initial step, a low-resolution FEM triangulated mesh system is constructed. The mesh is defined in the (vertex, face) format. The number of points or vertices should be selected such that it is coarse enough to ensure fast and efficient computation, and it is also refined enough to guarantee an accurate identification of the leak location. An example of a two-dimensional flattened triangulated uniform mesh of an ISS NODE module can be seen in Figure 3.

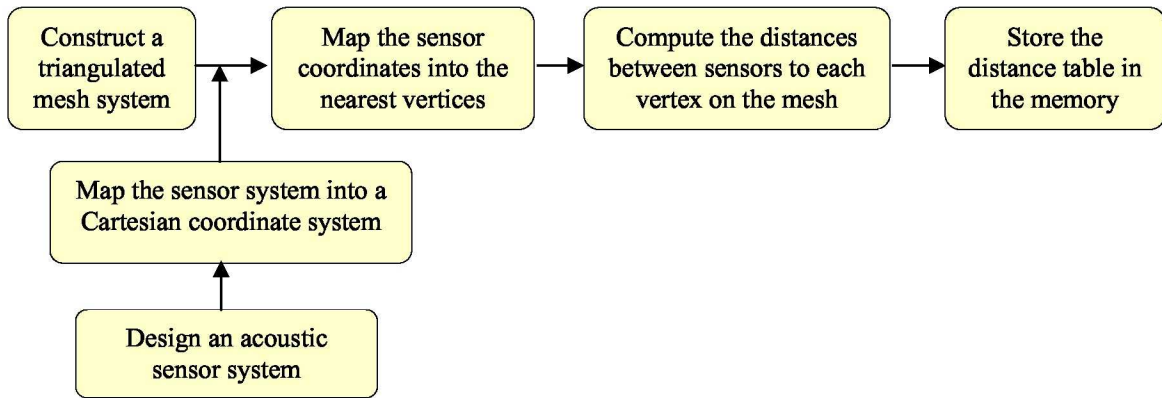


Figure 2. ISS surface mesh distance computation algorithm procedure.

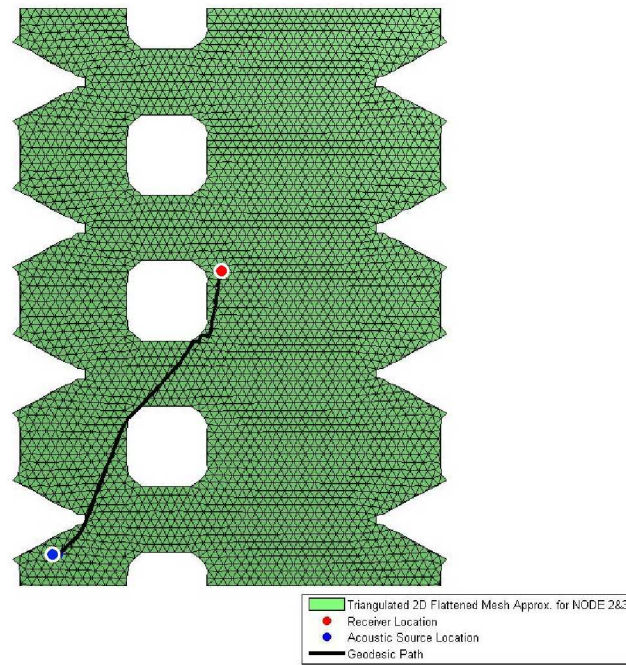


Figure 3. A geodesic path from an arbitrary source to a sensor on the 2-D flattened triangulated mesh of ISS NODE.

Once the mesh system is obtained for a particular NODE module, the next step involves the mapping of an acoustic sensor/detector system onto the mesh system. The design criteria of the sensor system include the number of sensors and their placements. Because the signal amplitude diminishes very rapidly as a function of distance, the sensor system must be sufficient enough to detect a leak signal from the background noise. In general, at any arbitrary location on the module, a leak signal needs to be detectable by at least two sensors simultaneously to produce a reasonable location estimate. In general, this suggests dispersing the sensor locations uniformly throughout the structure. Please refer to Section 3.2 for further discussion on sensor network

designs. The physical locations of the sensors are mapped into a Cartesian coordinate system, and then into the nearest vertices on the triangulated mesh model.

In the following stage, the shortest surface distances between sensors to each vertex on the mesh are computed and stored in memory. To compute the shortest surface distance between two points on the NODE module, we adopt the fast marching method (FMM). The FMM is a numerical solution for finding the shortest surface path between two points on an arbitrary surface using an iterative algorithm. The algorithm is performed on the discrete mesh system that has been obtained in the previous step. The computation of the shortest geodesic path, Γ , between A and B can be summarized in two steps. Given the input as the triangular mesh S and two points A and B on the surface of S , the algorithm generates an output of a discrete geodesic Γ joining A and B . In the first step, the initial approximation Γ_0 is obtained; the polygonal curve Γ_0 joining vertices A and B is constructed using the FMM [15-17].

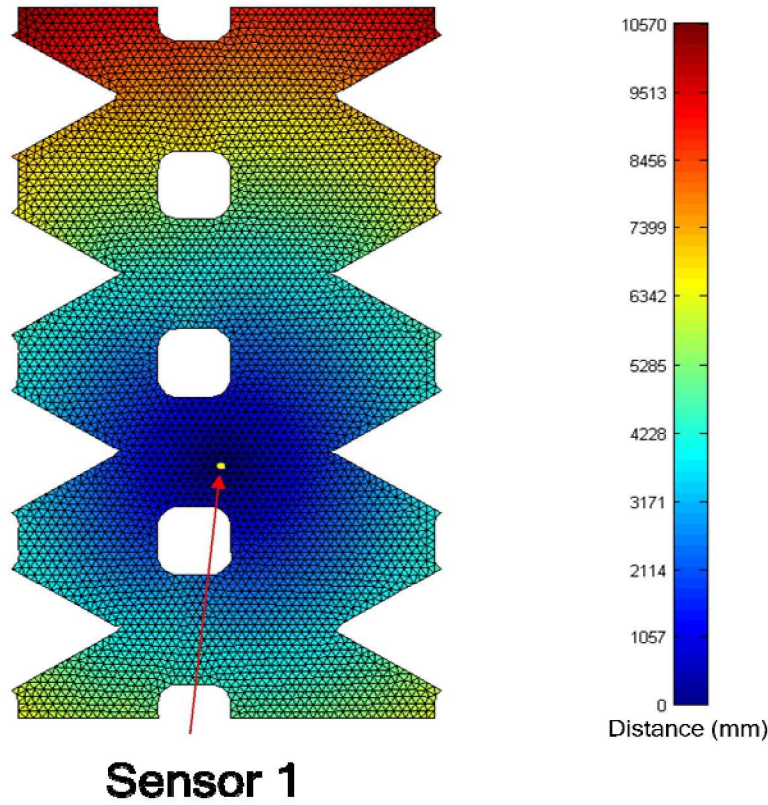


Figure 4. The distance gradient plot from an arbitrary location at Sensor 1 to the rest of the vertices (points) on the mesh.

The FMM solves for Eikonal equation $|\nabla T| = 1$, where $T(P)$ is the geodesic distance from point A to any point P on S . Once T is computed for every vertex, the following ordinary differential equation (ODE) is solved $\frac{d\chi(s)}{ds} = -\nabla T$; $\chi(s)$ is the geodesic path. In the second step, the initial estimate $\Gamma_i, i = 0, 1, \dots$ is iteratively corrected until it reaches a desirable

approximation Γ_n of Γ . In Figure 3, the geodesic path between an arbitrary source and a sensor is illustrated on the triangulated uniform mesh of an ISS NODE that was generated earlier. Figure 4 represents the geodesic distance from an arbitrary location at Sensor 1 to the rest of the vertices (points) on the mesh in a gradient plot. Lastly, the computed distance matrix of a pre-defined sensor network is stored in the memory, which can be expressed as $\mathbf{D}_r(v)$, in which r denotes the vertex number of the sensors/receivers and variable v represents an arbitrary location/vertex on the mesh model. The distance information can be retrieved during real-time leak localization process, which will be discussed in the following sections.

3. Amplitude-Based Leak Detection and Localization Algorithm

The leak detection and localization algorithm is designed based on knowing the acoustic field amplitudes. For demonstration purposes, we have calculated the acoustic fields based on our observation that the amplitudes measured by acoustic sensors are roughly inversely proportional to the distances between the sensors and the leak on a logarithmic scale. Intuitively, we can see that for an arbitrary leak location, sensors in the near vicinity of the leak measure high-amplitude signals whereas sensors further away from the leak source obtain low-amplitude measurements. An amplitude-distance decaying (attenuation) function is obtained using experimental data sets. The polynomial coefficients that represent the decaying function are computed and stored in the memory. For detailed derivation of the amplitude-distance decaying function, please refer to Section 3.1.

The detection and localization process includes several steps as depicted in Figure 5. Initially, the real-time acoustic measurement is compared with the stored background noise profile. If the RMS value of the difference between the current measurement and the background noise exceeds a threshold level, then a leak is detected, otherwise the decision sequence loops back. When a leak signal is detected, the algorithm selects three to four sensors that have the strongest leak signal strengths. This selection procedure is necessary because the signal amplitude diminishes very rapidly, as a function of distance, the sensors that are further away from the leak may not be able to detect the leak signal; therefore, only the strongest amplitude measurements hold essential information that can be used by the localization algorithm.

In the next stage, the algorithm iterates through every vertex on the mesh model. At each location, the surface distances from that location to the selected sensors are retrieved to generate a distance estimation function. Using the amplitude-distance decaying polynomial coefficients, we derive a real-time distance function via inversion. This function is correlated to the distance estimation function to produce a correlation coefficient. This calculation is repeated until the correlation coefficient is obtained for every location on the mesh model. In principle, the vertex with the highest coefficient value corresponds to the most likely location of the leak; however, in practice the level of random noise in the measurement may skew the position of the estimate. In addition, the real-time amplitude-distance decaying characteristics may be slightly different from the previously determined polynomials during real-time operation.

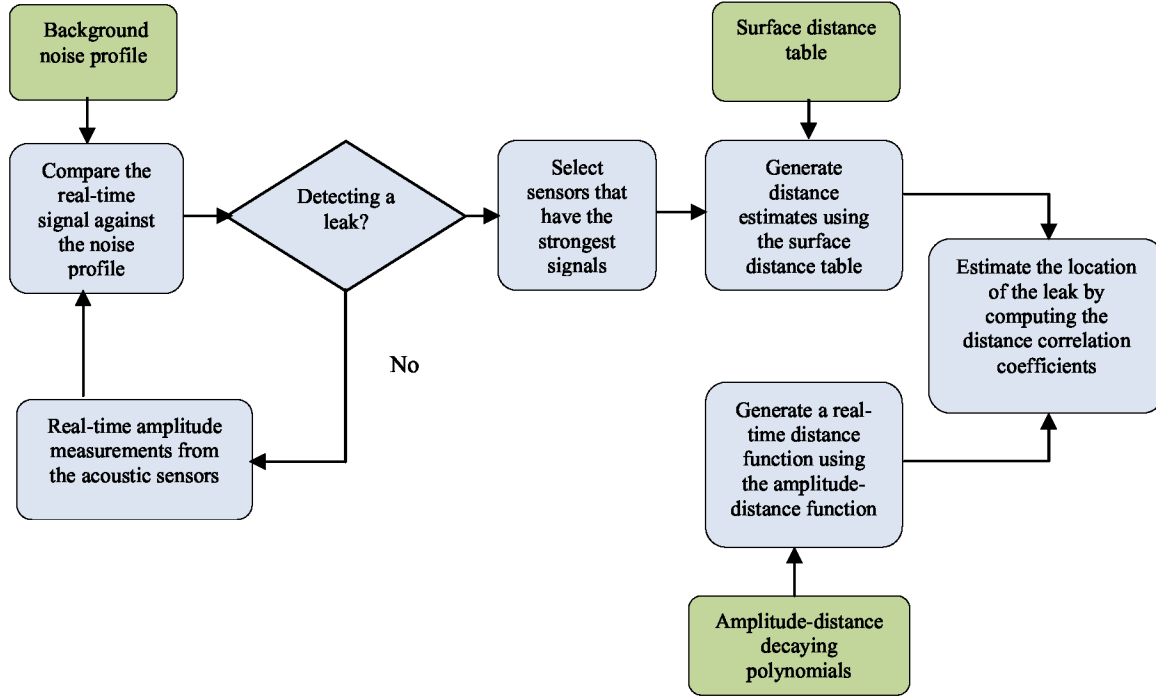


Figure 5. The amplitude-based leak detection and localization algorithm path.

3.1. Amplitude-Distance Decaying Function Model

The fundamental principle of the amplitude-distance localization method is based on the knowledge of the signal strength throughout the structure. We have observed in our measurements that the signal strength measured by a detector is roughly inversely proportional to the detector-to-source distance on a logarithmic scale. For instance, the detector observes a larger signal if a leak source is located nearby; conversely, the detector observes a smaller signal or no signal if a leak source is further away. This amplitude-distance decaying function can be characterized by the detector's performance specifications. For the specific type of sensors in our application, the amplitude-distance decaying function is determined using a set of experimental measurements. The amplitude data were obtained at several distances from the leak source. The decaying amplitude as a function of distance can be derived by interpolating the experimental data set, which is shown in Figure 6. Next we characterize the decaying slope using a 4th order polynomial function. Since the slope is highly nonlinear, we apply the polynomial fitting to the logarithm of the amplitudes, which can be written as $f(d) = \log(a)$ where $f(\cdot)$, d , and a represent the polynomial function, the distance parameter, and the amplitude variable, respectively. The resulting approximation is shown in Figure 7. The blue curve indicates the logarithmic interpolated amplitude-distance function whereas the red curve features its polynomial approximation. The inversion of the amplitude-distance function will be employed to predict the distances from real-time sensor measurements.

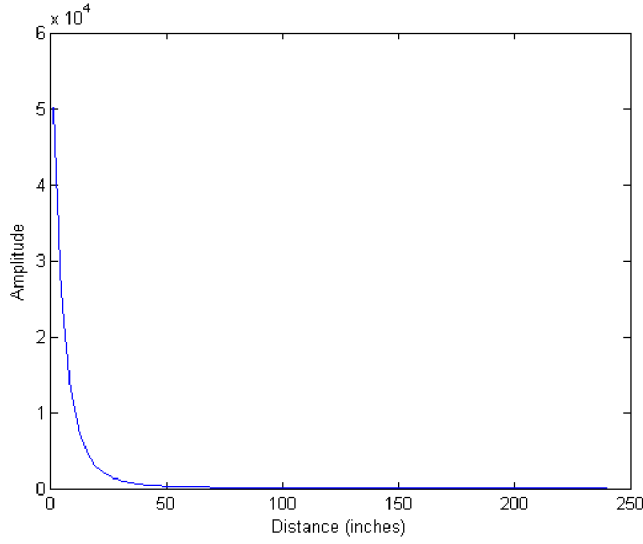


Figure 6. The interpolated amplitude-distance decaying function.

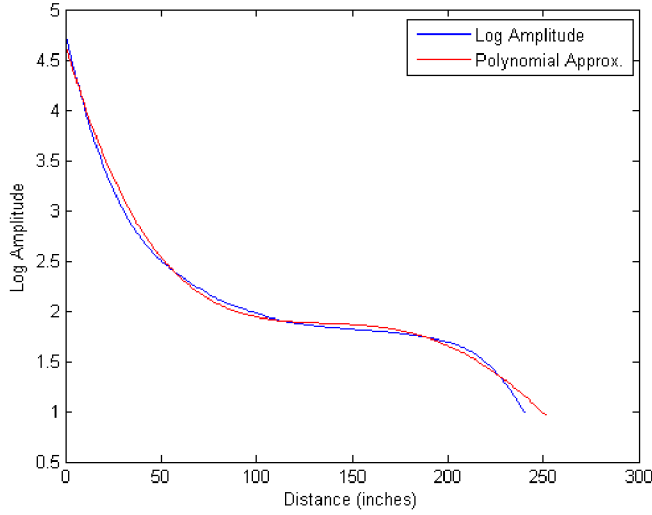


Figure 7. The logarithmic amplitude-distance decaying function (blue) and its polynomial approximation (red).

3.2. Acoustic Sensor Network Placement Strategy

In this section, we discuss the topic of choosing a suitable acoustic sensor network for the detection system. Our goal is to determine the number of sensors and their corresponding placements so that the cost is minimized while the sensor coverage is maximized. The number of sensors used in the distributed sensor network typically represents the cost factor. The constraint or requirement of the system is stated as every location inside the station module must be detectable by at least two sensors simultaneously for the leak location to be estimated accurately. This design problem can be treated as a combinatorial optimization problem, and the solution can be obtained by solving a system of linear equations. An alternative approach that involves an iterative technique is more desirable since it is computationally efficient for a large number of unknowns [18-20].

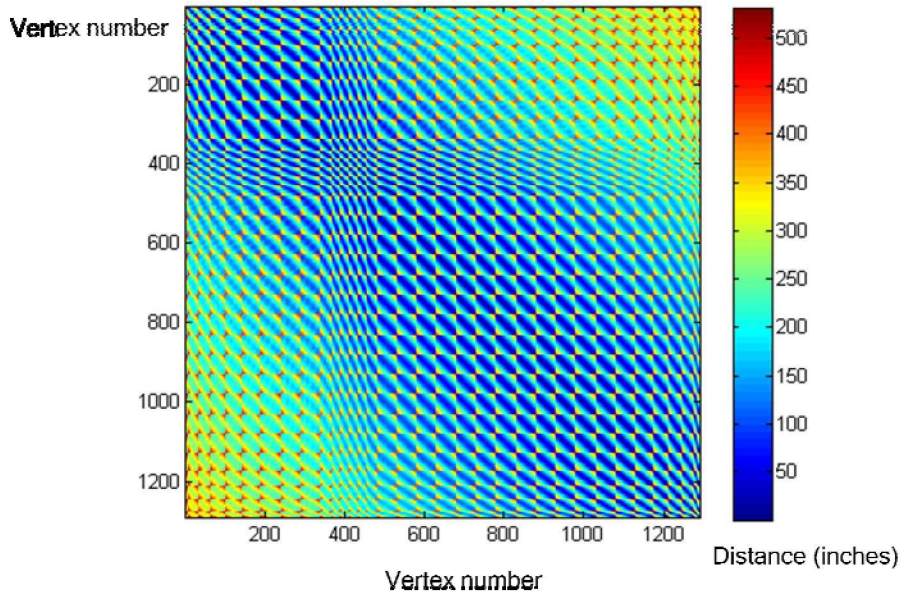


Figure 8. An example of the pair-wise distance matrix for all vertices on the mesh of Figure 4.

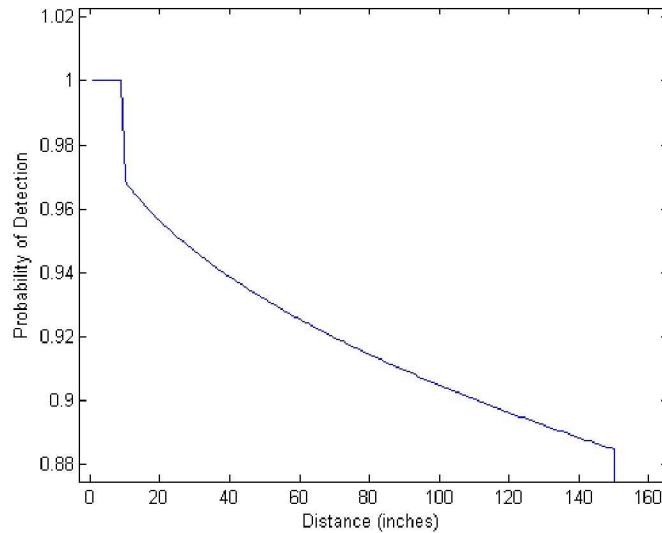


Figure 9. The detection probability as a function of distance.

In the iterative algorithm, we first compute a geodesic distance matrix that contains the pair-wise distances among all vertices on the ISS mesh. An example of the distance matrix that is based on the mesh in Figure 4 can be seen in Figure 8. The sensor coverage in the placement algorithm will be determined from the distance matrix. We assume that the probability of detection by the acoustic sensor varies exponentially as a function of the distance between the target and the sensor in the following approximation:

$$P(d_{ij}) = \begin{cases} 1, & d_{ij} < D_l, \\ e^{-\lambda d_{ij}}, & D_l \leq d_{ij} \leq D_u, \\ 0, & d_{ij} > D_u. \end{cases}$$

In this case, we assume the probability of detection is 1 if the target-to-sensor distance d_{ij} is less than $D_l = 10$ inches, and the probability of detection is 0 if the target-to-sensor distance is greater than $D_u = 150$ inches. If the target-to-sensor distance is between 10 and 150 inches, the probability of detection is an exponential function of the distance with parameters $\lambda = 0.01$ and $\mu = 0.5$. The detection probability function is shown in Figure 9.

The miss probability (the probability of failing to detect the target) matrix is defined as $M(d_{ij}) = 1 - P(d_{ij})$. Starting with one sensor, the algorithm iterates through each location (vertex) on the mesh model. At each location, the total value of the miss probability matrix is computed. The optimal sensor placement is determined to be the location that minimizes the total miss probability value. The miss probability matrix is updated after the placement of that particular sensor. The algorithm iterates with additional sensors until the total miss probability value is minimized. In Figure 10(a), the detection probability function is illustrated using the pair-wise distance matrix in Figure 8 and the probability detection function $P(d_{ij})$. Figure 10(b) rescales the image in Figure 10(a) to accentuate the details in the plot.

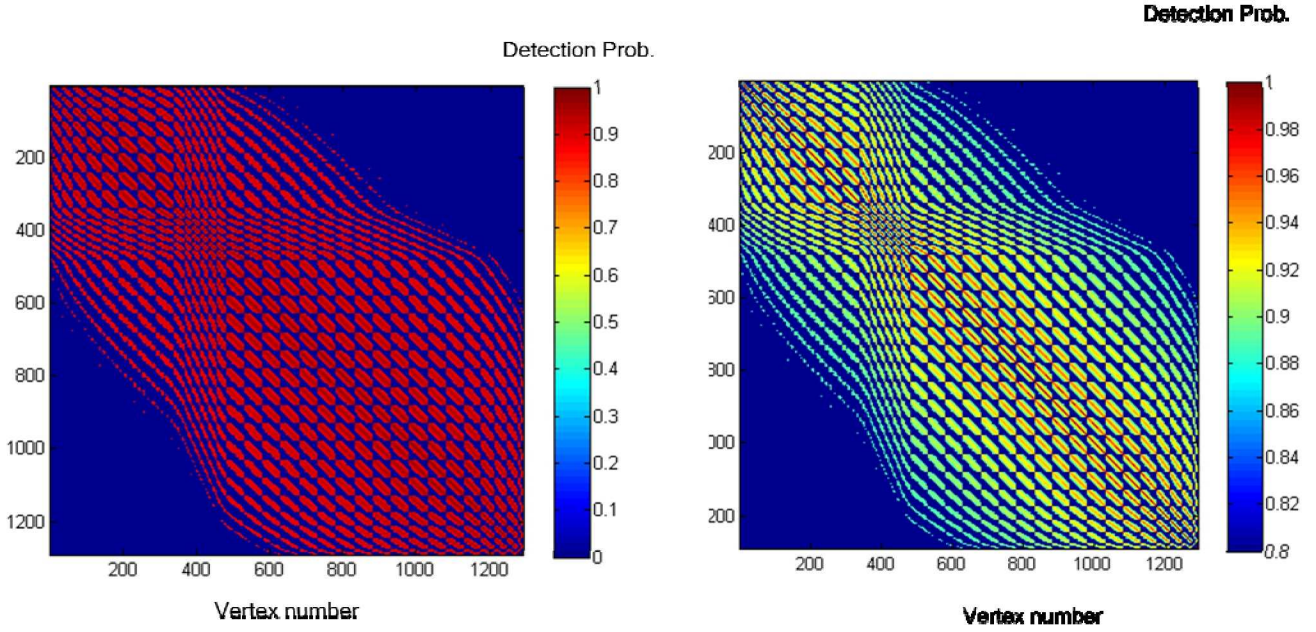


Figure 10. The detection probability: (a) the pair-wise probability detection function, and (b) its rescaled image.

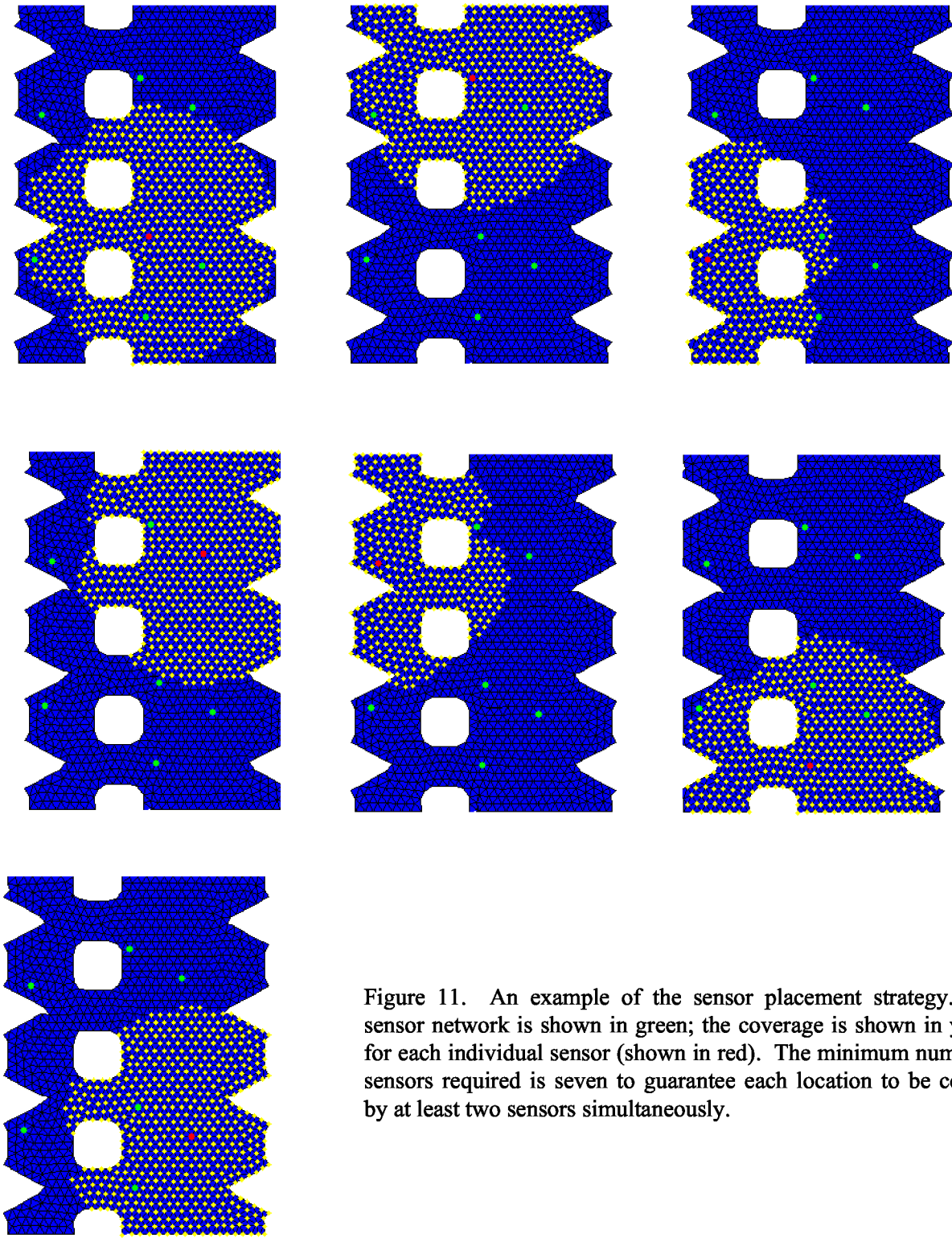


Figure 11. An example of the sensor placement strategy. The sensor network is shown in green; the coverage is shown in yellow for each individual sensor (shown in red). The minimum number of sensors required is seven to guarantee each location to be covered by at least two sensors simultaneously.

For the node mesh model shown in Figure 4, we apply the placement technique as described previously. The resulting placement configuration is shown in Figure 11. In this case, we impose that each location must be detectable by at least two sensors simultaneously. The required minimum number of sensors is seven. In practice, installing sensors at those exact locations may not be feasible because it can be difficult and time-consuming to place sensors in certain spots on-board of a space station. The easiest place to install a sensor is near the hatch doors and end cone areas. Figure 12 shows an alternative configuration of the sensor network (sensors are shown in green). In this case, eight sensors are required to accurately detection the leak location; a detection example will be given in the following section for this particular sensor placement.

3.3. Leak Detection and Localization Method

In the preceding sections, we have obtained the three required components of the real-time leak detection and localization process. The first component is the mesh representation of the ISS node model, in which the physical locations on the ISS node surface are mapped into corresponding vertices on the mesh. The second component is the sensor-network design. The locations of a number of acoustic sensors are strategically selected such that the sensor coverage is optimized subject to physical constraints of the ISS node geometry. The third component is a computation of the acoustic field. This was accomplished by pre-computing the surface distance matrix $\mathbf{D}_r(v)$, which contains the geodesic distances from the sensors to all other locations on the mesh. Then for demonstration purposes, we computed the acoustic field as an inverse distance formula using amplitude-distance decaying polynomial $f(d) = \log(a)$. The sensor-to-leak distance is determined based on the inversion of $f(d)$.

Suppose a leak is present at location v_0 , the detection system measures the received maximum amplitudes $\mathbf{A}_{r,max}$ and compares them to a threshold level. The system then identifies the incoming signal as a leak. Using the inverse amplitude-distance decaying polynomial function, the distances between the sensors and the leak can be estimated from $\hat{\mathbf{d}}_r = f^{-1} \log(\mathbf{A}_{r,max})$. Next, we will determine the actual leak location using $\hat{\mathbf{d}}_r$ and the pre-computed matrix $\mathbf{D}_r(v)$. The localization algorithm iterates through all vertices $v_l, l = 1, \dots, L$ on the mesh. At each vertex, the distances between that particular vertex and the sensors are computed from $\mathbf{D}_r(v)$, we denote this term as $\mathbf{d}_r(v_a), a \in [1, L]$. Then we compute the correlation coefficient between $\hat{\mathbf{d}}_r$ and $\mathbf{d}_r(v_a)$, and store the resulting coefficient. This process is repeated for all vertices $v_l, l = 1, \dots, L$. The vertex number that corresponds to the maximum correlation coefficient is the optimal estimate of the leak source location. The correlation computation can be formulated as

$$\begin{aligned} \rho(v_l) &= \rho(\hat{\mathbf{d}}_r, \mathbf{d}_r(v_l)) \\ &= \frac{\text{cov}(\hat{\mathbf{d}}_r, \mathbf{d}_r(v_l))}{\sigma_{\hat{\mathbf{d}}_r} \sigma_{\mathbf{d}_r(v_l)}} \\ &= \frac{E\{[\hat{\mathbf{d}}_r - \mu_{\hat{\mathbf{d}}_r}][\mathbf{d}_r(v_l) - \mu_{\mathbf{d}_r(v_l)}]\}}{\sigma_{\hat{\mathbf{d}}_r} \sigma_{\mathbf{d}_r(v_l)}} \quad \text{for } l = 1, \dots, L, \end{aligned}$$

whereas $\text{cov}(\cdot)$ denotes the covariance operation and $E\{\cdot\}$ denotes the expectation operation, and σ is the standard deviation. The optimal estimate of the leak location \hat{v}_o is determined to be the vertex number that maximizes the correlation coefficient, for instance, $\rho(\hat{v}_o) = \max_v \rho(v)$. In Figure 12, four leak sources (shown in red) are placed at random locations on the mesh model. We apply the algorithm described in this section to the leak, and the results are shown in Figure 13. These images contain the correlation coefficient gradients from our detection results. The four leak sources are colored in white. The concentrated dark red indicates high correlation coefficient value, which implies the leak source is most likely to be found within those areas. For the locations that are further away from the leak, the coefficient value decreases as shown in blue.

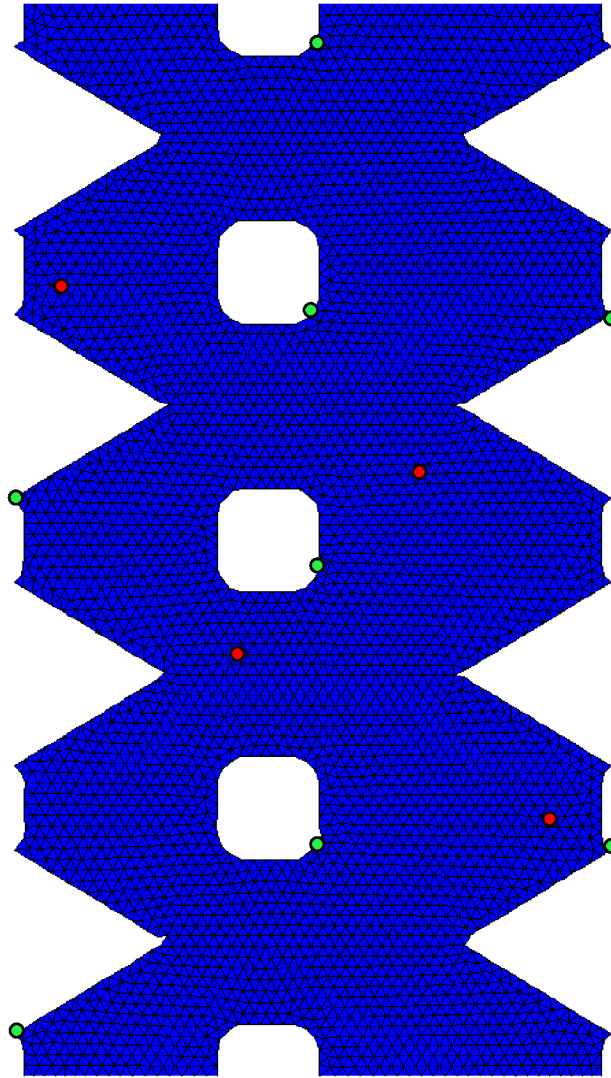


Figure 12. An example sensor placement and leak source configuration. The eight sensors are shown in green whereas the four leak sources are shown in red.

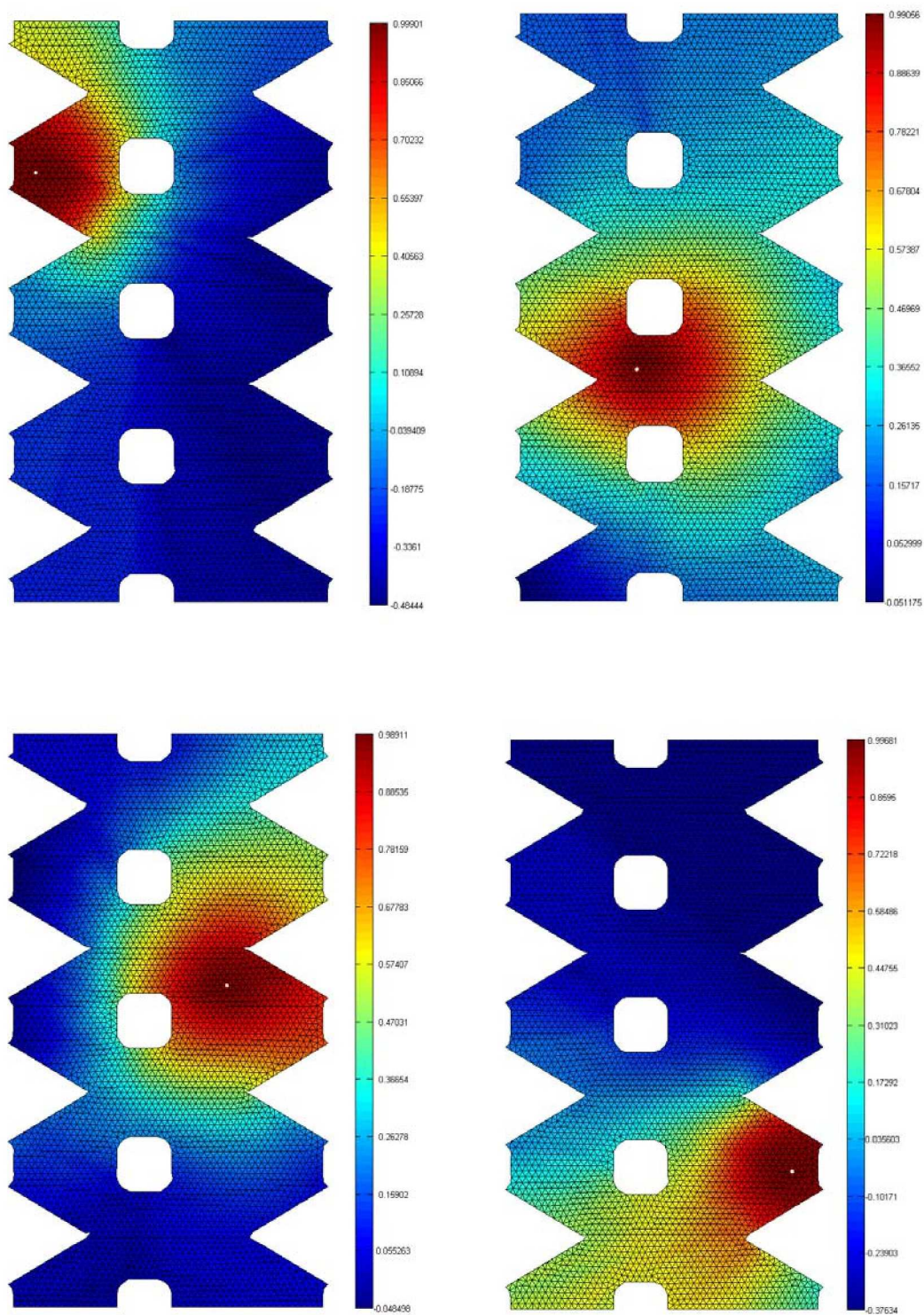


Figure 13. Correlation coefficient gradient plots for four random leak sources (shown in white).

In an ideal situation, the location that has the highest correlation coefficient corresponds to the leak source position. However, in practice the estimate can be affected by two factors. First, the random noise level in the amplitude measurements may skew the coefficient values. Second, the pre-determined amplitude-distance decaying function can be slightly different from the real-time amplitude-distance relationship, which causes the distance calculation to be slightly offset.

4. Conclusions and Future Work

The development of a robust and efficient leak detection and localization system within a space station environment presents a unique challenge. Most of the commonly known acoustic leak detection and localization systems are designed for far-field detection scenarios in which the acoustic signals travel within an airborne environment. These methods are ineffective if applied to a sensor detection system within the space station environment. In which case, a detection system that is capable of locating the leak in a near-field and structure-borne environment is required.

In this paper, we propose a novel technique that employs an amplitude-based method for ISS leak detection and localization using acoustic sensor networks. This method utilizes the structural uniqueness of the space station node module and emphasizes the amplitude decaying properties of the acoustic signals and the surface mesh system of the module. In this algorithm, a discrete mesh system is constructed for the ISS Node Module initially. A distance matrix that contains the shortest paths (geodesic paths) on the station surface is then generated using the discrete mesh. The sensors are characterized by the amplitude-distance decaying function using experimental data sets. The pre-defined components are applied to the detection and localization algorithm during real-time operation. This approach is especially effective when the computational and physical resources are limited since the most required algorithmic elements are pre-determined and stored in the memory.

The leak location is determined from the correlation coefficients between the estimated sensor-to-leak distances and the distances computed from amplitude measurements. The accuracy of the estimation can be affected by measurement distortions such as random noises. To compensate for the distortions, the spread of the correlation gradient can be taken into consideration. One method is to find the location that has the highest concentration of top coefficient values, and use it as the final estimate. Another method is to interpret the data as the level of confidence from a probabilistic standpoint instead of pin-pointing out a single location. These issues will be addressed in future research.

References

1. A. G. Piersol, "Time delay estimation using phase data," *IEEE Transactions on Acoustics, Speech, and Signal Processing*, Vol. ASSP-29, No. 3, June 1981.
2. Y. T. Chan and K. C. Ho, "A simple and efficient estimator for hyperbolic location," *IEEE Transactions on Signal Processing*, Vol. 42, No. 8, August 1994.
3. C. H. Knapp and G.C. Carter, "The generalized correlation method for estimation of time delay," *IEEE Transactions on Acoustics, Speech, and Signal Processing*, Vol. ASSP-24, No. 4, August 1976.
4. I. Ziskind and M. Wax, "Maximum likelihood location of multiple sources by alternating projection," *IEEE Transactions on Acoustics, Speech, and Signal Processing*, Vol. 36, No. 10, October 1988.
5. M. Brandstein and D. Ward (Eds.), *Microphone Arrays: Signal Processing Techniques and Applications*, Springer-Verlag, Berlin, 2001.
6. R.A. Altes, "Target position estimation in radar and sonar, and generalized ambiguity analysis for maximum likelihood parameter estimation," *Proc. IEEE*, Vol. 67, 1979.
7. W.C. Knight, R.G. Pridham and S.M. Kay, "Digital signal processing for sonar," *Proc. IEEE* Vol. 69, No. 11, 1981.
8. R.J. Urick, *Principles of Underwater Sound*, McGraw-Hill, New York, 3rd Ed., 1983.
9. D. Lockner, "The role of acoustic-emission in the study of rock fracture," *International Journal of Rock Mechanics and Mining Sciences & Geomechanics*, Vol. 30 No. 7, Dec. 1993.
10. M. Steven, S.M. Ziola and M.R. Gorman, "Source location in thin plates using cross-correlation," *J. Acoust. Soc. Amer.*, Vol. 90, No. 5, 1991.
11. L. Gaul and S. Hurlebaus, "Identification of the impact location on a plate using wavelets," *Mech. Systems Signal Process*, Vol. 12, No. 6, 1997.
12. H. Jeon and Y.S. Jang, "Wavelet analysis of plate wave propagation in composite laminates," *Composite Structures*, Vol. 49, No. 4, Aug. 2000.
13. Y.-C. Choi and Y.-H. Kim, "Impulsive sources localisation in noisy environment using modified beamforming method," *Mech. Systems Signal Process*, Vol. 20, No. 6, 2006.
14. S.D. Holland, D.E. Chimenti, R. Roberts, "Locating air leaks in manned spacecraft using structure-borne noise," *Journal of the Acoustical Society of America*, Vol. 121, No. 6, June 2007.
15. R. Kimmel and J. Sethian, "Computing geodesic paths on manifolds," *Proc. Natl. Acad. Sci. USA*, Vol. 95, pp. 8431-8435, July 1998.

16. J. A. Sethian, "A fast marching level set method for monotonically advancing fronts," *Proc. Natl. Acad. Sci. USA*, Vol. 93, pp. 1591-1595, 1996.
17. J.A. Sethian, *Level Set Methods and Fast Marching Methods: Evolving Interfaces in Computational Geometry, Fluid Mechanics, Computer Vision, and Material Science*, Cambridge University Press, Cambridge, 1999.
18. K. Chakrabarty, S. S. Iyengar, H. Qi, and E. Cho, "Grid coverage for surveillance and target location in distributed sensor network," *IEEE Transactions on Computers*, Vol. 51, No. 12, December 2002.
19. C. Wu, K. Lee, and Y. Chung, "A Delaunay triangulation based method for wireless sensor network deployment," *Proc. of IEEE 12th International Conf. on Parallel and Distributed Systems*, August, 2002.
20. S. S. Dhillon and K. Chakrabarty, "Sensor placement for effective coverage and surveillance in distributed sensor networks," *Proc. of IEEE Wireless Communications and Networking Conf.*, pp. 1609-1614, 2003.

REPORT DOCUMENTATION PAGE					Form Approved OMB No. 0704-0188	
<p>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p> <p>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</p>						
1. REPORT DATE (DD-MM-YYYY)		2. REPORT TYPE			3. DATES COVERED (From - To)	
01-11-2009		Technical Memorandum				
4. TITLE AND SUBTITLE An Amplitude-Based Estimation Method for International Space Station (ISS) Leak Detection and Localization Using Acoustic Sensor Networks				5a. CONTRACT NUMBER		
				5b. GRANT NUMBER		
				5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Tian, Jialin; Madaras, Eric				5d. PROJECT NUMBER		
				5e. TASK NUMBER		
				5f. WORK UNIT NUMBER 401769.06.03.04.02.12		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) NASA Langley Research Center Hampton, VA 23681-2199				8. PERFORMING ORGANIZATION REPORT NUMBER L-19789		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001				10. SPONSOR/MONITOR'S ACRONYM(S) NASA		
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) NASA/TM-2009-215948		
12. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified - Unlimited Subject Category 18 - Spacecraft Design, Testing and Performance Availability: NASA CASI (443) 757-5802						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT The development of a robust and efficient leak detection and localization system within a space station environment presents a unique challenge. A plausible approach includes the implementation of an acoustic sensor network system that can successfully detect the presence of a leak and determine the location of the leak source. Traditional acoustic detection and localization schemes rely on the phase and amplitude information collected by the sensor array system. Furthermore, the acoustic source signals are assumed to be airborne and far-field. Likewise, there are similar applications in sonar. In solids, there are specialized methods for locating events that are used in geology and in acoustic emission testing that involve sensor arrays and depend on a discernable phase front to the received signal. These methods are ineffective if applied to a sensor detection system within the space station environment. In the case of acoustic signal location, there are significant baffling and structural impediments to the sound path and the source could be in the near-field of a sensor in this particular setting.						
15. SUBJECT TERMS Acoustic sensor networks; Geodesic surface distance; ISS node module; International Space Station (ISS); Leak detection and localization; Spacecraft leak localization algorithm; amplitude-based estimation method						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	
a. REPORT	b. ABSTRACT	c. THIS PAGE			STI Help Desk (email: help@sti.nasa.gov)	
U	U	U	UU	24	19b. TELEPHONE NUMBER (Include area code) (443) 757-5802	