A Model for an Omnidirectional Radiometer

M. E. Jansen,[a] L. R. Gauthier, Jr.,[b] N. W. Rolander[c]
The Johns Hopkins University Applied Physics Laboratory
11100 Johns Hopkins Road, Laurel, MD, USA 20723-6099

ABSTRACT

Most radiometers are directionally sensitive. Measuring optical radiation in a given environment is typically done using a collection aperture pointing in the direction of the optical source. The collection aperture has a limited field of view, and the collection efficiency decreases as the angle from direct line of sight increases. Thus, radiometers typically have a limited solid angle for viewing sources. This paper describes a model of an omnidirectional, multi-channel, rotating radiometer that provides a framework for acquiring spatially comprehensive radiometric data from an environment. By exploiting the spatial diversity of multiple collection apertures in multiple directions, sources from all directions are measured via three-dimensional scanning. As the radiometer rotates, data are collected that denote the radiant flux seen by each collection aperture as a function of time. These waveforms are used to determine the directions and magnitudes of electromagnetic sources in the environment without requiring a priori knowledge about the directions of specific sources.

Keywords: omnidirectional, radiometer, radiometry

1. INTRODUCTION

The measurement of optical radiation is typically achieved through the orientation of a single directional collection aperture toward an electromagnetic source. Knowledge of the expected location of the source is key in the success of accumulation of radiometric data. In applications where the location of the source is unknown, and where the potential source space exceeds the field of view (FOV) of the collection aperture, conventional radiometry is not sufficient.

This paper presents a model of an omnidirectional, multi-channel, rotating radiometer that is capable of detecting optical sources located in any direction. The tailoring of collection apertures to achieve this goal, and the analysis algorithm used to resolve the source locations and magnitudes, are described.

2. CONVENTIONAL RADIOMETRY

Radiometry involves the measurement of a physical effect on a detector resulting from incident radiative flux [1]. An optical filter may be used in front of the detector element to tailor the spectral measurement band. In charge-based detectors, the physical effect is the release of charge carriers within the detector material. The freed charges produce a current that is converted to a measureable voltage by a transimpedance amplifier. In thermal detectors the physical effect is different, relying on temperature changes within the detector material rather than charge production. The measured temperature changes, when separated from background effects, provide the measurement of the incident radiation. Figure 1 illustrates the basic elements of a single-channel radiometer.

[a] Melissa.Jansen@jhuapl.edu, [b] Leo.Gauthier@jhuapl.edu, [c] Nathan.Rolander@jhuapl.edu

Fiber Optic Sensors and Applications VI, edited by Eric Udd, Henry H. Du, Anbo Wang, Proc. of SPIE Vol. 7316, 73160Q
 · doi: 10.1117/12.818650

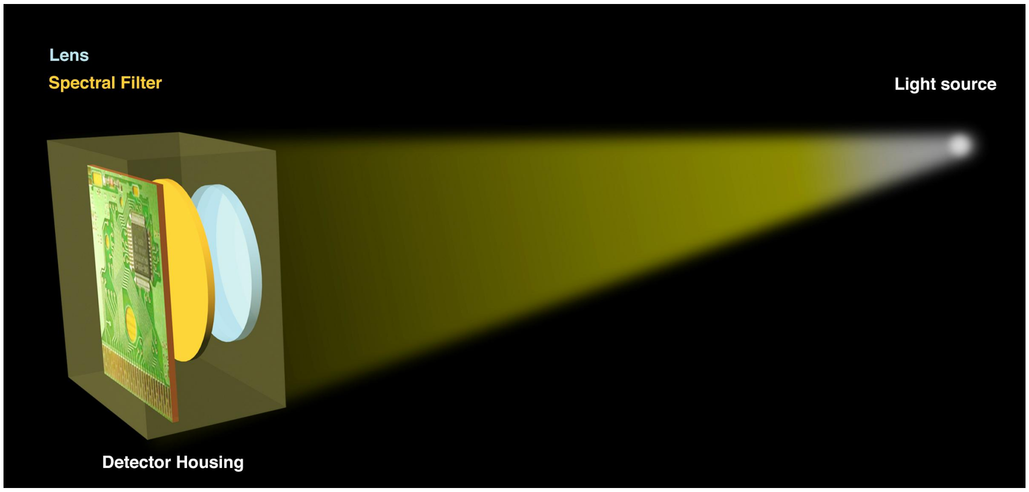

Figure 1 Directionality of Single Channel Radiometer

There are several aspects of radiation measurements that affect the feasibility and accuracy of the measurements in a particular application. These include the response time of the detector, the geometry between the radiation source and the detector, and the relative motion between the detector and the source. Detector response time is the critical physical characteristic of a detector. Charge-based detectors have very short response times, typically on the order of nanoseconds. The physical requirement is that the incident radiation is able to couple enough energy into the detector to break the bonds that hold the electrons. When capacitive and electronic effects are taken into account, the response time of the detection system is usually in the microsecond range. Thermal detectors have much slower response times, usually on the order of milliseconds. It takes longer for thermal detectors to change temperature because this involves diffusion of internal energy through the detector material.

With either type of detector, the typical usage involves maintaining a static geometry between the source and the detector while the measurement is being made. The detector is oriented to "view" the source, and this geometry is maintained over the measurement period. However, in some applications, the source location or direction relative to the detector is not known or changes over time. This poses many challenges. Most detectors are directionally selective. There is some direction vector, typically normal to the surface of the detector, that provides maximal response from the detector. The detector response is attenuated as the detector orientation with respect to the source is moved off normal. As the off-axis angle is increased, the detector response eventually goes to zero. The half-angle FOV of a detector is often defined as the off-axis viewing angle that results in half the detector signal as the direct view. Thus, it is clear that even in a fixed geometry situation, the pointing of the detector is an important aspect of the measurement. Figure 2 shows a typical fall-off function from a single detector. The sudden drop to 0, in this case at a 60 degrees off-axis viewing angle, is due to a typical mechanical stop that prevents stray light from entering a collection aperture [2].

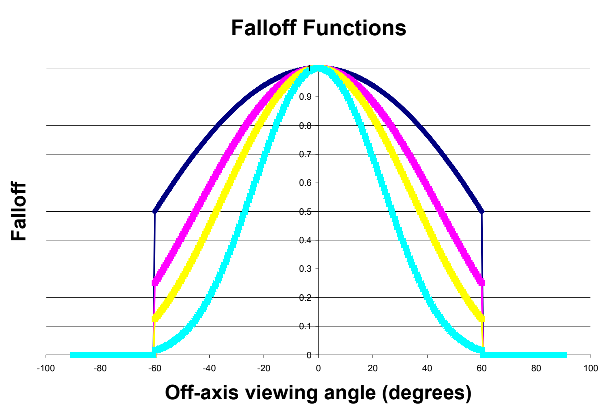

Figure 2 Typical Detection Aperture Falloff Functions

When the source position is unknown or moving relative to the detector, it is impossible to know whether the detector orientation of a particular detector is correct for properly measuring the radiation from the source. However, by using several detectors with overlapping FOVs, it is possible to ensure that at least one detector will always detect events of interest. For the purposes of this paper, the multi-channel measurement system will be a rotating sensor platform in three-dimensional space with a set of radially oriented directionally sensitive detectors with overlapping FOVs. Figure 3 illustrates the arrangement (dandelion). The typical scenario will include an environment with multiple sources of relatively constant radiation that constitute the "background" with superimposed events of interest that may happen at any time.

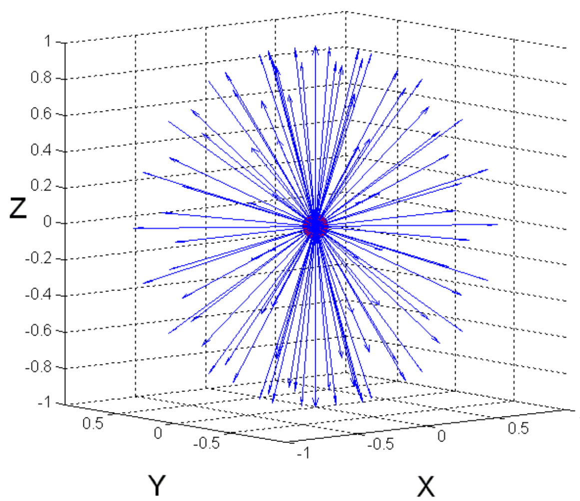

Figure 3 Omnidirectional Radiometer Multichannel Arrangement

It is necessary that the response times of the detectors are short enough such that the measurement system is essentially static over the measurement timeframe. For charge-based detectors, this criterion is easily met over the range of most moving detector platforms as a result of the very fast detector response time. For example, even if the detector platform was rotating at 10 Hz, a source would be in the FOV of a detector for several milliseconds, allowing for a good measurement.

In a static single-channel or multi-channel situation, the ambient or background signal changes very slowly over time. In a rotating multi-channel measurement system, the ambient background measurement consists of a set of periodic waveforms that are measured as the sensors scan the surrounding space. Events of interest are detected signals that are often not periodic and may not be of sufficient duration to be detected by all channels. In a single channel system, the source radiance measurement is calculated by subtracting the ambient background reading and correcting for off-axis viewing. In the multi-channel system, the separation of the ambient and background signals is more complicated; however, this complexity is offset by the elimination of the requirement to actively point detectors at the source.

3. MODEL FOR OMNIDIRECTIONAL RADIOMETRY

A model has been developed for an omnidirectional, multi-channel, rotating radiometer. The omnidirectional radiometer consists of multiple collection apertures oriented radially outward from a common center, allowing the radiometer to monitor the source space in multiple directions simultaneously. Each individual collection aperture corresponds to a single channel, pointing in a given direction with the collection efficiency of the channel decreasing as the angle from direct line of sight (LOS) increases. Thus, an individual channel has a limited solid angle in which to monitor the source space. By including multiple channels, and tailoring the falloff function of the channels, it is possible for a single radiometer to sufficiently view all of the source space.

The number of channels needed to adequately cover the solid angle of the full source space is dependent in part on the falloff function of the individual channels. In the case of a detection aperture with a narrow falloff function, the solid angle in view of each aperture is small, and numerous apertures, or channels, may be needed. Figure 3 shows a radiometer core with numerous detection apertures used to monitor the source space in all directions. As the falloff function of the individual channels is tailored, the number of channels to cover a full 4π steradians of the source space may be increased or reduced. Figure 4 shows a six-channel omnidirectional radiometer. The radiometer center is shown in red, and the collection apertures, extending radially, are shown in blue.

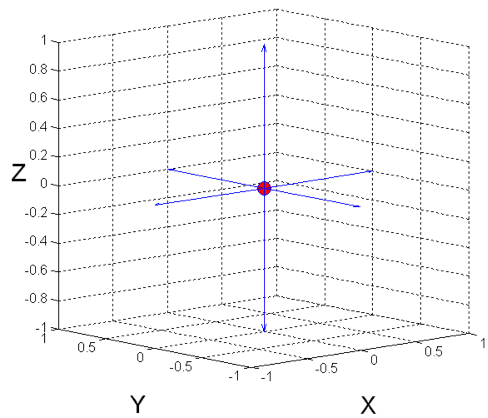

Figure 4 Omnidirectional Radiometer with Six Channels

4. TAILORING OF A FALLOFF FUNCTION FOR A GIVEN APPLICATION

Each channel on an omnidirectional radiometer is made up of multiple apertures. This section describes an approach for the design of a wide angle radiometry probe. This probe is used to drive a single radiometer channel. The wide angle probe is fundamentally an arrangement of apertures such that the summation of the individual falloff functions creates the desired response over the solid angle of interest. Thus, before the process can begin, the falloff function of an individual aperture must be characterized. With this measurement complete, the cumulative falloff function can be designed as an optimization problem to match the desired falloff shape. This problem has two variables: the number of apertures and the angular placement of each aperture relative to the probe's normal vector.

The cumulative falloff function is computed in spherical coordinates by sweeping through a 2π steradians solid angle in a nested loop structure. For each elevation angle step from 0 to 90 degrees, an angle of interest $\vec{a}$ is defined and swept though a radial revolution of 2π. During each radial step, the resulting falloff of $\vec{a}$ is computed as outlined in Figure 5.

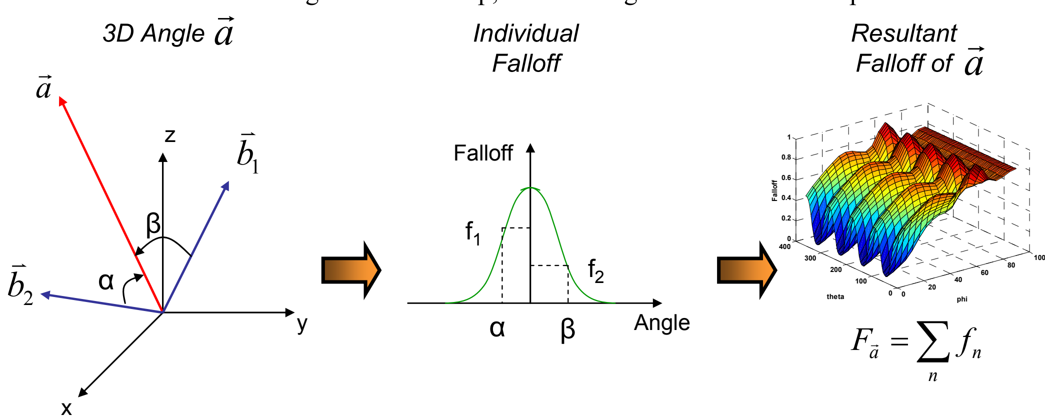

Figure 5 Computation of Cumulative Falloff

The angles between the vector of interest, $\vec{a}$, and all n apertures, $\vec{b}_n$, are computed using equation (1).

$$angle = \tan^{-1}\left(\frac{\left|\vec{a}\times\vec{b}_n\right|}{\vec{a}\cdot\vec{b}_n}\right) \tag{1}$$

The values of the individual falloff functions for each aperture, f_n, are then computed and summed to produce F_a, the net falloff for the angle of interest. The final cumulative falloff function is a two-dimensional lookup table of F_a values for all elevation and radial angles. An example of a cumulative falloff function for each aperture for a five-aperture system, with one aperture aligned with the normal and the other four equally distributed radially at 60 degrees of elevation to the normal axis, is shown in Figure 6.

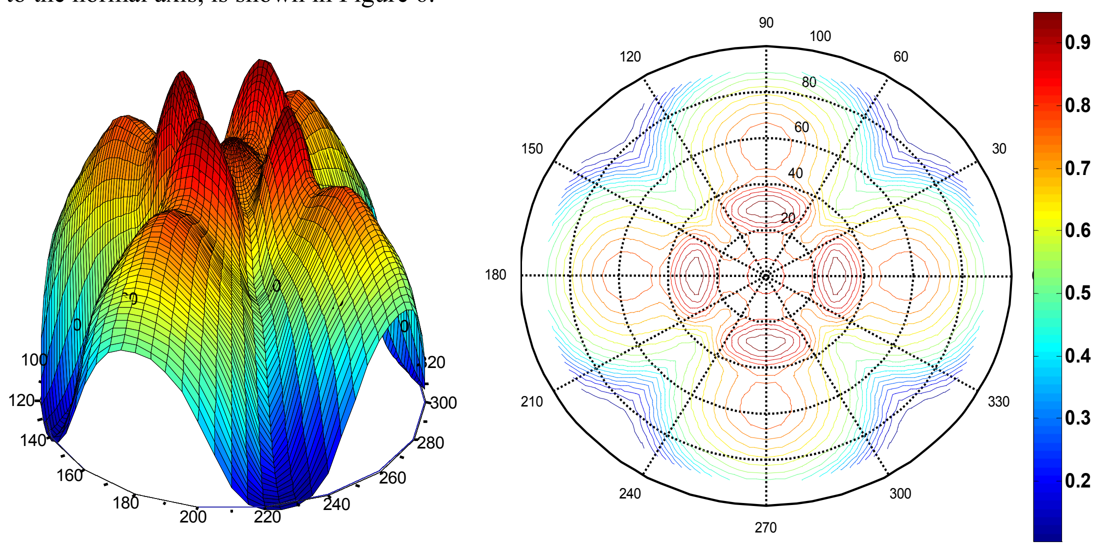

Figure 6 Sample Cumulative Falloff Function for Five-Aperture Probe

Optimization of this cumulative falloff function is a challenging problem because of the combination of discrete (number of apertures) and continuous variables (angle between apertures). Therefore, conventional gradient-based optimization techniques are not effective. However, provided the individual aperture falloff functions are reasonably broad, only a small number of apertures will be required. Therefore, only a few discrete configurations will be worthwhile for further investigation. The aperture angles of these configurations can be quickly optimized using conventional techniques and then normalized for comparison and final design selection. Suitable metrics for evaluation include deviation from the desired falloff, as well as the standard deviation in the solid angles of interest. Lastly, because of the complexity of manufacture, the use of superposition of individual apertures with a wide falloff can be used to create a similar effect to having multiple narrower apertures, but with less complexity and at a smaller scale.

5. OMNIDIRECTIONAL RADIOMETER WAVEFORMS

When an optical source is viewed by a non-rotating omnidirectional radiometer, it is possible for the source to be in a location that is not in direct LOS of any of the detection apertures. Proper tailoring of the falloff functions of the apertures ensures that one or more channels will detect the source even when not in direct LOS. Figure 7 shows a source being observed at an angle by adjacent channels. The two angles, γ_1 and γ_2, are the falloff angles for the two apertures viewing the source. In the absence of rotation of the radiometer, it is still possible to get an estimate of the direction of the source. The source will be located at an angle between the two channels that are viewing it. Analysis of the magnitudes of the signals recorded by the channels, and knowledge of the channel geometry, can be used to obtain an approximation of the direction of the source relative to the radiometer. The more channels that detect the source, the better the estimate will be of the direction of the source.

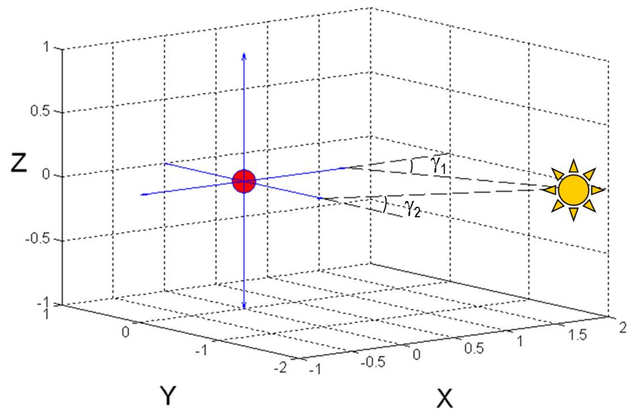

Figure 7 Source Being Viewed by Two Radiometer Channels

In addition to events of interest, the source space will contain some ambient radiation. This background radiation is generally relatively constant and produces predictable periodic waveforms on the channels. Figure 8 is an example of a background scan of a six-channel, non-rotating omnidirectional radiometer.

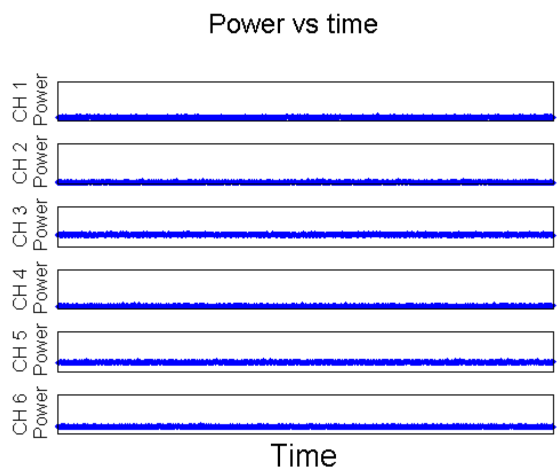

Figure 8 Ambient Radiation Waveforms for Non-rotating Radiometer

Often, ambient sources are located in the source space, which causes the background radiation to differ by direction. Rotation of the radiometer allows for additional information to be gained about the source space. With no events of interest in view, a three-dimensional scan of the source space through rotation of the radiometer provides a record of the ambient or background radiation in the environment. Figure 9 is an example of a background scan of a six-channel rotating omnidirectional radiometer with an existing background source.

As an omnidirectional radiometer rotates, any source within the source space will move into and out of view of various channels, producing a set of waveforms corresponding to the signal produced on each channel. If an ambient scan of the source space is performed, the background may be subtracted out. Figure 10 shows a simulated example of a set of waveforms from a six channel rotating omnidirectional radiometer viewing an impulse, with the ambient radiation removed.

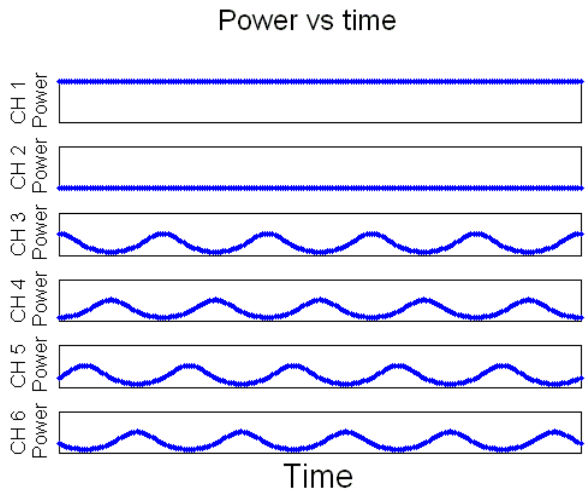

Figure 9 Ambient Radiation Waveforms for Rotating Radiometer

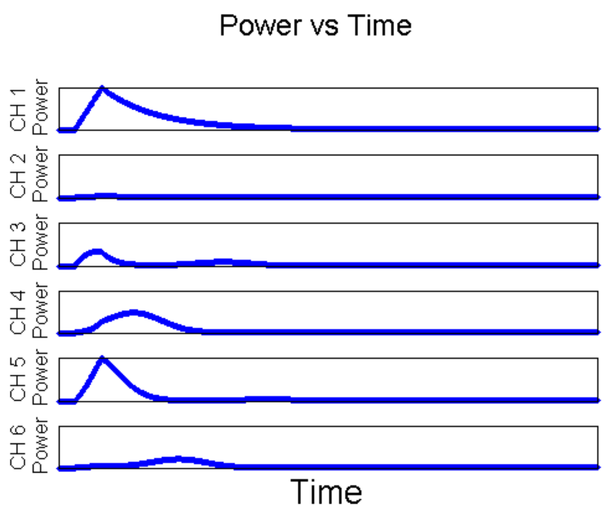

Figure 10 Example of Omnidirectional Radiometer Waveforms

These waveform patterns provide additional information as to the location of the source. Given the waveforms of the omnidirectional radiometer channels through the course of at least one rotation about a known axis, it is possible to calculate an estimate of the location of sources in the environment.

6. SOURCE LOCATION ALGORITHM

To determine the location of the source, a sphere of fixed radius is defined with the radiometer core at the center. If the expected distance of the source is known, that information can be used to set the initial radius of the sphere. Otherwise, an arbitrary initial radius may be chosen because the radius will be altered later on in the process. The surface of the sphere is broken down into a grid of points, each of which corresponds to a potential source location. Figure 11 shows a spherical grid surrounding the radiometer.

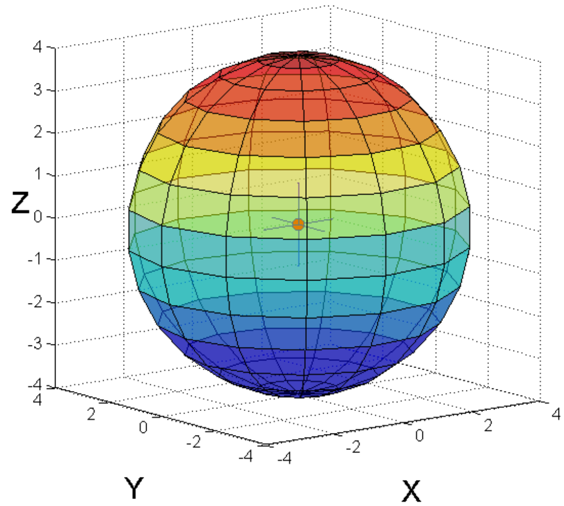

Figure 11 Spherical Grid of Potential Source Locations

For each point on the grid, the waveforms that would result if a single source was located at that grid point, and was the only source in the source space, are calculated. This process is completed for each grid point on the surface of the sphere. The resulting waveforms are then compared to the actual waveforms collected by the radiometer, and the least-squares error calculated, to determine which grid point results in waveforms that most closely match the actual waveforms. Any points of saturation must be removed prior to error calculations.

Once the best grid point has been determined, a surface in the vicinity of the best grid point, and with smaller granularity, is defined. Figure 12 is an example of such a surface.

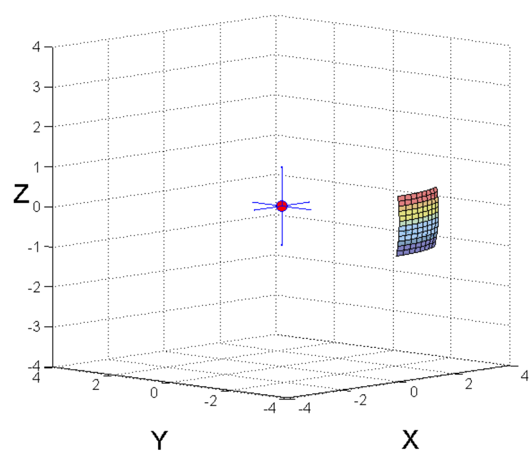

Figure 12 Surface of Potential Source Directions

Again, a source is assumed for each grid point on the surface in turn, and predicted waveforms are calculated. These sets of waveforms are then compared with the actual waveforms to determine the grid point with the closest match to the actual waveforms, indicating the direction of the source of interest.

The intensity of the source at this gridpoint and the distance of this source from the center of the radiometer are altered to further lower the error in the waveforms to determine the location and intensity of the source.

7. CONCLUSIONS AND FUTURE EFFORTS

A multi-channel, rotating, omnidirectional radiometer provides the ability to measure the intensity of an electromagnetic source without a priori knowledge of its direction or location. Given the waveforms of an omnidirectional radiometer, the location of a single source can be successfully determined. Future efforts include the location of multiple sources based on waveform analysis, the location of non-fixed sources, location of complex time-varying sources, and modeling of complex rotation of the radiometer body. In addition, the radiometric accuracy of the omnidirectional radiometer will be estimated based on model parameters.

8. ACKNOWLEDGEMENTS

The authors would like to acknowledge Dr. S. E. Hawkins, III, Dr. E. H. Darlington, and Mr. E. T. Donald, of the JHU/APL Space Department, who are developing hardware for the omnidirectional radiometer; Mr. M. W. Noble, of the JHU/APL Space Department, who performed optical modeling; and Mr. J. Elbaz of JHU/APL for his contributions to the technical illustrations.

REFERENCES

[1] Parr, A., Datla, R. and Gardner, J., [Experimental Methods in the Physical Sciences, Volume 41], Elsevier Inc., The Netherlands (2005).

[2] Egerton, R.F, and Wang, Z.L, "Plural-Scattering Deconvolution of Electron Energy-Loss Spectra Recorded with an Angle-Limiting Aperture", *Ultramicroscopy*, 32 (2), 137-147 (1990).