

# Characterization of rocket and jet noise using near-field acoustic holography methods

Alan T. Wall, Kent L. Gee, and Michael D. Gardner

*Brigham Young University, Provo, Utah 84602*

Michael M. James

*Blue Ridge Research and Consulting, Asheville, NC 28801*

As rockets and jets on military aircraft become more powerful, the noise they produce can lead to structural fatigue, hearing damage, and community disturbances. Noise-reduction technologies and sound radiation prediction require accurate characterization of the noise sources within rocket plumes and jets. Near-field acoustical holography techniques were used to visualize the sound field in the region of the jet exhaust on a high-performance military jet. Holography requires a coherent measurement of the sound field, but the size of the jet made a dense measurement over the entire source region impractical. Thus, a scan-based measurement was performed, after which a partial field decomposition (PFD) procedure was used to tie together incoherent scans. Then, the effective aperture of the measurement was extended utilizing the rigid ground reflection and a processing technique called analytic continuation. Finally, the three-dimensional sound field was reconstructed using statistically-optimized near-field acoustical holography (SONAH). This is the first time such a map has been obtained for a full-scale military aircraft. [Work supported by Air Force SBIR.]

## INTRODUCTION

Characterization of the spatial distribution of noise sources within a rocket plume or a jet provides insight into physical noise generation mechanisms in the turbulent flow field, which can contribute to noise reduction technologies and prediction of the radiated sound field. The high pressures associated with acoustic pressure waves emitted by such sources can cause structural damage to spacecraft or aircraft and shuttle launch pad structures, cause significant hearing loss for military personnel, and is a disturbance to communities.

Acoustical inverse methods are being used to attempt to localize noise sources within the jet of a full-scale military aircraft, because they employ a non-intrusive measurement of the sound field outside of the flow field, and then use the wave nature of sound to obtain sound field information at or within the source. Methods such as particle image velocimetry and hot-wire anemometry have been employed to localize noise sources within jets, but these methods are not practical for the hot, fast flows of full-scale military jets. Near-field acoustical holography (NAH) is the acoustical inverse method being employed in this study. NAH allows a three-dimensional map of the sound field to be generated from a single two-dimensional measurement. The process discussed in this work can apply as well to rocket noise, as both have similar noise-generation mechanisms and radiation properties.

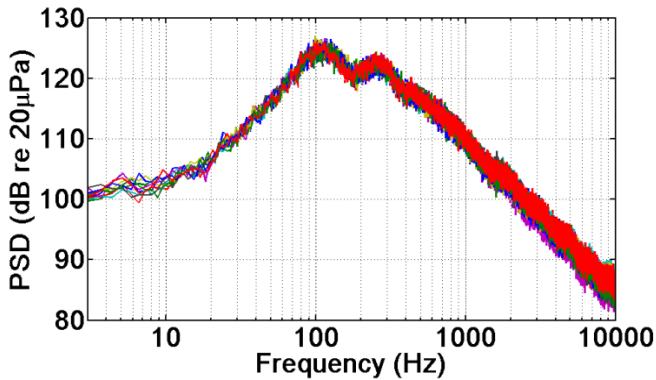
Before performing NAH, a coherent measurement plane is required. It also requires a grid

spacing fine enough to resolve multiple points per wavelength. This requirement has been met through a scan-based measurement of the sound field with a dense array of microphones. The coherent field is obtained from the series of incoherent scans with the use of fixed reference microphones and partial field decomposition (PFD) method called virtual coherence.

Section I of this paper discusses the properties of sound radiation from jets and other aeroacoustic sources. Section II gives an outline of the theoretical processes of performing NAH. In Section III, details of the physical experiment on a full-scale military aircraft are presented. Section IV contains holography reconstruction results of the three-dimensional sound field.

## I. SOUND RADIATION FROM AEROACOUSTIC SOURCES

The noise radiation from a jet is not well-understood. For jets on high-power military aircraft, the radiation is particularly complicated. The noise spectra measured near a high-power jet are dominated by very low frequencies. Typical spectra will follow the trends of those shown in Figure 1. These spectra were calculated from near-field sound pressures measurements of an F-22 Raptor, approximately 12 m from the jet centerline. Note that the noise is broadband with peak frequencies around 100-150 Hz. These spectra, with the characteristic “haystack” shape of jet noise, are generated by both small and large turbulent structures within the flow field that couple acoustically with the surrounding medium.



**Figure 1** Power spectral density measured at ten different times at about 12 m from the centerline of an F-22 at afterburner engine conditions. The sound power peaks between 100 and 150 Hz, and is highly stationary.

Many noise sources, especially those with characteristic lengths larger than a wavelength, do not radiate like simple sources. For example, a large vibrating plate will have significantly different radiation properties than will a point source. A vibrating plate may be considered a distribution of radiating monopoles. The phase relationships between each monopole on the plate will not be random, but fixed. This fixed-phase relationship causes all the point sources that make up the plate to be coupled in such a way as to generate acoustic radiation into the surrounding fluid very different from that which would be generated by a similar distribution of monopoles all vibrating independently. This fixed-phase relationship may be described by the *correlation* between each monopole.<sup>1</sup> The correlation between two signals describes the degree to which the two signals are related. If the two signals are perfectly related, then the correlation coefficient will have a value of unity. Two fully independent signals will have a correlation coefficient of zero. Because plate vibration is structural, it is a fully correlated source. Signals that are somewhat related will have a correlation coefficient somewhere in between zero and unity. It is well established that aeroacoustic sources are partially correlated over finite distances, and therefore radiate somewhat coherently.<sup>2, 3</sup> The correlation lengths within a jet tend to increase with a decrease in frequency. High frequencies radiate from compact regions and are monopole-like, but the low frequencies that dominate jet noise radiate from larger, non-compact regions and are more highly correlated over larger distances. The exact correlations of the radiating sources within the flow are difficult to measure directly or to simulate computationally.

The radiation of spatially-correlated sources may be described with a sum of multiple wave functions, each with a unique wavenumber. For a given frequency of vibration, certain wave functions will radiate into the far

field, while others will decay away exponentially. These two types of waves are referred to as radiating and evanescent waves, respectively. The energy of evanescently-decaying waves remains in the near field of the source. Both radiating and evanescent waves are important contributions to characterizing the source, so both types of waves must be measured if source radiation mechanisms in a jet are to be fully determined. If measurements are made in the far field, evanescent waves will not be detected. Thus, near-field measurements are necessary for accurate source localization. The sound field in the vicinity of a jet definitely contains both radiating and evanescent waves, but the details of the individual wave number contributions are unclear.

There are several acoustical inverse methods that have been employed to localize jet noise sources including the acoustic telescope technique, the acoustic mirror, the polar correlation technique, and beamforming.<sup>4,7</sup> Typically, these methods assume well-separated compact source. For example, beamforming utilizes an array of microphones and, based on the speed of sound, delays each signal by the proper amount for a given “look” direction, or an assumed angle of incidence. The signals are then summed. For a source truly coming from that direction, the signals will add coherently and describe the source, while waves arriving from other directions will add incoherently. This method does not perform as well for a distributed, partially correlated source.<sup>4</sup> This is one reason that beamforming tends to give accurate results for localizing high frequencies within a jet, but not low frequencies. These methods are also typically performed with measurements in the far field, and thus do not capture the evanescent waves necessary to fully characterize the source. Measurements made in the far field are also limited to source reconstructions of one-half wavelength. Efforts have been made to modify beamforming algorithms for near-field measurements, and to account for spatially non-compact sources.<sup>4</sup> However, we have developed NAH methods as an alternative noise-source-localization technique because of the finite correlations that exist in supersonic jet noise.

The basic theory of NAH is that, from a two-dimensional hologram measurement in the near-field of a noise source, the three-dimensional sound field properties such as pressure, particle velocity, and intensity may be reconstructed in the source region.<sup>8</sup> Measurement in the near-field captures some of the evanescent waves and allows for a more accurate reconstruction. The reconstruction is not limited to a resolution of one-half wavelengths. NAH makes no assumptions about the spatial correlation of the source, and can perform well for spatially extended sources, particularly at low frequencies.

NAH was developed in the 1980s for measuring the vibrations of solid structures. It has only been applied to jet noise within the past decade or so, and has been rather limited.<sup>9</sup> Lee and Bolton<sup>10, 11</sup> successfully performed NAH on a laboratory-scale subsonic cold jet with about a 1 cm nozzle, surrounding the jet exhaust region with 32 microphones. Applying NAH to jets on military aircraft is a large jump, and requires a more rigorous approach. In the following section the process of NAH is outlined.

## II. THE PROCESS OF NEAR-FIELD ACOUSTICAL HOLOGRAPHY

### A. Virtual Coherence

NAH requires a coherent measurement over the hologram to propagate the sound field in toward the source. This means that any fixed-phase relationship between any two points on the measurement plane must be captured. There are two ways to achieve this. All sound pressures may be measured simultaneously using an array of microphones that spans beyond the source region. This kind of measurement is impractical for large sources if a high-resolution is desired. For this work a patch-and-scan measurement is used. A small dense array of microphones is scanned over the hologram surface. The discontinuities in phase information between scans may be accounted for with an array of fixed microphones that measure sound pressures simultaneously with each scan, which may then be used to tie together the phases in a process called partial field decomposition (PFD).

In PFD, cross spectral matrices between the reference microphones and the array microphones for each scan are used to decompose the measurement hologram into a set of independent, but mutually coherent partial fields. These partial fields form an orthogonal basis set for the sound field. Summing these partial fields on an intensity basis will return the total measured hologram surface magnitude. Several PFD methods exist. In this work, the virtual coherence method is used.<sup>12, 13</sup> This PFD process performs a singular value decomposition (SVD) on the signals measured by the reference microphones. This generates an orthogonal basis of “virtual references”, each one containing information from all the individual physical reference signals. The singular values that describe the strength of each of these virtual references are sorted in descending order. The measurement is then decomposed into partial fields, each of which is fully correlated with one virtual reference. Therefore, the partial fields are also sorted by strength. This is mathematically the “ideal” decomposition, since as much of the sound field as is possible is packed into the first partial fields.

The total number of partial fields that come out of the decomposition will equal the number of reference microphones. The first partial fields will contain information relevant to the source, and the rest will contain lower amplitude noise. Therefore, a sufficient number of partial fields must be selected to reconstruct the source, and the rest discarded. Returning to the example of a vibrating plate, the entire source is correlated. Only one partial field will contain relevant information. Consequently, only one reference microphone is needed to perform PFD. A sound field generated by  $N$  independent sources will require  $N$  reference microphones, and will be decomposed into  $N$  partial fields. More reference microphones may be used, producing more partial fields, but only the first  $N$  will contain useful information. If the number of sources is unknown, the singular values of the SVD on the reference microphones may be observed. For  $N$  independent sources, there will be a sharp drop from the singular value  $N$  to the  $N+1$  singular value. For a jet, the number of independent sources is unclear. The singular values tend to decrease somewhat steadily and monotonically. The number of partial fields and the minimum number of reference microphones required to fully measure the source must be determined. The virtual coherence method provides a way to determine this number. This method is where virtual coherence gets its name.

For a chosen frequency, we calculate the cross spectral matrix containing cross spectra between each virtual reference, a second matrix containing the cross spectra between each reference microphone, and a third matrix containing cross spectra between each virtual reference signal and each measured hologram microphone signal. These are, respectively,  $\mathbf{C}_{vv}$ ,  $\mathbf{C}_{pp}$ , and  $\mathbf{C}_{vp}$ . Here, a subscript  $v$  denotes a virtual reference, and a subscript  $p$  denotes a hologram measurement position. The virtual coherence between the  $i$ th virtual reference and the  $j$ th measurement position in each scan is given by

$$\gamma_{j,i}^2 = \frac{|\mathbf{C}_{v_i p_j}|^2}{\mathbf{C}_{v_i v_i} \mathbf{C}_{p_j p_j}} \quad (1)$$

For perfect coherence between the same frequency of two signals,  $\gamma_{j,i}^2 = 1$ , and a value of zero would denote not relation. To select the number of partial fields used for NAH, this virtual coherence is summed over the first  $R$  elements of  $i$ , iteratively increasing  $R$  until the coherence criterion is met, namely

$$\sum_{i=1}^R \gamma_{j,i}^2 \geq \text{coherence criterion} \quad (2)$$

Once the coherence criterion is reached for every measurement position  $j$  in a scan, the  $R$  value is the necessary number of partial fields for that scan. The median of these  $R$  values is selected as the number of partial fields that are processed using NAH. In practice, a coherence of unity is nearly impossible to achieve. For this work we have, therefore, chosen a coherence criterion of 0.9. This corresponds to a signal-to-noise ratio of approximately 10 dB by the relation

$$\text{SNR} = 10 \log \left( \frac{\gamma^2}{1 - \gamma^2} \right) \quad (3)$$

The numerator in the log function represents the coherent power, and the denominator corresponds to noise, or incoherent power.

## B. Aperture Extension

In this work, it was determined that the total aperture of the measurement was insufficient to be able to reconstruct the sound field over the region of interest. Typical NAH reconstructions propagate a measured sound field several centimeters. We desired to reconstruct the field from very near the jet to approximately 25 m from the jet. To accomplish this aperture extension, it was assumed that the concrete ground beneath the aircraft was a perfect reflector of sound (a good approximation for the frequencies of interest), and the method of images was used. For each partial field, the measured sound pressures were mirrored over the location of the ground reflecting plane, and the data were interpolated between the two resulting regions.

After this interpolation was performed to give one large region, the entire result was extended numerically in a process called analytic continuation.<sup>14</sup> In this process the physically meaningful data is extended somewhat beyond the true measurement aperture, and then tapers smoothly down toward zero. First, the measured pressure values are zero-padded out to the edge of the desired aperture. Then the spatial Fourier transform of the data is filtered to smooth discontinuities, and the result is inverse-Fourier transformed. Finally, the original measured data in the original measurement region are replaced. This is repeated in an iterative process until a convergence is reached. The result is an extended measurement that is almost exactly correct in the original measurement region, as well as just outside it,

and then tapers down to small values compared to those in the measured region.

## C. Statistically optimized near-field acoustical holography

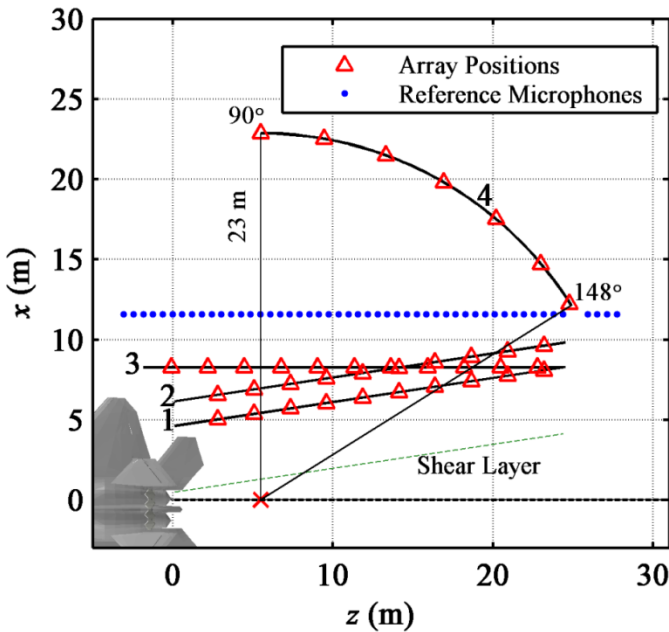
Once the appropriate number of partial fields has been determined using virtual coherence, and the effective apertures of each partial field has been extended, each one is propagated individually toward the source, using some NAH algorithm. The specific method employed in this work is statistically optimized near-field acoustical holography (SONAH).<sup>15,16</sup> SONAH is chosen because it avoids the windowing effects of typical NAH methods by avoiding the direct use of a spatial DFT operation on the measurement. This algorithm breaks up each partial field into a set of plane-wave functions. Then, it propagates these wave functions to a reconstruction surface using a transfer matrix, which quantifies the sound wave propagation between each of the geometrical locations of the hologram and reconstruction surfaces. After each partial field has been propagated to the reconstruction surface, the reconstructed partial fields are added on an intensity basis, giving the estimated total sound field at that location. For the jet, we will propagate from the measured hologram in towards the source as close as possible.

## III. EXPERIMENT

In July 2009, near-field measurements of the jet on a Lockheed Martin/Boeing F-22 Raptor were taken at Holloman Air Force Base in New Mexico. A 5 by 18 array of G.R.A.S ¼" microphones, with 0.15 cm spacing, scanned an approximately 2 m by 24 m region as near to the jet as would not cause the microphones to clip (see Figure 2). This was repeated for three more measurement planes some distance further from the jet. A measurement schematic is shown in Figure 3. In addition, 50 fixed reference microphones were placed on the ground with 0.6 m spacing, spanning more than 30 m, (shown in Figure 4). Measurements were repeated for four engine conditions ranging from idle to full afterburner. Figure 5 shows the overall sound pressure levels measured in relation to the aircraft location for the afterburner engine condition. There were more than 6000 measurement positions, making this the largest-scale acoustic measurement of a high-power jet ever performed.



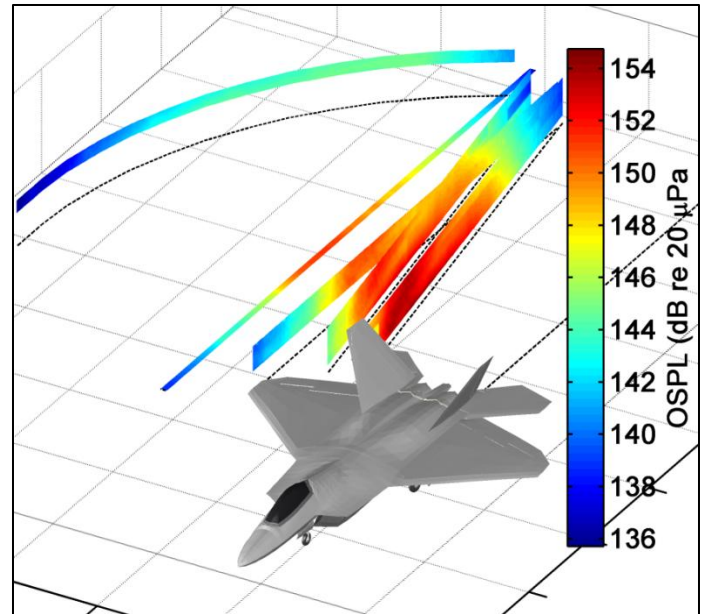
**Figure 2** Blue Ridge Research and Consulting 90-microphone array, scanning the near field of the jet on an F-22 Raptor.



**Figure 3** Holography measurement schematic near the jet on an F-22 Raptor. Planes 1 and 2 will be of interest for the results shown here.



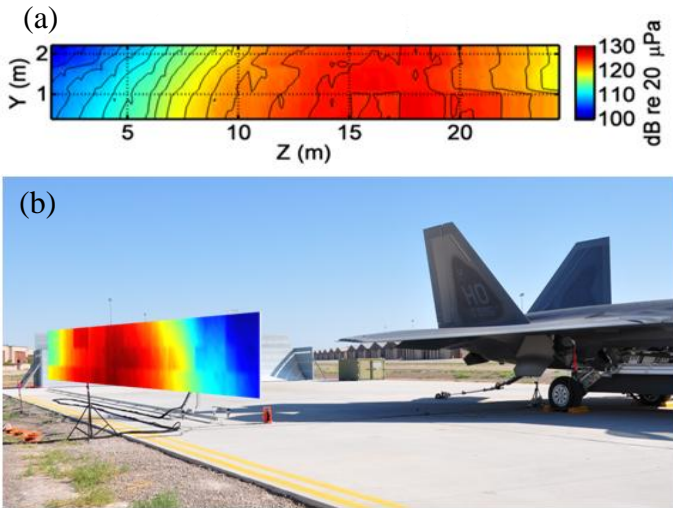
**Figure 4** Fifty reference microphones were placed on the ground 12 m from the jet centerline, which measured sound pressures simultaneously with each scan.



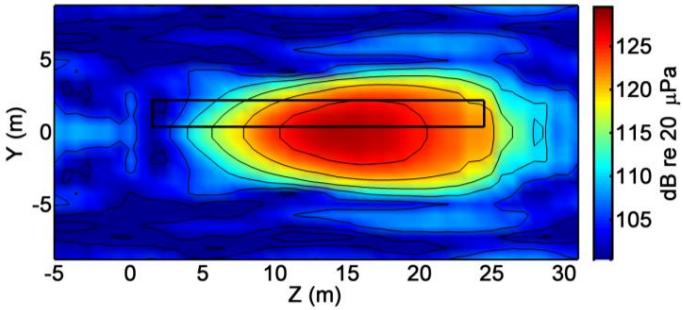
**Figure 5** Overall sound pressure levels measured in the jet vicinity for afterburner engine conditions.

#### IV. DATA PROCESSING RESULTS

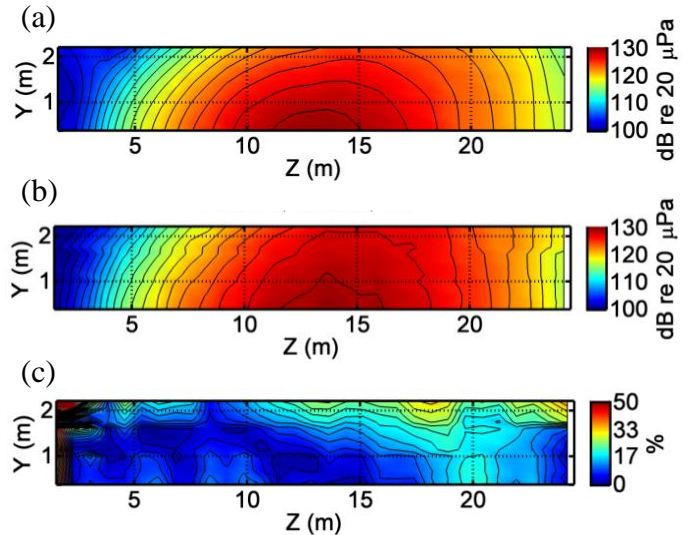
The results of the processing described above are shown here. In Figure 6, the measured sound pressure levels at 105 Hz and at measurement plane 2 (see Figure 3) are shown. After virtual coherence has been performed, the data are smoothed. Then the aperture is numerically extended several meters in all directions, giving the result in Figure 7. Finally, using SONAH, the pressure values are propagated to the location of plane 1 (shown in Figure 8a). As a comparison, the measured sound pressure levels are given in Figure 8b, and the percent error between the two level maps is shown in Figure 8c. Note that the higher errors tend to occur in areas of lower amplitude. The overall trends of the sound field are captured.



**Figure 6** An example (a) sound pressure level map, (b) overlaid with the jet photo at the approximate measurement location.



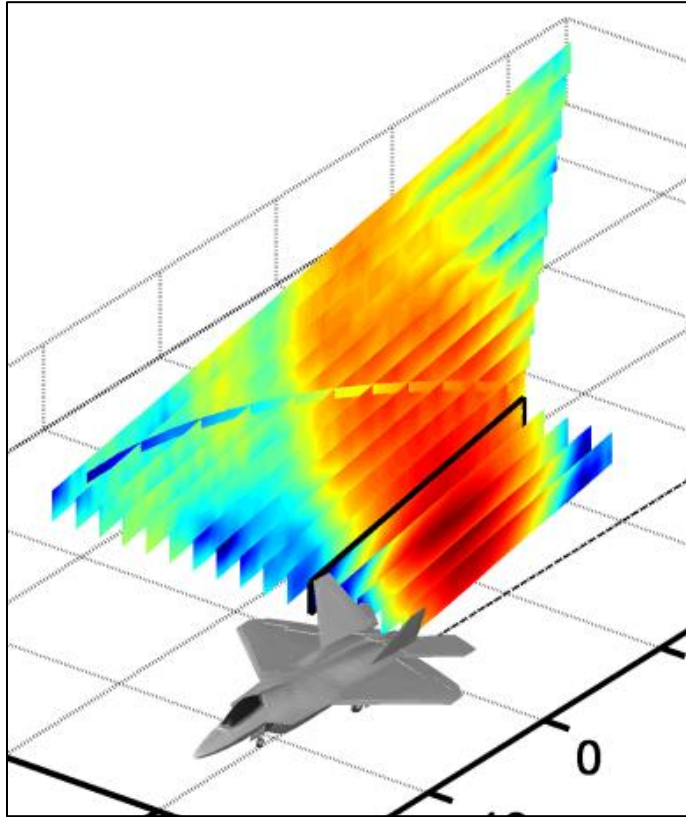
**Figure 7** The measured sound pressure levels after virtual coherence has been performed and the effective aperture has been extended, numerically.



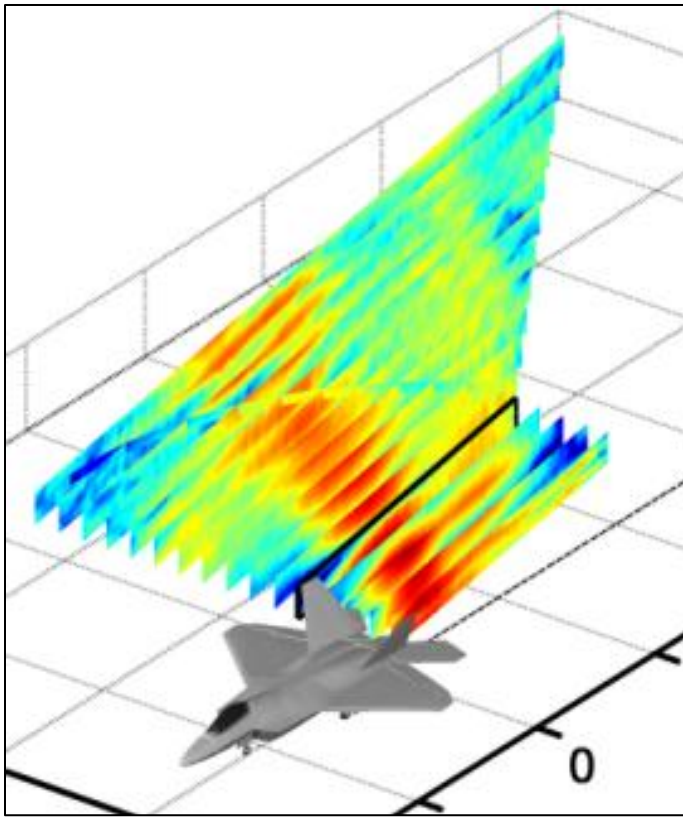
**Figure 8** (a) Reconstructed sound pressure level at plane 1 (see Figure 3); (b) benchmark pressure measured directly at plane 1; (c) percent error calculated between (a) and (b).

This entire reconstruction process was repeated for many measurement planes, to give a three-

dimensional representation of the sound field at 105 Hz for the afterburner engine condition shown in Figure 9. Here, the black rectangle indicates the actual measured data from which all the other sound pressure levels were generated. Note the strong directional lobe, which is consistent with established jet-noise theory and measurements. This reconstruction process was repeated for the 210 Hz frequency, shown in Figure 10. This is the first time such sound pressure level maps have been generated for a military aircraft!



**Figure 9** Three-dimensional map of the sound field at 105 Hz of the jet on the F-22 Raptor, generated using NAH techniques.



**Figure 10** Three-dimensional map of the sound field at 105 Hz of the jet on the F-22 Raptor, generated using NAH techniques.

## V. CONCLUSIONS

The results shown here are the preliminary near-field acoustical holography reconstructions of the three-dimensional sound field of the jet on a high-performance military aircraft. All elements of this process are being optimized for more accurate reconstructions and a more robust process on the whole. For example, the aperture extension procedure is being investigated to find an optimal resulting aperture, as well as to remove some of the artifacts introduced in this processing. There are many parameters to vary that can optimize the SONAH reconstruction process, as well, which are being explored.

In addition to this reconstruction using SONAH, other NAH techniques are being investigated to reconstruct the sound field. The ultimate goal is to accurately characterize the sound field directly at the source, the location of which is somewhat tenuous for a jet or a rocket. However, connecting the acoustic source properties to turbulent flow structures could greatly contribute to the understanding of noise-generation mechanisms, and lead to radiation prediction and noise reduction by rocket and aircraft designers.

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