Receiver-based auralization of broadband aircraft flyover noise using the NASA Auralization Framework

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ABSTRACT

The NASA Auralization Framework (NAF) consists of a set of dynamic link libraries (DLLs) to facilitate auralization of aircraft noise. Advanced capabilities for synthesis, propagation, and external interfaces are provided by the NAF Advanced Plugin Libraries (APL); a separate set of DLLs that are made accessible through the NAF's plugin architecture. In the typical time domain use case, the sound is first synthesized at the source location based on a source noise definition, and is then propagated in the time domain to a receiver on or near the ground. Alternatively, it may be desirable to synthesize the sound at the receiver, after it has been propagated in the frequency domain, e.g., when the source definition is inaccessible or when alternative propagation methods are needed. Receiver-based auralization requires three new developments in the NAF APL: a component plugin to interpolate the propagated noise spectra as a function of time for input to sound synthesis, and a path finder and path traversal plugin to calculate the effects of the differential propagation path length between the direct and ground reflected rays. This paper describes those developments and demonstrates their use in the auralization of broadband flyover noise.

1 INTRODUCTION

Auralization is a technique for creating audible sound files from numerical data[1]. It has been applied to air vehicle flyover noise ranging from small, unmanned aerial vehicles to large

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commercial transports.[2] Auralization can serve several purposes: it provides a means of communicating noise impact to stakeholders in a natural form; it provides feedback to the noise analyst regarding the system under design; and it serves as an integral element of perception-influenced design of new air vehicles.[3]

Common to any purpose are several elements of auralization. Following a source-path-receiver paradigm, these elements include sound synthesis, sound propagation, and listener simulation. Sound synthesis is the process by which a pressure time history is generated. Propagation conveys the sound from the source to the observer. The synthesis operation may either precede or be subsequent to the propagation operation. If sound synthesis precedes propagation, synthesis is performed at the source and propagation is performed in the time domain. If sound synthesis is subsequent to propagation, propagation is performed in the frequency domain and synthesis is performed at the receiver. Finally, the sound may be optionally prepared for reproduction to a listener in a monaural, binaural or multichannel sense. A simple flowchart depicting the above processes is shown in Figure 1. Both processing strategies result in an *n*-channel ($n \geq 1$) pseudo-recording at the receiver suitable for sound reproduction.

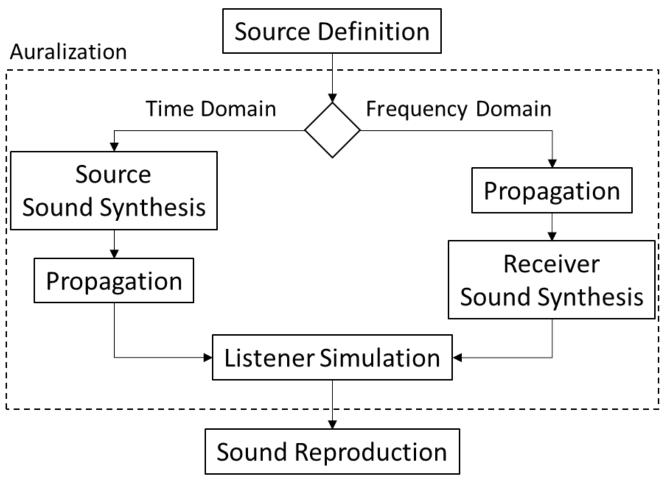

Figure 1 – Flowchart depicting the auralization process in the time and frequency domains.

The most common auralization approach is in the time domain. This approach is amenable to the introduction of source noise unsteadiness during the synthesis process, turbulent atmospheric effects during the propagation process, and has the advantage that phase information is not lost through the propagation process, as is often the case in the frequency domain approach.[2] Although less common, there are some advantages to the frequency domain approach[4] that may make it attractive in some instances, e.g., when the source definition is inaccessible or when alternative propagation methods are needed. Time-marching simulation programs like the NASA Aircraft Noise Prediction Program (ANOPP)[5] and the Advanced Acoustic Model (AAM)[6] essentially operate in the frequency domain and provide a series of propagated noise spectra at the receiver. This paper describes the developments needed to utilize such data for a frequency domain auralization approach using the NASA Auralization Framework (NAF) and Advanced Plugin Libraries (APL).[7] A review of the NAF architecture and typical time domain use case is first given in Section 2. Developments required for auralization of broadband noise using the frequency domain approach are then discussed in Section 3. Finally, three use cases are considered in Section 4 to demonstrate the approach.

2 NAF ARCHITECTURE

The NAF is a collection of dynamic link libraries (DLLs) with basic functions common to auralization. The NAF architecture is briefly summarized here; the reader is referred to a prior work for additional details.[7] The NAF consists of six DLLs, as depicted in Figure 2. There are two foundational libraries; the NAFIPP and the NAFCore. The four remaining libraries (NAFScene, NAFPath, NAFSynth, and NAFGTF) perform the auralization functions described in Figure 2. A user-written application code calls the NAF DLLs to perform the desired auralization operations.

The NAF Advanced Plugin Libraries (APL) serve to supplement the basic functionality within the NAF itself. The NAF APL are a set of DLLs for synthesis, ground reflection and impedance, atmospheric absorption, metrics calculations, and interfaces to other programs.

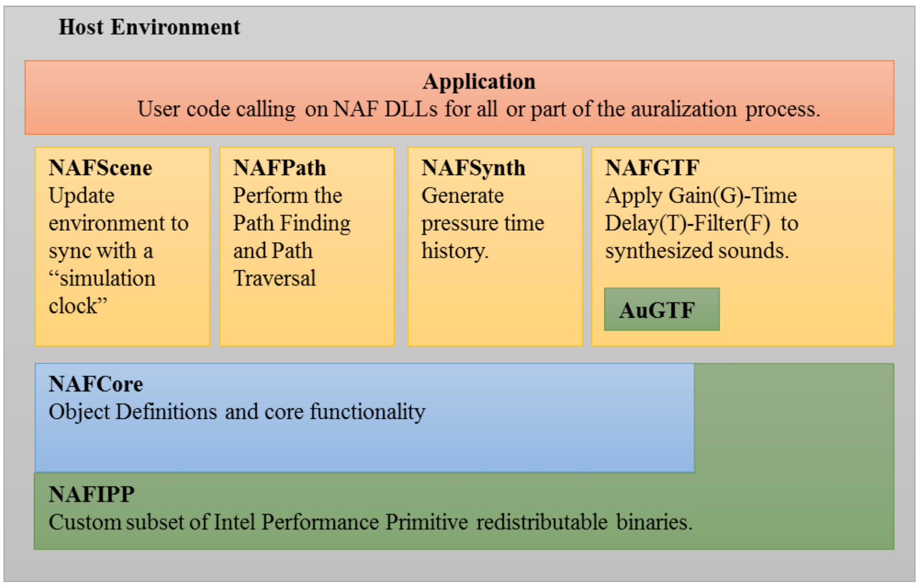

Figure 2 – Depiction of the NAF architecture.

2.1 Typical Time Domain Use Case

The NAF building blocks are assembled in a user-written code in a particular manner depending on its use. One time step of a typical use case for the time domain approach is depicted in Figure 3. For each scene update, the Path Finder obtains the paths and emission angles for each source based on its and the receiver's positions. Here, a source refers to a collection of collocated noise components. For a receiver above the ground, there are two paths for straight-line propagation: a direct path (r') and a two-segment ground reflected path (r_1'', r_2''), as shown in Figure 4. For each path, component synthesis engines generate sample buffers of pressure time history, which may optionally be summed back to the source level. In parallel, the Path Traverser(s) generate a gain, time-delay, filter (GTF)-series for the specified atmosphere and ground. The GTF processor propagates the sound through application of the GTF-series to the sample buffer. The outputs of all the paths for a given source are shown summed to generate a pseudo-recording at the receiver. Because the phase is retained through the time domain approach, the summation of the direct and ground reflected paths creates the distinctive comb-filtering effect.[8]

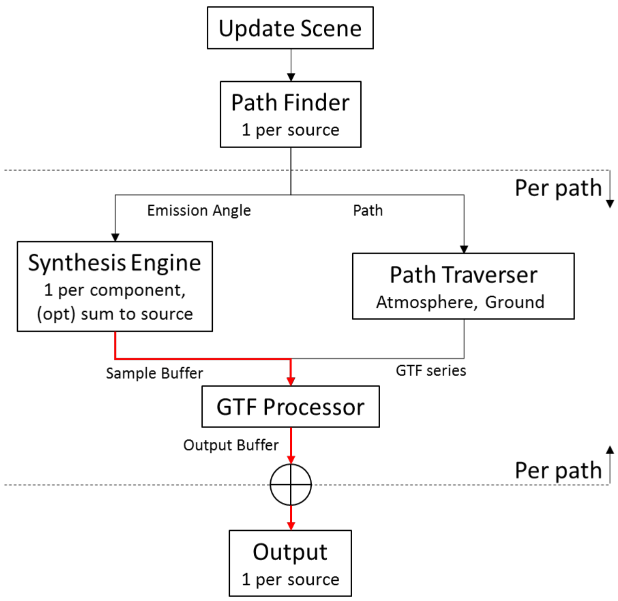

Figure 3 – Block diagram of a typical time domain use case for the NAF. Black connecting lines indicate data and red connecting lines indicate samples (audio).

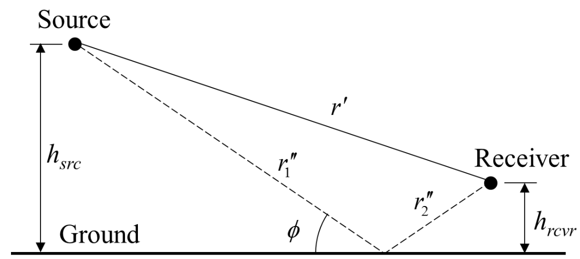

Figure 4 – Geometry of direct and ground reflected paths for a receiver above the ground.

3 FREQUENCY DOMAIN APPROACH

The frequency domain approach minimally requires the propagated spectral time history at the receiver, the speed of sound, the fixed receiver position, and the 4D trajectory of the source (t, x, y, z). Because the method outlined herein is based on straight-line propagation, a constant speed of sound is used. If a frequency domain propagation method provides only a single receiver spectral time history, it is assumed to contain both the direct and ground reflected paths, denoted by (′) and (″), respectively (see Figure 4). Such is the case for data propagated with the ANOPP PRO module, or any recorded flight test data. A significant portion of the effort associated with the frequency domain approach is related to separating the two paths. If the direct and ground reflected spectra are provided separately, the auralization task is more straightforward.

It is assumed that the receiver spectra are specified at the reception time, not at the emission time. The first step in separating the direct and ground reflected portion of the data is to establish the path data. A new NAF Path Finder plugin was written to perform the following at each receiver time:

- calculate the emission position according to a recursive method,[8] and
- find the path(s) between the source and receiver in terms of the starting point (emission position), ending point (receiver position), path length, and elapsed time of the full path.

The first step is based on the direct path. It assumes the same emission time for the direct and ground reflected paths. Note that if the receiver is on the ground ($h_{rcvr} = 0$) or if there was no ground included in the simulation, then only the direct path is needed. If the receiver is above the ground, then the direct and ground reflected paths and angle of incidence, ϕ, are needed, see Figure 4. Further note that there is no need for the emission angle to be provided by the new Path Finder, as the source directivity is already reflected in the receiver spectra.

In this paper, we only consider broadband sources, e.g., jet noise. Frequency domain auralization of tonal sources will be considered in a future work. The synthesis of sound at the receiver, that is, the process by which a pressure time history is generated from the receiver spectra, is performed according to the existing overlap-add broadband synthesis method in the NAF APL. What differs here is the computer program object that generates the synthesis specification, that is, the particular 1/3-octave band spectrum to synthesize at the current time. This object is referred to as the Component in the NAF. For frequency domain auralization, the standard Component is replaced with a new Component plugin, which reads the spectral time history at the receiver, attributes a portion to each path, and interpolates the data in receiver time. The method of apportionment is specific to the use case, as described in Section 4.

The last step is the path traversal process. Recall from Section 2.1 that the function of the Path Traverser is the generation of the GTF series for propagation. For frequency domain auralization, the propagation to the receiver has, for the most part, already been performed. The caveat here is that we need to propagate the ground reflected sound by an incremental amount associated with the difference in the path lengths between the direct and ground reflected paths. A new Path Traverser plugin was written to generate that series and is depicted by the flowchart in Figure 5. As in Figure 3, this operation is performed for each path.

For the direct path (the left hand leg), the gain, time delay and filter are set to zero as the data have already been propagated to the receiver. For the ground reflected path (the right hand leg), the difference in the path length is found as $\Delta r = r_1'' + r_2'' - r'$. From the path length difference, the additional spreading loss, time delay and atmospheric absorption are found. Additionally, the spectral modification resulting from the ground plane reflection, simulated through application of a linear phase finite impulse response filter, is determined from the angle of incidence, ϕ, and includes a negative time delay to compensate for the positive delay in the filter. The time delays are added, and filters serialized into a GTF series that is provided to the NAF GTF Processor.

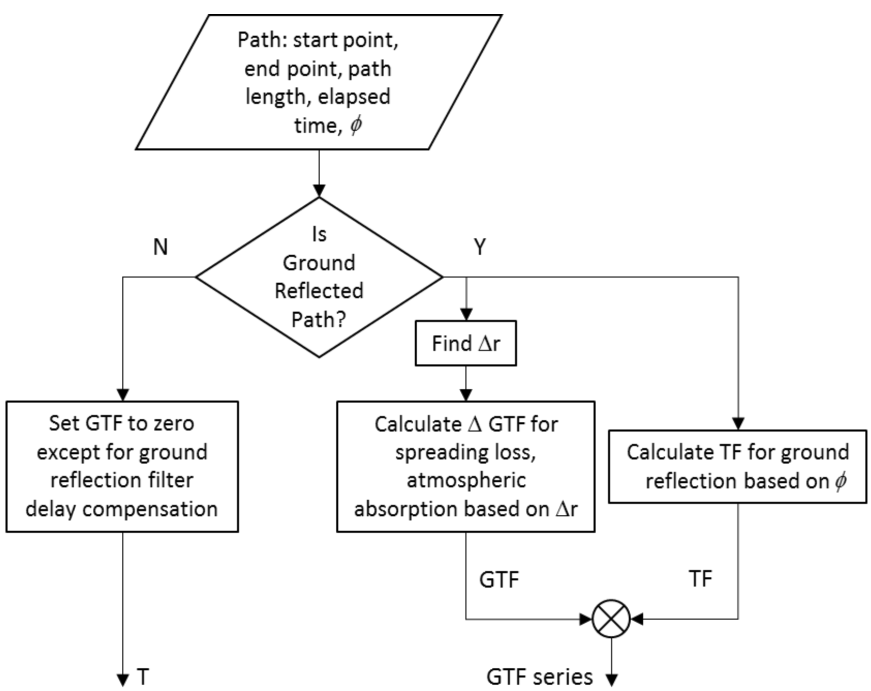

Figure 5 – Flowchart of new Path Traverser plugin for frequency domain auralization.

The NAF GTF Processor requires its GTF inputs to have a positive time delay. Therefore, the negative time delay added to the reflected path must not cause the total delay of that path to become negative. In the time domain approach, this is not normally an issue because of the much larger (positive) absolute delay between the source and receiver. However, in the frequency domain approach, the incremental delay approaches zero at shallow angles and low receiver heights. To ensure the total delay along the reflected path is greater than zero, a small positive delay greater than ½ the filter length is added. Because the phase between the direct and ground reflected paths is important, a matching positive time delay is also added to the direct path. The added delay can be removed upon output.

In summary, the frequency domain approach essentially follows the flowchart of the typical time domain use case in Figure 3, but uses new plugins for the Path Finder, the Path Traverser, and the Component for sound synthesis.

4 FREQUENCY DOMAIN USE CASES

Three use cases are next considered to demonstrate the frequency domain approach. Each case is based on a NASA model of the Boeing 777-200ER with GE90-like engines. Only the jet noise component is considered for a take-off operating condition at full power with a centerline observer under the flight path. The trajectory consists of a 10,000 ft straight and level segment (5,000 ft on either side of the observer), at an altitude of 1000 ft above ground level and speed of 180.4 kt. At this speed, it takes the aircraft 32.8 s to travel the length of the segment. Details are provided in Rizzi et al.[9]

4.1 Use Case 1: Receiver simulation and auralization in free space

In the first use case, the receiver data were generated using ANOPP for a position 996 ft below the flight path in free space (no ground surface). This use case primarily serves as a test of the Component plugin. The receiver 1/3-octave band sound pressure level (SPL) data from 50 Hz – 10 kHz were calculated every 0.5 s, and are shown in Figure 6. The 4.6 s delay at the start of the run reflects the propagation time from the starting point. Likewise, the ending receiver time exceeds the 32.8 s travel time by the same amount.

For the auralization, the Path Traverser plugin applies a zero GTF series to the receiver data, that is, the output of the broadband synthesis directly results in the desired spectrum. Here the pseudo-recording was post-processed to obtain the narrowband SPL with a frequency resolution of 21.5 Hz. The narrowband spectrogram of the pseudo-recording in Figure 7 bears the expected likeness to 1/3-octave band receiver data from which it was derived. When the narrowband SPL data are summed with each 1/3-octave band, the original receiver data are recovered (not shown). The banded appearance of Figure 7 is due to the uniform distribution of sound power with frequency within each 1/3-octave band in the sound synthesis.

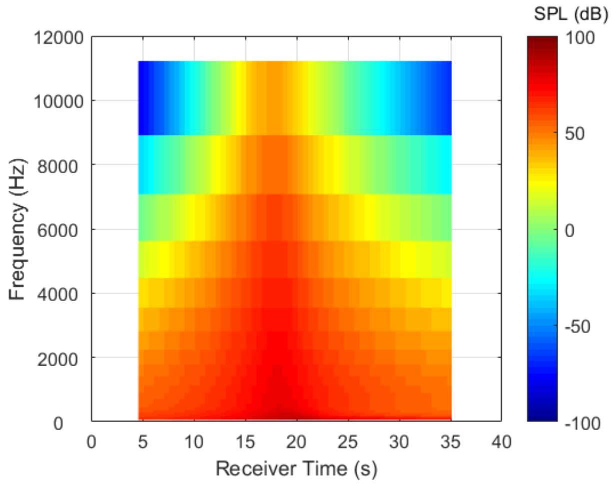

Figure 6 – 1/3-octave band spectrogram of receiver data in free space.

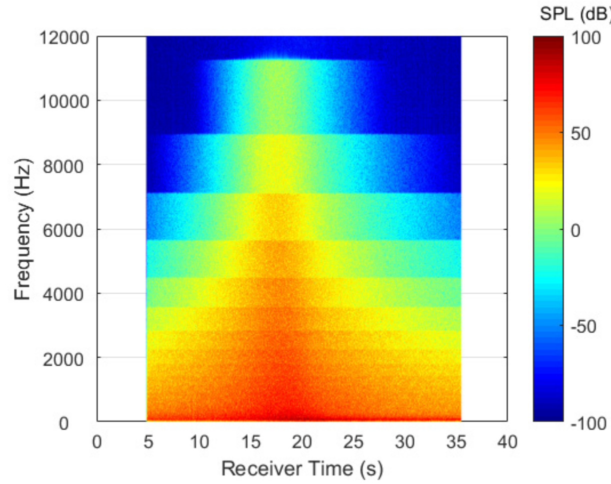

Figure 7 – Narrowband spectrogram of the pseudo-recording for use-case 1.

A comparison of the A-weighted SPL (L_A) of the pseudo-recording with the A-weighted receiver data, also shows a favorable comparison, see Figure 8. Small differences are due to the random nature of the broadband source; other realizations of the same flyover (not shown) indicate similar small differences. The pseudo-recording for this case is available for auditioning.[10]

4.2 Use Case 2: Receiver simulation in free space, auralization above half space

The next use case starts with the same receiver data as use case 1, but here the auralization is performed for an observer 4 ft above a hard ground surface. In other words, we use a free space solution as the starting point for an observer above a half space. In this case, the combination of the direct and ground reflected paths are seen to generate the expected interference pattern in the narrowband spectrogram, as seen in Figure 9. The effect is prominent upon auditioning the pseudo-recording.[10]

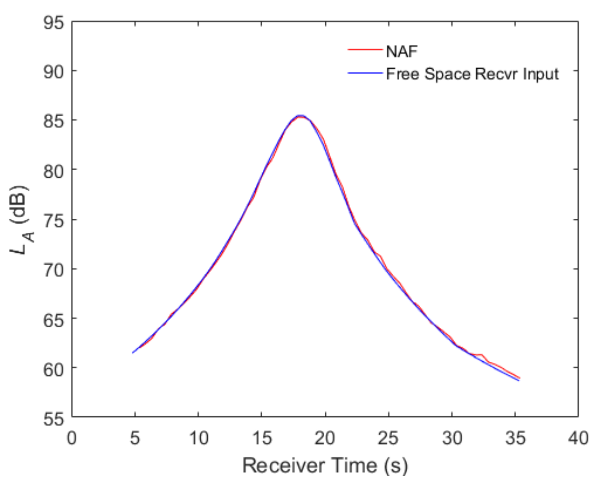

Figure 8 – Comparison of L_A for use case 1.

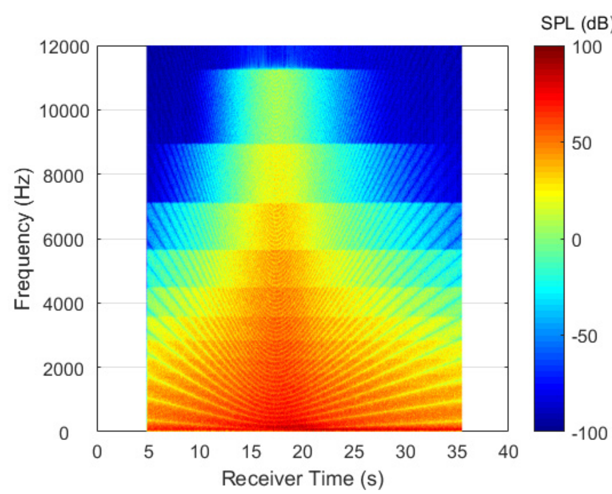

Figure 9 – Narrowband spectrogram of the pseudo-recording for use-case 2.

The truth model for this case was generated using ANOPP for an observer 4 ft above the hard ground plane. The comparison of the pseudo-recording L_A with that of the truth model is excellent, as shown in Figure 10. Again, small deviations are attributable to the random nature of the broadband source. As expected, L_A is higher for the observer above the half space than the free space receiver.

4.3 Use Case 3: Receiver simulation on hard ground, auralization above half space

In each of the previous use cases, the apportionment of the receiver data to the direct and ground reflected paths was trivial because the receiver was simulated in free space. In this next case, the apportionment is only slightly more involved because the receiver is simulated on a hard ground surface, 1000 ft below the aircraft flyover, but the sound is auralized for a 4 ft observer. Here, the direct and ground reflected paths for the auralization each receive half of the receiver data (or a level of -6 dB) because of pressure doubling at the ground. The spectrogram of the pseudo-recording (not shown) is similar to that shown in Figure 9. Additionally, the auditioned sound exhibits the pronounced interference pattern.[10] The truth model in this case was the same as in use case 2. A comparison of L_A is shown in Figure 11, where it is seen that pseudo-recording compares favorably with the truth model. Also shown is the ground receiver data from which the pseudo-recording was derived.

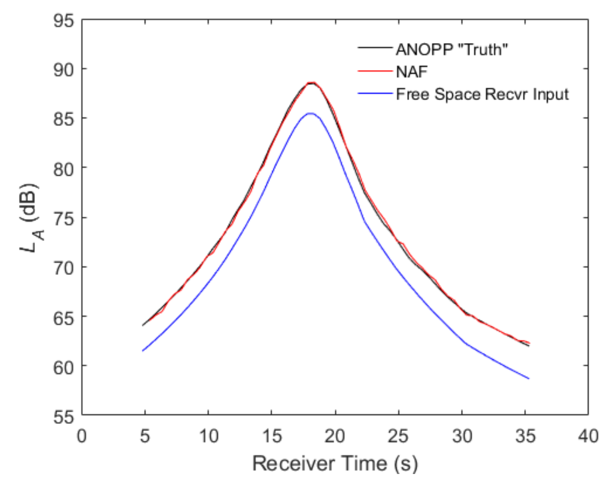

Figure 10 – Comparison of L_A for use case 2.

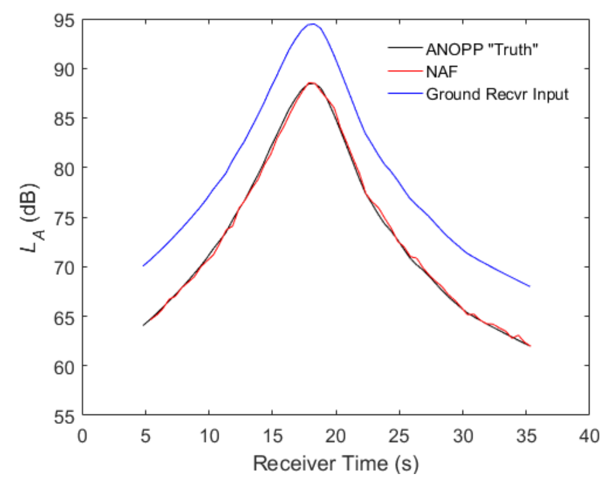

Figure 11 – Comparison of L_A for use case 3.

5 DISCUSSION

A receiver-based auralization method using propagated spectra at the observer and knowledge of the source trajectory and observer position has been developed for use in the NAF. Three new plugin libraries were developed to make that possible. These include a Component plugin to prepare the receiver spectra for sound synthesis, a Path Finder plugin to determine the differential path length between the direct and ground reflected path (if any), and a Path Traverser plugin to determine the differential spreading loss, time delay, and filters associated with the atmospheric attenuation and ground reflection. The approach was demonstrated for receiver data defined in free space and on a hard ground, and results were found to be comparable to the more customary time domain approach.

Additional aspects of receiver-based auralization are next briefly discussed. The process for separating the contributions from direct and ground reflected paths becomes more difficult when the receiver is not defined in free space or on hard ground. Such cases include, for example, a receiver above a hard ground, a receiver above a ground with finite impedance, and receivers far above the ground. For receivers near the ground, it is necessary to correct the receiver spectra for the effect of spreading loss, time delay, and atmospheric attenuation and ground impedance included in the mixed (direct and ground reflected) data. An additional complication for receivers high above the ground arises because the direct and ground reflected paths cannot be assumed to have the same source emission angle. If the propagation program, e.g., ANOPP PRO or AAM, provided propagated spectra per path, many of these difficulties would be resolved.

Finally, aircraft noise typically consists of both broadband and tonal sources. An extension of this approach for tonal sources, not addressed in this paper, has the added challenge that tones may be either summed into 1/3-octave bands in the source noise definition, or through the propagation process. Therefore, some additional information is likely needed, at a minimum, to determine tonal frequency and amplitude for high frequency sources, e.g., turbofan noise, and to additionally determine tonal phase for lower frequency sources, e.g., helicopter rotor noise, in which replication of the waveform is important to perception. NAF interfaces to propagation programs therefore will be highly specific due to the differing nature in how such data are provided.

6 ACKNOWLEDGMENTS

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