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SonicBAT: Some highlights and subsequent developments

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ABSTRACT

The Sonic Booms in Atmospheric Turbulence (SonicBAT) project concluded in 2018. The overall goal of SonicBAT was to develop tools to predict the influence of atmospheric turbulence on shaped sonic booms for newly proposed low-boom supersonic passenger aircraft. There was a substantial experimental component to obtain statistically-useful datasets of recorded sonic booms in both dry and humid environments. The project was carried out by a large team, and the authors of this paper are a small subset of the individuals involved. The purpose of this presentation is to highlight some of the main findings of SonicBAT and to provide pointers to the primary technical report and other publications that are now becoming available, both from SonicBAT and from subsequent findings. Overall, SonicBAT was successful in developing multiple ways of predicting the influence of atmospheric turbulence on the propagation of arbitrarily shaped sonic boom waveforms as they propagate through the earth's planetary boundary layer. The influence of turbulence is profound for N-wave sonic booms but is reduced for low-boom sonic boom signatures.

Keywords: Sonic Boom, Turbulence, Aircraft

1. INTRODUCTION

During the 1960's and early 1970's there were a number of theories attempting to explain why sonic boom signatures became distorted during their passage to the ground. It was observed that the distortion of the spiking and rounding of N-wave sonic booms would occur most times of the day with the exception of early in the morning, sometimes (1). A theory of Pierce and Maglieri (2) was eventually accepted and built upon by others, identifying that atmospheric turbulence in the planetary boundary layer was responsible for distorting the N-wave sonic booms. However, in those early years, it was not possible to recreate the sonic boom distortion with a fidelity such that one could know the statistical occurrence of the spiking and rounding. It was also not possible to know whether non-N-wave signatures would be similarly distorted, and this point was concerning to both NASA and airframers interested in developing low-boom supersonic aircraft that might be quiet enough to be acceptable to the public.

The SonicBAT project, standing for SONIC Booms in Atmospheric Turbulence, began as a proposal from Wyle Laboratories, Inc. (now KBR) and The Pennsylvania State University (Penn State) to NASA through their NASA Research Announcements (NRA) solicitation in 2014. Penn State and Wyle had been talking with NASA for several years prior to 2014 to request that a large-scale study of atmospheric turbulence effects on sonic booms be initiated. As the joint proposal was selected for funding, the size of the effort became clear: there would be multiple prediction models investigated and validating those models would require field measurement campaigns in widely varying atmospheric conditions. It would also require NASA to deploy aircraft and sonic boom measurement equipment at remote locations and make direct measurements of atmospheric turbulence and other meteorological parameters almost simultaneously with making microphone measurements. The other project partners grew to include Boeing, Eagle Aeronautics, Lockheed Martin, Gulfstream

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Aerospace Corporation, Technical & Business Systems, and the Laboratory of Fluid Mechanics and Acoustics at Ecole Centrale de Lyon. This paper will focus primarily on the work of Penn State and Wyle working with NASA. The project was technically challenging and stretched everyone involved.

Other than the most recent developments, most of the material regarding SonicBAT will be available later in 2019 in a NASA Contractor Report (CR), and that report will give much greater detail and specificity in the descriptions (3). The remainder of this summary paper is arranged as follows: The next section briefly describes the field measurements of conventional N-wave sonic booms used for validating the prediction methods described in Section 3. Section 4 describes the primary results coming out of the SonicBAT. Section 5 extends those results beyond SonicBAT to the work reported by Stout in his Ph.D. thesis (4). Section 6 provides additional links to the literature coming out of SonicBAT in the near future for those wanting to know more, and Section 7 concludes this paper.

2. FIELD MEASUREMENTS

2.1 Overall Considerations

A distinguishing feature of the SonicBAT field measurements was the effort undertaken to carefully characterize the atmosphere and atmospheric turbulence at the same time the microphone recordings were acquired. To the authors' knowledge, this is the first time sonic boom tests were conducted with such elaborate measurements of the atmosphere. And as will be explained, those measurements were critical for the success of SonicBAT.

In the original planning for SonicBAT it was well understood that the developed prediction models would need to work well anywhere in the continental U.S., if one wanted to consider overland civil supersonic flight. Both dry and humid conditions would need to be included, as it was understood in the 1990s that humid conditions would lead to louder sonic booms, due to decreases in the sonic boom rise time. After a detailed survey of possible locations, the dry conditions at NASA's Armstrong Flight Research Center and the humid conditions at NASA's Kennedy Space Center were selected for the field tests. Hence one test was for low-humidity extreme and the other for high.

Another important aspect of the field measurements was the attempt to minimize, for most of the aircraft flight passes, any variation in course, altitude or Mach number between the flights. In SonicBAT the emphasis was on obtaining a large body of sonic boom measurements where the primary influence on the microphone recordings was from variations in the atmosphere. The philosophy was to keep all other flight parameters as unchanged as possible, so the statistical variations in received levels would be due to the atmosphere, not to other changes in experimental conditions. Since future civilian supersonic aircraft are envisioned to fly overland at Mach numbers on the order of 1.6, the tests were conducted at the highest Mach numbers possible given the aircraft available and the prevailing atmospheric conditions. At the two measurement sites the test Mach numbers were usually around M=1.39 at NASA's Armstrong Flight Research Center and around M=1.35 at NASA's Kennedy Space Center. The aircraft used for both tests was a McDonnell Douglas F/A-18 Hornet (F-18). The F-18 altitude was between 10.4 to 10.5 km (34,000 to 35,000 feet) msl for both tests.

An additional notable aspect of SonicBAT is that most of the data analysis in the project employed modern loudness metrics, such as Steven's Mark VII Perceived Level (PL). This is important because subjective tests have shown that human hearing does not correlate loudness with maximum pressure very well (5), and in the older sonic boom literature only maximum pressure values are reported. PL is a much better metric for assessing loudness of sonic booms.

2.2 Aircraft Deployed and Meteorological Measurements

For the flight tests NASA utilized F-18 jet aircraft to create the sonic booms, and they also flew a TG-14 motorized sailplane with a microphone probe mounted under and forward of the wingtip. The TG-14 was flown on a trajectory so that it would be in between the supersonic F-18 and the ground microphone array, and it would be well-positioned to capture the sonic boom signature before it entered the planetary boundary layer. The TG-14 pilot was instructed to fly just above the boundary layer, staying out of the rough air created by the boundary layer cap. To deploy these aircraft assets, including the pilots, aircraft, fuel, maintenance crew, ground control engineers, and other required staffing and supplies was an enormous undertaking by NASA.

In addition to the usual weather balloon launches to get atmospheric profiles, NASA obtained and brought to each of the field tests ultrasonic anemometers and a mini-SODAR. The purpose of the ultrasonic anemometers was to directly characterize the structure parameters of the turbulence, and they were very effective for this purpose. In addition, a measurement of the atmosphere with a mini-SODAR at each site allowed for a better picture of the atmosphere above the microphone arrays, giving information such as the 3-D winds and the height of the atmospheric boundary layer, confirming the data from the weather balloons. For the more humid atmosphere at Kennedy Space Center, a humidity flux sensor was also acquired and utilized. This allowed for an adjustment to the dry structure parameter values due to the humidity that were not necessary in the dry desert environment at Armstrong Flight Research Center.

2.3 Measurements at NASA's Armstrong Flight Research Center

NASA's Armstrong Flight Research Center (AFRC) is the base for NASA's aircraft research, and it is located in the Mojave Desert, within the boundaries of Edwards Air Force Base, north of Palmdale, CA, itself north of Los Angeles, CA. Supersonic flights for SonicBAT were conducted during July 2016, and most of the days were cloudless. There were three microphone arrays. The details of the other arrays are available in the Contractor Report, but the primary array was linear, with 16 microphones spaced approximately every 30.5 m (100 ft), along the flight direction. All microphones were ½" diameter infrasonic devices placed on groundboards. All data were acquired using 24-bit A/D at 51200 samples/s. The TG-14 data were acquired at the higher sample rate of 65,535 samples/s. The TG-14 was in proper position for 60 of the 69 supersonic flight passes made by the F-18. It was determined that 96 percent of the 2059 signatures recorded across all microphone arrays were affected by atmospheric turbulence.

2.4 Measurements at NASA's Kennedy Space Center

NASA AFRC deployed their assets to NASA's Kennedy Space Center (KSC) during August 2017. KSC is located adjacent to the Atlantic Ocean on Florida's East coast. A primary consideration was to eliminate, as much as possible, any impact of supersonic testing activities on the residents of nearby Titusville, FL affectionately known to the planning and measurement team as the "wall of humanity." There was much effort placed into reducing to near zero any members of the public hearing sonic booms, and this was primarily accomplished through careful flight planning by NASA.

The majority of the instrumentation at KSC was very similar to the instrumentation used in the AFRC tests, with the addition at KSC of the humidity flux sensor mentioned in Section 2.2. One major difference at KSC, however, was that the weather conditions included clouds and occasional rain showers and thunderstorms. This required multiple postponements and some cancellation of planned flights. Further the ground microphone team needed to run and cover up microphones to protect them from rain on multiple occasions on very short notice. Some microphones were susceptible to fine sand being blown into their active areas, making them inoperable. For the KSC test the TG-14 was in proper position for 35 of 56 passes of the F-18 aircraft. Approximately 1883 signatures were obtained, and 95% of those were affected by turbulence. As predicted, the more humid environment of KSC led to shorter rise times and many "crackier" booms heard by the field technicians. However, some booms were substantially softened, and these may be booms that had passed through thick cloud layers. Another difference from AFRC is that there was often a sea breeze occurring at KSC, affecting the atmospheric boundary layer, and this is described more in the Contractor Report.

3. PREDICTION OF SONIC BOOM PROPAGATION THROUGH TURBULENCE

There were two prediction models developed under the auspices of SonicBAT. The first was TURBO, a classically-based model developed by John Morgenstern of Lockheed Martin. Because of space limitations, that model will not be covered here. One can find a complete description in the SonicBAT Contractor Report, available later in 2019.

3.1 Two-dimensional Simulations

The second prediction model will be described briefly here, as the present authors are more familiar with it. The numerical model used was the Khokhlov-Zobolotskaya-Kuznetzov (KZK) equation, and prior to SonicBAT it had shown good potential for modeling sonic booms and similar types of waves propagating through atmospheric turbulence, see Averiyanov 2011 (6). Due to space limitations the details of the KZK implementation will not be provided here. The propagation would occur through inhomogeneous temperature fluctuations (scalar turbulence) and inhomogeneous wind fluctuations (vector turbulence). The Random Fourier Modes approach of Blanc-Benon (7) was utilized for implementing the turbulent distributions in the atmosphere, and the turbulence model of Wilson (8), repeated in Ostashev and Wilson (9), provided the structure of the turbulence as a function of height above the ground. The actual turbulence and other atmospheric measurements from the field tests were used to provide inputs to the numerical model. All the details of the KZK numerical model and the inputs are provided in the Ph.D. dissertation of Trevor Stout (4), and the appendices of that dissertation include the actual model source code in C++. Support for running the KZKFourier code, as it is called, was provided by NASA on their Pleiades High Performance Cluster. The sampling rate used was usually 200 kHz, although that sampling rate was reduced to 51.2 kHz when examining shaped waveforms without short rise times.

All of the KZKFourier results reported in the SonicBAT Contractor Report were two-dimensional, meaning the 3rd transverse dimension parallel to the ground was assumed constant. This restriction was due to the very high computational cost of fully three-dimensional simulations which will be described in Section 5.3 below.

4. PRINCIPAL RESULTS OF SONICBAT

4.1 Large High-Quality Database of Sonic Booms and Atmospheric Turbulence

Since no databases of sonic booms with coordinated turbulence and atmospheric measurements were available previously, this is an important product of the SonicBAT program. The major limitation to this database is that it is exclusively for conventional N-wave signatures.

4.2 New Prediction Models

Both the KZKFourier and TURBO models are available to NASA and its designates, and modifications of the approaches will allow for further developments going forward. As already mentioned, the KZKFourier prediction model is included in Trevor Stout's Ph.D. dissertation. This should supply ample opportunity for new understanding.

4.3 Validation between prediction and measurement of N-wave booms

One of the first tasks after the KZKFourier model was working and the near simultaneous measurement of sonic booms in atmospheric turbulence were processed was to see how closely the statistical distribution of PLs compared between model and measurement. The Contractor Report and Trevor Stout's Ph.D. dissertation have more details. There is excellent agreement between the histograms between calculation and measurement when comparing the PL values received on the ground, relative to a nominal (no turbulence) signature. This figure will be available soon in a peer-reviewed journal article, and the comparison will be shown at the ICA2019 meeting.

4.4 PCBoom Improvements, including New Finite Impulse Response Filters for PCBoom

SonicBAT also required new features be added to the sonic boom prediction program PCBoom. One of these developments is that PCBoom will now allow one to use NASA's sBoom program to propagate the signature to the ground instead of using PCBoom's built in FOBoom module based on the Anderson Algorithm. sBoom instead uses a time-domain Burgers Equation solver.

Further, PCBoom's WCON module was updated to handle high-resolution signatures with a user-defined sampling rate. In addition, program flow was updated to allow Burgers-evolved signatures (from the PCBurg module) to interface properly and be used with the turbulence models.

Locey and Sparrow (10) had introduced the concept of using a finite impulse response (FIR) filter to model sonic boom propagating through turbulence in 2007. The concept was to use measurements from a sailplane and ground measurements to show exactly how the sonic boom was affected by turbulence. Using the KZKFourier prediction model developed in SonicBAT, a much larger set of FIR filters were developed for use in predicting the effects of turbulence on sonic boom waveforms. These new KZKFourier-developed FIR filters have been incorporated into PCBoom in the WCON module. Hence the new capability allows anyone using the modified version of PCBoom to apply the influence of turbulence to any signature in PCBoom. The filters incorporated will provide a mean Perceived Level signature, and signatures with plus or minus one standard deviation from the mean. Hence, one can see the range of turbulence effects and both the spiking and rounding (for N-waves). The turbulence effects can be seen on the standard metrics of SELA, SELB, SELC, SELE, PL, and NASA's ISBAP (indoor sonic boom annoyance predictor), as well as maximum overpressure.

4.5 New Understanding of Turbulence Effects on Shaped Boom Waveforms

Once the validation was complete, showing good statistical agreement between predicted and measured sonic boom loudness results for N-waves, the effort switched to the original question: Are shaped sonic booms less prone to spiking and rounding than conventional N-waves? In SonicBAT the team members of Boeing, Lockheed-Martin, and NASA all provided shaped signatures for low boom concept aircraft which were used as inputs to the KZKFourier prediction program. In summary the results show that there are definitely fewer high-PL or high-ISBAP events for the shaped waves when compared to N-waves, and this was true for all the shaped signatures considered. Thus, the study corroborates the previous analysis using NASA shaped sonic boom demonstrator (SSBD) aircraft, see Morgenstern *et al.* 2005 (11) and Plotkin *et al.* 2005 (12), that the benefits of boom shaping loudness reduction persist even in the presence of turbulence. SSBD only had front-shock shaping, and SonicBAT has extended the result to fully-shaped supersonic aircraft. Additional simulations showed that this shaping benefit would exist over a wide range of atmospheric conditions.

5. RESULTS SUBSEQUENT TO SONICBAT

Much of the research formally supported through SonicBAT concluded in the Spring of 2018, but subsequent follow-on studies in the Ph.D. Dissertation of Trevor Stout and journal articles continued for almost a full year later. Some of the primary new findings are now summarized.

5.1 Effect of Nonlinearity for N-wave and Shaped Signatures

One assumption in the FIR filter approach taken in Section 4.4 is that the propagation effects of nonlinearity are negligible over the propagation distance through the boundary layer. To investigate this, a study was undertaken by T. Stout in his Ph.D. dissertation, which was later reported upon at the 21st International Symposium on Nonlinear Acoustics in Santa Fe, NM, USA, July 9-13, 2018 (13). Simulations of both N-waves and shaped waves were run with and without the nonlinear terms of the KZK equation included. The results show that for N-waves the effects of nonlinearity can be important, but for waves having longer rise times the effects of nonlinearity can be neglected; thus, for smooth sonic boom waves it may not be necessary to explicitly include nonlinearity. The study comparing propagation with and without nonlinearity also showed the criticality of including nonlinearity for prediction comparisons with the SonicBAT experimental data, all N-waves.

5.2 Efficient time-domain spline interpolation

To ensure a large number of 2-D simulations could complete in a reasonable time, and to make attempting 3-D simulations tractable in any sense, it was necessary to identify the fastest algorithm to integrate the KZK equation for nonlinearity, temperature fluctuation, and advection. A study published in September 2018 JASA Express Letters has shown that using an exact time-domain solution implemented using natural splines preserving C^2 continuity are best and can give a 50% speedup or more over other choices (14). This cut the computation time for the “production runs” in SonicBAT significantly.

5.3 Three-dimensional Simulations

Having derived a fast method to solve the KZK equation, 3-D simulations became more tractable. While the calculations and results for the two-dimensional simulation are all along a line parallel to the ground, the three-dimensional simulations are in a plane aligned with that same line and the perpendicular to that line. The calculation rectangular array is perpendicular to sound rays heading down to the ground. For simplicity, it is assumed that the sound rays are straight, so the 3-D calculation domain is a rectangular prism. When comparing 2-D to 3-D simulations the sampling rate was held at 51.2 kHz for all calculations. The 2-D domain was 1000 m in length and the 3-D domain was 400 m by 400 m with all grid sizes discretized at 0.5 m. For a 1.76 km propagation distance, the 2-D simulations each took 13 hours using 3 cores each, and the 3-D simulations took 9 days each utilizing 28 cores on a Broadwell node. Therefore the 3-D runs were about 150 times more computational expensive than the 2-D runs.

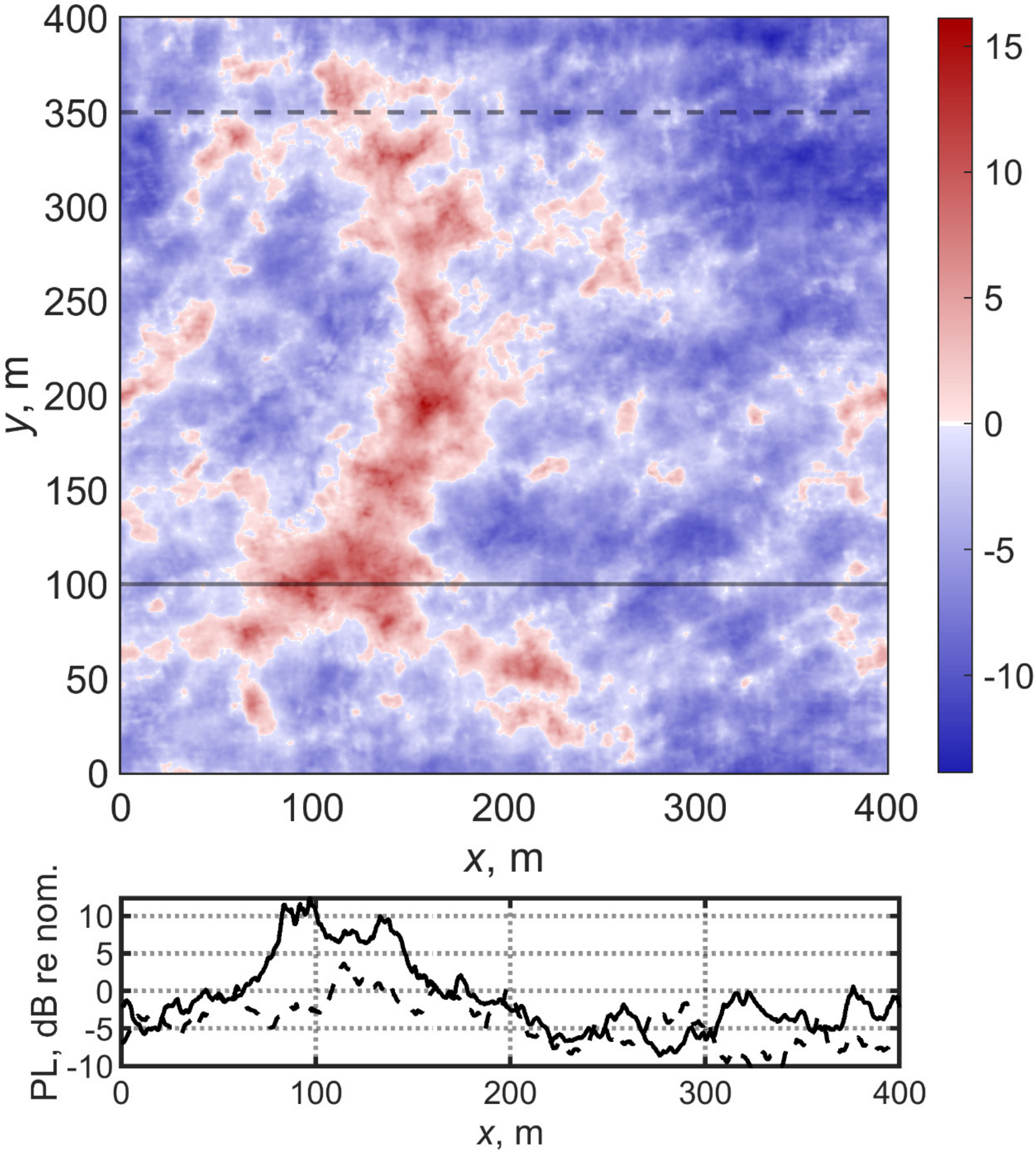

Figure 1: Normalized PL spatial map at bottom of the computational domain near ground for one realization of a KZKFourier 3-D run (top). Data along y = 100 m (solid) and 350 m (dashed) are also plotted (bottom). Red color shows PL increases where energy focused and blue indicates PL decreases where there was defocusing. Variation in PL is seen across any line across the 2-D spatial map.

5.4 Comparing 2-D and 3-D results

Using the capabilities of NASA Pleiades cluster, a limited number of 3-D simulations were performed. At the bottom of the computational domain, a plane of microphone measurements can be extracted. This plane is not parallel to the ground, but at an angle perpendicular to the raypaths. However, this still gives a good indication of how the sounds are distributed on the ground. An example output of the PL metric is shown in Figure 1, where line slices across the domain show what lines of microphones would receive on the ground. The white color corresponds to the nominal sonic boom result without turbulence, and deeper red or blue colors show higher or lower deviation in PL from the nominal, respectively. The results provide a spatial window onto how sonic booms can be spiked and rounded. A different random number seed for the turbulence would have produced a different realization of the spatial map.

In addition, one might wonder whether the statistical occurrence of spiking would change, now including the third dimension in a 3-D prediction. There is no room in the present ICA 2019 paper to include all the details, but it was observed, given a very limited number of 3-D runs, that the PL standard deviation increased by 11% going from 2-D to 3-D. Further for 3-D, the mean values of turbulized PL decreased, but there was an increase in the number of spiking events. This should be investigated further in the future with additional 3-D runs with a wider range of turbulence parameters.

These results were first reported in Stout's Ph.D. dissertation and the 2019 AIAA/CEAS Aeroacoustics Conference in Delft, The Netherlands, as were the results in the next section (15).

5.5 3-D result implications for microphones arrays at field tests

Having the capability to predict 3-D spatial maps allows one to do a better job in thinking about how microphones should be arranged on the ground to capture the spiking and rounding of sonic boom waves. A Monte Carlo experiment was performed where different virtual array types (linear layout, cross layout, 2-D rectangular grid layout) were used to sample the 3-D spatial maps. The sonic boom metrics sampled by the different array types were compared with the overall metric distribution to see how well the arrays could sample the metric's spatial variation. Separation between adjacent microphones was kept to 30.5 m (100 ft) for all arrays, but arrays were tried of different lengths. Using 1 million array samples of the computational domain, across many array types, it was found that the microphone arrays systematically under-predict the PL standard deviation. At the same time the PL mean is correctly estimated. The cross array had the best precision and accuracy, and the grid array the worst. It was also found that increasing the effective span of the array lessened the bias in the sampled PL standard deviation and increased the PL mean precision. Increasing the number of microphones increased the precision of the PL standard deviation. More details are available in the May 2019 AIAA/CEAS paper (15).

6. LINKS TO THE LITERATURE

The authors are currently involved in getting the SonicBAT results and subsequent findings written into peer-reviewed journal articles, and at the time of the writing of the current ICA 2019 summary paper, May 2019, those articles are currently undergoing review by NASA and others (16, 17). The interested reader is very welcome to contact the first author (vws1@psu.edu) after the ICA 2019 meeting to request the updated list of references.

7. CONCLUSION AND FUTURE WORK

The SonicBAT project was very successful in advancing our knowledge of how sonic booms are affected by atmospheric turbulence. One important take-away is that shaped sonic booms really will spike less frequently than do conventional N-waves. In future efforts many more 3-D simulations need to be performed with a greater spread of input parameters corresponding to different atmospheric states. The KZKFourier programs, both 2-D and 3-D, assume that the relative humidity is constant throughout the computational domain and that geometrical spreading is negligible, and clearly neither of those are strictly true; hence, including spatially varying relative humidity and geometrical spreading should be implemented. Another point is that the KZKFourier simulations assume an atmosphere with strong buoyancy forcing as this is inherent in the Wilson model used. In the future, different atmospheric turbulence models could be implemented that correspond to turbulent conditions on cloudy days or at night. The FIR filters implemented in PCBoom now provide an important capability not seen before, and this should be thoroughly exercised for a wide variety of input shaped sonic boom signatures. And with new turbulence models and more 3-D simulations available, the FIR filter coefficients can be updated. Other suggestions for future work are given in T. Stout's Ph.D. dissertation.

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