Synthetic vision display with integral sonic boom predictions

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ABSTRACT

Synthetic vision systems are becoming common in the business jet community. The perspective display of terrain information provides a display of complex information in a visual manner that pilots are accustomed to. Research and flight testing is underway to allow low noise supersonic business jet operations. Widespread acceptance will require regulatory changes, the ability for pilots to predict, and manage where the generated sonic boom will impact people on the ground. A display of the sonic boom impact will be needed for preflight and inflight planning. This paper details the CONOPS, algorithm development, and human machine considerations of a synthetic vision display design incorporating a sonic boom carpet. Using a NASA developed algorithm, sonic boom prediction, Mach cut-off, and sound pressure levels are calculated for current and modified flights plans. The algorithm information is transformed into georeferenced objects, presented on navigation and guidance displays, where pilots can determine whether the current flightplan avoids the generation of sonic booms in noise-sensitive areas. If pilots maneuver away from the flightplan, a dynamically computed predicted boom carpet is presented in which the algorithm is fed an extrapolation of the current flightpath. The resulting depiction is a sonic boom footprint which changes location as the aircraft maneuvers. Using a certain look-ahead time for the prediction, the pilot has the ability to shift the location where boom intensity will be at a maximum. Considerations of allowable sound levels for various locations on the ground are incorporated for comparison of the real-time and predicted sonic boom.

Keywords: Sonic Boom Display Synthetic Vision NASA CONOPS

1. INTRODUCTION

Supersonic flight over land will require pilots to understand and manage noise in real-time. During the flight planning stages, the critical time for acceleration from subsonic to supersonic speeds will require careful consideration of the boom created, the strength of the boom and where the boom will impact people on the ground. The cruise phase will require planning around sensitive areas. The deceleration phase again creates issues that have to be managed. While in flight both the pilots and air traffic control (ATC) need to have shared responsibility for managing changes that negatively impact the plan. Boom propagation depends on weather, so the plan needs to be compared to the actual weather encountered to ensure the plan is still valid. For humans to understand the complex relationships of wave propagation in the atmosphere and where it impacts terrain, a perspective display of this information is a natural extension of current efforts using synthetic vision displays. This paper introduces a few concepts of operations (CONOPS), some that will require regulatory changes, and the development of a perspective flight display along with strategic map displays that allow pilots to visualize and understand the impacts to changes in flight parameters and future ground boom impacts. Pilot studies were used to determine the effect of design parameters including computational speed and display of real-time boom predictions.

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Degraded Environments: Sensing, Processing, and Display 2017, edited by John (Jack) N. Sanders-Reed, Jarvis (Trey) J. Arthur III, Proceedings of SPIE Vol. 10197, 1019708 · © 2017 SPIE
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2262356

2. BACKGROUND

Although the British/French Concorde and Russian Tupolev TU-144 aircraft reached production, the promise of prolific supersonic flight was never realized. The NASA High-Speed Research (HSR) program[1], with focus on a high speed civil transport, seemed poised to bring the dream to a reality. Like many technology programs, the technology to provide true commercial benefit had not all been developed. In particular, inefficient engine and airframe design and the noise impact due to supersonic flight. Research has been ongoing in all these areas and recent advances may allow for commercial success. The research on airframe for efficiency and low noise are the enabling technologies. Our research is focused on aids to help pilots manage and limit the noise that is produced.

Regulations[2] have been in place that prohibits civil supersonic flight over land in the United States. The latest noise policy[3] states that any future supersonic airplanes not create any more noise than currently certified subsonic aircraft. New noise standards will be developed when the noise impacts of supersonic flight are shown to be acceptable. There are two aspects to the creation of noise. One is the normal sonic boom or muffled boom on future aircraft that is produced in unaccelerated level flight with no maneuvering. The second is a concentrated boom that will be produced during periods of acceleration and/or maneuvering. It may be possible that noise levels for unaccelerated flight are acceptable but other conditions may not be. The other aspect for noise is that like now, there are areas that are more sensitive to noise than others. Even newly certified subsonic aircraft that meet the most stringent noise regulation still must follow published noise abatement procedures.

Lower noise supersonic aircraft will likely have no forward visibility. The Concord solution of dropping the nose for visibility during landing is not acceptable from a noise or design complexity standpoint. This restricted forward visibility will drive display design criteria. The NASA external vision program (XVS)[4] is addressing this limitation in visibility, providing a large display in place of the normal aircraft windscreen. XVS will use sensors and synthetic vision to provide pilots with a forward view of the aircraft flight path.

Pilots of future supersonic aircraft will be required to manage noise created during flight. Depending on regulatory changes and the noise limits, they will likely have to make qualitative and quantitative judgements of the noise and the local impact of areas on the ground. Noise abatement procedures will further limit where noise is acceptable. This information will need to be assessed in preflight planning, validation of the plan on existing conditions encountered in actual flight, and impacts due to flight plan changes due to weather or ATC constraints. This information will be difficult to understand without providing a visualization of the complete dynamics. Synthetic vision and terrain map displays are currently envisioned so adding this information to these displays was explored. The paper explores a concept of operations for supersonic flight overland and the pilot's display considerations for determining whether noise impacts are within limits for the operation.

3. DISCUSSION

3.1 Concept of operations

A CONOPS[5] was developed to identify activities, operator roles, and responsibilities in utilizing a sonic boom display during supersonic flight. The CONOPS provides a frame work to document the overall concept of the human machine interface (HMI) for the sonic boom display. The purpose of the display is to:

- Enable pilots to see where their sonic boom will impact the ground
- Display feedback to help pilots determine if the impact is acceptable
- Provide a guidance capability to help pilots avoid unacceptable sonic boom impacts

Data was generated through literature review and structured interviews with both Rockwell Collins commercial flight test pilots[6] and NASA Armstrong supersonic flight test pilots[7]. In addition, interviews were conducted with a Concorde pilot[8] and an enroute air traffic controller[9]. Standard flight operations[10-12] were extracted from the literature to provide a baseline of detailed activities and updated based on current commercial operations from pilot interviews[6].

The work is currently targeted for business jet aircraft. A project was recently awarded to Lockheed Martin to provide the preliminary design for a supersonic demonstrator[13]. This demonstrator will conduct noise research to help inform the FAA and other regulators to determine acceptable noise limits for overland flight. Until overland flight is approved, some companies such as Aerion Corporation, plan to fly initial operations based on Mach cut-off[14]. Mach cut-off is defined as the speed (based on a cruise altitude within the stratosphere) at which the shock wave is refracted upward through the atmosphere and does not reach the ground[15]. For altitudes under consideration, this is at Mach ≤ 1.15. In this condition an evanescent wave, similar to rumbling thunder, may be heard even though the sonic boom will not be heard on the ground[16]. All pilots felt that Mach Cut-off operations will be very useful even when overland supersonic flight is allowed.

3.1.1 Roles & responsibilities

It is envisioned that the FAA will create standard arrivals & departures for allowable boom waypoints and identify no/low boom areas. The primary responsibility for determining route of flight for supersonic operations will fall to the pilots and aircraft dispatch teams. ATC and the Traffic Managements Units will also require minor route evaluation support to determine course route limitations in issuing clearances. This is the case with today's current noise abatement operations and is not expected to be different for supersonic operations. Detailed below is a high level description of activities in a flight that would utilize a sonic boom display.

3.1.2 Preflight & predeparture

Supersonic aircraft will have much of the same preflight activities as a subsonic aircraft[11, 12]. It is also expected that the route of flight will not be much different except for a higher cruising altitude[11]. They will have to carefully consider noise in the preflight planning. However, pilots expressed a need to perform a sonic boom assessment via dispatch and or while doing the initial flight planning to avoid excessive flight plan modification once ready for departure. The flight planning task involves selecting the optimal routing (minimum time, minimum fuel, best ride conditions, etc.), and generating a flight plan which takes into consideration aircraft type, weather conditions during all phases, aircraft loads and operating weights, aircraft mechanical condition, airport limitations, and any additional noise limitations due to sonic boom. This flight plan gets filed with flight service and sent to clearance delivery.

Flight planning is dependent on forecasted weather. As the pilot enters the flight plan into the flight management system (FMS) during preflight, the sonic boom impact assessment will need to be updated based on current weather data and updated forecast data along the route of flight. When programming the FMS is complete, the crew performs a route check, where one crewmember reads the FMS waypoints and steps through the map depiction on the navigation display. If the flight is impacted, the route area should be displayed to the pilot and allow the pilot to dig down to understand the impact and implement flight plan changes to resolve the problem. As there are many variables that can impact where and how strong a sonic boom is, the system will provide options to the pilot in how to mitigate the impact i.e. a higher cruise altitude or moving 10 nm to the east so that the boom impacts a mountain instead of crossing over into a valley that contains a city. The pilot will also need to take into consideration any changes to the flight plan clearances made via ATC, once ATC provides the crew their final clearance. This is usually completed twenty minute before leaving the gate and the final updates may be reprogramed into the FMS on the way to the runway[10].

3.1.3 Cruise climb

During the climb, the cockpit crew checks the FMS to compare optimal and maximum cruise altitudes with the planned data and desired cruise Mach. An optimal cruise altitude will be coordinated with ATC. Sonic boom impacts will need to be factored into this decision with the other variables (many of which impact the boom calculation) such as wind data and ride (turbulence) conditions, en-route convective weather, minimum equipment list contingencies, traffic-induced speed restrictions and fuel consumption issues. Winds aloft notwithstanding, in most cases higher altitudes provide for more efficient engine operation. This is especially true for supersonic aircraft. A Concorde pilot[8] expressed the concern that a supersonic transport aircraft must climb to its final supersonic cruise altitude and cruise Mach as quickly as possible in a continuous manor to minimize fuel burn. If the flight is restricted to a lower altitude due to weather or traffic, the crew must consider the effects on total fuel burn and reserves. In addition, supersonic aircraft are much more fuel sensitive to off-optimal cruise Mach than other aircraft, which will also limit the cruise altitude options. It would be more economical and easier to clear traffic if there was a standard departure corridor[9] for supersonic operations. This corridor may allow for operations to be speed unlimited so the aircraft could get up to cruise altitude and speed as fast as possible and limit the impact of subsonic traffic[8, 9] as well as provide for allowable boom areas during acceleration[8].

Additionally, a constant acceleration profile provides the least noise impact during the phase where the impact may be significant.

In an analysis of air traffic operations for supersonic operations[11] a subsonic intermediate level off altitude was suggested to clear a corridor for the aircraft to increase speed and climb to its final cruise altitude and Mach number. Transition from subsonic to supersonic would have two trajectory phases. The first is a lowering of the flight path angle while climbing subsonic via a calibrated air speed (CAS) to go to a transonic region of flight (Mach 0.95 – Mach 1.05) as quickly as possible. Once this transition region is reached, the aircraft will continue the climb at a supersonic climb CAS value, holding this constant at maximum climb thrust to the cruise altitude. This transition is the crucial phase for a sonic boom display and it is assumed that the pilot will actively be using the display during this time to determine and or monitor where this transition and subsequent boom would occur. Conversations with NASA[7] has stated that to reduce the boom effect the pilot may need to level off so slowly that an autopilot may be required to do the task.

3.1.4 Cruise

Cruise operations would hold both altitude and Mach number constant using variable thrust. At high altitudes variations of weather will be minor however weather, such as crossing frontal boundaries, could greatly impact the sonic boom. The sonic boom system will still be required to monitor where/if the sonic boom impacts the ground and determine if these are within acceptable limits. Accurate in flight weather updates will be required for ongoing impact calculations. The pilots will be notified to resolve any impacts not within acceptable limits. Pilots may also need to do cruise climb/descents and or deviations that required them to evaluate sonic boom impacts in flight plan changes and negotiate capabilities with ATC. Currently supersonic operations enroute are conducted with an airway offset to separate subsonic traffic[9]. Controllers indicated that this would not likely change.

3.1.5 Deceleration & initial descent

The descent profile is determined by both ATC limitations and optimal aircraft performance. Two possible profiles were reviewed. The first assumed a performance based approach for a supersonic aircraft. The deceleration and initial descent is proposed to begin approximately 230 nm from the airport[7, 9, 11]. This is almost twice the distance from the airport than a subsonic aircraft due to faster speeds and higher altitudes. This initial descent is to slow down from cruise Mach to Mach 0.95 via a shallow continuous descent from cruise altitude to the approach altitude within the first 100 nm. This is a critical area for the pilots to monitor where their sonic boom impacts the terrain and may determine where they start the descent as well as lateral navigation to place the sonic boom impacts in appropriate areas. The second profile would have the supersonic aircraft stay at cruise Mach as long as possible and do a steep descent profile[7]. This was preferred by all pilots as the aircraft would slow down to subsonic prior to the top of descent limiting the possibility of a focus boom as well as allowing fuel savings by not having to slow down so early. Other factors that will go into calculating the descent profile include wind direction and intensity, speed restrictions, high barometric local pressure at the transition level and turbulence. The vertical navigation (VNAV) function of the FMS is used to determine an optimum top of descent point and will need to take sonic boom placement/prevention into account. Once the crew has slowed down to subsonic speeds they would begin their approach and landing preparations. The arrival, approach, and landing are expected to be conducted similar to current commercial operations today approximately 130 nm from the destination at subsonic speeds.

3.2 Human machine interface considerations

This section includes a brief outline of high level considerations for the Sonic Boom Display HMI. Iterative HMI pilot working groups [8, 17, 18] were conducted to define data and functionality needs as well as to verify design assumptions for the sonic boom visualization.

The objective of a sonic boom display is to provide the pilot the capability to plan and carry out a flight that allows them to reduce their sonic boom and or avoid hitting populated areas. This requires a flight planning capability that can assess the impact of their flight plan and display areas for resolution to the pilot. The optimal solution would provide viable solutions for pilot evaluation and approval rather than pilots making educated guesses and repeated impact assessments to flight plan changes. It is also necessary to have a predictive capability while in flight that will provide an alert if conditions have changed significantly to effect negative sonic boom impacts along the route of flight. Pilots will need to be alerted to the change in conditions early enough to implement flight plan changes and coordinate them with ATC. It is important to note that generally pilots have very few waypoints in their flight plans and often fly direct i.e. JFK to LAX[17]. Currently weather data is only provided for selected waypoints in a flight plan. Pilots suggested not tying weather data to waypoints in the flight plan, but create waypoints every so many miles or so along the route of flight for the sonic boom calculation[17]. This data should include the vertical profile for a larger area that encompasses the current flight plan and the generated trajectories to allow the Sonic Boom Display system to evaluate impacts and find other suitable routes.

Pilots were in favor of a strategic view and a tactical view. The tactical view consists of a "Real-Time" guidance function to provide for maneuver guidance to avoid creating a focus boom and to allow pilots to monitor their current sonic boom impacts. Real-time is a bit of a misnomer in that a sonic boom can hit the ground as much as two minutes after it is generated. Here "Real-Time" means that pilots have the ability to investigate and adjust their path in real-time far enough in advance to affect minimization/placement of the sonic boom. This was especially important in providing flight guidance and in providing pilots the flexibility to implement momentary flight changes without having to modify their flight plan. The look-ahead capability required improvements in the algorithm calculation and processing time of the boom prediction which we have been successful in making. In addition a Mach Cut-off function is included so that pilots can fly a particular altitude and speed to avoid their sonic boom reaching the ground. These limits are displayed on the Primary Flight Display (PFD) similar to how airspeed would be displayed today with an airspeed bug to delineate a Mach Cut-off speed and a digital readout of the value below the current airspeed value. The altitude tape would depict the Mach Cut-off altitude limit and a digital flight level readout below the barometric readout. Two options were investigated in how to treat airspeed and altitude in the case of preventing sonic boom while using Mach Cut-off values. The first option was to treat these limits as minimums. The second was to treat these limits as an altitude floor similar in how radio altitude is currently used. The HMI considerations in determining which method to use are: what is the most salient indication and what level of concern is there for busting these limits. Pilots did not have a preference at this moment in time and how these limits are treated may depend on results of FAA research and the potential impacts.

The strategic view would consist of a route impact function that would look ahead within a 30 minute window to notify the pilot of an unacceptable sonic boom impact. Pilots felt that a farther look ahead would require changing the route of flight needlessly due to how dynamic weather can be. In addition, this look ahead is highly dependent on availability of weather data. In addition pilots felt the need to review their entire route of flight for planning purposes should they need to deviate from the executed flight plan. This requires the ability to run a leg or perhaps entire flight through the algorithm timely enough to pin point impacts to be resolved and to negotiate route clearances.

Pilots were divided on whether or not they need to see the "current" impact as this would be impacts that they would not be able to do anything about. A main comment was "we need to see them to know if we unwittingly busted a limit and need to file a NASA report". This was stated "tongue in cheek", but may very well be true. Pilots also indicated that more than 3 levels would clutter the display and lead to potential confusion.

Pilots wanted to be able to see the areas that were noise sensitive and their impacts on these areas. Pilots felt that it would be easier to plan a route around these areas with this additional situation awareness. It was also suggested that since the weather data has variability to it and a certain level of uncertainty that pilots may want to provide an error margin and or a selectable parameter to implement their own noise limits. Other pilots would prefer that one was incorporated into the system so that they would not have to think about such things. All pilots agreed that computing the decision space was essential to limit workload as the problem space was large with many parameters to modify in which one or more could affect a result, positive or negative, in their sonic boom impacts.

As discussed in the CONOPS the Mach Cut-off capability was perceived as valuable even with the capability to fly supersonic over land. Conversations with NASA test pilots and engineers indicated that it could be tricky to fly on the edge of sonic propagation during the Mach Cut-off. Failure could cause focus booms that are 3-5 times louder than a normal boom. Pilots suggested being able to select an altitude at which they could designate as the fake "ground" for the system to provide altitude and speed so their boom does not pass through this boundary. Another suggestion was to provide a capability where they could place a waypoint and designate an impact limit and the system would calculate a vertical profile that would provide this desired result.

3.2.1 Sonic boom depiction

Supersonic flight decks will have very limited outside visuals and are expected to have enhanced vision systems. In fact, current optimized designs have no natural forward visibility and only have side windows[18]. It is expected that both the PFD and the Multi-function Display (MFD) will be used to display the sonic boom as a selected overlay similar to weather overlays. Sonic boom data will be overlaid with terrain and synthetic vision data. In addition the FMS map may need to show a 3D perspective display to adequately provide a decision aid to the pilot to determine how best to modify the flight plan. Early on in the project three different ways of displaying the sonic boom (**Figure 1**) were discussed in the pilot working groups. These are a gridded carpet, a painted carpet, and the traditional sonic boom ray format seen in previous depictions on the bottom. In **Figure 1**, color coding was arbitrarily selected as the focus was on where the data would be displayed, and how the boom carpet would be interpreted.

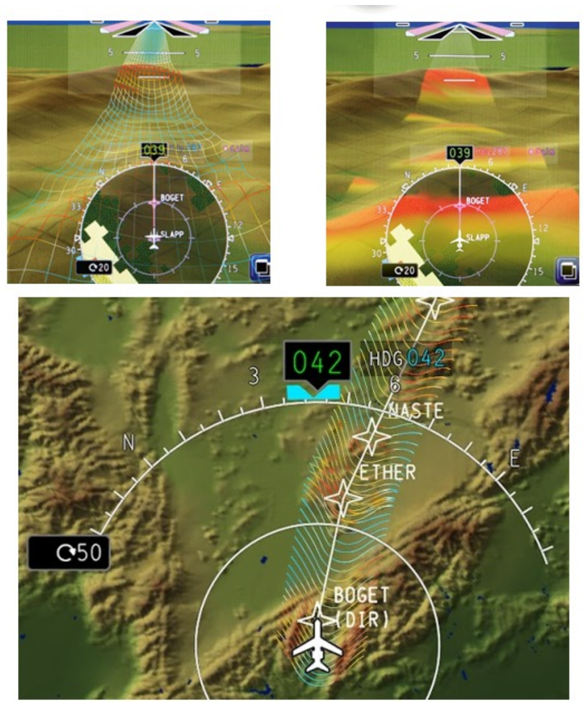

Figure 1: Sonic Boom Concept Drawings

An investigation was conducted in how to depict the boom carpet so that it is explicitly different than terrain avoidance and weather data coding with 8 pilots[8, 17, 18]. In addition adding a priority for overlays and or transparency was also investigated. The upper right image shows an example of only showing yellow and red sonic boom areas and not displaying nominal data (boom pressure levels below a particular limit). Two out of 8 pilots commented that the painted depiction was too similar to terrain awareness warning system coding (TAWS)[17]. Both the grid and traditional rays were much easier to see where the impact was hitting the ground. All commercial pilots preferred the gridded sonic boom depiction, but also felt that the traditional ray format was acceptable as well[8,17]. NASA pilots tended to prefer the traditional ray trace as this is what they are used to seeing[18]. Commercial pilots indicated that transparency would be key to not cluttering the display, however instead of completely leaving out the data; they wanted to see the shape of where the impact was[17]. This would also provide them the information of whether or not their boom was reaching the ground at all and provide feedback that the system was still working properly. **Figure 2** below shows the Sonic Boom Display prototype and illustrates an example of how a pilot would interpret and use the display to modify their flight plan. This area of the flight plan occurs in the Death Valley region. For ease of discussion, areas of the terrain that are below sea level are color coded blue. In looking at the depiction, pilots were able to see how the sonic boom carpet was inhibited from going into the valley by the mountains. In addition pilot were able to understand that if they wanted to avoid the critical red boom impact area from going over the mountains and into the valley, they could either turn sooner or off set their current flight path by moving 10 nautical miles to the left. Visually this is indicated by the scalloped edges of the boom carpet along the terrain data. In addition pilots were able to see how the boom carpet disperses in the turn and understand how the change in acceleration affected their boom pattern to anticipate boom carpet placement based on flight plan changes. A real-time trial application was implemented to further help pilots determine how to resolve sonic boom impacts. This will be discussed further in the next section.

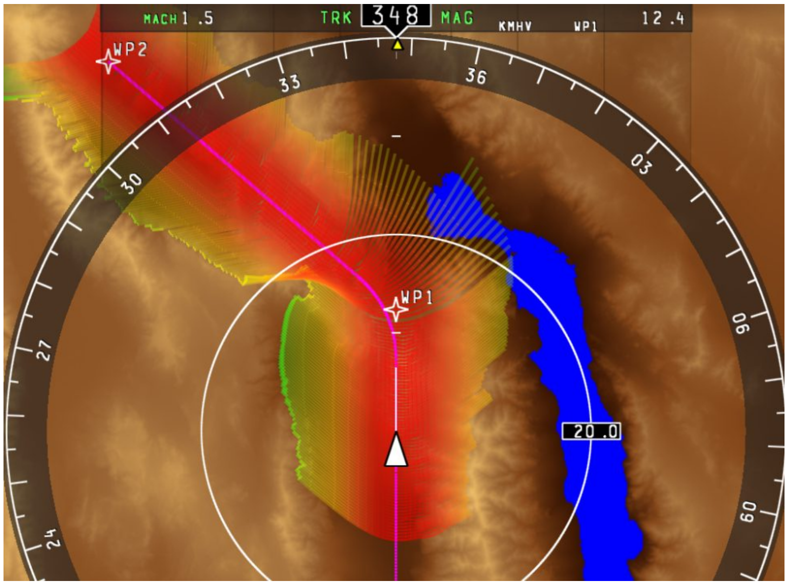

Figure 2: Sonic Boom Display prototype illustrating mountain occlusion of the boom carpet.

3.3 Sonic boom visualization

3.3.1 Earlier work: pre-computed sonic boom footprint

In various research projects the depiction of a pre-computed footprint of the overpressure generated by a supersonic aircraft has been addressed[19-22]. **Figure 3** shows an example on a navigation display in north-up plan mode.

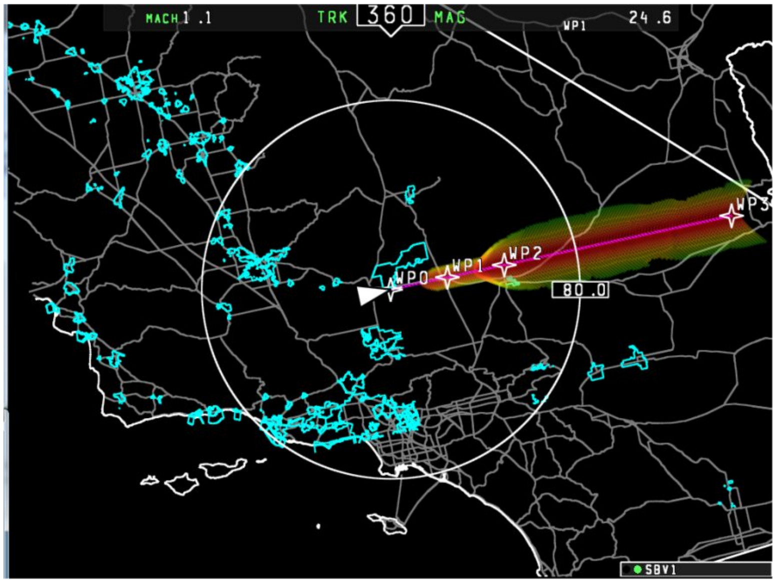

Figure 3: Pre-computed Sonic Boom Footprint

Besides the depiction of pre-computed footprints, it may be of use to have the capability to compute and depict the expected near-term footprint in real-time. By feeding the sonic boom algorithm with an extrapolation of the current state instead of the planned trajectory, the pilot is presented with a predicted footprint. The next section discusses this concept, design questions, prototype implementation, and the refinement of such capability.

3.4 Prediction

3.4.1 Concept

To provide the pilot with actionable information, (presentation of) the future footprint should contain information that is reasonably close to what will occur if the current state is maintained (i.e. sufficiently accurate) and be far enough ahead in time that a change in state also has an impact on location and/or magnitude of the footprint. Thus, the predicted trajectory that is used as an input to the sonic boom computation should be sufficiently accurate and the time horizon used by the prediction should not be below a value where the impact of changes in state only has a minimal effect. A typical problem with trajectory predictors is the lack of information concerning the pilots maneuvering intentions. The most basic form of trajectory prediction is a first order model. With such a model, the future position follows from an extrapolation along the current direction of flight. A slightly more sophisticated model is one in which velocity and bank angle are used to compute the radius of the curve that best approaches ownship future trajectory from the current position.

A sonic boom footprint based on a first order model provides the pilot with information on the impact area and magnitude for the situation in which the aircraft continues its flight along the current track, i.e. in case the pilot does not maneuver. Such a real-time visualization is likely to be a good approach in case the pre-computed profile no longer applies (e.g. due to deviations in path, speed, atmospheric data). However, once a pilot starts to maneuver, a first order model will lag and show the footprint along a path of constant direction that the aircraft has already passed by.

A second order path predictor may yield a trajectory that is sufficiently accurate as long as the roll angle (used in the computation of the turn radius) remains fairly constant. During wings-level flight, the predicted trajectory is the same as the one obtained with a first order model. The fundamental limitations of a second order model, is that the predicted trajectory will only resemble the true future trajectory for the time that the pilot does not change the roll angle. For a constant prediction (i.e. look-ahead) time, there will always come a point beyond which the predicted trajectory is still curved whereas the actual trajectory will have a constant heading. As a result, only the footprints up to this time provide useful information. This issue exists only during the time that the pilot is maneuvering. Once the aircraft is wings level, the full extent of the preview provides actionable information.

If the pilot interaction is only through the automation, the predictor model may be enhanced to provide a more accurate prediction. If during certain critical phases the pilot only makes strategic flight plan changes and the automation always flies an accurate path change throughout the entire maneuver, the future predicted state may be able to be determined with enhanced accuracy.

3.4.2 Implementation related design questions & considerations

Real-time computed boom footprint for a limited number of sample points: With the current sonic boom computation function implementation running on an I7-3770 PC, real-time performance limitations allow for approximately 10 footprints to be generated each second. This raises the design question on how to allocate these 10 footprints, i.e. up to what time horizon is it useful to predict. Hence there is a trade-off between spacing and look-ahead horizon.

Another aspect concerns the choice of the model used to extrapolate the current state. Any prediction requires assumptions regarding the inputs to the system and the disturbances acting upon the system during the prediction time.

3.5 Design iterations

Pilot feedback was utilized to help weigh the tradeoffs shaping the detailed design of the sonic boom display format and functionality[23]. Examples of these design tradeoffs are the spacing between footprints, the representation of the data that informs the pilot about areas that should not be covered with the higher intensities of the boom footprint, the model used to generate the prediction of the future state and the minimum required and practical look-ahead time for the real-time boom depiction.

For the model and 2nd order extrapolation of the current system state in the horizontal dimension was used and a 1st order extrapolation for the vertical dimension.

To obtain the information needed to make these design decisions, a usability demonstration and pilot working group[23] was organized at NASA Armstrong. A total of eight 1-hour sessions were held with a total of 10 pilots. Each session started with a 14-slide briefing to the participating pilot.

Look-ahead horizon was varied in terms of look-ahead time. Because a pilot cannot affect the current footprint, it was hypothesized that there was additional trade-space by having the first computed footprint start some time ahead of current state. The start location of the real-time footprint depiction was varied from current location (t=0) to 60 seconds from the current location (t=60). The underlying reasoning was that by sacrificing data that could not be changed anyway (i.e. not computing and displaying it), the preview range can be extended without reducing the resolution.

3.5.1 Results

Prediction timespan: In spite of the fact that the pilot cannot influence the location and magnitude of the current boom, several pilots preferred the real-time footprint to start at the current location, i.e. t=0. Furthermore, even when extending the preview up to 180 seconds, the spacing that results from 18 seconds between the footprints was not regarded as too large.

Prediction model: Although depiction of the sonic boom footprint using a second order trajectory prediction was well received by the pilots, the limitations also became apparent. In an example in which the prediction showed that the current path would yield a boom over a built-up area (in about 2 minutes), pilots maneuvered a little bit to the right or left to move the predicted footprint away from the built-up area. Typically, already rather quickly (i.e. at a small roll angle) the prediction showed the built-up area clear of the footprint[1]. However, if based on this the pilot immediately rolled back, part of the footprint also overlapped the built-up area again. Pilots quickly figured this out and adopted a strategy to maintain roll a bit longer before rolling back. Also, given the width of the footprint at the location of interest it was rather straightforward to estimate the amount of heading change needed to get the area clear of the footprint. Although this generally worked well, it became more difficult when having to maneuver to position a footprint between two built-up areas.

Pilot Feedback & Usability: All 10 NASA pilots provided positive feedback in relation to the sonic boom depiction as it related to terrain and flight path. There were no performance issues observed in interpreting impact and placement along the flight plan or path. The Depiction was acceptable and required no changes. For the real-time application, interpreting look-ahead time was easier when the start time of the prediction is zero though not all pilots preferred this. Starting at a different time would require a spatial and temporal mental adjustment and the display should accommodate this by adding further information. Even though the maximum spacing between footprints was 180 seconds, pilot did not regard this as too large and were still able to effectively interpret and use the prediction. Pilots also used the look-ahead time in different ways dependent on the variability of the terrain and their perceived level of boom risk i.e. confidence in system prediction, flying style, and potential need to negotiate route changes with ATC.

3.5.2 Enhancements & refinements

Prediction timespan: Given that the need for a certain amount of look-ahead time may vary, it was decided to provide the pilot with the capability to modify the look-ahead time in steps of 1 minute and have the look-ahead path always start at current time.

Prediction model: A potential solution to the limitation of the second order model is the use of the pilot's intended change in heading[2], e.g. as entered on the Mode Control Panel. In this concept, the pilot uses the knob for heading (HDG) select to setup a "trial-heading", and a first order prediction is used to generate a trajectory along this heading. With an update-rate of the real-time footprint of 1 Hz, this provides the capability to interactively select a heading for which it can be observed that the (high intensity part of the) predicted footprint is clear of any built-up areas. To obtain feedback, an initial implementation was realized the day after the workshop and it was confirmed that this represented the intended function.

An issue that still existed was the fact that using a first order prediction for the trajectory along the selected heading basically assumes an instantaneous rate of turn to go from current heading to selected heading. This will cause a certain offset between the predicted and true trajectory which will increase with an increase in heading change.

To reduce this error, a second order predictor can be used for the period of time that the aircraft is expected to be turning. This requires an assumption on the turn rate or bank angle that will be used. **Figure 4** illustrates the difference between the trajectory of a second order predictor based on bank angle (blue) and a trajectory predictor using the trial heading

[1] Because if the area is still 90 seconds away, the location of the footprint is based on the curved trajectory maintained for 90 seconds.

[2] This idea was proposed by Brett Pauer during the Sonic Boom Pilot Workshop on Nov. 2, 2016.

(red). This data shows the actual predicted path as generated during a simulation run from one of the pilot working groups. The Y-axis is latitude and the X-axis is longitude.

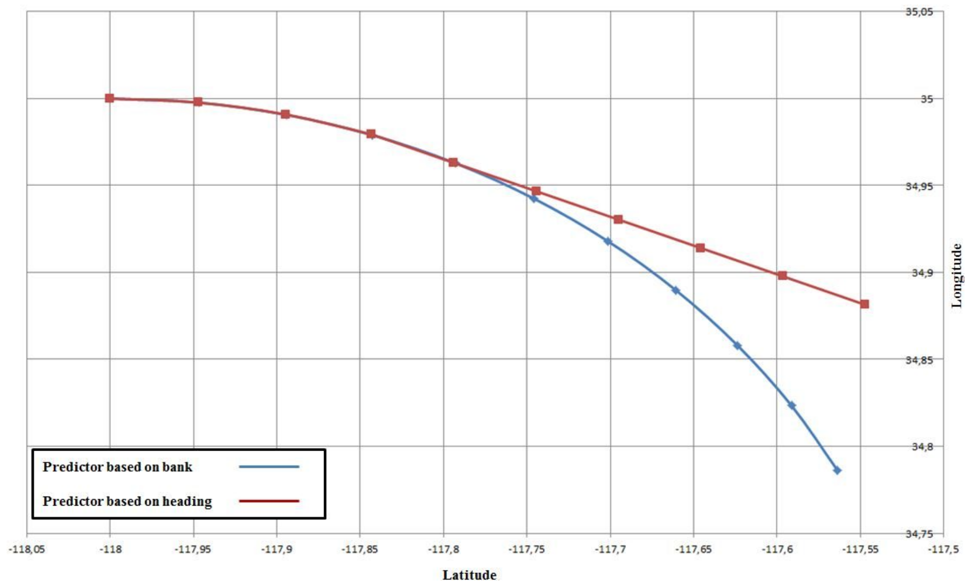

Figure 4: Differences in predicted trajectory using bank angle (second order predictor) & heading (first order predictor).

For both trajectories the prediction time is 2 minutes. The bank angle is 20 degrees and the velocity is Mach 1.3. The selected change in heading is 22 degrees. For the second order predictor (blue) the change in heading after 2 minutes is approximately 60 degrees, almost a factor 3 larger than the heading change needed to put the footprint in the desired direction.

Figure 5 shows the footprint associated with the trajectory generated by the second order predictor (bank).

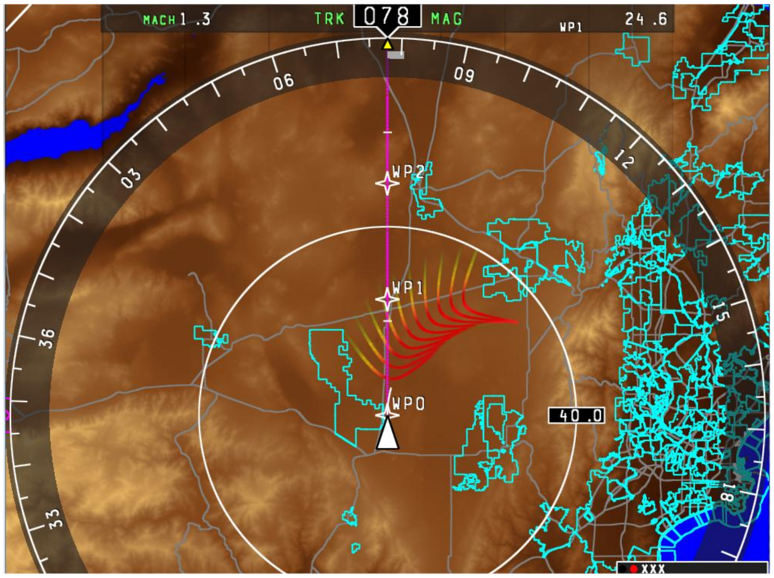

Figure 5: Sonic Boom footprint via second order trajectory prediction that uses bank angle for trajectory predictions. The second order predictor is used for the period of time that the aircraft is expected to be turning (using standard rate turns to selected heading).

Figure 6 shows the footprint that is predicted to occur if the aircraft were to turn to the selected heading.

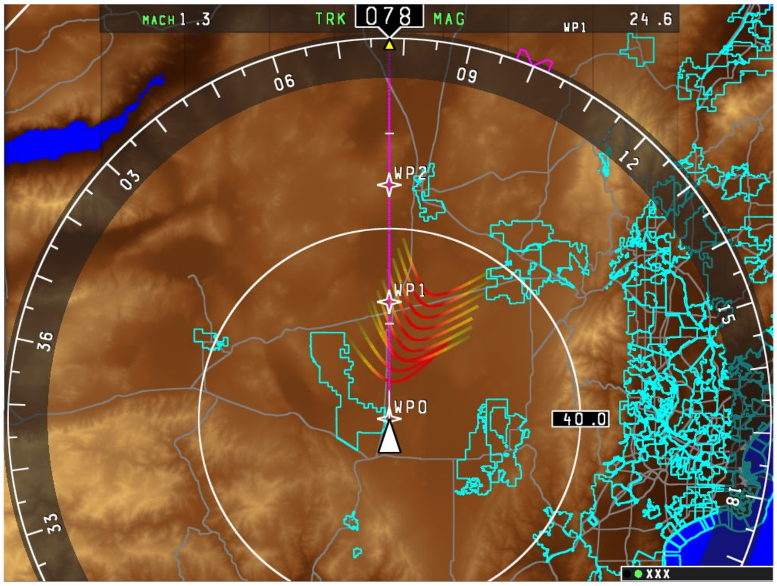

Figure 6: Sonic Boom Footprint via first order predictor that uses heading for trajectory prediction. A first order predictor using heading assumes an instantaneous rate of turn to go from current heading to selected heading. This introduces error into the prediction for larger heading changes.

To explore this capability and provide the pilot with the possibility to change all relevant parameter values a dedicated (virtual) control panel was designed (**Figure 7**). The resulting implementation was integrated into the NASA QueSST simulator (**Figure 8**).

Figure 7: Virtual sonic boom display control panel used to demonstrate prototype.

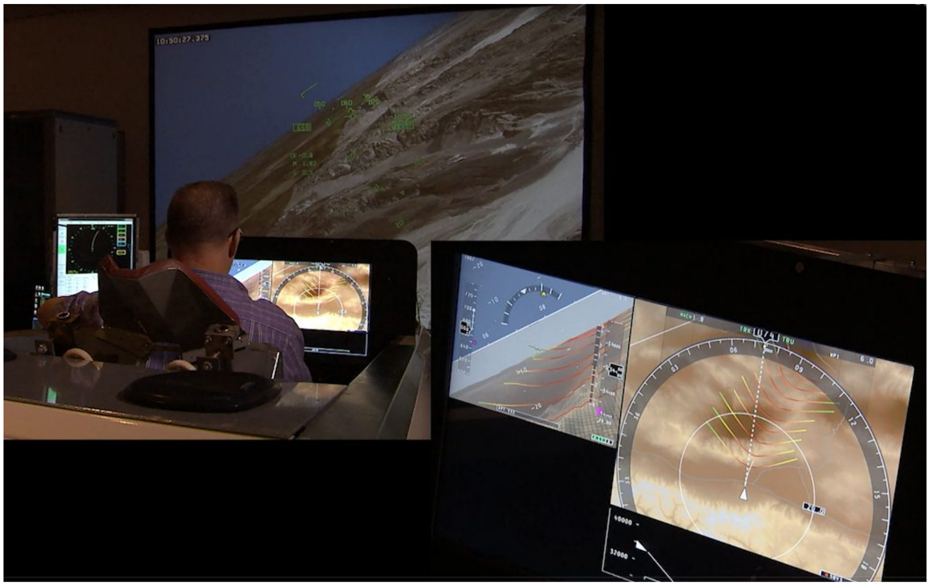

Figure 8: Sonic boom display integrated into NASA's QueSST simulator at NASA Armstrong Flight Research Center.

3.6 Future work

Earlier it was indicated that the first order predictor seems a good alternative in case the pre-computed footprint is no longer valid. Here too there are limitations and opportunities. In case the reason for invalidity does not follow from the trajectory itself, but from velocity or changed atmospheric conditions, a limited part of actual planned trajectory can be used to create the trajectory for the real-time footprint computation. This allows the algorithm to take future changes in direction into account before the pilot is actually changing the aircraft state.

This research represents a portion of the human machine interface and sonic boom visualization work to implement a Sonic Boom Display into business jet avionics. Proposed future work includes pilot alerting mechanisms and automated impact evaluations to include mapping out a pilot decision space to help pilots resolve impacts and including the sonic boom impacts into an integrated hazard prediction and flight optimization system such as the NASA Traffic Aware Strategic Aircrew Request (TASAR), NASA Strategic Conflict Resolution (Stratway) tool sets and or industry developed systems.

4. CONCLUSION

We present a concept of operations that may allow supersonic flight over land. Before regulatory changes, this operation may take advantage of flying supersonic above Mach cut-off. To meet noise regulations, a visual depiction of where noise impacts the ground and some indication of the strength of the noise is required. Pilots preferred this information on both a tactical perspective display and a strategic display on a moving map. The displays were optimized for use in planning and in-flight. Noise from pilot maneuvers will not reach the ground until sometime in the future. To be useful, pilots will require a prediction to determine noise impacts to their flight path and the capability to determine how to modify their maneuvers for avoidance. The accuracy of the prediction and the ability of the pilot to interpret the information to modify their flight plan were explored. A usability demonstration was conducted at NASA Armstrong with ten pilots/navigators investigating path management, "Real-Time" boom depiction, look-ahead time functionality, updated boom depiction, and adding additional background information[23]. This demonstration simulated a CONOPS in which pilots use the system to evaluate and manipulate a flight. There was no performance issues observed in interpreting impact and placement along the flight plan or path. All feedback of the sonic boom depiction was positive. Pilot feedback and capability improvements described in this paper have been implemented in updated software to include improved processing performance (now at 16% of the original processing time) of the sonic boom algorithm allowing real-time in flight boom predictions.

ACKNOWLEDGEMENTS

The Sonic Boom Display project was funded by NASA Armstrong Research Center under contract NND15AA50C. The authors would like to give thanks to Brett Pauer, David Brian Spivey, and Ed Haering for their support in participating in usability demos, providing supersonic pilot participants, integrating the prototype into the QueSST simulator, and answering the myriad of technical questions for the CISBoomDA algorithm. Many thanks also go out to the NASA Flight Test pilots/navigators, the Rockwell Collins Flight Operation Center pilots, and to Concorde pilot and engineer Gérard Duval, who all provided invaluable feedback in the iterative Pilot Working Groups throughout the program. Without this iterative design input so much could not have been accomplished in a short period of time to result in a quality prototype with capabilities centered on usability and the human machine interface.

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