

Simultaneous Masking Between Audio Alarms in Terminal Air Traffic Control for Raytheon's  
Standard Terminal Automation Replacement System

by

Corey Hall

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This work is dedicated to Abigail, the most consistent source of motivation and support during the journey that is graduate school and life. I cannot thank you enough. This work is also dedicated to my family, whose contributions were vital to my success.

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## **Abstract**

Raytheon Systems Company proposed the Standard Terminal Automation Replacement System (STARS) in effort to replace the current systems of alarms being used in Air Traffic Control (ATC). STARS worked to eliminate unnecessary alarms and to lessen confusion among air traffic controllers. STARS uses six alarms to identify the various issues that are attended to by an air traffic controller. These alarms are tonal melodies with associated frequencies and sounding periods. Due to this, the alarms are susceptible to simultaneous masking, the phenomenon where one tone or sound cannot be perceived (total masking) or can only be partially perceived (partial masking) in the presence of another tone or sound due to limitations of the human sensory system. Simultaneous masking of STARS alarms has not previously been researched. This work uses a computational method to analyze the STARS alarms to determine if any masking is possible among the potential configurations. The method, created by Dr. Matthew Bolton for use in the medical field, was modified to fit the needs of this research. In this paper, we describe the method, present and discuss the results, and identify areas for future research.

## Introduction

Raytheon Systems Company proposed the Standard Terminal Automation Replacement System (STARS) in effort to replace the current systems of alarms being used in Air Traffic Control (ATC). STARS was created to address several issues facing the industry such as effectiveness, consistency, and discriminability of alarms. Prior to the introduction of STARS, there were three versions of another system being used (Newman & Allendoerfer, 2000). While STARS was previously compared to its predecessors, the specifics of the alarms were not directly addressed. The similarity of the tones utilized by STARS are susceptible to simultaneous masking; the phenomenon where one tone or sound cannot be perceived (total masking) or can only be partially perceived (partial masking) in the presence of another tone or sound due to limitations of the human sensory system (Fastl & Zwicker, 2006).

In work environments at large, auditory masking has been observed and reported on; it has also been recorded extensively within the medical field (Bolton & Bass, 2009, 2010; Bolton, Bass, & Siminiceanu, 2012; Bolton et al 2018a, 2018b; J. Edworthy & Hellier, 2006; Konkani, Oakley, & Bauld, 2012). The phenomenon has been detected at the clinical level (Toor, Ryan, & Richard, 2008) and shows that, as a result, critical errors can be made in safety-critical environments. It is likely that this information would translate to Air Traffic Control and errors may be able to be contributed to this effect. There is little research connecting aircraft accidents to the simultaneous masking of alarms in ATC. However, there are documented reports, made by controllers, that the discriminability of alarms poses a problem (Newman & Allendoerfer, 2000).

Bolton et al. (2018) developed a computational method that is able to address the complexity issues that have prevented comprehensive masking analyses previously. The method used model checking (a method for automatically proving properties about computational

modeling) with the psychoacoustics of simultaneous masking (mathematical models of the masking phenomenon) to determine if masking could manifest in a modeled set of alarms.

For this research, Bolton's computational method is employed to evaluate the six STARS alarms, at iterative intervals between 70 dB and 80dB, to determine the level to which the individual alarms are masked by each other. Below, we provide background on material necessary for understanding this research. We then provide a description of the objectives and method that were used to achieve our results. We discuss these results and the implications they pose for the industry moving forward.

## **Background**

The following section describes, in detail, both the method utilized and the alarm sounds of Raytheon's STARS.

## **Method**

Using Dr. Bolton's computational method, we are able to discern if any of the STARS alarms can be masked. Bolton's method uses a combination of psychoacoustics and model checking to detect if a given configuration of the alarms is susceptible to simultaneous masking (Bolton et al., 2018a, 2016; Hasanain et al., 2016, 2014, 2017).

Psychoacoustics of simultaneous masking mathematically represent how the physical characteristics of a sound affects its ability to be perceived. The basis of this is derived from a decrease in sensitivity of sensory cells on the basilar membrane when the membrane is exposed to multiple sounds. Because there is an additive effect per the number of sounds, there is a greater chance that a single sound will be masked when there are multiple sounds present (Lufti, 1983). This additive affect is depicted as a curve and is often referred to as the masking curve.

In formal methods, a model is created to explain a systems behavior and then checked against desirable properties to see if those properties are always true. Dr. Bolton's method uses formal methods, and specifically a technique called model checking, to automatically, mathematically prove properties about masking in models of alarms (Clarke, Grumberg, & Peled, 1999). It has been found that when combining Dr. Bolton's method with a given alarm system, formal models can be created for the alarms, along with their specifications, to prove if masking can occur. Dr. Bolton's method has been applied to medical alarms (Hasanain et al., 2016, 2014) and validated experimentally (Bolton et al., 2018b). The method was ultimately extended with a computer software frontend called MAASC (Medical Alarm Audibility System Checker),<sup>1</sup> This desktop application enables medical alarms to be modeled and evaluated using simple point-and-click interactions. It is worth noting that one feature of MAASC is its ability to visualize counterexamples, the trace produced by the model checker that shows how a specification violation occurred. This shows exactly which alarm was masked and what timing is required between alarms to produce the masking.

Despite its power, the method has not been applied to alarms in ATC.

## **STARS**

Previous research has found that the alarm systems used in ATC struggled to help controllers identify and differentiate the aural tones used as signals. Raytheon Systems Company developed STARS to replace existing systems in effort to relieve this problem. STARS acts to eliminate confusion among the several versions of the current alarm system and standardize the ATC alarm system at large. This new system utilizes six alarms with frequencies ranging from 800 Hz to 2000 Hz with variable sounding periods. Each alarm is classified as low priority and is

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<sup>1</sup> <http://fhs.eng.buffalo.edu/MAASC/>

comprised of two events. An event is defined as an audible tone at a specific frequency followed by a space of a specific time frame. The alarm name, frequency (in hertz) and period (in milliseconds) are outlined in the following table (Newman & Allendoerfer, 2000).

Table 1. Standard Terminal Automation Replacement System Low Priority Alarms

Alarm	Frequency	Period
Conflict Alert	1600 Hz	60 ms / 60 ms
Minimum Safe Altitude Warning	1600 Hz to 2000 Hz warble	260 ms / 180 ms
Mode C Intruder	1600 Hz	130 ms / 130 ms
Default	800 Hz	60 ms / 60 ms
Special Transponder Emergency	1400 Hz	600 ms / 250 ms
Critical Subsystem Failure	800 Hz	250 ms / 500 ms

### Objective

A prior review of all current and proposed alarm systems in ATC suggests that there are still issues with the discriminability of the alarms being utilized. For this project, the alarm specifications, set forth by Raytheon Systems Company in their Standard Terminal Automation Replacement System, were evaluated using Dr. Bolton’s computational method. The primary objective of this research is to determine any masking, total or partial, that may exist among these alarms at realistic volumes. The following sections outline the method and results and discuss the implications of the results.

### Methods

While MAASC was originally created for application in the medical field, we modified it to fit the needs of this research. Specifically, we update the mathematical computations used for converting alarm descriptions into formal models. This was necessary due to the different frequency ranges found in STARS alarms. Note that we also manually overrode some of the medical alarm standard values that were incompatible with the STARS alarms (this was something that was supported by MAASC). Thus, MAASC was used to model and analyze all of

the alarms listed in Table 1. Note that because no volumes are specified for the STARS alarms (Newman & Allendoerfer, 2000), we started our analysis by using a fairly standard, listenable volume of 70 dB. This gave us a standard baseline from which to consider relative volumes between alarms.<sup>2</sup> Note that volumes of the STARS alarms can be set by individual controllers. Then, based on results observed between alarms, we systematically varied alarm volumes to investigating masking conditions more deeply.

### Results

All six alarms and the associated configurations were analyzed simultaneously for both total and partial masking. MAASC provided the following results with a mean verification time of 4.4 seconds with a standard deviation of 1.58 seconds. At the 70 dB level, no total masking was found. However, several situations where alarms could be partially masked were identified. The following charts display the counterexample visualizations of these results.

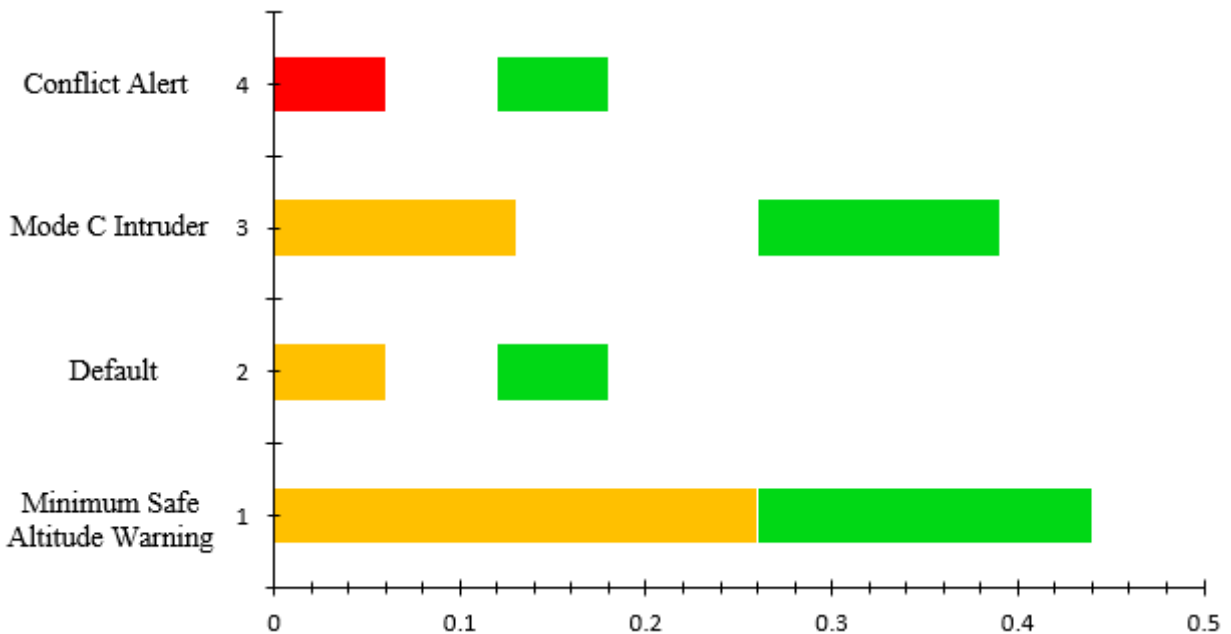


Figure 1. Conflict Alert is partially masked

<sup>2</sup> While volume can impact the shape of masking curves, the impact is very minor. Thus, masking observed between any relative volumes will generally hold for any given reference volume (10 dB in our analyses).

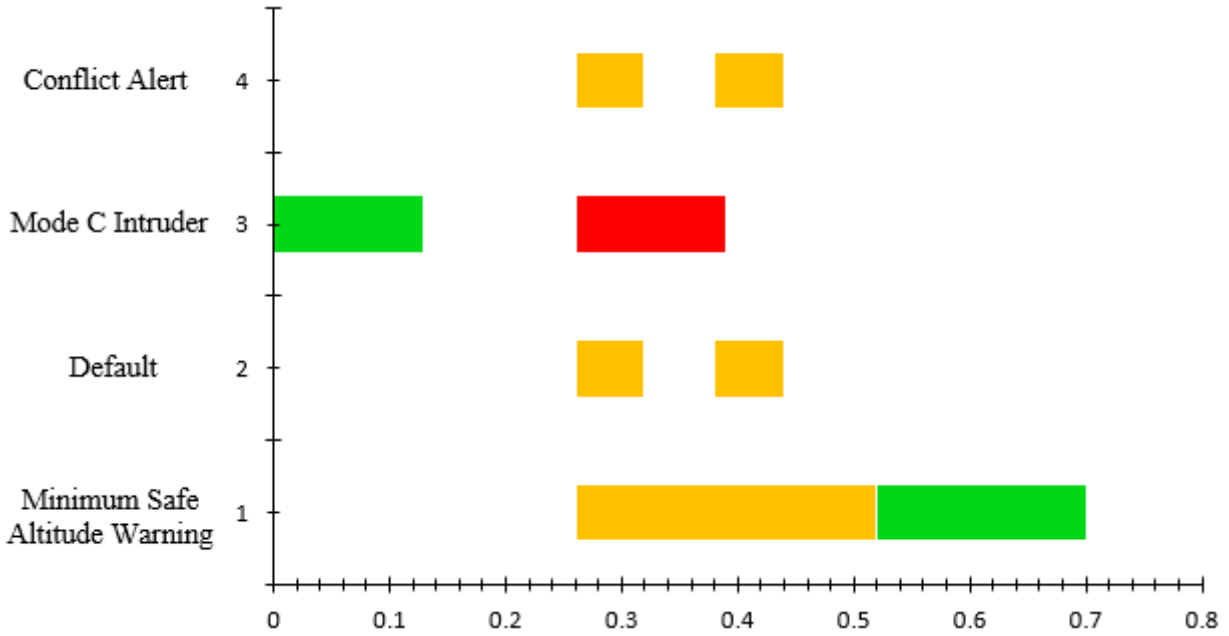


Figure 2. Mode C Intruder is partially masked

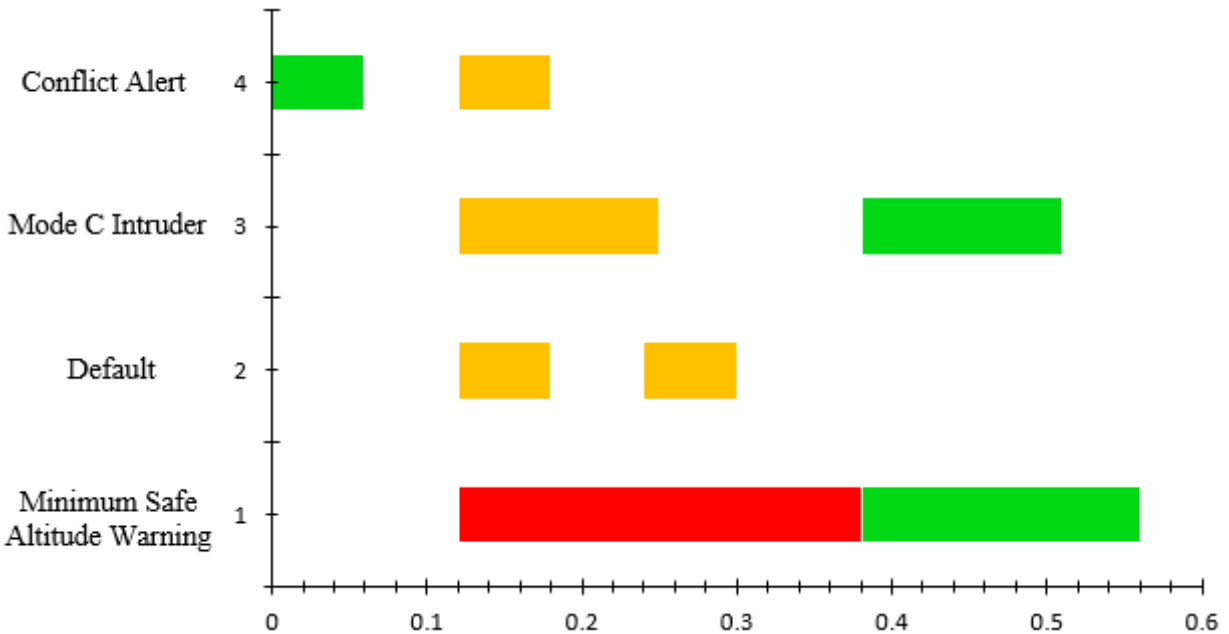


Figure 3. Minimum Safe Altitude Warning is partially masked

While these results may not look drastic, the findings are quite interesting. First, MAASC did not identify any total masking at the 70 dB level. This indicates that no configuration of the alarms renders any single cycle of any of the alarms completely unperceivable. However, the Conflict Alert, Mode C Intruder, and Minimum Safe Altitude Warning are all susceptible to

partial masking. This masking only occurs in the presence of all three target alarms and the Default alarm. Also, only one event for each of those alarms is masked in a given configuration.

For the Conflict Alert, at 70 dB, the first event is masked by the combination of the first events of the Mode C Intruder, Minimum Safe Altitude Warning, and Default alarms. For Mode C Intruder, at 70 dB, the second event is masked by the combination of both events from the Conflict Alert and the Default alarms as well as the first event of the Minimum Safe Altitude Warning alarm. Finally, at 70 dB, the first event of the Minimum Safe Altitude Warning alarm is masked by the combination of the second event of the Conflict Alert, the first event of the Mode C Intruder, and both events of the Default Alarm. All the alarms were analyzed; these were the situations in which MAASC identified masking at 70 dB.

Given the potential variation in alarm volumes due to controller interaction, we conducted a second set analyses on the alarms that were identified to be susceptible to masking. The objective of these analyses was to identify any situations where variations in the volume of a single alarm could lead to it becoming totally masked. The volume of the alarms was systematically varied within a reasonable range and the given configurations were then analyzed. MAASC identified total masking of the Conflict Alert alarm at 61 dB when the other three alarms remained at 70 dB. Because of the nature of volume, it is safe to assume that these results could be found in any 9 dB difference between the Conflict Alert and the other alarms. The following chart displays the counterexample visualizations of this result.

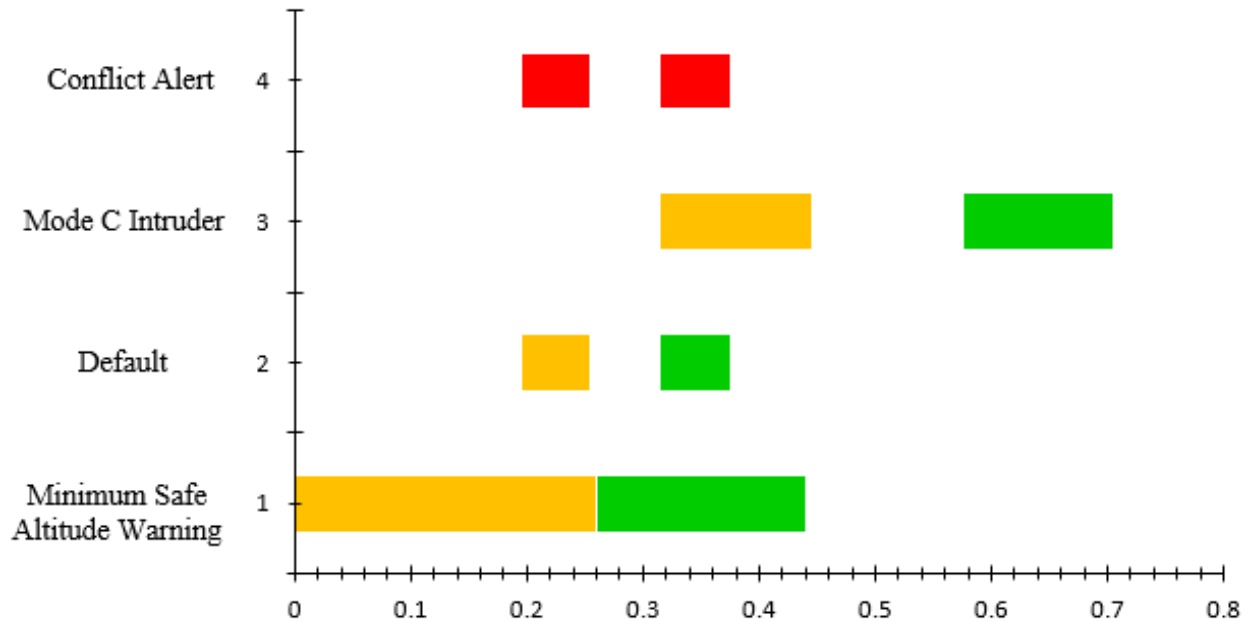


Figure 4. Conflict Alert is totally masked

### Discussion and Conclusion

After analyzing the alarm configurations using Dr. Bolton’s method, the results show that masking is possible and a concern for the alarm system. 3 out of the 6 alarms analyzed are susceptible to partial masking at the standardized 70 dB level and 1 alarm is susceptible to total masking when there is a variation of 9 dB or more.

There is no current consensus regarding the number of aural tones that can be distinguished between, regardless of masking. However, there is ultimately a maximum number of tones a given individual can distinguish between. It can then be assumed that masking decreases an individual’s threshold. Given this, if masking cannot be avoided, the best practice would be to increase the minimum number of alarms necessary before masking has an effect on the distinguishability of the alarms. Therefore, the results for the STARS alarms, at 70 dB, are promising. Each situation where masking is possible requires a minimum of three other alarms to also be present in order for the masking to occur. The masking detected in these configurations is only partial, whereas the total masking of the Conflict Alert poses a larger concern.

The results presented here are encouraging for STARS. With only one example of total masking identified and a relatively higher number of alarms necessary for any masking to materialize, the system works to eliminate this problem. Unfortunately, the fact that combinations of four of the alarms resulted in three being masked at some level poses an issue. If these alarms sound in unison or close proximity, it is likely that one or more could be missed. In the safety-critical environment of air traffic control, even one missed alarm could have potentially costly consequences and could be the difference in life or death.

It is important to note that, while variations in volume have minor impact (Bosi & Goldberg, 2003), air traffic controllers have the ability to manipulate the volume of the alarms. This does pose an immediate concern, illustrated by the total masking of the Conflict Alert, and a standardized volume set for STARS would help to further eliminate any situations in which masking could occur.

### **Future Considerations**

Given the results produced with this method, there are several ways in which this topic could be researched further. This research isolates the alarms and models configurations of them. Ultimately, no other variables are accounted for such as ambient noise. To continue, research identifying the specific volumes of the alarms and other ambient noises that controllers face could provide more insight into the extent of the problem.

Next, it is important to understand these alarms and air traffic control at a more specific level. Variables such as number of STARS terminals that a controller is exposed to in a given environment and the associated values with missing any given alarm should be further studied. It is possible that temporal spacing of the alarms is sufficient to eliminate masking altogether but

the frequency of unnecessary or redundant alarms remains high (Newman & Allendoerfer, 2000).

Finally, there may exist combination of frequencies and spacing that would completely eliminate masking. For air traffic control alarms and specifically STARS, such a combination could be identified and implemented to provide controllers with the most clear and discriminable alarms.

While this research presents interesting results, the full extent of this problem is unknown. Any effort to expand the understanding of an air traffic controller's interaction with the alarm system will aid in interpreting these results and work to make air traffic control more effective. The ability of MAASC to be implemented and used in an effective and timely manner suggests that is practical to apply the application to further research on this topic and in the field at large.

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