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14 CFR Part 23 Automatic Ground Collision Avoidance System (Auto GCAS) Certification Roadmap

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16. Abstract

Automatic Ground Collision Avoidance System (Auto GCAS) can be integrated on 14 Code of Federal Regulations (CFR) Part 23 general aviation aircraft with existing certified autopilot systems to reduce controlled flight into terrain (CFIT) to below the current mishap rate. To ensure safe and effective Auto GCAS implementation, regulators must assure the system has minimal probability of unsafe behaviors while limiting nuisance rates during normal aircraft operations.

Regulatory barriers, technology limitations, and cost previously limited implementation of Auto GCAS on 14 CFR Part 23 general aviation aircraft. Acceleration of the aviation industry into automated technologies and additional flexibility from 14 CFR Part 23 Amendment (Amdt) 64 rules, make the Auto GCAS certification path achievable.

Auto GCAS has the prospect of converting an already catastrophic situation back into a normal and acceptable one. Properly substantiated, Auto GCAS capabilities will save lives. This is clearly in the public interest and warrants serious consideration by the Federal Aviation Administration (FAA).

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Acronyms

Acronym	Definition
Auto GCAS	Automatic Ground Collision Avoidance System
AC	Advisory circular
ACAT	Automatic Collision Avoidance Technology
ACAS	Airborne collision avoidance system
AFTI	Advanced Fighter Technology Integration
AFM	Aircraft flight manual
AFMS	Aircraft flight manual supplement
AGL	Above ground level
Amdt	Amendment
AOC	Adverse operating condition
ART	Available reaction time
ASTM	American Society for Testing and Materials
CFR	Code of Federal Regulations
CFIT	Controlled flight into terrain
DQR	Data quality requirements
DAL	Design Assurance Level
DER	Designated Engineering Representative
DDS	Detailed Design Standard
DQR	Data quality requirements
EVAA	Expandable Variable-Autonomy Architecture
EFIS	Electronic flight instrument system
FAA	Federal Aviation Administration
FGS	Flight guidance system
FHA	Functional hazard assessment
FRRP	Fighter Risk Reduction Project
GCAS	Ground Collision Avoidance System
IFR	Instrument flight rules
ILS	Instrument landing system
IMC	Instrument meteorological conditions
MASPS	Minimum Aviation System Performance Standard
MOPS	Minimum Operational Performance Standards
MW	Middle Wear
NASA	National Aeronautics and Space Administration
NTSB	National Transportation Safety Board
PBR	Performance-based regulations
RA	Resolution advisory
RTA	Run-time assurance

RTCA	Radio Technical Commission for Aeronautics
ROC	Required obstacle clearance
RTC	Required terrain clearance
SRE	Single engine reciprocating
STC	Supplemental type certificate
sUAS	Small unmanned aircraft system
TSO	Technical standard order
TAWS	Terrain awareness and warning system
TCAS	Traffic alert and collision avoidance system
TSM	Time Safety Margin
USAF	United States Air Force
USOC	Unsafe system operating condition
VMC	Visual meteorological conditions
VFR	Visual flight rules

Executive summary

Controlled flight into terrain (CFIT) mishaps occur in both general aviation and commercial aviation despite enhanced technologies, like terrain awareness and warning system (TAWS), available in the cockpit. Automatic Ground Collision Avoidance Systems (Auto GCASs) can be integrated on 14 Code of Federal Regulation (CFR) Part 23 general aviation aircraft with existing certified autopilot systems to reduce CFIT below the current mishap rate.

Auto GCAS implementation has proven successful on military fighter aircraft, significantly reducing CFIT rates where manual systems failed to achieve the desired mishap reduction. Regulatory barriers, technology limitations, and cost previously limited implementation of Auto GCAS on 14 CFR Part 23 general aviation aircraft. Meanwhile, CFIT by this population remains unacceptably high, even with manual TAWS or similar systems installed. Acceleration of the aviation industry into automated technologies and additional flexibility from 14 CFR Part 23 Amendment (Amdt) 64 rules make the Auto GCAS certification path achievable.

This report summarizes applicable regulations, identifies a means of compliance, and proposes a certification roadmap for Auto GCAS on general aviation aircraft while still relying on a prescriptive 14 CFR Part 23 Amdt 63 certification basis to achieve means of compliance safety objectives where appropriate. Wherever possible, this report relies on prescriptive 14 CFR Part 23 Amdt 63 requirements and pre-Amdt 64 means of compliance publications to simplify the approach and show that, while novel, the guidelines and directives provided in pre-Amdt 23-64 are sufficient with few changes required to meet performance-based safety objectives.

The recommended means of compliance were derived from lessons learned during a limited scope flight test campaign using the National Aeronautics and Space Administration (NASA) Expandable Variable Autonomy Architecture (EVAA)/Middle Wear (MW) 1.4 and associated Ground Collision Avoidance System (GCAS) module integrated with a commercially available electronic flight instrument system (EFIS), autopilot, and autothrottle. This experimental Auto GCAS demonstrated low nuisance operations during a limited flight test campaign (53 sortie/61.3 flight hour), throughout the enroute, low level, and terminal operating environment.

Although the FAA has accepted consensus standards as a means of compliance with 14 CFR Part 23 Amdt 23-64, some are redundant to existing pre-Amdt 64 guidelines and do not provide any additional specificity or flexibility to the Auto GCAS design requirements. However, where useful in clarifying hazard analysis and risk mitigation, consensus standards are utilized to augment traditional means. The high-level assumptions for the proposed 14 CFR Part 23 Auto GCAS certification roadmap include:

Guidance	Category	Role
Automatic Pilot	Safety	Ensure safety via functional independence of the autopilot and Auto GCAS components Provide guidance for coupling collision avoidance system to autopilot and autothrottle from TCAS II/ACAS II Utilize guidance from AC 23.1309-1E and ASTM F3061/F3061M − 22b
TAWS	Performance	RTCA DO-367 MOPS set desired performance requirements for unimpeded operating altitude and terrain clearance requirements
TCAS II/ ACAS Xa	Nuisance & Safety	Leverage AC 20-151C for non-standard hazard severity, probability and residual risk ratio from TCAS II/ACAS Xa for Auto GCAS
Digital Database	Performance & Safety	Ensure system is not undermined by improperly managed digital databases

Ultimately, for a single commercial applicant under 14 CFR Part 23 Amdt 23-64, their Detailed Design Standard (DDS) and selected means of compliance will become a prescriptive set of evaluation criteria for that particular Auto GCAS.

Auto GCAS can be integrated on 14 CFR Part 23 general aviation aircraft with existing certified autopilot systems to reduce CFIT below the current mishap rate. To ensure safe and effective Auto GCAS implementation, regulators must assure the system has minimal probability of unsafe behaviors while limiting nuisance rates during normal aircraft operations. Auto GCAS has the prospect of converting an already catastrophic situation back into a normal and acceptable one. Properly substantiated, Auto GCAS capabilities will save lives. This is clearly in the public interest and warrants serious consideration by the FAA.

1 Introduction

Controlled flight into terrain (CFIT) mishaps occur in both general aviation and commercial aviation despite enhanced technologies, like terrain awareness and warning system (TAWS), available in the cockpit. Automatic Ground Collision Avoidance Systems (Auto GCAS) can be integrated on 14 Code of Federal Regulation (CFR) Part 23 general aviation aircraft with existing certified autopilot systems to reduce CFIT below the current mishap rate. This technology can be a significant contributor in achieving the Federal Aviation Administration (FAA) goal of reducing general aviation fatal accidents from a baseline of 0.98 per 100,000 flight hours in fiscal year 2019 to a target of 0.89 fatal accidents per 100,000 flight hours by fiscal year 2028. Certification of safety technology, like Auto GCAS, is one of the FAA's FY2023 agency priority goal strategies to develop innovative methods to increase general aviation safety, including "supporting the installation of new safety-enhancing technology in general aviation aircraft by streamlining the certification and installation process and encouraging aircraft owners to install such equipment" (Aviation Safety, 2023):

Auto GCAS implementation has proven successful on military fighter aircraft, significantly reducing CFIT rates where manual systems failed to achieve the desired mishap reduction. Regulatory barriers, technology limitations, and cost previously limited implementation of Auto GCAS on 14 CFR Part 23 general aviation aircraft. Meanwhile, CFIT by this population remains unacceptably high even with manual TAWS or similar systems installed. Acceleration of the aviation industry into automated technologies and additional flexibility from 14 CFR Part 23 Amendment (Amdt) 64 rules, make the Auto GCAS certification path achievable.

This report summarizes applicable regulations, identifies a means of compliance, and proposes a certification roadmap for Auto GCAS on general aviation aircraft defined as Class 1 instrument flight rules (IFR) - single engine reciprocating (SRE) 6,000 lbs or less maximum certificated gross takeoff weight, or § 23.2005 Level 2 (two to six passengers), low speed, Normal category, using the 14 CFR Part 23 Amdt 23-64 processes, while still relying on prescriptive 14 CFR Part 23 Amdt 63 certification basis to achieve means of compliance safety objectives where appropriate. While there are significant benefits to an Auto GCAS system integration with higher Class/Level aircraft, this effort focused on the least restrictive requirements and the Class with high CFIT rates to ensure a pathway to successful integration. This approach will facilitate near-term implementation of life-saving technology while paving the way for future Part 25 aircraft integration and Part 121 operations.

The recommended means of compliance were derived from lessons learned during a limited-scope flight test campaign using the National Aeronautics and Space Administration (NASA) Expandable Variable Autonomy Architecture (EVAA)/Middle Wear (MW) 1.4 and associated Ground Collision Avoidance System (GCAS) module integrated with a commercially available electronic flight instrument system (EFIS), autopilot, and autothrottle. This experimental Auto GCAS demonstrated low-nuisance operations during a limited flight test campaign, throughout the enroute, low level (500 ft above ground level), and terminal operating environment.

The intent of this research is to provide a performance-based set of safety requirements as a foundation for a complete set of Detailed Design Standard (DDS) and means of compliance for any Auto GCAS utilizing 14 CFR Part 23 Amdt 23-64 procedures (Federal Aviation Administration, 2022). Wherever possible, this report relies on prescriptive 14 CFR Part 23 Amdt 63 requirements and pre-Amdt 64 means of compliance publications to simplify the approach and show that while novel, the guidelines and directives provided in pre-Amdt 23-64 are sufficient with few changes required to meet performance-based safety objectives.

Although the FAA has accepted many consensus standards as a means of compliance with 14 CFR Part 23, Accepted Means of Compliance; Airworthiness Standards: Normal Category Airplanes, Amdt 23-64 (Federal Aviation Administration, 2022), many are redundant to existing pre-Amdt 64 guidelines without providing additional specificity or flexibility to the Auto GCAS design requirements. However, where useful in clarifying hazard analysis and risk mitigation, consensus standards are utilized to augment traditional means. Some consensus standards provide the only detailed prescriptive and performance objectives, e.g. the Radio Technical Commission for Aeronautics (RTCA) DO-367, Minimum Operational Performance Standards (MOPS) for Terrain Awareness and Warning Systems (TAWS) Airborne Equipment (RTCA, Inc., 2017). Therefore, this report should also serve as the foundation for an Auto GCAS advisory circular (AC) and updates to the RTCA and American Society for Testing and Materials (ASTM) publications.

Ultimately, for a single commercial applicant under 14 CFR Part 23 Amdt 23-64 (Federal Aviation Administration, 2022), their DDS and selected means of compliance will become a prescriptive set of evaluation criteria for that particular Auto GCAS certification campaign. This report aims to ensure that those efforts are efficient and effective to proliferate life-saving technology and ensure critical performance standards are met.

2 Transitioning Automatic Ground Collision Avoidance Systems from military to civilian applications

The project team included developmental test pilots and flight test engineers who were extensively involved in developing and testing Auto GCAS on F-16 and F-35 aircraft. This experience provided valuable insight into the technology's strengths and weaknesses and helped to guide effective system tests. However, the team recognized that requirements for military aircraft are different than for civilian aircraft.

Military Auto GCAS applications mandate low nuisance rates, however some nuisance is expected due to technological limitations and combat mission requirements. On average, most general aviation flying operations do not stress a collision avoidance system in the same way as military operations. However, a small portion of civilian operations in low-altitude, mountainous terrain is especially challenging for a low-authority Auto GCAS.

General aviation CFIT mishap rates continue to identify the ineffectiveness of nuisance-prone collision avoidance safety systems, which are often ignored or disabled by operators. Thus, implementation of Auto GCAS into general aviation aircraft must strive for lower nuisance rates than traditionally implemented terrain avoidance systems to ensure utilization and effectiveness.

NASA Automatic Collision Avoidance Technology studies (Skoog, 2007) and Auto GCAS implementation on military aircraft showed that an Auto GCAS should use near the same G-load (+Nz) a pilot would use during a manually flown recovery maneuver to ensure low nuisance rates. High-G recoveries for military aircraft allow for closer approaches to terrain before Auto GCAS activation, which minimizes the nuisance rate. However, initial Auto GCAS general aviation fight test data indicate that for an effective system with low nuisance rates, the G-requirements may be significantly less than previously thought with the inclusion of multiple trajectory escape options. This is a positive indicator for implementation of Auto GCAS on both 14 CFR Part 23 and 14 CFR Part 25 aircraft, as certified autopilots generally command maneuvers less than +2G (Nz).

Regulatory standards to ensure public safety are nuanced relative to military applications. Flawed safety systems in 14 CFR Part 23 general aviation aircraft are not tolerated, as they may erode public trust in industry and regulators. However, every safety system that assists with primary or secondary aircraft functions has a non-zero probability of causing harm. Risk assessment for safety system certification must include the probability of system failure and the severity of possible failure conditions. In turn, these outcomes must be weighed against the rate of CFIT fatalities in general aviation aircraft.

This posture of risk-reward analysis and acceptance is emphasized in the final ruling on revisions to 14 CFR Part 23 airworthiness standards, stating "...there is a logical and acceptable inverse relationship between the average probability and severity of failure conditions" (AC 23-24 - Airworthiness Compliance Checklists for Common Part 23 Supplemental Type Certificate (STC) Projects, 2005). This report identifies the specific regulatory mechanisms and system safety assumptions for achieving the proper risk reward on Part 23 general aviation aircraft.

3 Utilization of the 14 CFR Part 23 flight test to generate a certification roadmap

The Blackbird Aerospace Auto GCAS system under test consisted of a research and development aircraft with a commercially available EFIS, autopilot, autothrottle, computer hardware, the EVAA software application, sensor source, and coupler.

The NASA Resilient Autonomy Project developed EVAA, a software framework that implemented a run-time assurance (RTA) modular architecture with the intent to leverage ASTM International's F3269 Standard Practice for Methods to Safely Bound Behavior of Aircraft Systems Containing Complex Functions Using Run-Time Assurance (ASTM International, 2021). This government-owned system was designed to be platform- and mission-agnostic where platform specifics were behind a hardware abstraction layer, referred to as a *coupler* in Resilient Autonomy in the Face of Adversity (Williams, 2021).

EVAA leveraged the improved General Collision Avoidance System (iGCAS) algorithms developed by NASA to transition GCAS from the Department of Defense (DoD) Automatic Collision Avoidance Technology (ACAT) and Advanced Fighter Technology Integration (AFTI) programs to small unmanned aerial vehicle (sUAV) applications, as described in Development and Flight Demonstration of a Variable Autonomy Ground Collision Avoidance System (Less & Skoog, 2014).

EVAA was utilized by Blackbird Aerospace as a demonstrator technology to illustrate how an autonomous behavior-based system could be fielded with existing certified autopilot systems to reduce Part 23 CFIT below the current mishap rate. Several milestones achieved during this 53 sortie/61.3 flight hour limited-scope flight test included:

- Fully integrated Auto GCAS with commercially available autopilot and autothrottle
- Successful terrain avoidance during recreation of National Transportation Safety Board (NTSB) CFIT mishaps

- Identification of critical deficiencies in EVAA software and lessons learned to be incorporated in future collision avoidance system solutions
- Existing regulatory and consensus documents utilized as the evaluation criteria for flight test data collected

For additional details, please see the Blackbird Aerospace NASA EVAA/MW1.4 Auto GCAS Technical Report.

4 Automatic Ground Collision Avoidance Systems functional design

The general aviation Auto GCAS function and performance objectives can be derived by leveraging the many design lessons learned from military Auto GCAS implementations. Auto GCAS is designed to act as a last-resort safety net to prevent ground collision. It is intended to work both autonomously and independently but in concert with the aircraft navigation equipment, sensors, and autopilot. The use of Auto GCAS function must not require human intervention, as system activation to avoid terrain may occur as a result of pilot who is experiencing performance degradation, possibly including channelized attention, task saturation, spatial disorientation, or incapacitation.

4.1 Tenets of Automatic Ground Collision Avoidance Systems

To ensure safe and effective Auto GCAS implementation, regulators must assure the system has minimal probability of unsafe behaviors while limiting nuisance rates during normal aircraft operations. Once these requirements are met, the goal of protecting against CFIT can be achieved. The project identified three categories of Auto GCAS performance objectives: safety, nuisance, and protection. These Auto GCAS requirements categories are correlated below with the established tenets of Auto GCAS:

- Do No Harm (Safety)
- Do Not Interfere (Nuisance)
- Prevent Collisions (Protection)

Leveraging the Tenets of Auto GCAS enabled the generation of performance-based objectives which resulted in the Auto GCAS 14 CFR Part 23 Certification Roadmap means of compliance.

Auto GCAS behaviors that induce a risk of collision where there was none violate the tenet of "Do No Harm" and are considered an unsafe system operating condition (USOC) in accordance with the ASTM International definition in Standard Specification for Systems and Equipment in Aircraft (2022), or an adverse operating condition (AOC) per AC 23.1309-1E (Federal Aviation Administration, 2011).

- An *unsafe system operating condition (USOC)* exists when a major or less failure condition would escalate to a hazardous or catastrophic failure condition (or a hazardous failure condition escalating to catastrophic) if the crew did not observe appropriate precautions and/or take appropriate action.
- An *adverse operating condition (AOC)* is a set of environmental or operational circumstances applicable to the airplane, combined with a failure or other emergency situation that results in a significant increase in normal flight crew workload.

The tenet "Do Not Interfere" ensures minimal impact to normal mission operations. Activations that simply interfere with mission execution are defined as nuisance in accordance with TAWS MOPS (RTCA, Inc., 2017):

- A *nuisance alert* is an alert generated by a system that is functioning as designed but which is inappropriate or unnecessary for the particular condition.

Nuisance alerts are not considered a USOC. It is assumed nuisance alerts do not require timely intervention to avoid a follow-on hazard. For example, a nuisance alert may be early, but no pilot intervention is required to avoid the threat. If an alert can escalate to hazardous or catastrophic without intervention, it is not considered a nuisance.

The performance-based system safety objectives for "Prevent Collisions" are challenging. Similar to traffic alert and collision avoidance system (TCAS)/airborne collision avoidance system (ACAS), by design, the system must delay as much as possible to avoid interference with normal operations while achieving an acceptable level of statistical performance for avoiding collisions. Minimally sufficient terrain clearance is the evaluation criteria to determine Auto GCAS system performance requirements. However, the acceptable rate of failure when attempting to avoid terrain is not straightforward.

4.2 Automatic Ground Collision Avoidance System functional design phases

The basic Auto GCAS operational sequence is conceived as follows and is shown in Figure 1:

1. Threat Detected: Detection of impending terrain threat based on belief of own aircraft dynamic model and multi-trajectory predictions. Trajectory prediction methods can range

from limited trajectory options to highly complex, model-based state estimates (e.g. fixed uncertainty volumes with fixed sensitivity levels; aircraft dynamic and sensor models to develop state estimate).

2. Pilot Alerted of Impending Activation: Determination of most appropriate maneuver action based on design criteria to meet functional design performance objectives. These options include simple deterministic, rule-based lookup, more complex deterministic statistical models (e.g. Markov Decision Process as utilized by ACAS X), and non-deterministic models trained on large data sets (e.g. last available viable maneuver selection; deterministic table lookup; least cost function weighted by mission type; optimized or non-deterministic statistical probability weighted by cost function).

3. System Activation: Automatic activation of the autopilot terrain avoidance mode to climb and maneuver away from terrain threat with appropriate visual and aural annunciations (e.g. Manual thrust control: the pilot maybe directed by visual and aural alerts to adjust power; automatic thrust control: automatic control of thrust may be utilized if autothrottle is also implemented).

4. Termination of Activation when Clear of Threat: Transition of autopilot out of terrain avoidance mode when immediate terrain threat is clear with appropriate visual and aural annunciations. This basic functional sequence concludes with either the Auto GCAS remaining engaged or disengagement of the autopilot with appropriate notification and delay. Auto GCAS termination options are discussed in more detail in the autopilot section (e.g. Autopilot remains engaged in a non-terrain avoidance mode until pilot disengagement; autopilot is disengaged and aircraft control returned to pilot; autopilot is disengaged if autopilot was disengaged at Auto GCAS activation or remains engaged if it was engaged at activation).

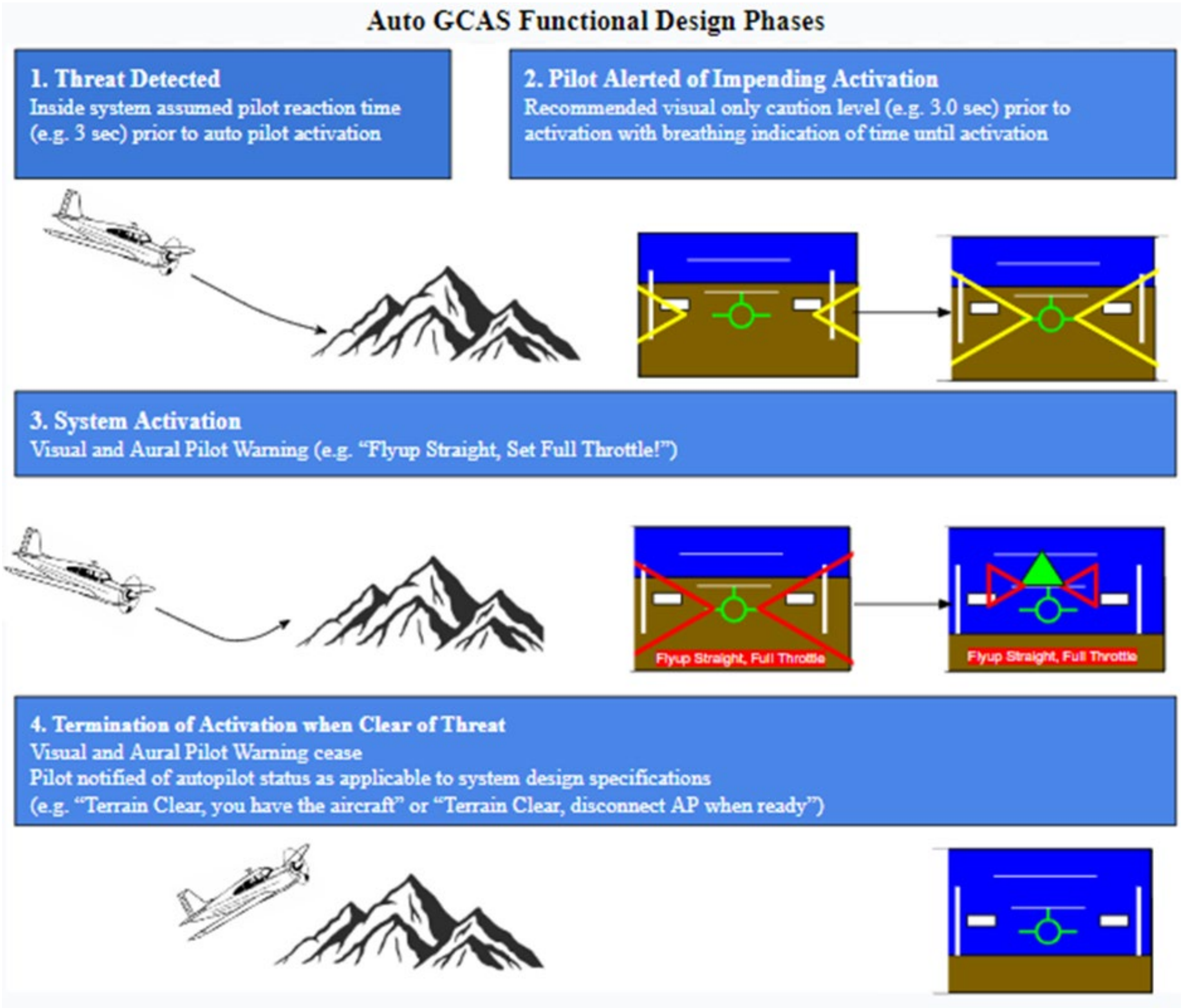

Figure 1. Auto GCAS Part 23 functional design phases

4.3 Automatic Ground Collision Avoidance System functional design assumptions

To account for potential nuisance or rare erroneous activations that could result in a USOC, Auto GCAS must have a means of manual intervention and disconnect of the system allowing for the pilot to immediately exercise manual control of the aircraft. Most likely this manual disconnect will be in accordance with baseline aircraft autopilot disconnect design requirements. Auto GCAS will not be required to restore an out-of-control aircraft to "normal" maneuvering, which is characteristic of autopilot systems certified in accordance with existing standard guidance material.

Airspeed, bank, or pitch angle exceedances outside of normal autopilot engagement parameters should not preclude an Auto GCAS activation, even if the probability of success is reduced as compared to the normal engagement envelope. This behavior is consistent with emergency-level command and envelope protection features integrated with existing commercially available autopilots. As a functionally independent system from the autopilot, Auto GCAS does not serve a “critical function” or “essential function” per AC 23.1309-1E, but that does not prevent it from potentially creating a hazard:

> Design features should be taken into account to prevent hazards either by ensuring that the failure condition will not occur or by having redundancy or annunciation with the associated flight crew’s corrective action. In either case, the hazards should be addressed to the least practical amount to the point at which the effort to further reduce a hazard significantly exceeds any benefit in terms of safety derived from that reduction that is practical for this type of airplane. Additional efforts would not result in any significant improvements of safety and would inappropriately add to the cost of the product without a commensurate benefit. This determination should come from an experienced engineering judgment based on the criticality of the hazard and the intended kinds of operation. (Federal Aviation Administration, 2011, p. 18)

This mitigation philosophy in the advisory circular balances benefits with potential risks. However, the mechanisms for achieving the means of compliance to mitigate residual risk are better described in ASTM F3061/F3061M − 22b (ASTM International, 2022). Thus, that accepted means of compliance for addressing USOC is incorporated as part of the proposed Auto GCAS DDS. However, achieving traditional system performance and proving failure hazard probabilities is increasingly difficult with complex deterministic systems. A deviation from classical methods may be required to achieve the CFIT prevention performance objectives, just as has been done for TCAS/ACAS and Emergency Autoland and Envelope Protection systems.

5 Automatic Ground Collision Avoidance System 14 CFR Part 23 certification roadmap

The goal of this roadmap is to provide a performance-based set of safety requirements as a foundation for a complete set of DDS and means of compliance for an Auto GCAS utilizing 14 CFR Part 23 Amdt 23-64 procedures (Federal Aviation Administration, 2022). Wherever possible, this roadmap relies on prescriptive 14 CFR Part 23 Amdt 63 requirements and pre-Amdt 64 means of compliance publications to simplify the approach and identify that while novel, the guidelines and directives provided in pre-Amdt 64 are sufficient with few changes required to meet performance-based safety objectives.

Although the FAA has accepted consensus standards as a means of compliance with 14 CFR Part 23 Amdt 23-64 (Federal Aviation Administration, 2022), some are redundant to existing pre-Amdt 64 guidelines and do not provide any additional specificity or flexibility to the Auto GCAS system design requirements. However, where useful in clarifying hazard analysis and risk mitigation, consensus standards are utilized to augment traditional means. Some consensus standards provide the only detailed prescriptive and performance objectives, e.g. TAWS MOPS (RTCA, Inc., 2017). This report also serves as the foundation for an Auto GCAS Advisory Circular and updates to the RTCA and ASTM publications.

Ultimately, for a single commercial applicant under 14 CFR Part 23 Amdt 23-64, their DDS and means of compliance will become a prescriptive set of grading criteria for that particular Auto GCAS. This report aims to ensure that those efforts are efficient and effective to proliferate the life-saving technology and ensure critical performance standards are met.

Leveraging the intent of 14 CFR Part 23 Amdt 23-64 in AC 23.2010-1 - FAA Accepted Means of Compliance Process for 14 CFR Part 23.

> Performance-based rules require a safety outcome, rather than a single prescriptive approach to achieving that outcome. The flexibility gained by the performance-based approach gives industry an incentive to innovate and find new, non-traditional ways to achieve the required safety outcome. (Federal Aviation Administration, 2022, p. 8)

The flow chart in Figure 2 describes the proposed 14 CFR Part 23 Amdt 23-64 performance-based Auto GCAS means of compliance for two scenarios:

- An add-on or modification to an existing supplemental type certificate (STC) autopilot and EFIS system.
- A new combined Auto GCAS and EFIS system.

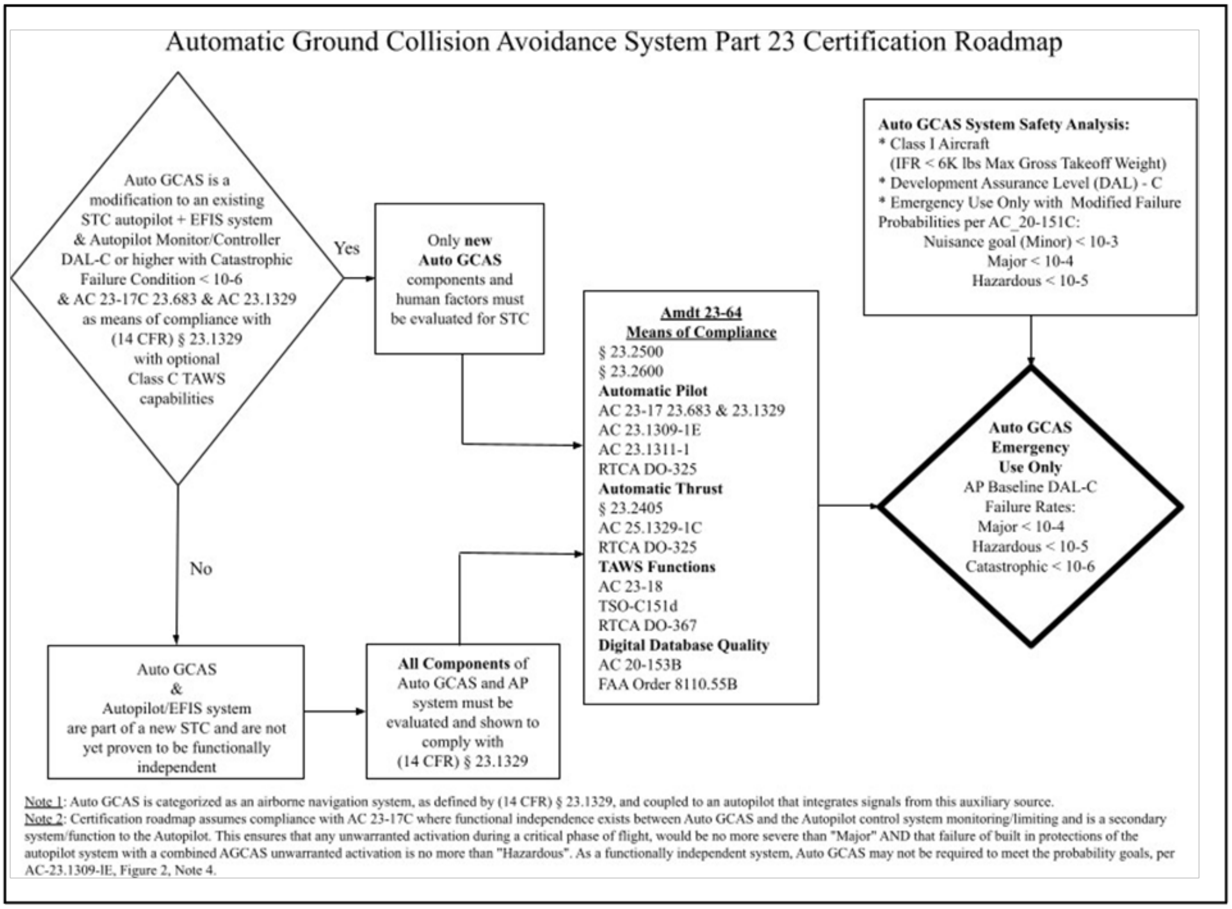

Figure 2. Auto GCAS Part 23 certification roadmap

5.1 Automatic Ground Collision Avoidance System means of compliance

The recommended means of compliance were derived from lessons learned during a limited-scope flight test campaign using the NASA EVAA/MW 1.4 and associated GCAS module integrated with a commercially available EFIS, autopilot, and autothrottle. This experimental Auto GCAS demonstrated low nuisance operations during a limited flight test campaign, throughout the enroute, low level (500 ft above ground level (AGL)), and terminal operating environment.

Utilizing the DDS methodology, a set of requirements can be collated and used to comply with 14 CFR § 23.2010 in order to achieve a means of compliance. Applying a performance-based approach to Auto GCAS for 14 CFR Part 23 general aviation aircraft, these systems can be certified utilizing 14 CFR Part 23 regulations, Advisory Circulars, and consensus documents. Additionally, 14 CFR Part 25 means compliance documents provide additional considerations for manufacturers of Auto GCAS, particularly when implementing an autothrottle/autothrust capability in conjunction with Auto GCAS.

The Auto GCAS functional design performance objectives are such that traditional, pre-Amdt 64 means of compliance support the performance-based objectives of Amdt 23-64 for Auto GCAS certification as specified by AC 23.2010-1 (FAA, 2017). Specifically, automatic pilot system, TAWS, TCAS/ACAS, and Digital Database regulatory and means-of-compliance published material can be utilized with minimal changes through use of a DDS.

The figure below identifies the regulations or consensus standards utilized for both unique and overlapping means of compliance categories to achieve safety, nuisance, and performance objectives.

Amendment 23-64 Means of Compliance

Performance Based Rules

§ 23.2500 Airplane level systems requirements
- § 23.2505 Function and installation
- § 23.2510 Equipment, systems, and installations
- § 23.2515 Electrical and electronic system lightning protection
- § 23.2405 Automatic power or thrust control systems

§ 23.2600 Flightcrew interface
- § 23.2605 Installation and operation
- § 23.2610 Instrument markings, control markings, and placards
- § 23.2615 Flight, navigation, and powerplant instruments
- § 23.2620 Airplane flight manual

Prescriptive Requirements and Detailed Design Standards (DDS)

Prescriptive 23-63 Rule Language
- § 23.1329 Automatic pilot system

Accepted Consensus Standards

Systems and Equipment in Aircraft
- F3061/F3061M − 22b

Automatic Pilot/Automatic Thrust Collision Avoidance Coupling
- RTCA DO-325

TAWS Functions
- RTCA DO-367

Traditional Means of Compliance (ACs & Policy Memos)

Automatic Pilot
- AC 23-17 23.683 & 23.1329
- AC 23.1309-1E
- AC 23.1311-1

Automatic Thrust
- AC 25.1329-1C

TAWS Functions
- TSO-C151d
- AC 23-18

TCAS II/ ACAS Xa Functions (Non-standard hazard probabilities)
- AC 90-ACAS
- AC 20-151C

Digital Database Quality
- AC 20-153B & FAA Order 8110.55B

Figure 3. Auto GCAS Amendment 23-64 means of compliance

5.2 Certification roadmap assumptions

Amdt 23-64 performance-based objectives with desired safety outcomes enables the certification of Auto GCAS while mitigating risk using accepted and appropriate methods. The high-level assumptions for the proposed 14 CFR Part 23 Auto GCAS certification roadmap include:

- Class 1 Instrument Flight Rules (IFR) - SRE 6,000 lbs or less Maximum Certificated Gross Takeoff Weight, or § 23.2005 Level 2 (two to six passengers), low-speed, Normal category, using the 14 CFR Part 23 Amdt 23-64 processes.
- Auto GCAS can be categorized as an independent airborne navigation and safety system (e.g. TAWS, TCAS/ACAS) as defined by 14 CFR § 23.1329 if integrated with functional independence from the primary autopilot control system monitoring/limiting.
    - Independence exists between Auto GCAS commands and the Autopilot control system monitoring/limiting.
    - Functionally independent integration assumes primary autopilot compliance with AC 23-17C Systems and Equipment Guide for Certification of Part 23 Airplanes and Airships (AC 23-17C: Automatic pilot system, 2011).
    - As is the case with navigation systems that provide autopilot coupled with instrumented approach guidance, this implies that no single failure of the Auto GCAS can result in a hardover, per 14 CFR § 23.1329, because the autopilot system only commands normal rates and gains regardless of the command received from the Auto GCAS. Thus, the worst-case single failure is a “command hardover.” This is significantly less severe than an autopilot servo hardover at the servo authority limits.
    - A single failure of an autopilot system, as defined by AC 23.1309-1E (Federal Aviation Administration, 2011), is defined as “major” hazard severity. AC 23.1309-1E defines dual failures as “hazardous” severity. Thus, a single failure of the Auto GCAS can potentially be defined by a hazard severity as low as “major.”
    - Even with functional independence, it is acknowledged that a single failure can easily escalate to a USOC and severity level of “hazardous” or “catastrophic” without appropriate alerts and procedures guiding timely intervention.
    - If functionally dependent with the autopilot monitoring and limiting, an Auto GCAS should be categorized as an autopilot system, and the inherent assumption cannot be made that a single failure will not result in a servo hardover condition without additional system design mitigations. This theoretical implementation is shown on the Part 23 Auto GCAS Certification Roadmap figure but is not discussed in this paper.

- Automatic engagement of an autopilot system has been certified for use on Part 23 aircraft to include automatic envelope protection, engagement of level command, and Emergency Autoland System, e.g. Garmin Emergency Autoland System, as described in Flight Deck Solutions, Technologies and Services: Moving the Industry Forward (Garmin, 2020) when specific criteria are met. This certification roadmap assumes that regulatory agencies will apply similar relaxation of redundancy and thus hazard probability acceptance given the off-nominal and emergency situation with a high probability of catastrophic outcome without intervention.

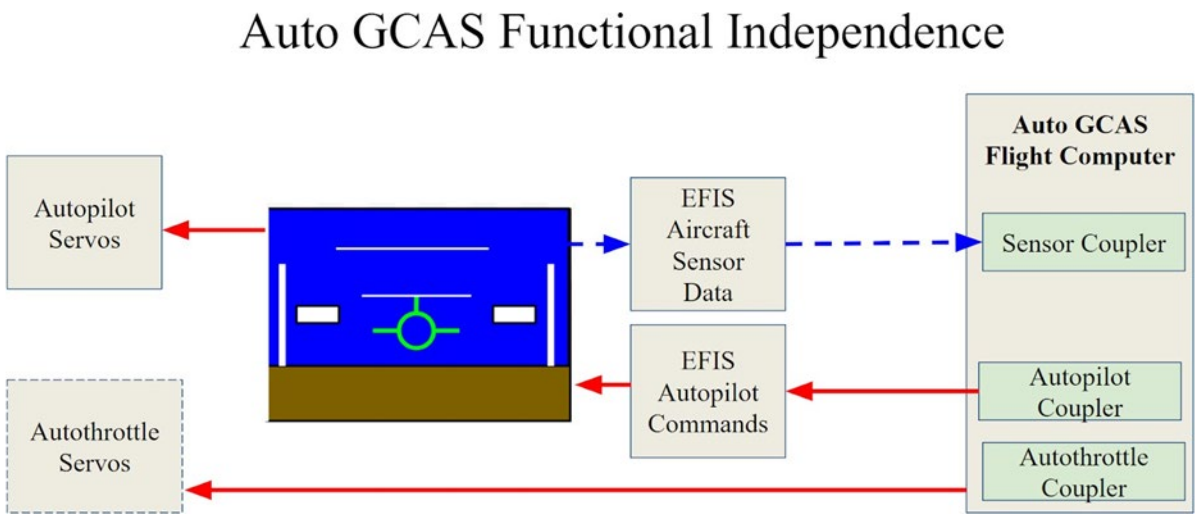

Figure 4. Auto GCAS functional independence

5.3 Reconciliation of terms within regulations and guidance material

Auto GCAS means of compliance includes a number of regulatory and consensus documents that contain potentially confusing or different terminology and definitions that are essential to the certification roadmap.

As a means of compliance, this roadmap utilizes:

- Class I aircraft per AC 23.1309-1E (Federal Aviation Administration, 2011)/Level 2, Low Speed (14 CFR § 23.2005 - Certification of normal category airplanes, 2017)
- Class C TAWS, in accordance with TAWS MOPS (RTCA, Inc., 2017)
- Class D, autothrust/autothrottle from 14 CFR Part 25 autoflight autothrust/autothrottle per RTCA DO-325 MOPS for Automatic Flight Guidance and Control Systems and Equipment (RTCA, Inc., 2010)

5.4 Defining acceptable hazards and probabilities

The system safety approach outlined in this roadmap utilizes the following logic to justify a non-traditional risk probability for a given severity and thus permit Auto GCAS to be certified with a small probability of residual induced risk and causing a hazard where none existed:

1. Leverage the concept of Risk Ratio, as presented by TCAS/ACAS.
2. Define the severity of Auto GCAS hazards.
3. Establish non-standard hazard probabilities while staunchly ensuring design standards, prioritize minimizing the potential to induce hazards.
4. Utilize TSM/ ART as a metric from which to establish the baseline hazardous flight condition, warranting Auto GCAS intervention.
5. Establish a Design Assurance Level (DAL).
6. Establish mitigation procedures to minimize the probability of hazardous outcomes from an erroneous activation and USOC.

In Return to Service of the Boeing 737 MAX Aircraft, mishaps induced by safety systems identified that it is not sufficient to demonstrate that Auto GCAS will prevent collisions that might occur in its absence (Federal Aviation Administration, 2020). The risk that Auto GCAS logic could cause collisions in otherwise safe circumstances must be fully considered and minimized. Minimizing the induced collision risk is difficult to prove in a complex deterministic system and necessitates Monte Carlo simulation or similar with sensitivity analysis. Functional independence of system logic and hardware components ensures that inevitable erroneous Auto GCAS activations are less likely to escalate to a hazardous or catastrophic outcome.

5.5 Relative safety benefits and Automatic Ground Collision Avoidance System risk ratio

An important concept for the implementation of a safety system that may include residual risks is a *risk ratio*. The Airborne Collision Avoidance System Guide describes this concept in the context of TCAS II/ACAS Xa air-to-air collision avoidance, but it is also applicable to ground collision avoidance systems (EUROCONTROL, 2022). In order to determine if a system makes overall safety better or worse, the risk ratio is expressed as the ratio of the risk of collision without Auto GCAS over the risk of collision with Auto GCAS. Expressed with respect to Auto GCAS, the risk ratio is given by:

$$Auto\ GCAS\ Risk\ Ratio\ = \frac{\sum Risk\ of\ collision\ with\ Auto\ GCAS}{\sum Risk\ of\ collision\ without\ Auto\ GCAS} \quad (1)$$

A risk ratio approaching zero would indicate the number of collisions with Auto GCAS is sufficiently small relative to the number of collisions. On the other hand, a risk ratio approaching one would indicate that the Auto GCAS had no impact on overall safety and is an ineffective system that does neither good nor harm. A system with undesirable safety impact and which elevates overall risk would have a risk ratio greater than one.

The risk of collision with Auto GCAS encompasses:

- Non-Auto GCAS preventable collisions: A collision that cannot be prevented by Auto GCAS because it is beyond the design performance objectives (e.g. landing gear down interlock).
- Unresolved risk of collision: An error where the system attempts but fails to resolve the threat conflict, resulting in collision.
- Induced risk of collision: An erroneous activation that quickly escalates to a USOC; in other words, a situation in which there is no risk of collision and the Auto GCAS activation creates the collision hazard.

The Auto GCAS risk ratio can be adapted to:

$$Auto\ GCAS\ Risk\ Ratio\ = \frac{\sum non\text{-}AutoGCAS\ preventable\ collisions + (Auto\ GCAS\ unresolved\ risk + Auto\ GCAS\ induced\ risk)}{\sum Risk\ of\ collision\ without\ Auto\ GCAS} \quad (2)$$

AC 20-151C Airworthiness Approval of Traffic Alert and Collision Avoidance Systems has concluded for TCAS/ACAS for Part 25 aircraft:

> The probability of failure of the installed system to perform its intended function from a reliability and availability perspective should be shown to be no greater than 1.0 x10^{-3} per flight hour.
>
> The probability of a false RA [resolution advisory] aural and visual alert due to a failure of the system should be shown to be no greater than 1.0 x 10^{-4} per flight hour in the terminal environment and 1.0 x 10^{-5} per flight hour in the enroute environment.

> Software that presents incorrect RA aural and visual alerts, or results in a missing RA, is considered a hazardous failure condition. (Federal Aviation Administration, 2017, p. 2.22)

Adapting the same values as TCAS/ACAS for Auto GCAS would set the following failure probabilities:

- Nuisance activation is a failure of the installed system to perform its intended function: 1.0 $x10^{-3}$ for enroute cruise operations.
- Unresolved risk of collision/failure to clear terrain: 1.0 $x10^{-3}$.
- Erroneous activation leading to induced collision risk: 1.0 x 10^{-4} (terminal)/1.0 x 10^{-5} (enroute cruise).

Leveraging AC-23.1309-lE System Safety Analysis and Assessment for Part 23 Airplanes (Federal Aviation Administration, 2011), a hazardous condition with required probability of $<10^{-4}$ in the terminal environment and $<10^{-5}$ in the enroute environment is already a significant deviation from classical accepted severity and probability, even for Class I aircraft. Class I aircraft require $<10^{-5}$ probability for "hazardous" conditions and Class IV Part 23 aircraft, which are most similar to rigorous Part 25 requirements, require $<10^{-7}$. Thus, AC-20-151C allowing for a increase in acceptable probability of three orders of magnitude for "hazardous" failure modes is an acknowledgement of the value of safety systems even with residual induced risk of collision.

Table 1. Relationship among airplane classes, probabilities, severity of failure conditions, and software and complex hardware DAL

(Federal Aviation Administration, 2011)

Classification of Failure Conditions	**No Safety Effect**	**<----Minor----->**	**<----Major---->**	**<--Hazardous--->**	**< Catastrophic>**
Allowable Qualitative Probability	**No Probability Requirement**	**Probable**	**Remote**	**Extremely Remote**	**Extremely Improbable**
Effect on Airplane	No effect on operational capabilities or safety	Slight reduction in functional capabilities or safety margins	Significant reduction in functional capabilities or safety margins	Large reduction in functional capabilities or safety margins	Normally with hull loss
Effect on Occupants	Inconvenience for passengers	Physical discomfort for passengers	Physical distress to passengers, possibly including injuries	Serious or fatal injury to an occupant	Multiple fatalities
Effect on Flight Crew	No effect on flight crew	Slight increase in workload or use of emergency procedures	Physical discomfort or a significant increase in workload	Physical distress or excessive workload impairs ability to perform tasks	Fatal Injury or incapacitation
Classes of Airplanes:	**Allowable Quantitative Probabilities and Software (SW) and Complex Hardware (HW) Development Assurance Levels (Note 2)**				
Class I (Typically SRE 6,000 pounds or less)	No Probability or SW and HW Development Assurance Levels Requirement	$<10^{-3}$ 10^{-3} Note 1 P=D Nuisance	$<10^{-4}$ $10^{-4}/10^{-5}$ Notes 1 and 4 P=C, S=D Erroneous	$<10^{-5}$ 10^{-5} Note 4 P=C, S=D Induced Collision	$<10^{-6}$ 10^{-3} Note 3 P=C, S=C Unresolved Collision

Utilizing the AC-23.1309-lE Appendix 1 Part 23 guidance on failure modes and hazard severity as shown in Table 2, it can be argued:

- Failures of an Auto GCAS producing erroneous command guidance to an autopilot can be classified as "major," since a misleading or malfunction without warning for both TAWS and input to autopilot guidance is categorized as "major."
- There are also numerous erroneous activation failure scenarios in the enroute cruise or terminal environment that would have no greater impact on flight crew or occupants than "minor."
- However, it could be argued that an erroneous command to the autopilot from an Auto GCAS is a multi-axis limited authority autopilot malfunction without warning. If this were also to be considered a "hardover" (which is not the opinion of the authors of this paper), it would be categorized as "hazardous."

In reality, the truth is somewhere in between "major" and "hazardous" and very much situationally dependent. Further discussion on autopilot failure modes is included in the Autopilot and flight guidance systems section of this report.

Table 2. Partial list of functional hazard assessment (FHA) for consideration to meet 14 CFR Part 23 requirements for IFR Class I airplanes (AC 23-17C: Automatic pilot system, 2011)

Aircraft Function	Classification of Failure Conditions			Analysis Consideration
	Total Loss of Function	Loss of Primary Means of Providing Function	Misleading and/or Malfunction Without Warning	
Terrain Awareness and Warning System (TAWS)	Minor	R	Major	The loss of that system should be no greater than 10^{-3} per average flight hour, and the possibility of misleading information on the display due to undetected or latent failures should be no greater than 10^{-4} per average flight hour. For a Class A TAWS, the software development assurance level should be at least to Level C as defined in RTCA DO-178B or an acceptable alternative approved by the FAA. For Class B TAWS, the software development assurance level should be at least to Level D providing the required alerts and visual annunciations are independent of the terrain display(s). If the required alerts and visual annunciations are integrated on the displays, the DAL should be at least Level C. NOTE: A terrain display is not mandatory for Class B equipment. See AC 23-18 for more information.
Autopilot guidance or flight director cue on display	Minor	Minor	Major for pitch. Minor for roll.	Pilot must monitor autopilot operation and disconnect autopilot to recover flight promptly. May cause go around and reductions in safety margins.
Autopilot	Minor, with warning. Major, without warning.	R	Major, single axis and limited authority. Hazardous, multi-axis and limited authority. Catastrophic, if authority is unlimited.	Malfunction effects of autopilot hardovers are very dependent on the design and installation details. Maximum inputs (hardovers) or (slowovers) to aircraft primary control surfaces should not exceed aircraft structural limits. See AC 23.17C under section 23.1329 for additional information.

5.6 Proposed definitions for Auto GCAS activations and failure severity

Leveraging AC 20-151C (Federal Aviation Administration, 2017) and AC-23.1309-lE (Federal Aviation Administration, 2011) as means of compliance, the following are proposed definitions for Auto GCAS activations in the context of failure severity classification:

- Warranted or Useful Activations: This is the baseline design objective of the system. They are activations to clear a threat, with minimal TSM/ART, before a manual pilot flown recovery would require excessive skill or aircraft load factor.

- Nuisance Activations (categorized as a “minor” failure condition): Nuisance activations are generated by a system that is functioning as designed but which are inappropriate or unnecessary for the particular condition, e.g., activations that occur earlier than desired but for predictable reasons. Nuisance activations alone are categorized as a “minor” failure condition. Nuisance activations are not considered a USOC as defined by ASTM F3061/F3061M − 22b (ASTM International, 2022) or AOC per AC 23.1309-1E (Federal Aviation Administration, 2011).

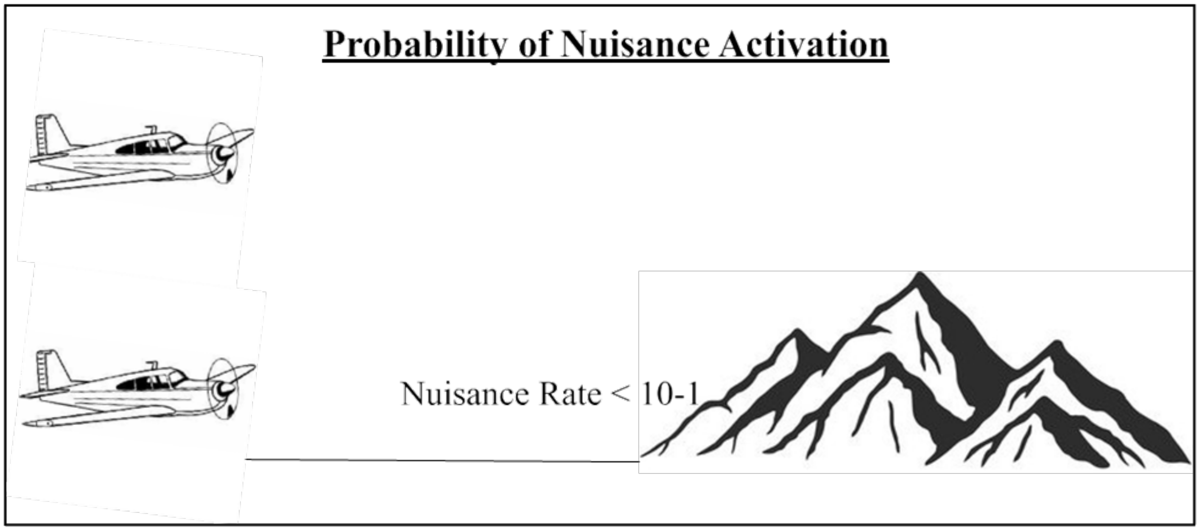

Figure 5. Auto GCAS probability of nuisance activation

- Erroneous activations are initially categorized as “major”: Erroneous activations are those that occur for no obvious reason, are not predicted OR are sufficiently early due to a system anomaly (e.g. an error in the terrain database or serious system trajectory prediction error).
    - Erroneous activations alone are categorized as a “major” failure condition severity, but they can escalate to a “hazardous” failure condition depending on the phase of flight or flight conditions.
    - Erroneous activations can lead to an induced risk of collision and a USOC as defined by ASTM F3061/F3061M − 22b (ASTM International, 2022) or AOC per AC 23.1309-1E (Federal Aviation Administration, 2011).

Table 3 summaries the proposed addition to AC-23.1309-lE Appendix 1 for Auto GCAS FHA classification. The justification for these values and probabilities are discussed in the following sections.

Table 3. Proposed Auto GCAS addition to AC-23.1309-lE, Appendix 1 Auto GCAS FHA classification

Aircraft Function	Classification of Failure Conditions			Analysis Considerations
	Total Loss of Function	Loss of Primary Means of Providing Function	Misleading and/or Malfunction Without Warning	
Auto GCAS	Minor	R	**Erroneous Major** for enroute cruise or higher altitude operations **Hazardous** when failure or flight condition can lead to an induced risk of collision, most likely from Instrument Meteorological Conditions (IMC), night, and or low altitude operations	Erroneous activations are those that occur for no obvious reason, are not predicted OR are sufficiently early due to a system anomaly (e.g. an error in the terrain database or serious system trajectory prediction error). Erroneous failure conditions result in an activation no more severe than a command hardover and thus are analogous to an autopilot guidance failure. Erroneous activations alone are categorized as a major failure condition severity but can escalate to higher failure conditions depending on the phase of flight or flight conditions. Erroneous activations that can lead to an induced risk of collision and an unsafe system operating condition (USOC) as defined by ASTM F3061/F3061M − 22b or Adverse Operating Condition (AOC) per AC 23.1309-1E are *Hazardous.* The probability of an erroneous Auto GCAS activation that results in an induced *risk* of collision and a USOC due to a failure of the system should be shown to be no greater than 1.0×10^{-4} per flight hour in the terminal environment and 1.0×10^{-5} per flight hour in the enroute environment.
Auto GCAS			**Minor** for nuisance activations	Nuisance activations are generated by a system that is functioning as designed but which is inappropriate or unnecessary for the particular condition. Nuisance activations are those that occur earlier than desired, but for predictable reasons. Nuisance activations alone are categorized as a Minor failure condition. Nuisance activations are not considered a USOC as defined by ASTM F3061/F3061M − 22b or AOC per AC 23.1309-1E. Nuisance rate probability goal is 1.0×10^{-3} for enroute cruise at or above 1000 ft AGL in mountainous terrain within normal operationally representative flight parameters. Higher nuisance rates are allowable for lower altitude operations but should not exceed 1.0×10^{-1} flight hours for operations continuously at TAWS Small Aircraft Required Obstacle Clearance (ROC) in mountainous terrain.
Auto GCAS		Unresolved Risk of Collision **Catastrophic**		Unresolved Risk of Collision is an error where the system attempts but fails to resolve the threat conflict, resulting in collision. This is categorized as Catastrophic**.** The probability of failure of the installed system to perform its intended function from a reliability and availability perspective should be shown to be no greater than 1.0×10^{-3} per flight hour.

5.7 Assigning Design Assurance Level

The logic that enables the DAL outcome is presented in section 23.1329 of AC 23-17C Systems and Equipment Guide for Certification of Part 23 Airplanes and Airships (AC 23-17C: Automatic pilot system, 2011) and categorized for Class I IFR aircraft in AC 23.1309-lE (Federal Aviation Administration, 2011). When combined with ASTM F3061/F3061M − 22b (ASTM International, 2022), there is a comprehensive approach through which to arrive at an appropriate and achievable DAL.

The Auto GCAS single failure mode of "erroneous activation" is an USOC and is classified as "major" severity (Federal Aviation Administration, 2011) with the potential to escalate to Hazardous or Catastrophic as described in ASTM F3061/F3061M − 22b (ASTM International, 2022). For the Auto GCAS with a properly functioning autopilot, this "major" failure condition can lead to hazardous or catastrophic outcomes if appropriate crew action is not taken. Thus, it is a USOC.

Per ASTM F3061/F3061M − 22b (ASTM International, 2022), this results in the requirement for timely and effective dedicated alerts as well as dedicated abnormal or emergency aircraft flight manual (AFM) procedures. The flow to arrive at this risk mitigation is shown in Figure 6.

In the event of an Auto GCAS erroneous activation, the likelihood of correct pilot intervention due to timely and effective dedicated alerts is high during day visual meteorological conditions (VMC) conditions, even at relatively low altitudes. In instrument meteorological conditions (IMC), even with timely and effective dedicated alerts, the pilot must cross check other sources of information to assess if the activation is erroneous. In most cases, this would result in reduced safety margins and aligns with a classification of "hazardous" with the potential for a "catastrophic" outcome.

The causes of erroneous activations resulting in USOCs are complex and can include errors in the terrain database, trajectory errors, or system logic errors. The classical requirement is to demonstrate these errors are "remote" and less likely to occur than at least one in ten-thousand flight hours (10^{-4}) for "major" and 10^{-5} for "hazardous" severity. Regardless of the hazard severity and probability assignment, as the primary provider of Auto GCAS functionality, this requires DAL-C as defined in RTCA DO-187C Software Considerations in Airborne Systems and Equipment Certification (RTCA, Inc., 2011).

The worst-case failure classification for this system is assumed to be "hazardous" for baseline aircraft with limited-authority Auto GCAS, as the escape maneuver requires multi-axis capability. Given this information, AC-23.1309-lE (Federal Aviation Administration, 2011) offers a preliminary DAL for the primary system providing the Auto GCAS function.

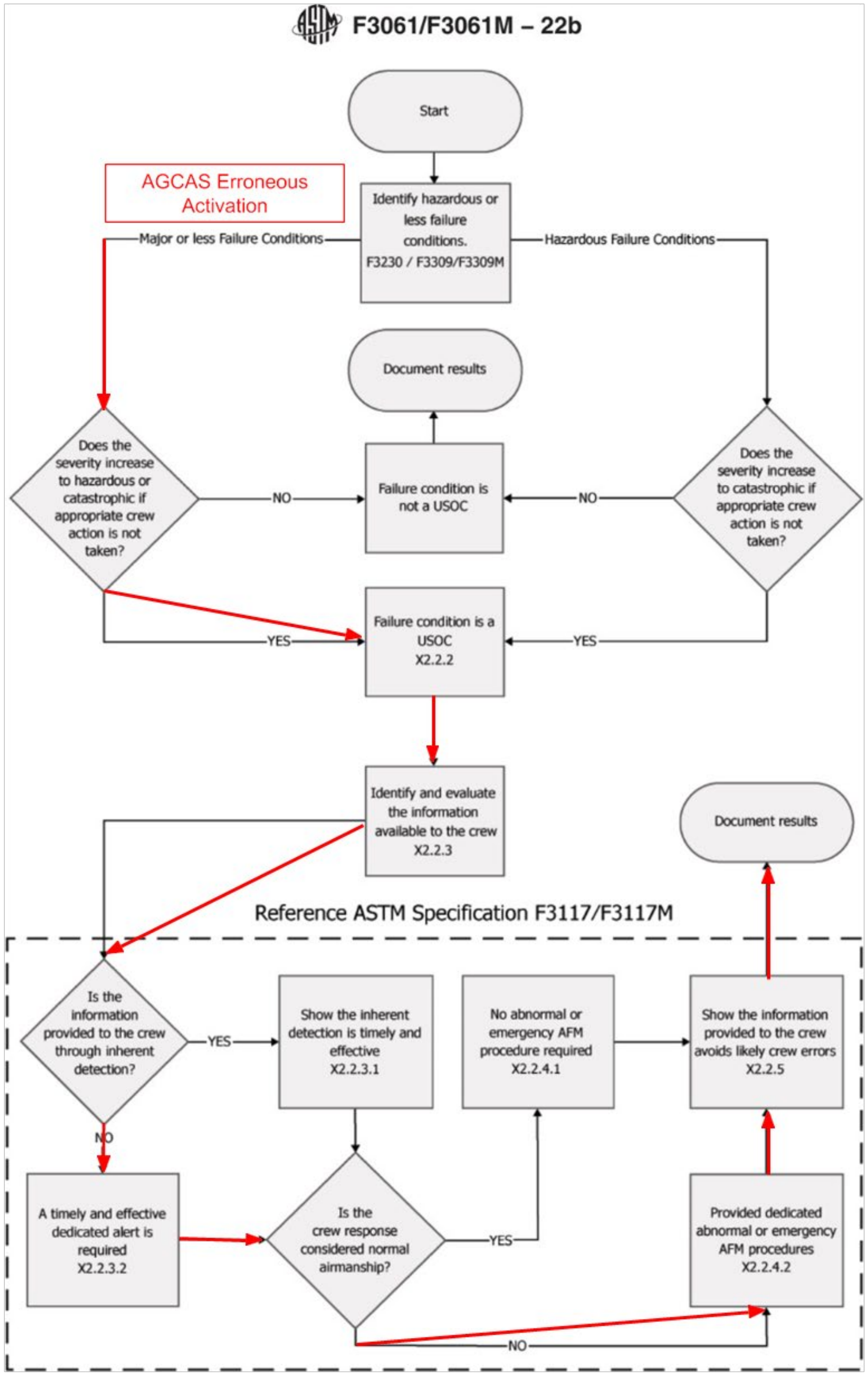

Figure 6. Process to identify and mitigate a USOC

(ASTM International, 2022)

Table 4. Auto GCAS failure classification

Hazardous failure classification: Primary system limited authority Auto GCAS DAL requirements			
Airplane Class		Required Hazardous Failure Probability[1]	Hazardous
Class I	<6,000 lbs gross weight Single Reciprocating Engine	1.0 x $<10^{-5}$	DAL-C

DALs are set based on the worst-case failure condition. Other failure conditions likely exist with Auto GCAS. Required failure probabilities are based on the severity of each individual failure condition. Setting these individual failure probabilities can be done with normal guidance material for 14 CFR Part 23.1309 Equipment, Systems, and Installations compliance (2023).

Out of context, a potential residual hazard severity that can escalate to "catastrophic" could be assessed as unacceptable and inconsistent with AC-23.1309-lE (Federal Aviation Administration, 2011), even with AFM procedures as a mitigation. However, this is no more severe, and perhaps much less severe, than an envelope protection system activating the autopilot and pitching the aircraft down in an erroneous attempt to prevent a stall due to pitot tube icing and incorrect airspeed detected. The rate, magnitude, and direction of severity of this electronic stability protection failure mode is potentially greater than the Auto GCAS input, which is more aligned with an erroneous navigation command. The probability of this frozen pitot scenario is also much higher.

It is also difficult to assign a probability based on flight conditions for average aircraft. If one were to assert that all flight time was in IMC, this could have a significantly different outcome on the severity than if the majority of flight time was in VMC. This is where the probability and the average severity must be accounted for as well as the potential to improve relative safety in the context of an imminent CFIT catastrophic outcome.

5.8 Acceptable failure rate resulting in induced risk of collision

What hazardous failure rates are acceptable for an Auto GCAS when it creates an induced risk of collision? As presented previously, AC 20-151C (Federal Aviation Administration, 2017) for

[1] Probability is at the total-system level. No single failure is permitted to result in a Catastrophic failure (i.e., even if a single failure meets the probability requirement, it is still not permitted to result in a catastrophic failure)

certification of TAWS/ACAS provides one set of probabilities for air collision avoidance, but further defining the hazard for ground collision is prudent.

Failing to clear factor terrain in an already high-risk situation is potentially acceptable from a certification approach, and so long as no harm is done due to other system errors, saving an occasional life is still positive from a risk-reward perspective. However, failures that increase flight hazard severity are a completely different situation philosophically and from a regulatory perspective and thus deserve a lower probability of occurrence than failure to achieve terrain clearance when warranted.

Establishing failure rates of autonomous systems is difficult. These failures can be discrete logic errors, repeatable one hundred percent of the time if found, or they can be intermittent failures that are difficult if not impossible to predict or repeat. Nonetheless, complex autonomous systems require a certifiable approach.

Although complex, Auto GCAS is deterministic, and its behaviors are fully understandable and bound by clear rules, all of which can be tested via unit tests and in aggregate. However, even with a low level of complexity, the challenge of finding unsafe behaviors is significant. It is unlikely complex system failure rates can be adequately characterized by flight test or simulator testing alone. A Monte Carlo approach is necessary to find both performance and failure probabilities.

Since most time critical situations are during the takeoff and landing phases of flight — close to the ground — a system that aggressively suppresses activations during terminal operations can be shown to sufficiently mitigate these risks, even if they have the potential to happen due to errors in logic, trajectory, or digital terrain databases. If the terminal phases of flight are effectively mitigated, it remains to prove that other low-altitude flight operations have sufficiently low failure rates based on the proportionally low frequency of operations in this environment.

Relative to erroneous failure modes that result in "hazardous" USOCs and an induced risk of collision, Auto GCAS failure conditions only need to be rarer than the residual error to show its use will reduce the rate of fatal outcomes.

$$\underbrace{\text{Auto GCAS Risk Ratio}}_{<1} = \frac{\sum(\overbrace{\text{non-Auto GCAS preventable collisions}}^{\text{No change}} + \overbrace{\text{Auto GCAS Unresolved risk}}^{\text{better}} + \overbrace{\text{Auto GCAS Induced risk}}^{\text{worse}})}{\underbrace{\sum \text{Risk of Collision without Auto GCAS}}_{<1}} \qquad (3)$$

The risk ratio concept demonstrates that the number of unresolved collisions need only be decreased more than the number of induced collisions to drive the total risk ratio to a value less than one and thus produce an overall improved outcome. However, a system that added zero induced collision risk but also was only rarely successful at avoiding the terrain would not be very useful or worth the expense and fail to perform its intended function per TCAS guidelines (Federal Aviation Administration, 2017).

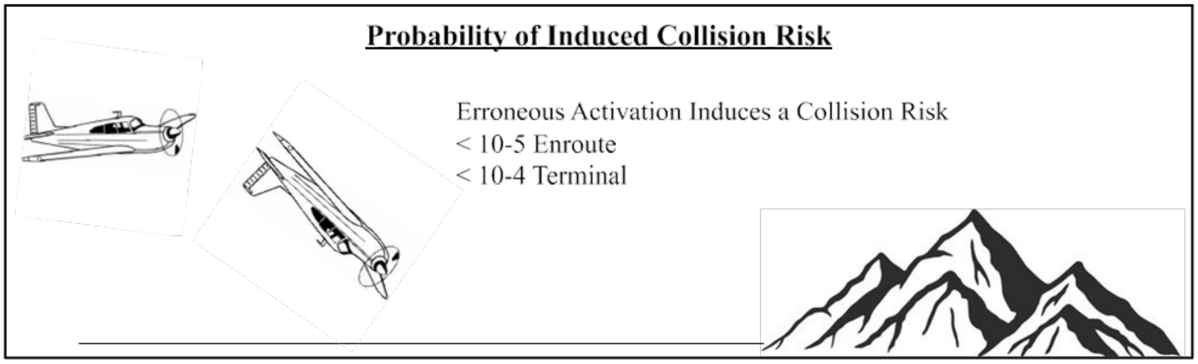

Figure 7. Probability of induced collision from erroneous activation

But how much better does Auto GCAS need to make the collision risk in non-failure conditions? The next section discusses how to derive an acceptable probability to fail to clear the terrain during an attempted terrain avoidance maneuver.

5.9 Acceptable system collision avoidance performance

CFIT results in at best "hazardous" and most likely "catastrophic" outcomes; thus, system activation may appear to be justified whenever risk of CFIT exceeds 10^{-6} or becomes more likely than "extremely improbable." This extreme example could be interpreted as justification for a poorly performing system, which is not the intent.

AC-23.1309-lE states:

> Historical evidence indicates that the probability of a fatal accident in restricted visibility due to operational and airframe-related causes is approximately one per ten thousand flight hours or 1 x 10^{-4} per flight hour for single-engine airplanes under 6,000 pounds. (Federal Aviation Administration, 2011)

The assumption is that operational related causes are pilot error or system failures, and thus probability of catastrophic outcome is 10^{-4} in these situations. Regarding the concept of relative safety, the "classical" traditional system safety approach assigns an acceptable probability to a given hazard severity. It does not consider the probability of a catastrophic outcome if the Auto GCAS was not integrated at all.

Classical guidance material assumed that normal flight was occurring, that initial conditions were acceptable, and that any function being assessed cannot turn that situation unacceptable too frequently. With the Auto GCAS, the pre-activation conditions are instead such that a catastrophic outcome is likely, if not certain, without system intervention. However, it is insufficient to intervene and successfully avoid terrain only some of the time if there remains a higher probability that human intervention would have succeeded more often than the Auto GCAS.

A notional simplified probability function permits factoring in the hazard level already reached through operation of the aircraft when evaluating the probability of successful collision avoidance. This methodology aligns with the guidelines and intent of TCAS means of compliance and the previously discussed risk ratio.

The proposed requirement can be abstracted to:

> The probability of Auto GCAS successfully avoiding threat terrain must be greater than the probability of a catastrophic outcome for an average pilot at that point in remaining TSM/ART.

Fundamentally, this identifies that the system does not need to be perfect to achieve certification performance requirements. Failure to avoid terrain in all warranted activations is not required to gain the safety objectives of the system integration. If this approach were established in an approved DDS means of compliance, the function would only need to show failure to resolve the potentially catastrophic terrain collision at less than the residual rate of CFIT.

Using the United States Air Force Test Center definition, *high risk* is when CFIT or “catastrophic” outcome is more probable than 10^{-3} or a 0.1% chance of occurrence (Gray, 2016). Using this example, if the Auto GCAS activation were considered to occur at a point where 1 in 1,000 such operations would impact terrain, then continued operation of the aircraft would have led to a situation where catastrophic outcome is more probable — 10^{-3} for this hypothetical example — than would be the case for normal and acceptable aircraft operations of 10^{-6} (Federal Aviation Administration, 2011).

The result of this approach would be that the system’s own performance failures would only need to be less than the residual probability level of CFIT. In this hypothetical example, the system’s failure would need to occur less than 10^{-3}. A system with less than 10^{-3} catastrophic-outcome failure condition, which functions successfully in the rest of the probability space (i.e., 1 minus 10^{-3}), would result in a higher aggregate safety level, beginning from the point of Auto GCAS activation, than would have existed without the system available. Classical guidance material, however, indicates a 10^{-3} probability as unacceptable for a system with a severity level of “catastrophic” outcome. It must be stressed that this hypothetical scenario illustrates that having the (1 minus 10^{-3}) upside probability outweighs the downsides even at the 10^{-3} level.

This scenario is depicted in Figure 8. Auto GCAS performance should achieve a terrain avoidance performance failure rate that is 10^{-3} or less, where statistically, it would fail at clearing terrain less often than the pilot.

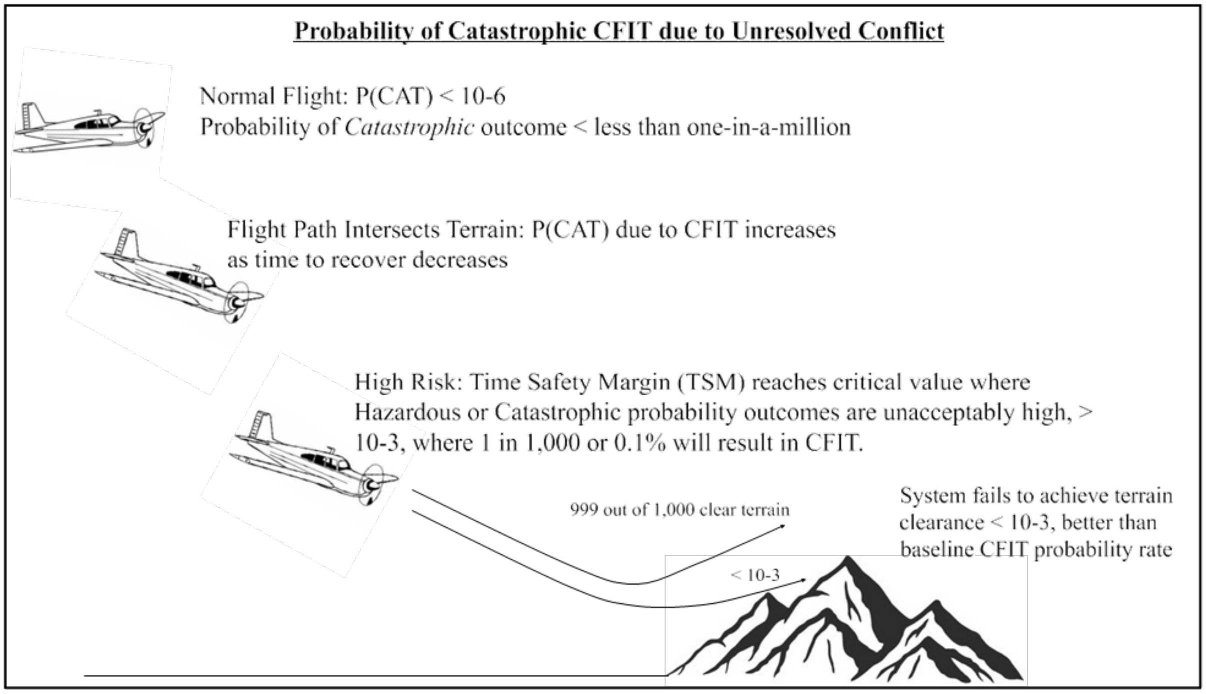

Figure 8. Probability of catastrophic outcome and Auto GCAS performance depiction

TCAS/ACAS risk ratio with certification means of compliance grounded in classical methods aligns this apparent departure from classical system safety guidance. In this example, the risk ratio would be driven to a value less than one with an improved overall safety impact. Any new guidance along these lines would need to be clearly applied only to systems and functions like TCAS/ACAS and Auto GCAS, which have the prospect of converting an already catastrophic situation back into a normal and acceptable one. It is not generally applicable to automated or autonomous system failure rates.

Continuing this logical flow, it is thus sufficient to show that system performance at avoiding terrain need only be better than the probability of "catastrophic" outcome, when the aircraft has reached a "hazardous" flight condition, close to the point of no return.

What is sufficiently close to no return? In the time domain, this is the point where an average pilot has a sufficiently small available reaction time in which to make a decision and execute an appropriate threat avoidance maneuver within the limits of the aircraft and pilot ability.

5.10 Time Safety Margin/Available reaction time

Although this paper utilizes TSM and ART interchangeably, TSM is the value that emerges from the planning process, is dependent on the quality of the planning, and can be dependent on many factors. In the context of this paper, ART is the true remaining reaction time based on actual flight conditions and a given recovery maneuver assumption. Nonetheless, these terms are used interchangeably, as the term TSM ties the value indistinguishably to safety hazard severity and probabilities:

> Time Safety Margin captures the residual CFIT risk of a diving maneuver in a single numerical value that approximates the minimum amount of time available to recognize errors[…] When TSM approaches human reaction time, minimization of uncertainty becomes a life-or-death task. (Gray, 2016, p. 39)

To gain an intuitive understanding for TSM/ART, an understanding of currently accepted timelines is necessary:

- AC 20-151C for TCAS assumes:
  - 5-sec pilot reaction time to respond to a resolution advisory (RA).
  - RAs are specified to occur 15-35 sec prior to the time of closest approach.

It has been generally accepted in the United States Air Force flight test community that TSMs greater than 8 sec are considered routine with a hazard assessment of low risk. The risk level is not substantially increased until a TSM of less than 4 secs is encountered, which is categorized as medium risk. Any TSM less than 2.5 secs is considered high ris,k and anything less than 1.5 sec requires an automatic recovery system that is well tested and trusted. In this context, high risk assumes a probability of 10^{-3} of "catastrophic" CFIT (Gray, 2016).

Given the context of deliberate maneuvers and attentive test aircrew, these time values do not apply directly but give context and a methodology that can be applied to flight hazard risk assessment in the time domain for general aviation aircraft. The numbers discussed are for trained flight test teams that have narrowed the margins of human reaction time to the minimum in order to push the limits of safe testing. An allowance for increased time margins can be expected in most civilian operations. Additionally, the probability of CFIT associated with these risk qualifiers is set but by no means validated statistically. Nevertheless, they are a good starting point for regulatory discussion on certification of Auto GCAS.

Based on limited flight test observations, for an unaware and disoriented civilian pilot, Auto GCAS activations in the range of 4-10 sec are assessed as acceptable and are in the flight regime where baseline has reached "hazardous" if not "catastrophic," depending on flight conditions. In situations of high closure, potentially earlier Auto GCAS intervention is warranted. This is based on:

- Highly trained test pilots on specific test conditions reach elevated "medium" risk between 4 and 2.5 sec TSM (Gray, 2016).

- A relatively aware commercial pilot is expected to respond within approximately 5 sec to a TCAS RA. The RA is a vertical avoidance maneuver to increase separation when the system predicts the threat aircraft is between 15-35 sec from the closest point of approach.
- For a 2,000-fpm descent rate, TAWS allows for 4-9 sec or greater TSM before the assumed maneuver clears the terrain by zero margin.

An autoflight system cannot create "hazardous" deviations in the flight path when the function is active per 14 CFR Part 23.1329, Automatic pilot system (Federal Aviation Administration, 2011). Since the primary hazard for Auto GCAS is impact with terrain, any eventual guidance material should identify a concrete definition and/or examples of when a flight path is considered "hazardous."

In the context of Auto GCAS collision avoidance performance probabilities, it is recommended that a "hazardous" flight be defined in terms of TSM/ART using the following criteria:

- The desired safety performance objective is to decrease the risk ratio and improve the relative probability of successful outcome using TSM/ART to define "hazardous" flight conditions.
- The value for TSM/ART considered "hazardous" should be set with the 14 CFR Part 23.1309 guidance material definition of "hazardous."

It is recommended any guidance given here not be stated as one size fits all, since the probabilities involved vary based on aircraft class. This guidance on hazard probability can be applied only to systems and functions like TCAS/ACAS and Auto GCAS, which have the prospect of converting an already catastrophic situation back into normal and acceptable. It is not generally applicable to automated or autonomous system failure rates. Properly substantiated, this system will save lives. We believe this is clearly in the public interest and warrants serious consideration by the FAA.

6 Pre-Amendment 64 means of compliance analysis

Implementing Auto GCAS on Part 23 general aviation aircraft is truly new and novel. As such, no complete means of compliance currently exists. However, the coupling of an autopilot to a collision avoidance system is not new.

The European Organisation for Civil Aviation Equipment (EUROCAE) has published Minimum Aviation System Performance Standards (MASPS) for Flight Guidance System (FGS) Coupled to Traffic Alert and Collision Avoidance System (TCAS) (European Organisation for Civil Aviation Equipment, 2014) for resolution advisory avoidance maneuvers to include autothrottle control, as RTCA DO-325 specifies in Minimum Operational Performance Standards (MOPS) for Automatic

Flight Guidance and Control Systems and Equipment (RTCA, Inc., 2010). This sets a clear precedent for engagement of collision avoidance autopilot modes, the corollary being an autopilot coupled to a TAWS-like system for ground collision avoidance.

The following pre-Amdt 64 guidance was leveraged to generate the means of compliance performance objectives for Auto GCAS as applied to the categories of Safety, Nuisance, and Protection.

Table 5. Mapping Auto GCAS Tenets to achieve performance objectives

Guidance	Category	Role
Automatic Pilot	Safety	Ensure safety via functional independence of the autopilot and GCAS components Provide guidance for coupling collision avoidance system to autopilot and autothrottle from TCAS II/ACAS II Utilize guidance from AC 23.1309-1E and ASTM F3061/F3061M − 22b
TAWS	Performance	RTCA DO-367 MOPS set desired performance requirements for unimpeded operating altitude and terrain clearance requirements
TCAS II/ ACAS Xa	Nuisance & Safety	Leverage AC 20-151C for non-standard hazard severity, probability and residual risk ratio from TCAS II/ACAS Xa for Auto GCAS
Digital Database	Performance & Safety	Ensure system is not undermined by improperly managed digital databases

The following sections identify applicable portions of this guidance utilized for the Auto GCAS means of compliance.

6.1 Autopilot and flight guidance systems

The 14 CFR Part 23 requirements for automatic pilot systems do not specifically preclude Auto GCAS implementation and certification, but the means of compliance failure conditions require further discussion. The means of compliance for existing 14 CFR Part 23 certified autopilots applies to Auto GCAS. The combination of Amdt 23-64 with AC 23-17C section 23.1329 (Federal Aviation Administration, 2011) provides appropriate design requirements and safety standards, but with allowance and credit for the potential safety benefit.

Existing guidance states that no single failure may be permitted to have a catastrophic outcome (Federal Aviation Administration, 2011). Requiring Auto GCAS to be exclusively implemented with autopilots that can monitor and trap hardovers would risk being cost prohibitive and an unnecessary impediment to general aviation aircraft integration. Nonetheless, this proposed certification roadmap simplifies the approach by assuming functionally independent integration with a modern autopilot system where the worst-case scenario is a command hardover and not a full control hardover as described 14 CFR Part 23.1309E (Federal Aviation Administration, 2011).

Flight guidance systems (FGSs) for transport category aircraft have many prescriptive requirements, as described in 14 CFR § 25.1329 Flight guidance system (2023). The corollary for Part 23 aircraft, 14 CFR § 23.1329 is relatively straight forward, limited in length, and is more performance-based, even without Amdt 23-64 (FAA, 2017). Further, guidance for means of compliance with § 23.1329 is provided by AC 23-17C section 23.1329 Automatic Pilot System (Federal Aviation Administration, 2011). Amendment 23-64 provides the performance-based requirements with respect to hazard severity and probability in 14 CFR § 23.2510 Equipment, systems, and installations (2023).

The table below identifies the primary autopilot regulations with which Auto GCAS must demonstrate compliance. Other applicable regulatory requirements are contained in 14 CFR § 23.1301 Function and installation (1977), 14 CFR § 23.1322 Warning, caution, and advisory lights (1976), and 14 CFR § 23.1585 (j) Operating Procedures (1996).

Table 6. Autopilot Regulations Applicable to Auto GCAS

Regulation			**Compliance Plan**			
Pre-Amdt 64		**Amdt 23-64**				
Section	**Title**	**Section**	**Method of Compliance**[2]	**Means of Compliance**	**Substantiating Document**	**Specialist Finding(s)**[3]
14 CFR 23.1329 (e)(g)(h) Amdt 23-49	Automatic pilot system	14 CFR 23.2500(a)(b) & 23.2505 & 23.2510(a)(b)(c) & 23.2600(a)(b) & 23.2605(b)(c) Amdt 23-64	Design Review	Detailed Design Standard (DDS) with Auto GCAS MoC Issue Paper	System Design Compliance Report	Electrical Systems & Equipment Test Pilot Flight Analyst

[2] As defined in AC 23-24 - Airworthiness Compliance Checklists for Common Part 23 Supplemental Type Certificate (STC) Projects (2005) and in Policy Statement Number PS-ACE100-2001-004, Guidance for Reviewing Certification Plans To Address Human Factors for Certification of Part 23 Small Airplanes (2002).
[3] FAA or Designated Engineering Representative (DER) specialty needing to make corresponding finding of compliance

14 CFR 23.1329 (e)(g)(h) Amdt 23-49	Automatic pilot system	14 CFR 23.2500(a)(b) & 23.2505 & 23.2510(a)(b)(c) & 23.2600(a)(b) & 23.2605(b)(c) Amdt 23-64	Simulation Analysis	Detailed Design Standard (DDS) with Auto GCAS MoC Issue Paper	Simulation Analysis Plan & Report	Flight Analyst
14 CFR 23.1329 (e)(g)(h) Amdt 23-49	Automatic pilot system	14 CFR 23.2500(a)(b) & 23.2505 & 23.2510(a)(b)(c) & 23.2600(a)(b) &	Ground Test (Aircraft)	Detailed Design Standard (DDS) with Auto GCAS	System Ground Test Plan & Report	Electrical Systems & Equipment

Previous assumptions of functional independence are derived from 14 CFR § 23.1329 (Federal Aviation Administration, 2011). Auto GCAS should be categorized as a functionally independent airborne navigation system that integrates signals from auxiliary controls to an autopilot. 14 CFR § 23.1329 Automatic pilot system section (f) and (h) (Federal Aviation Administration, 2011) state the following requirements:

> (f) …If the automatic pilot integrates signals from auxiliary controls or furnishes signals for operation of other equipment, positive interlocks and sequencing of engagement to prevent improper operation are required.
>
> (h) If the automatic pilot system can be coupled to airborne navigation equipment, means must be provided to indicate to the flight crew the current mode of operation.

6.1.1 Autopilot visual and aural warnings and alerts

Although Auto GCAS will be capable of operating without direct human involvement, the pilot is still present at the controls and requires notification to prevent disorientation, avoid mistaken disconnect of the system when a valid threat exists, or intervene in the case of a nuisance or erroneous activation. Thus, it is important the pilot is notified of the system status utilizing both visual and aural indications to satisfy this performance requirement. Visual alerts and warnings should be implemented in accordance with 14 CFR § 23.2600 Flightcrew interface (14 CFR 23.2600: Flightcrew interface, 2016), Standard Specification for Systems and Equipment in Aircraft (ASTM International, 2023), 14 CFR § 23.1329, AC 23.1311-lC Installation of Electronic Display in Part 23 Aircraft (Federal Aviation Administration, 2011), and TAWS MOPS (RTCA, Inc., 2017). Although TAWS MOPS provide additional visual and aural alerting guidance, implementation of the TAWS alerting MOPS may produce nuisances, especially if implementing any caution level alerting criteria.

The following are recommended Auto GCAS visual and aural warnings and alerts:

- Visual annunciation of Auto GCAS autopilot automatic mode changes:
    - A means should be provided to alert the pilot of an imminent activation of the Auto GCAS immediately prior to activation of the flight controls.
        - The timeliness of this alert should be carefully considered to avoid any additional nuisance potential. It is not recommended that this alert have an aural component due to the nuisance potential.
        - This alert should be coupled to assumed pilot reaction time during the given phase of flight or similar criteria to prevent nuisance alerts.
    - A means shall be provided to induce a pronounced mode change to assure pilot situation awareness.
        - The means used to annunciate Auto GCAS protection mode shall be distinctly different from normal flight guidance system mode changes.
    - The visual indication of Auto GCAS activation and flight control engagement should be a warning.
        - The visual indication will be presented in the pilot's primary field of view, when the Auto GCAS is engaged and executing an avoidance maneuver to escape terrain threat.
        - The visual indications should be clearly distinguishable such that it is clear to the pilot that the Auto GCAS is conducting an avoidance maneuver.
        - The visual indication will remain annunciated so long as the immediate terrain threat is present for which the system activated, regardless of pilot manual disconnect of Auto GCAS coupling from the autopilot servos.
        - The pilot should be directed to adjust power (as required).
        - Autopilot disconnect indications during an avoidance maneuver may be different than normal indications to emphasize the continued presence of the threat.
        - The autopilot status should be clearly annunciated at the termination of the threat avoidance maneuver, depending on the termination option implemented.

- Loss of autopilot Auto GCAS mode:
  - The loss of the Auto GCAS mode requires immediate pilot awareness. If the autopilot remains engaged and reverts to a non-Auto GCAS mode, an appropriate visual alert shall be provided.

- Aural annunciation of Auto GCAS autopilot automatic mode changes:
  - An aural alert should be provided to the pilot of an activation of the Auto GCAS.
  - The Aural alert should have the priority of a warning.
  - The means used to annunciate Auto GCAS protection mode should be distinctly different from normal flight guidance system mode changes. This should take place regardless of manual pilot disconnect of autopilot engagement.
  - The pilot should be directed via voice aural alerts to adjust power per the trajectory performance assumptions.
  - The autopilot status should be clearly enunciated at the termination of the avoidance maneuver.

6.1.2 Navigation/sensor accuracy and integrity monitoring

Navigation sensor accuracy and integrity monitoring is critically important to the safe and effective functionality of Auto GCAS. Aside from trajectory modeling, this is the most critical component of the system.

The following are recommended Auto GCAS navigation/sensor accuracy and integrity monitoring:

- The proper functionality of the Auto GCAS requires aircraft position and velocity accuracy sufficient to satisfy the performance requirements as specified in TAWS MOPS (RTCA, Inc., 2017).
- The navigation system accuracy should meet requirements for the actual phase of operation as defined in RTCA DO-229D Change 1 Minimum Operational Performance Standards for Global Positioning System/Satellite Based Augmentation System Airborne Equipment (RTCA, Inc., 2020) and TAWS MOPS (RTCA, Inc., 2017).
- The Auto GCAS shall be aware of the navigation and sensor state and have appropriate integrity monitoring.

- The Auto GCAS shall automatically revert to a standby mode if the navigation position, altitude, or airspeed accuracy are sufficiently degraded to preclude performing the intended function.

6.1.3 Minimum altitude for use of autopilots

The performance objectives of Auto GCAS are to prevent CFIT while not interfering with normal operations. Thus, by definition, the system must be allowed to engage at low altitudes and remain engaged during a recovery maneuver below many current aircraft flight manual supplement (AFMS) limits.

Part 91 minimum altitude autopilot operations are listed in the AFMS. Many existing AFMS autopilot limits are incompatible with Auto GCAS system performance requirements unless provisioned as part of an appropriate stability and protection system, level command, or other emergency-use-only mode such as autoland.

A survey of commercially available autopilot systems identified that some AFMS minimum engagement altitudes are incompatible with the Auto GCAS performance objectives to allow unimpeded low altitude and terminal operations, while still providing protection. The good news is these limitations are driven by the manufacturer during the certification and could be amended based on demonstrated Auto GCAS performance to allow for automatic emergency engagement below current AFMS operating limitations. Two examples are shown below, which, with minor changes to the AFMS, would facilitate Auto GCAS integration:

- Garmin GFC 500, Piper Cherokee (PA-28): The autopilot must be disengaged below 200 ft AGL during approach operations and below 800 ft AGL during all other operations (Garmin, 2018).
- Dynon HDX, Beechcraft Bonanza (B-36): Minimum Altitude: Use of the autopilot below 200 ft AGL is prohibited (Dynon Avionics, Inc., 2023).

Minimum altitudes for use of autopilots are specified in 14 CFR § 121.579 and 14 CFR § 135.93 and discussed in the ruling 79 FR 6082, Minimum Altitudes for Use of Autopilots (Federal Aviation Administration, 2014). Although this ruling is applicable to Part 121 scheduled regional and major air carriers and not applicable to Part 91 general aviation or Part 135 commuter operations, the potential for use as clarification of intent and a means of compliance warrants discussion.

Additionally, phase of flight incompatibilities, as discussed below, may limit Auto GCAS implementation and effectiveness in Part 135 and Part 121 operations. In spite of these incompatibilities, none preclude certification of Auto GCAS today. The solution to this incompatibility is a single exception that allows for autopilot engagement below 14 CFR § 121.579 and 14 CFR § 135.93 minimums when authorized by the AFMS as part of a stability and protection system, level command, Auto GCAS, or other safety function. From 79 FR 6082:

> […] this final rule is based on the performance capabilities of the equipment being utilized, not the operating certificate held […] Each paragraph in this final rule has a base minimum autopilot use altitude for the intended phase of flight that all aircraft may utilize. In order to protect the use of all legacy systems, the base altitudes will remain identical to the altitudes in the current rule. Lower minimum use altitudes are based on certification of the autopilot system and limitations found in the AFM. (Federal Aviation Administration, 2014)

Additionally, the final ruling allows for operations to touchdown for performance-based landing systems but requires a landing system mode, which is too limiting for efficient and broad adoption of Auto GCAS: "This action will allow new performance based landing systems to be approved and implemented for autoland operations as they become available" (Federal Aviation Administration, 2014).

The following paragraphs identify autopilot limitations per phase of flight as identified in 14 CFR § 121.579 and 14 CFR § 135.93. Each phase has an escape clause that allows for lower engagement altitudes than previous guidance and complies with the language from the final ruling 79 FR 6082 (Federal Aviation Administration, 2014). The altitude requirements are based on AFMS-specified altitude loss or are more restrictive in some cases.

6.1.3.1 Takeoff and initial climb (14 CFR § 121.579(b)/14 CFR § 135.93(b))

These guidelines are compatible with Auto GCAS performance objectives.

Takeoff and initial climb minimum altitude are conservative but acceptable for initial Auto GCAS arming altitude and engagement, if required. 14 CFR § 121.579(b) and 14 CFR § 135.93(b) specify 500 ft AGL with an exception, which is worded differently than the other phases of flight and potentially allows engagement altitude less than 500 ft AGL, as specified by the AFM:

> (b) Takeoff and initial climb. No person may use an autopilot for takeoff or initial climb below the higher of 500 ft or an altitude that is no lower than twice the altitude loss specified in the Airplane Flight Manual (AFM), except as follows—
>
>> (1) At a minimum engagement altitude specified in the AFM; or
>>
>> (2) At an altitude specified by the Administrator, whichever is greater. (Federal Aviation Administration, 2014)

6.1.3.2 Enroute (14 CFR § 121.579(c)/14 CFR § 135.93(c))

These guidelines are incompatible with Auto GCAS performance objectives for low-altitude operations or enroute descent without negatively increasing nuisance rates.

The enroute altitude restriction of 500 ft AGL does not have the same exception to defer to the AFM for a lower specified engagement altitude. Although 500 ft AGL is the small aircraft required obstacle clearance (ROC) as specified in TAWS MOPS, it does not allow for inevitable transients below this altitude during normal operations or an Auto GCAS recovery. These transients could be as low or slightly lower than the intended TAWS MOPS required terrain clearance (RTC) of 200 ft AGL during the recovery maneuver (2017). Per 14 CFR § 121.579(c) and 14 CFR § 135.93(c):

> (c) Enroute. No person may use an autopilot enroute, including climb and descent, below the following—
>
> > (1) 500 ft;
> >
> > (2) At an altitude that is no lower than twice the altitude loss specified in the AFM for an autopilot malfunction in cruise conditions; or
> >
> > (3) At an altitude specified by the Administrator, whichever is greater. (Federal Aviation Administration, 2014)

6.1.3.3 Approach (14 CFR §121.579(d)/14 CFR § 135.93(d))

These guidelines are compatible with Auto GCAS performance objectives but are overly restrictive based on coupled instrument approach or coupled landing mode requirements.

The least restrictive language for autopilot use during approach phase is 50 ft AGL, which is lower than required for acceptable Auto GCAS performance. However, dependencies on instrument approach procedures, as well as potential precoupling of autopilot to approach modes or certified landing modes, complicate the implementation and are not optimized to include special visual flight rules (VFR) pattern operations. Per 14 CFR §121.579(d) and 14 CFR § 135.93(d):

> (d) Approach. No person may use an autopilot at an altitude lower than 50 ft below the DA(H) or MDA for the instrument procedure being flown, except as follows—
>
> > (3) For autopilots with an AFM specified negligible or zero altitude loss for an autopilot approach mode malfunction, the greater of—
> >
> > > (i) 50 ft; or

(ii) An altitude specified by Administrator. (Federal Aviation Administration, 2014)

6.1.3.4 Go-around/missed approach (14 CFR § 121.579(e)/14 CFR § 135.93(e))

These guidelines are compatible with Auto GCAS performance objectives but potentially overly restrictive based on coupled instrument approach or coupled landing mode requirements.

Go-around/missed approach minimum use altitude restrictions allow for Auto GCAS but force some loss of protection in certain conditions, but the unique AFMS exception from Takeoff and Initial Climb section allows for no loss of protection. Per 14 CFR §121.579(e) and 14 CFR § 135.93(e):

(b) Go-Around/Missed Approach. No person may engage an autopilot during a go-around or missed approach below the minimum engagement altitude specified for takeoff and initial climb in paragraph (b) in this section. An autopilot minimum use altitude does not apply to a go-around/missed approach initiated with an engaged autopilot. (Federal Aviation Administration, 2014)

6.1.4 Maneuver termination specific logic and autopilot commands

Several maneuver termination options have been explored, such as disengagement of the autopilot, as implemented on F-35 and F-16; commanding level flight; maintaining a last left climbing or turning command; and a continuous climb on the termination heading. There are tradeoffs with each solution, but generally, they can be categorized as follows.

6.1.4.1 Indefinite climb on heading of maneuver termination

The maneuver termination point has the highest probability of being the best escape solution in the general direction the pilot was attempting to go, while ensuring the shortest duration intervention by the Auto GCAS, and thus the least impact to the mission (do not interfere). This also minimizes the potential of elevating follow-on risk (do no harm) and is the earliest point at which the system has achieved functional design success and avoided CFIT (prevent collisions). This termination logic is recommended.

6.1.4.2 Autopilot disengagement at termination

This solution is desired for users that require low-altitude operations with a higher likelihood of nuisance engagement. This potentially leads to another terrain avoidance engagement maneuver due to low pilot situational awareness. Unlike in aggressive low-altitude military flying, where immediate continuation of the mission is required, the potentially lower situational awareness, training, and proficiency of general aviation pilots may warrant this as a customizable feature but not the default termination logic. This termination logic is recommended depending on the mission requirements and nuisance probability for that mission.

6.1.4.3 Level command at termination

This solution is not advisable due to the potential for immediate conflict with the original threat, especially for systems that terminate when the flight path angle is clear of the threat. For climbing avoidance maneuvers to clear elevated terrain relative to the aircraft altitude, this can potentially create a scenario that results in immediate reactivation of the system or even terrain impact. This termination logic is not recommended.

6.1.4.4 Last left autopilot settings

If the Auto GCAS has a limited set of avoidance maneuvers and/or does not continuously scan and select a maneuver path and safe termination heading, this can result in flying past the termination point and the safe escape direction, resulting in follow-on activation or impact with terrain. For example, if the commanded maneuver is a 180-degree turn but the aircraft clears the threat after only 45 degrees, there are several consequences to continuing the maneuver. First, the point at which the pilot decides to disengage the autopilot and resume control may be suboptimal or even hazardous at an arbitrary point during the remaining turning maneuver. Second, there is almost certainly reduced position uncertainty after 180 degrees of turn based on changes in wind condition and/or minor trajectory model discrepancies. Third, the consequences of a longer duration climb potentially forces the aircraft into marginal or poor weather conditions, which most likely contributed to the activation to begin with, when the pilot may have been attempting to fly in the most appropriate direction for the conditions but made an error in aircraft maneuvering. This termination logic is not recommended.

6.1.5 Autopilot and automatic flight guidance system Safety Analysis

Appendix 1 of AC 23.1309-1E, System Safety Analysis and Assessment for Part 23 Airplanes, (Federal Aviation Administration, 2011) provides a partial list of FHAs for meeting 14 CFR Part 23 Requirements for IFR Class I airplanes. The failure condition severity guidelines from 14 CFR § 23.2510, Equipment, systems, and installations (2023) remain in alignment with AC-23.1309-lE.

An Auto GCAS failure condition in the most severe single failure situation is an erroneous Auto GCAS autopilot activation due to an error in the underlying system digital terrain database or other anomalies. Most notably, 14 CFR § 23.1329 Automatic pilot system sections (f), (g), and (h) provide guidance for this example and other erroneous activation scenarios that could cause a potential safety conflict with terrain or other aircraft (Federal Aviation Administration, 2017).

The most challenging requirement is given by 14 CFR § 23.1329, section (f) states: “Each system must be designed so that a single malfunction will not produce a hardover signal in more than one control axis” (Federal Aviation Administration, 2017).

However, the assumptions stated previously provide some relief from this requirement:

- Auto GCAS is functionally independent system.
- If Auto GCAS logic is assumed to be integrated with a modern commercial autopilot system, invoking normal autopilot gains, authority, and hardover prevention, then erroneous Auto GCAS can be considered to control multiple axes but only command hardover.

It is important to define "hardover," "command hardover," and "slowover" in the context of autopilot failure mode descriptions and AC 23-17C 23.1329, Automatic pilot system (Federal Aviation Administration, 2011):

- Hardover: AC23-17C does not provide a definition of hardover signals with respect to failure modes. This paper defines a *hardover* as signal that can drive the autopilot servos to their mechanical limit of travel in either pitch or roll at maximum autopilot gains/rates, or as any failure of the autopilot system which will cause a rapid and sustained displacement of an aircraft aerodynamic control surface to the full extent permitted by physical constraints within the autopilot actuator system. This paper does not assume failure of any mechanical stops or sheer screws. Each system must be designed so that a single malfunction will not produce a hardover signal in more than one control axis. Based on the primary assumption that the Auto GCAS is functionally independent from the autopilot, the Auto GCAS itself is incapable of a failure mode that would result in a hardover condition.
- A *command hardover* is defined as any erroneous activation outer loop command that requests an autopilot maneuver where the autopilot servos are commanded at normal rates and positions (i.e. less than maximum servo gains/rates or less than servo mechanical limit of travel, in either pitch, roll, or both axes). This erroneous outer loop command could be from a variety of sources to include an Auto GCAS or navigation system.
- A *slowover* is defined as a malfunction or phenomena where the autopilot is following an insidious and erroneous command, usually associated with attitude system failures, which can be masked by a display following the erroneous attitude. Thus, in the context of Auto GCAS, this would not be a failure mode except during or after an avoidance maneuver in which the command function is lost and the autopilot reverts unannounced to baseline autopilot modes.

Moreover, AC 23-17C section 23.1329 (Federal Aviation Administration, 2011) provides further allowance for erroneous Auto GCAS autopilot activation, clarifying and providing guidance for the purposes of means of compliance with 14 CFR § 23.1329 (Federal Aviation Administration, 2017). The advisory circular clarifies that any single malfunction can impact multiple axes and not be considered hazardous as defined in AC 23.1309-1E (Federal Aviation Administration, 2011) if the signals are “slowover,” not “hardover,” and easily controllable. This paper assumes erroneous Auto GCAS signals are a command hardover in the worst-case scenario.

In aggregate, these enablers provide a means for an Auto GCAS to meet the requirements of 10-4 probability of “major” severity, which is an achievable certification goal.

The following Auto GCAS means of compliance should be updated in a subsequent release of AC 23-17C section 23.1329 (Federal Aviation Administration, 2011), thus providing means of compliance guidance for 14 CFR § 23.1329 section (f) and (h) for Auto GCAS:

> (f) An Auto GCAS coupled autopilot shall contain proper interlocks and integrity monitoring of system functionality to prevent improper operation. Examples include loss of accurate pitot static information, degraded GPS position accuracy, etc. Sequencing of engagement and prioritization shall ensure normal navigation functions are overridden by terrain avoidance recovery activation.
>
> (h) An Auto GCAS coupled autopilot shall contain effective means to indicate to the crew the current mode of operation, e.g. Auto GCAS mode is active as opposed to enroute navigation functions. (Federal Aviation Administration, 2017)

Table 7 summarizes the AC 23.1309-1E hazard severity for applicable failure modes of TAWS and Autopilot.

Table 7. Autopilot and TAWS failure classification

Aircraft Function	**Failure Condition Classification**			
	Total Loss of Function		**Misleading and/or Malfunction without Warning**	
Autopilot	With warning	Minor	Multi-axis and limited authority	Major
	Without warning	Major	Unlimited authority/monitor loss	Hazardous
TAWS	Minor		Minor (Class C)	

The additional stipulations outlined in AC 23-17C section 23.1329 can be applied to Auto GCAS:

> (a) The malfunction evaluations are acceptable even with the maximum drive signal due to the limited rate of change authority of the powered controlling element and flight control surfaces,

(b) The monitor/limiting device [i.e. autopilot servo command system] is independent of the automatic pilot element [e.g. the code, logic, processor, and input command]

(c) The signal [from Auto GCAS] is less than the hardover signal due to the monitor/limiting device, and

(d) An acceptable fault analysis shows the functional hazard of a combined monitor failure and automatic pilot malfunction is not catastrophic, including:

(1) The functional hazard of a failure of a lockout device/system to inhibit autopilot engagement until the pre-engagement check is successfully completed is hazardous or less,

(2) Pre-engagement check of the monitor system [non-Auto GCAS, traditional autopilot portion of the system] is mandatory with either a manual or automatic activation means, and

(3) Automatic pilot authority is not greater than necessary to satisfactorily control the airplane. (Federal Aviation Administration, 2011, p. 250)

Further examples of autopilot failure condition severity categorization can be found in AC 23.1309-1E (Federal Aviation Administration, 2011). AC 23-17C 23.1329 section (4)c states alternate means of compliance for recovery of flight control from the engaged autopilot system can be accomplished "either by manual use of a quick disconnect or by physically overpowering the system" (Federal Aviation Administration, 2011). The inability to disengage the autopilot with the autopilot disconnect switch is listed as a severity level of "major." This indicates that any normal autopilot commands up to and including "slowover" erroneous activation are at most the severity level of "major." In the context of a "slowover" failure of an autopilot coupled instrument landing system (ILS) approach to minimums on final, the Auto GCAS risk of erroneous activation in the same conditions is no more severe. This important failure condition classification is necessary to prove Auto GCAS can utilize AC 23-17C (Federal Aviation Administration, 2011) as guidance for means of compliance with 14 CFR § 23.1329 (Federal Aviation Administration, 2017).

The remaining means of compliance guidance contained in AC 23-17C section 23.1329 (Federal Aviation Administration, 2011) is universally applicable to all autopilot systems. Given compliance with previously discussed guidelines, and with the assumption that Auto GCAS is integrated with functional independence, Auto GCAS should not require further testing than is required for baseline autopilot certification under 14 CFR § 23.1329 (Federal Aviation Administration, 2017).

6.2 Terrain awareness and warning system Minimum Operational Performance Standards

The goal of terrain avoidance systems, both manual and automatic, is to prevent CFIT. TAWS MOPS section 1.5 states, "The operational goal of TAWS is to reduce the occurrence of CFIT accidents" (RTCA, Inc., 2017). TSO-C151d is the regulatory source for this stated goal, outlined in section 3.a:

> Functionality. This TSO's standards apply to equipment intended to provide flight crews with aural and visual alerts aimed at reducing the risk of CFIT accidents through increased terrain awareness. (Federal Aviation Administration, 2017, p. 1)

TAWS MOPS defines CFIT in section 1.9 as "an accident or incident in which an airworthy aircraft, under the full control of the pilot, is unintentionally flown into terrain, obstacles, or water" (RTCA, Inc., 2017). The important clarifying statements in this definition are an "airworthy aircraft," meaning ground collision due to damage or aircraft systems failures do not qualify under this category. Further, "full control of the pilot" requires the aircraft to be in controlled flight.

Further assumptions of TAWS are stated in section 1.7:

> The design requirements and guidelines presented in this document assume several system characteristics and applications as listed below:
>
> 1. The TAWS may be stand-alone or part of an integrated system.
> 2. The TAWS display may be stand-alone or part of a multi-function display.
> 3. The TAWS has access to terrain and airport/runway data.
> 4. The TAWS is an alerting system. The system does not guarantee successful recovery from a conflict due to factors such as pilot response, aircraft performance, and database limitations. (RTCA, Inc., 2017)

These design assumptions and definitions are consistent with the objectives of Auto GCAS, however, TAWS alone has not achieved the FAA CFIT reduction objectives.

In order for TAWS MOPS (RTCA, Inc., 2017) to apply to an Auto GCAS, it is necessary to update the assumptions to meet the performance objectives:

- The Auto GCAS may be standalone or part of an integrated system.
- The Auto GCAS display may be standalone or part of a multi-function display.
- The Auto GCAS has access to terrain and airport/runway data.

- The Auto GCAS is a functionally independent system that provides autopilot-assisted threat avoidance. However, the system does not guarantee successful recovery from a conflict due to factors such as pilot response, aircraft performance, and database limitations.
- Caution alerts, where not required, are not implemented or driven to lowest possible sensitivity. Where only cautions exist for a required capability, no Auto GCAS activation is required, and TAWS RTC performance applies.
- Warning alerts are commensurate with an Auto GCAS activation but do not relieve the requirement for appropriate warning alert indications.

Given these assumptions, it is the determination that TSO-C151d (Federal Aviation Administration, 2017) and TAWS MOPS (RTCA, Inc., 2017) are appropriate guidelines for certification of Auto GCAS integration as written if the system meets the qualitative or quantitative failure modes, severity and, probabilities as prescribed by AC 23.1309-1E (Federal Aviation Administration, 2011) and recommended in this report.

Extensive work was completed by RTCA Special Committee 231 in Recommended Solutions to Address TAWS Manual Inhibition CFIT Cases Raised by NTSB Safety Recommendations A-17-035 and A-18-015 and GAJSC CFIT WG SE-54 (RTCA, Inc., 2020) to provide potential options to address National Transportation Safety Board (NTSB) Safety Recommendations to reduce manual inhibition CFIT cases resulting from the nuisance rates of the TAWS implementation. The committee proposed sixteen potential options to improve TAWS, including implementation of a situational awareness tool based on NASA GCAS and certified TAWS based on NASA GCAS (RTCA, Inc., 2020). As a result of this recommendation and project goals provided by the FAA, the Blackbird team evaluated Class C TAWS MOPS as the means of compliance for Auto GCAS on 14 CFR Part 23 general aviation aircraft.

6.2.1 TAWS Class C attributes and performance objectives

Per the TAWS MOPS, "Class C systems are not required by regulation, but are optional for General Aviation class aircraft." The operational applications and classes of TAWS are listed below (RTCA, 2017):

> The Class A TAWS requirements are the most stringent. Class A TAWS are intended for use in large turbine powered aircraft which are equipped with at least one radio altimeter.
>
> The Class B TAWS requirements are less demanding than Class A requirements. Class B TAWS are intended for use in smaller turbine powered aircraft which might not be equipped with a radio altimeter.

The Class C TAWS requirements are the least stringent. Class C TAWS are intended for use in small general aviation aircraft which are not required by rule to have any TAWS installation, but whose operator desires to have TAWS functionality.

Table 8 identifies functions or features applicable to each TAWS Class ((RTCA, Inc., 2017).

Table 8. Key attributes by Class

Function or Feature	**Class A**	**Class B**	**Class C**
Terrain Display	**Required**	*Not Required*	*Not Required*
Forward Looking Terrain Avoidance (FTLA)	**Required**	**Required**	**Required**
Premature Descent Alerting (PDA)	**Required**	**Required**	**Required**
Excessive Rate of Descent (Mode 1)	**Required**	**Required**	**Required**
Excessive Closure Rate to Terrain (Mode 2)	**Required**	*Not Required*	*Not Required*
Negative Climb Rate or Altitude Loss after Take-off or Go Around (Mode 3)	**Required**	**Required**	**Required**
Flight Near Terrain when Not in Landing Configuration (Mode 4)	**Required**	*Not Required*	*Not Required*
Excessive Downward Deviation from an ILS Glideslope or LPV/GLS Glidepath (Mode 5)	**Required**	*Not Required*	*Not Required*
Five Hundred Foot Altitude Callout	**Required**	**Required**	**Required**
Altitude Callouts for Altitudes other than 500ft	*Not Required*	*Not Required*	*Not Required*
Human-Made Obstacle Avoidance	*Not Required*	*Not Required*	*Not Required*
Blank Angle Alert	*Not Required*	*Not Required*	*Not Required*

Decision Height, Minimums Callout	*Not Required*	*Not Required*	*Not Required*
Radio Altitude Interface	**Required**	*Not Required*	*Not Required*

Class C TAWS is proposed as one element of a DDS means of compliance. Flight test and simulator data were used to determine the utility of each MOPS and if they are sufficient certification criteria to ensure a safe, low nuisance system that will provide terrain deconfliction.

Class C Auto GCAS are proposed for the enroute and terminal environments utilizing TAWS MOPS flight environment ROC and TAWS RTC, shown in Table 9 (RTCA, Inc., 2017).

Table 9. Summary of FLTA thresholds

Flight Environment	**Small Aircraft ROC (FT)**	**TAWS RTC (FT)**
Cruise	500	200
Take-off/Landing	250	100

The 14 CFR Part 23 Amdt 23-64 states, "performance-based rules require a safety outcome, rather than a single prescriptive approach to achieving that outcome" (Federal Aviation Administration, 2022). The performance objectives for terrain clearance requirements in the Class C TAWS MOPS are sufficient criteria for Auto GCAS performance. Specifically, the RTC listed, achieve the desired safety outcome and are a sufficient performance metric for terrain clearance (RTCA, Inc., 2017):

- 200 ft AGL for Cruise Operations
- 100 ft AGL for Take-off/Landing Operations

Further, the performance objectives for unimpeded operations (nuisance) are also sufficient as specified as ROC (2017):

500 ft AGL for Cruise Operations

250 ft AGL for Take-off/Landing Operations

For the purposes of consistency between collision avoidance documents, "Terminal Environment" is used interchangeably with "Take-off/Landing" defined by the TAWS MOPS as within 3 nmi of the nearest airport and less than 1,000 ft AGL. Likewise, "Enroute Environment" used interchangeably with "Cruise " defined as greater than 5 nmi from the nearest airport and greater than 1,000 ft AGL (RTCA, Inc., 2017).

An Auto GCAS that achieves these performance objectives is expected to be effective. Per 14 CFR Part 23 Amdt 23-64, "Performance-based rules require a safety outcome, rather than a single prescriptive approach to achieving that outcome" (Federal Aviation Administration, 2022). TAWS MOPS also encourages this in section 1.6: "the TAWS may optionally be designed with additional features" (RTCA, Inc., 2017).

6.2.2 Terrain awareness and warning systems Minimum Operational Performance Standards as means of compliance to achieve performance objectives

Blackbird's limited flight test campaign of Auto GCAS on a general aviation aircraft, integrated with a low authority autopilot, can meet the TAWS MOPS performance requirements. However, those performance requirements do not guarantee an effective system. Nonetheless, the TAWS performance objectives provide sufficient guidance for the desired terrain clearance as the performance objective for avoiding CFIT. In general, if an Auto GCAS were to achieve the TAWS RTC performance objectives of 200 ft terrain clearance for enroute and 100 ft for the terminal environment, it would save lives. However, TAWS MOPS section 2.1.4 states, "In the alert criteria section, when Must Alert, May Alert and Must Not Alert regions are defined, a manufacturer may define the alert threshold anywhere within the May Alert region" (RTCA, Inc., 2017).

The flexibility stated in the performance objective within the "May Alert" region allows for an overly broad range of TAWS behaviors across vendors. Meanwhile, the overly prescriptive nuisance criteria do not effectively bound system performance to ensure unimpeded operations to the ROC.

The prescriptive performance requirements state when the system must and must not issue a warning alert, complicating and sometimes conflicting with the performance objectives for a low-nuisance system that avoids collisions. The "Must Not Alert" criteria for almost all scenarios are insufficient guidance to create an acceptable low-nuisance system. Subjective test pilot comments obtained during the limited-scope flight test with a low authority autopilot identified some Auto GCAS activations as nuisance. However, flight test data show these test conditions met TAWS nuisance standards. Further, all activations of the Auto GCAS passed the performance criteria for "Must Not Alert," even those that were confirmed nuisances or poor system performance due to system errors.

The nuisance criteria listed in the TAWS MOPS for "Must Not Alert" are insufficient to achieve the Auto GCAS nuisance goals with unimpeded operations down to the ROC. Flight test data are shown in Figure 9 below. Circled in red are example test points, which the flight test team declared as nuisance events but are not considered a nuisance by TAWS MOPS "Must Not Alert" criteria.

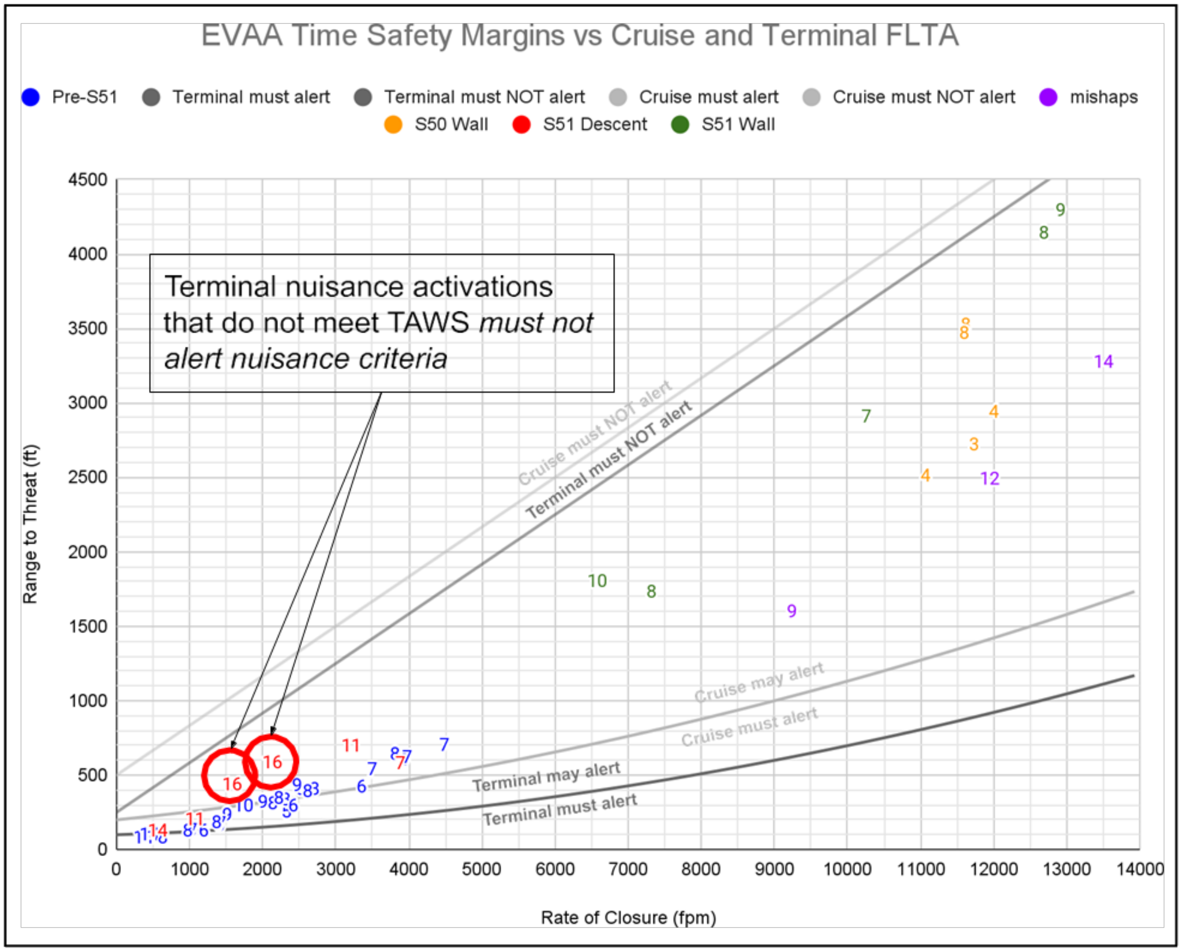

Figure 9. Flight test TSM data applied to TAWS FLTA alerting criteria

As shown in Figure 10 below, flight test data show that operations at altitudes less than 500 ft AGL and descent rates less than 1500 fpm correlate well to the requirements for Terminal "Must Alert." However, TAWS "Must Not Alert" criteria are too permissive for Auto GCAS and allow for excessive nuisance activations. Altitudes above 500 ft AGL and descent rates greater than 1500 fpm do not adhere to the "Must Alert" criteria for cruise or terminal but are still within the "May Alert" zones. For descent rates greater than 2,000 fpm, Enroute "Must Alert" and Terminal "Must Alert" activation criteria approach small TSM that may be hazardous for a low authority autopilot, as shown in Figure 11.

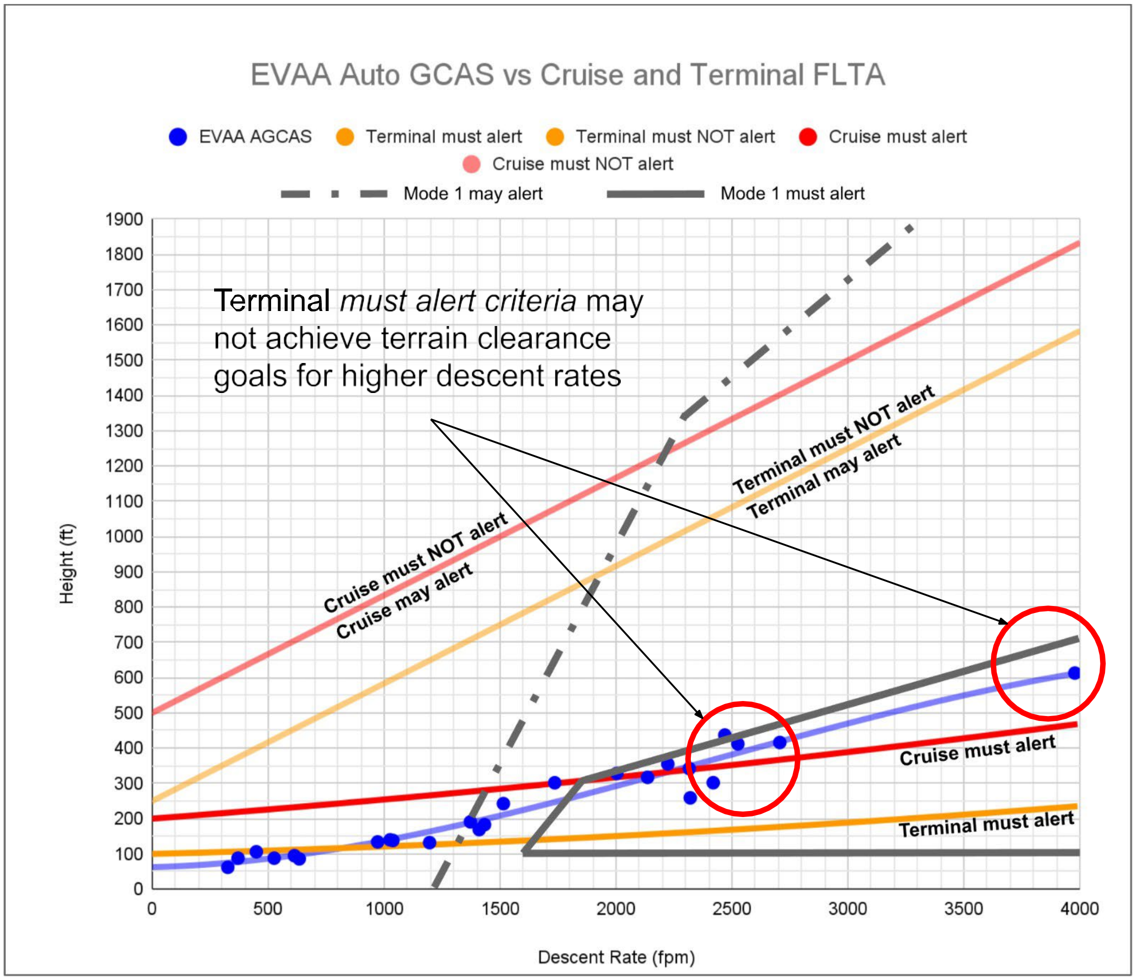

Figure 10. Flight test data applied to TAWS FLTA alerting criteria

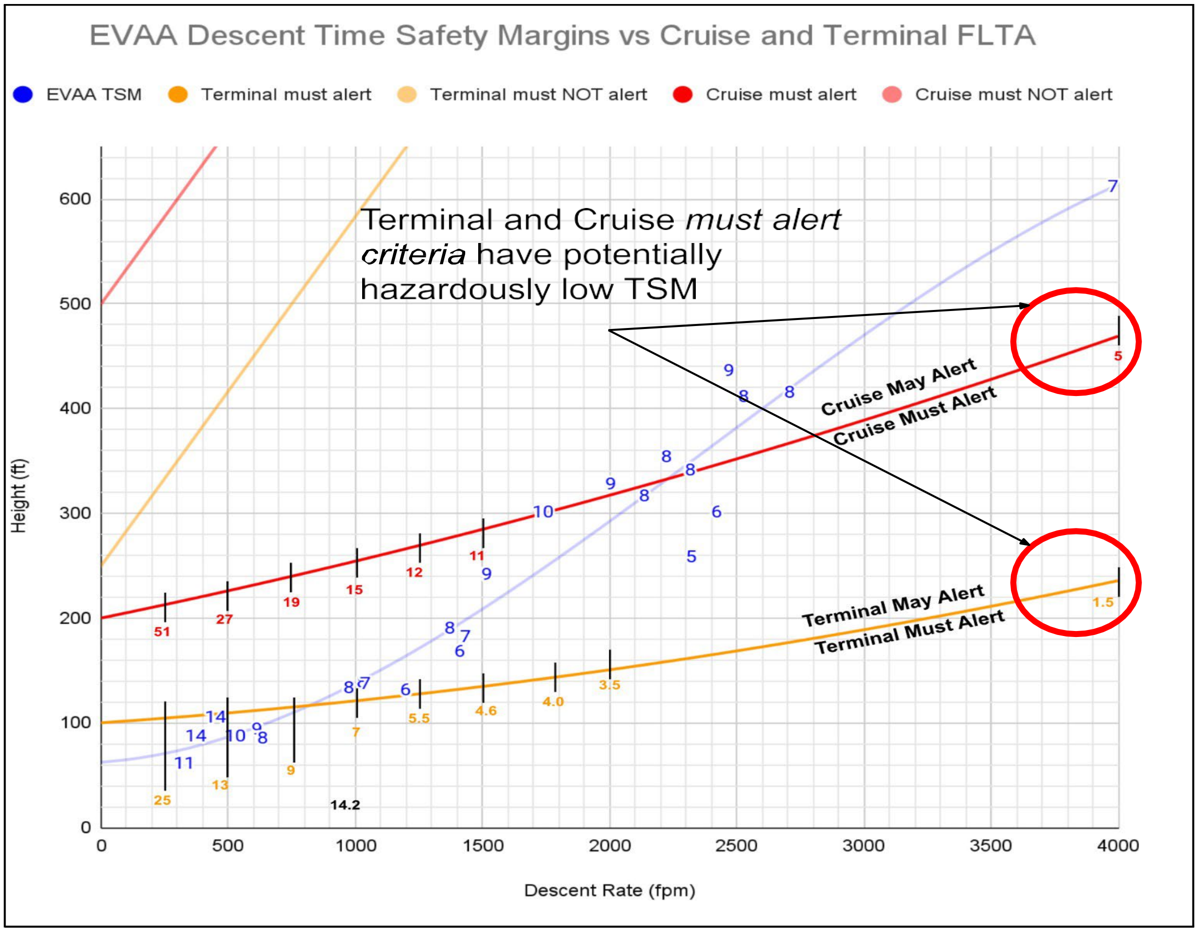

Figure 11. Flight test descent data and TSM applied to TAWS FLTA alerting criteria

6.2.3 Terrain awareness and warning systems limitations and Time Safety Margin

This report postulates that the TAWS RTC minimum approach to terrain values have sufficient community acceptance to be considered a hazard level of "hazardous" or "catastrophic" if unintentional penetration of these distances were to occur. Subjective test pilot assessments of hazard level have been correlated to be a function of time. As discussed previously, TSM/ART identify time as the critical factor in determining both safety and nuisance criteria.

TAWS utilizes a blended method of attempting to combine the time domain and distance domain to achieve the goal of a nuisance-free system. Operationally, however, it has been found that TAWS requirements drive the tendency towards a nuisance-prone system and pilots disregard or inhibit the system, thus minimizing its effectiveness. However, this is not because the concept of

TAWS is insufficient; rather, the nuisance-prone nature of the system is due to TAWS requirements for earlier cautions and warnings than are most likely necessary, resulting in alerts during safe normal operations. Said another way, the TSM and ART are too large to achieve the desired nuisance-free operation. This is partially due to the incomplete application of the concept of time domain.

TAWS MOPS combines a TSM, pilot delay, and maneuver assumption, and then it adds an altitude pad for both desired nuisance and terrain clearance requirements. This report attempts to reconcile these TAWS altitude margins in the time domain to demonstrate that combining a TSM approach with an altitude pad for nuisance criteria is relatively incompatible with this concept:

> Time Safety Margin is designed to make altitude margins unnecessary measures of safety. Altitude margins are only applicable within a limited—and often unacknowledged or misunderstood—range of conditions. The TSM should be calculated as a margin for CFIT, not for flight through a minimum altitude. (Gray, 2016, p. 45)

Applying the intent of the TAWS RTC and ROC to a TSM momentarily resolves this conflict in pursuit of a pure TSM definition for the TAWS grading criteria. TSM test experience and time assumptions from TCAS II/ACAS Xa are used to evaluate the validity of the values listed in the TAWS MOPS.

The assumptions for TAWS TSM calculations are as follows:

- The +1.0G maneuver is considered additive to current aircraft G, so total Nz for a wings level pull would be +2.0G Nz from a +1.0G Nz starting condition.
- The time to achieve the peak Nz is instantaneous.
- To expose and baseline the time to impact, all human reaction time is removed from the TSM values.

A summary of the TAWS MOPS requirements converted to TSM is shown below.

6.2.3.1 Must Alert Time Safety Margin

TAWS Cruise performance criteria requires that TAWS must alert the pilot before terrain clearance is 317 ft or less for a 2,000 fpm descent. Consider Table A-8 (RTCA, 2017):

317 ft = 200 ft (TAWS RTC)

+ Height loss from 1.0G maneuver

+ Height loss from 3 sec pilot delay.

Applying TSM calculations to the TAWS 2,000 fpm criteria, 200 ft of terrain clearance equates to 6 sec. Combined with the height loss from a 3 sec pilot delay results in a TSM of 9 sec. Table 10 lists calculated TSM for varying TAWS cruise descent rates.

As shown in the table below, for descent rates less than 2,000 fpm, the Cruise "Must Alert" criteria are nuisance-prone, with TSM requirements increasing from 9 sec at 2,000 fpm to 51 sec or more with shallow descent rates less than 250 fpm.

Terminal TSM, which utilizes a 100 ft RTC and 1 sec pilot delay, starts increasing above 13 sec for descents less than 500 fpm, and 25 sec for 250 fpm. As a "Must Activate" criteria, these TAWS TSM values could force nuisance activations. The Terminal "Must Alert" criteria appear to be a reasonable performance requirement for descent rates less than 2,000 fpm but greater than 500 fpm. At a greater than 2,000 fpm descent rate, the TSM is less than 4 sec, decreasing to 1.5 sec at 4,000 fpm. This is certainly well clear of any nuisance potential and is potentially too low for a low-authority autopilot.

Table 10. Limitations of TAWS MOPS "Must Alert" as shown by equivalent TSM

Equivalent TSM for TAWS Must Alert Criteria Per Phase of Flight		
Descent Rate	**Phase of Flight**	
	Cruise (200 ft + 3 sec)	**Terminal (100 ft + 1 sec)**
250 fpm	51 sec	25 sec
500 fpm	27 sec	13 sec
2000 fpm	9 sec	4 sec
4000 fpm	6 sec	2.5 sec

6.2.3.2 Must Not Alert Time Safety Margin

The nuisance criteria listed in the TAWS MOPS for "Must Not Alert" is insufficient to achieve the Auto GCAS nuisance goals with unimpeded operations down to the ROC. This can be shown to be directly resulting from a large altitude buffer combined with a minimum TSM of 20 sec.

For example, for a relatively steep 2,000 fpm descent in a cruise scenario, the TSM is 31.5 sec, far greater than an acceptable nuisance criterion. For shallower descents, this increases to well over two minutes of TSM.

For Cruise, the TAWS MOPS dictate an alert when the predicted 20 sec trajectory penetrates 500 ft; for Terminal, when this 20 sec trajectory penetrates 250 ft.

Using the previous calculations, a 2,000 fpm descent rate results in a 117 ft altitude loss for a +2G Nz instantaneous wings level recovery. If we assume a TSM to zero feet terrain clearance, this results in 383 ft of extra altitude buffer. At 2,000 fpm, this is 11.5 sec. Adding this to the baseline 20 sec of trajectory prediction, the total TSM is 31.5 sec. The TSM for other descent rates using the TAWS MOPS Cruise and Terminal environments are shown in Table 11.

Table 11. Limitations of TAWS MOPS "Must Not Alert" as shown by Equivalent TSM

Equivalent TSM for TAWS Must Not Alert Criteria Per Phase of Flight		
Descent Rate	**Phase of Flight**	
	Cruise (500 ft + 20 sec)	**Terminal (250 ft + 20 sec)**
250 fpm	137 sec	76.9 sec
500 fpm	76.9 sec	46.9 sec
2000 fpm	31.5 sec	24.0 sec
4000 fpm	23.5 sec	19.7 sec

The limitations of the prescriptive TAWS MOPS for must alert and must not alert are clear utilizing a time based approach and assuming a TSM to a zero foot recovery. However, the allure of applying a purely prescriptive based approach is undeniably enticing because it provides clear certification criteria, even if it doesn't result in an optimal collision avoidance system.

6.2.4 TAWS MOPS as a Prescriptive Means of Compliance

When applying TAWS MOPS to Auto GCAS, 14 CFR Part 23 Amdt 23-64 Performance Based Regulations (PBR) CFIT safety objectives can be achieved using the TAWS Class C RTC for performance objectives, with ROC altitude for unimpeded operations, without prescribing the method of achieving those objectives. However, if prescriptive TAWS MOPS are utilized as a means of compliance, two general assumptions apply:

- Trajectory predictions for Auto GCAS warning alert/activation can utilize the May Not, May, and Must Alert zones listed in the MOPS but may utilize alternative trajectory prediction methods and zone results so long as performance meets the Small Aircraft ROC and TAWS RTC requirements, regardless of the method chosen. The performance-based objectives must supersede specific MOPS prescriptive guidelines.
- The performance objectives are applicable to all modes of operation listed for TAWS and all Flight Environments. No separate modes are required except as needed to achieve performance objectives for cruise and terminal operations.

Table 12 is a summary of the overall assessment of each TAWS MOPS function as a means of compliance for Auto GCAS certification based on flight test and simulator data (RTCA, Inc., 2017). The specific MOPS, Function or Feature are listed as well as if they are required for Class C TAWS. A summary of abstracted notes were derived from flight test and simulator data.

An Auto GCAS that achieves the performance-based objectives of TAWS ROC and RTC is expected to be effective. If the prescriptive MOPS are utilized, they must be taken with extreme care to avoid unnecessary alerts and activations. However, even a system that has flawless logic and behavior utilizing the performance-based objectives can be undermined by poor database management and integrity.

Table 12. TAWS MOPS Class C Status Summary as Auto GCAS Means of Compliance

RTCA DO-367 Class C TAWS MOPS Status Summary as Auto GCAS Means of Compliance		
Function or Feature [MOPS #]	**Class C GCAS**	**Class C GCAS Notes**
Terrain Display	Not Required	No change to Class C if optional terrain display is implemented
Forward Looking Terrain Avoidance (FLTA) Cruise level flight FLTA [247_248] Cruise descent FLTA [251_252] Takeoff/Landing level flight FLTA [249_250] Takeoff/Landing descent FLTA [253_254]	**Required**	Level Flight (Cruise) - Warning Alerts, terminal FLTA envelope is less nuisance prone than cruise envelope Descent (Cruise, Takeoff, Landing) - Warning Alerts, terminal FLTA is less nuisance prone than cruise envelope At higher rates of descent, Terminal criteria may have insufficient Time Safety Margin. Nuisance prevention must not alert criteria (Cruise or Terminal) is insufficient for any flight envelope. Imminent Terrain Impact (Level) - Tests Warning Alert and terrain clearance with up to 200 ft of alt error and database robustness. Altimeter errors alone have no impact on the GPS based Auto GCAS. A system performance criteria for GPS error will require the system to revert to a standby mode before reaching the specified 200 ft of GPS alt error.

RTCA DO-367 Class C TAWS MOPS Status Summary as Auto GCAS Means of Compliance		
Function or Feature [MOPS #]	**Class C GCAS**	**Class C GCAS Notes**
Premature Descent Alerting (PDA) [264_265]	**Required**	PDA is a caution alert, not a warning alert. Closest test point is 1nm from runway, which is close to recommended protection at 1 sm. GCAS arming altitude must be sufficiently low to ensure protection for PD after takeoff and meet the terrain clearance performance requirements.
Excessive Rate of Descent (Mode 1) [273_274]	**Required**	Warning must activate criteria applied to normal and steep approaches for Mode 1 does provide appropriate must activate criteria where cruise and terminal are potentially late trigger points for high sink rates in excess of 2500 fpm. EVAA/MW1.4 activations with descent rates steeper than 2,000 fpm trend closely to the Mode 1 must alert envelope. Mode 1 must alert envelope is not useful for shallow descents.
Excessive Rate of Closure to Terrain (Mode 2)	*Not Required*	Mode 2 is not required for Class C and should not be implemented as it is considered a legacy backup mode to FLTA
Negative Climb Rate or Alt Loss after Take-off or Go-Around (Mode 3) [286_287]	**Required**	Caution only requirement thus not applicable to Auto GCAS. Utilize baseline ROC and RTC performance objectives. Method 1 (TAWS MOPS 286 and 287) is very nuisance prone. The must alert envelope starts at 500 ft/min at 600 ft height. At 500 ft/min Auto GCAS avoidance maneuvers are commanded at 100 ft height without a buffer. Additionally, protection may not be possible in the "Must Alert" region due to arming criteria.

RTCA DO-367 Class C TAWS MOPS Status Summary as Auto GCAS Means of Compliance		
Function or Feature [MOPS #]	**Class C GCAS**	**Class C GCAS Notes**
		The values listed in this table may have to change significantly based on the GCAS database system or a specific GCAS "Mode 3" assumptions change from currently implemented GCAS to fit either method 1 or method 2.
Flight Near Terrain when Not in Landing Configuration (Mode 4)	*Not Required*	The criteria to sense Gear and Flap position is not desired for Class C implementation. Additionally, for Class A, landing zone awareness, if implemented correctly, would potentially negate the need to know gear/flaps position and the TAWS mandate would mean this functionality would still be covered by Class A TAWS.
Excessive Downward Deviation from Glidepath (Mode 5)	*Not Required*	Mode 5 is not required for Class C. This is an inherent capability of Auto GCAS and an additional terrain clearance callout is not required. IAP testing could be executed using the Class A methodology but is not a separate requirement. "Must Alert" Criteria as written have points of high nuisance potential for GCAS and must be adjusted, for example, 900 ft and 1.5 dots low is too early for a required activation depending on sink rate
500' Altitude Callout [293]	**Required**	GCAS can calculate AGL Altitude and thus should be able to implement the required Class-C 500 ft Callout (TAWS MOPS 292, 293) (Mode 6).

RTCA DO-367 Class C TAWS MOPS Status Summary as Auto GCAS Means of Compliance		
Function or Feature [MOPS #]	**Class C GCAS**	**Class C GCAS Notes**
Altitude Callout other than 500' Alt Callout	*Not Required*	Conflicts with TAWS are a concern if a different datum (e.g. GPS alt is used rather than TAWS, which can use baro altitude)
Human-Made Obstacle Avoidance	*Not Required*	Although potentially in the database, obstacles have a high nuisance potential. This should be an optional capability for GCAS and synthetic objects have been extensively tested
Bank Angle Alert	*Not Required*	A commonly included feature with TAWS equipment but not required. Bank Angle Alert could be performed by GCAS equipment, but should be left as optional
Decision Height, Minimums Callout	*Not Required*	A commonly included feature with TAWS equipment but not required. Could be performed by GCAS equipment, but should be left as optional
Radio Altitude Interface	*Not Required*	Radio altimeters are rarely fitted to Class C aircraft, but where available GCAS could benefit from a radio altimeter interface as a potential error checking integrity monitor but not as a primary sensor due to potential spurious signals. This should remain optional for Class C GCAS

RTCA DO-367 Class C TAWS MOPS Status Summary as Auto GCAS Means of Compliance		
Function or Feature [MOPS #]	**Class C GCAS**	**Class C GCAS Notes**
System Performance Aural and Visual Alerts [294_295_296_297]	*AC 25-23 and AC 23-18 For more details* Should be required with small changes	Can be implemented with no changes other than consideration for the following section: "Class C Equipment shall (TAWS_MOPS_297) be capable of accepting and processing airplane performance-related data or airplane dynamic data and providing the capability to update aural and visual alerts at least once per sec." 1hz has historically been insufficient to provide nuisance free operations.
Alert Performance - Unwanted Alerting Reduction [298]	**Required**	This section lists nuisance-prone instrument approaches and these should be test cases as listed. Not all are required to be tested in live flight, simulator evaluation should be acceptable once other performance is proven. Passing these tests is unlikely to guarantee a nuisance free system.
Alert Envelope - Timeliness of Alerting [299]	**Required**	This section lists historic accidents and can be implemented as written. More examples could be added.

RTCA DO-367 Class C TAWS MOPS Status Summary as Auto GCAS Means of Compliance		
Function or Feature [MOPS #]	**Class C GCAS**	**Class C GCAS Notes**
Alert Prioritization [300]	required with changes	*The Alert Prioritization criteria will need to be changed if GCAS is implemented with or without Caution criteria.* *Additionally, prioritization of Alerts between TAWS and GCAS will need to be considered and documented here.* *Aural caution alerts contribute significantly to the nuisance rate of the system and diminish the effectiveness of TAWS. It is not recommended that Auto GCAS aural caution alerts be a requirement.*
Aircraft Position and Velocity [301_302_303_304_305]	required with changes	TAWS allows for backup means of functionality when GNSS is unavailable or unreliable to include the use of barometric altitude for vertical position. This is most likely unadvisable for GCAS and should be eliminated as an option for an Auto GCAS and probably for manual as well to avoid nuisances
Equipment Performance – Environmental Conditions See DO-367 2.3	**Required**	
Required Performance See DO-367 2.3.1.1	Requires careful review but potentially can be implemented without changes	*Sensors, inputs, terrain and obstacle databases. The requirements listed here may be insufficient to guarantee a safe and nuisance free system. RTCA/DO-200B and AC 20-153B potentially provide additional useful guidance for digital databases. In any event, the requirements for the system to meet the intended function are clear in the TAWS MOPS.*

6.3 Digital database

Digital database accuracy and integrity monitoring are fundamental to a safe and effective Auto GCAS. Nearly all major or hazardous Auto GCAS deficiencies initially discovered in military aircraft applications were related to inaccurate, corrupted, or missing portions of the digital terrain database. The digital database must be accurate, complete, and uncorrupted from inception to real-time system utilization. However, a properly designed Auto GCAS must account for these inevitable database issues, including corruption, voids, and other database anomalies, and ensure graceful degradation without erroneous or nuisance activations.

TAWS MOPS identify that digital database requirements must support the intended function in accordance with RTCA DO-200B Standards for Processing Aeronautical Data (RTCA, Inc., 2015). This requirement conforms to guidance in AC 20-153B Acceptance of Aeronautical Data Processes and Associated Databases (Federal Aviation Administration, 2016) for Data Quality Requirements (DQR) as directed by Order 8110.55B, How to Evaluate and Accept Processes for Aeronautical Database Suppliers (Federal Aviation Administration, 2016), and is directly applicable to Auto GCAS, as shown in Figure 12 below.

For Auto GCAS, the DQR equates to the Auto GCAS performance objectives identified previously. Depending on the unique Auto GCAS design, there may be more than one system database requiring certification. As an example, EVAA Auto GCAS relied on a terrain database, runway database, and an obstacle database.

Regardless of the system implementation, accurate digital databases are required to ensure safe, effective, and low-nuisance Auto GCAS operations to meet system performance requirements.

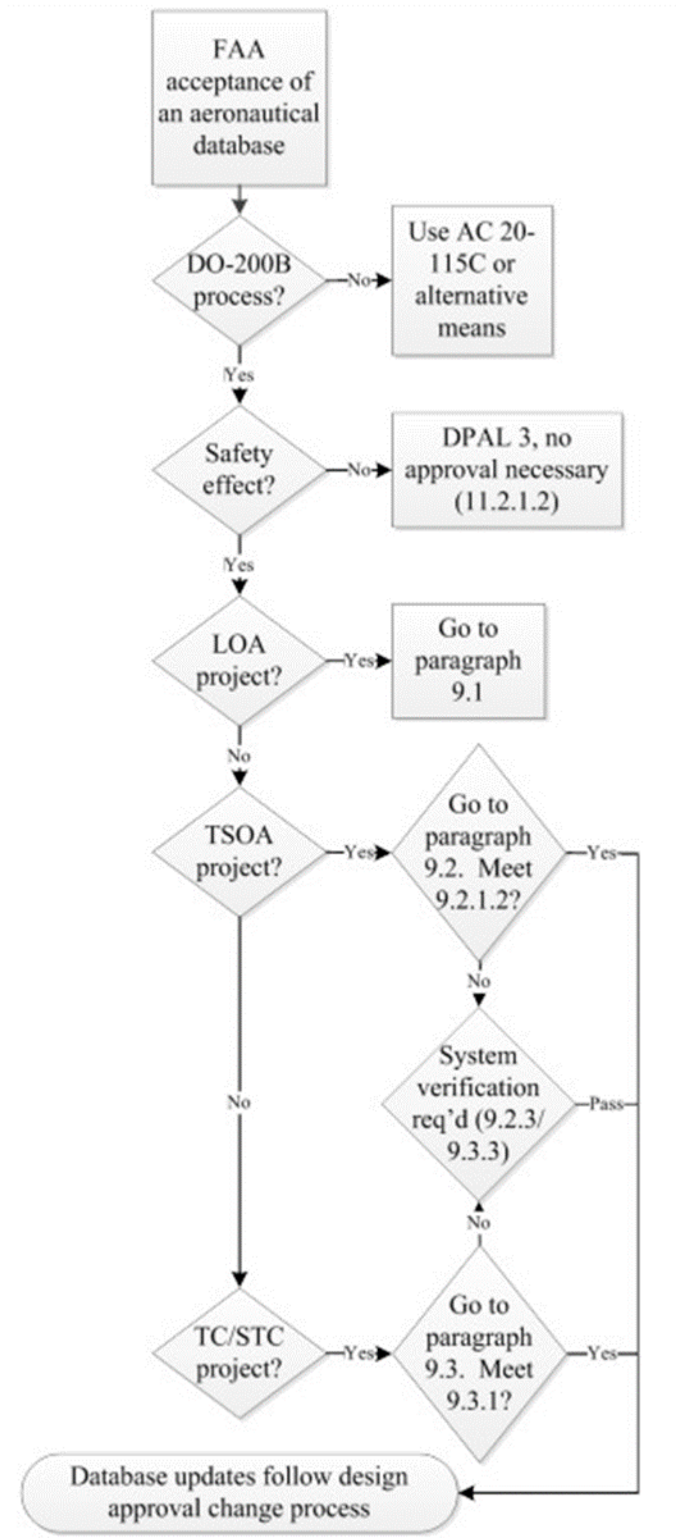

Figure 12. FAA acceptance of an aeronautical database

(Federal Aviation Administration, 2016)

6.4 Summary of pre-Amdt 64 Auto GCAS performance objectives

Table 13 summarizes the pre-Amdt 64 performance objectives utilized for the Auto GCAS means of compliance.

Table 13. Auto GCAS performance objectives

Tenet	Category	Performance Objectives
Do No Harm	Safety	Erroneous activations are categorized as a "major" failure condition severity but can escalate to a "hazardous" failure condition depending on the phase of flight or flight conditions. Erroneous activations can lead to an induced risk of collision and a USOC. Safety Failure Rate: An erroneous activation leading to induced collision risk due to a failure of the system is considered "hazardous" with probability of 10^{-4} (Terminal)/10^{-5} (Enroute/Cruise).
Do Not Interfere	Nuisance	A Nuisance is an activation generated by a system that is functioning as designed but which is inappropriate or unnecessary for the particular condition. Auto GCAS shall allow for unimpeded operations at the TAWS small aircraft ROC. 500 ft AGL for Cruise operations 250 ft AGL for Takeoff and Landing/Terminal Operations Nuisance Failure Rate: A "minor" failure with probability goal of 10^{-3} for enroute cruise at or above 1,000 ft AGL in mountainous terrain within normal operationally representative flight parameters. Higher nuisance rates are allowable for lower altitude operations but should not exceed 1 per 10 flight hours for operations continuously at Small Aircraft ROC in mountainous terrain.
Prevent Collisions	Protection	Auto GCAS shall provide automatic activation of the autopilot terrain avoidance mode to climb and maneuver away from terrain threat with appropriate visual and aural annunciations in order to achieve obstacle clearance at the TAWS RTC for takeoff and landing and the enroute cruise environments. 200 ft AGL for Cruise operations 100 ft AGL for Takeoff and Landing/Terminal operations Protection Failure Rate: An unresolved risk of collision/failure to clear terrain: Probability 10^{-3}.

7 Conclusions

Auto GCAS can be integrated on 14 CFR Part 23 general aviation aircraft with existing certified autopilot systems to reduce CFIT below the current mishap rate. To ensure safe and effective Auto GCAS implementation, regulators must assure the system has minimal probability of unsafe behaviors while limiting nuisance rates during normal aircraft operations.

Regulatory barriers, technology limitations, and cost previously limited implementation of Auto GCAS on 14 CFR Part 23 general aviation aircraft. Acceleration of the aviation industry into automated technologies and additional flexibility from 14 CFR Part 23 Amdt 64 rules, make the Auto GCAS certification path achievable.

Given the flexibility allowed by 14 CFR Part 23 Amdt 23-64 to define a diverse means of performance-based compliance, existing regulations and traditional means of compliance support Auto GCAS certification. Specifically, Autopilot, TAWS, TCAS II/ACAS Xa, and digital database regulatory and means of compliance publications can be utilized with minimal changes.

Auto GCAS has the prospect of converting an already catastrophic situation back into a normal and acceptable one. Properly substantiated, Auto GCAS capabilities will save lives. This is clearly in the public interest and warrants serious consideration by the FAA.

8 References

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