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STATE UNIVERSITY "KYIV AVIATION INSTITUTE"  
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'\_\_' \_\_\_\_\_ 2025

# QUALIFICATION PAPER

(EXPLANATORY NOTES)

FOR THE DEGREE OF «BACHELOR»

SPECIALITY 173 'AVIONICS'

**Theme: 'Analysis of the effectiveness of the  
operational indicators of the early warning  
system of the approach of the ground'**

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Kyiv 2025

МІНІСТЕРСТВО ОСВІТИ І АУКИ УКРАЇНИ  
ДЕРЖАВНИЙ УНІВЕРСИТЕТ "КИЇВСЬКИЙ АВІАЦІЙНИЙ ІНСТИТУТ"  
ФАКУЛЬТЕТ АЕРОНАВІГАЦІЇ, ЕЛЕКТРОНІКИ ТА ТЕЛЕКОМУНІКАЦІЙ  
КАФЕДРА АВІОНІКИ ТА СИСТЕМ УПРАВЛІННЯ

ДОПУСТИТИ ДО ЗАХИСТУ

Завідувач кафедри

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«\_\_\_» \_\_\_\_\_ 2025

## **КВАЛІФІКАЦІЙНА РОБОТА**

**(ПОЯСНЮВАЛЬНА ЗАПИСКА)**

ВИПУСКНИКА ОСВІТНЬОГО СТУПЕНЯ «БАКАЛАВР»

ЗА СПЕЦІАЛЬНІСТЮ 173 «АВІОНІКА»

**Тема: «Аналіз ефективності експлуатаційних**

**показників системи раннього**

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Київ 2025

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Specialty 173 'Avionics'

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**TASK**  
**for qualification paper**

Karas Oleh Andriyovych

1. Theme: 'Analysis of the effectiveness of the operational indicators of the early warning system of the approach of the ground'
2. Duration of which is from 15 May 2025 to 17 June 2025.
3. Input data of graduation work: The effectiveness of an early ground proximity warning system (EGPWS) is intrinsically connected to the broader context of aviation safety culture. Safety culture is a combination of shared beliefs, values, and practices—formal or informal—that shape the perception and implementation of safety across an entire organization. It reflects the genuine commitment of a company—from top-level management to line personnel—to maintaining safety in all day-to-day operations.
4. Content of explanatory notes: List of conditional terms and abbreviations, Introduction, Chapter 1, Chapter 2, Chapter 3, Chapter 4, Chapter 5, Chapter 6, Conclusions, References.
5. The list of mandatory graphic materials: figures, charts, and graphs.

## 6. Planned schedule

№	Task	Duration	Signature of supervisor
1.	Validate the rationale of the graduate work theme	18.05.2025	
2.	Carry out a literature review	22.05.2025	
3.	Develop the first chapter of the graduate work	28.05.2025	
4.	Develop the second chapter of the graduate work	30.05.2025	
5.	Develop the third-seven chapter of the graduate work	1.06.2025	
6.	Tested for anti-plagiarism and obtained a review of the graduate work	10.06.2025	
7.	Preparation of presentation and report	17.06.2025	

8. Date of assignment: ‘ \_\_\_\_ ‘ \_\_\_\_\_ 2025

Supervisor \_\_\_\_\_

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## **ABSTRACT**

Explanatory notes to graduation work "**Analysis of the Operational Efficiency of the Enhanced Ground Proximity Warning System (EGPWS)**" contained **71** pages, **3** figures, **4** graphs, and **4** references.

**Keywords:** AIRCRAFT, SAFETY, TERRAIN AVOIDANCE, GROUND PROXIMITY, EGPWS, FLIGHT SIMULATION, PILOT REACTION, HUMAN FACTOR.

**The object of the research** – the process of functioning of the aircraft warning system regarding terrain proximity.

**The subject of the research** – analysis of the operational indicators of the Enhanced Ground Proximity Warning System (EGPWS) in various flight conditions.

**Purpose of graduation work** – to analyze the effectiveness of EGPWS functioning and determine factors influencing its operational performance under different conditions.

**Research Method** – Methods of decision theory, reliability theory, probability theory, statistics theory, modeling, and expert judgment were used to solve this goal.

**Scientific novelty** – proposed recommendations for improving the operational use of EGPWS and increasing the reliability of terrain avoidance alerts in complex flight environments.

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### **List of abbreviations**

GPWS — Ground Proximity Warning System  
EGPWS — Enhanced GPWS  
CFIT — Controlled Flight Into Terrain  
ICAO — International Civil Aviation Organization  
IATA — International Air Transport Association  
TAWS – Terrain Awareness and Warning System  
EASA - Union Aviation Safety Agency  
FAA - Federal Aviation Administration

## INTRODUCTION

### **Relevance of the topic**

Flight safety is one of the most priority tasks of modern aviation. Despite significant achievements in the field of aviation technology and automated flight control systems, the problem of preventing aircraft collisions with the ground or obstacles remains relevant. This is especially true for flights in difficult weather conditions, mountainous terrain and in conditions of limited visibility, when the risk of an emergency situation increases due to spatial disorientation of the crew or untimely detection of danger.

Early warning systems for approaching the ground (EGPWS - Enhanced Ground Proximity Warning System) are one of the key means of reducing the risk of accidents such as CFIT (Controlled Flight Into Terrain), i.e. controlled flight into the ground. It is thanks to these systems that it is possible to warn the crew in advance about potential danger and take the necessary measures to avoid a collision. However, the effectiveness of such systems depends not only on their technical characteristics, but also on operating conditions, timely maintenance and adequate response of the crew to system signals.

### **Purpose of the work**

The purpose of this work is to analyze the effectiveness of the operational indicators of the early warning system for approaching the ground in different flight conditions.

### **Research objectives:**

To analyze existing research and publications devoted to EGPWS systems.

To determine the main operational characteristics of the early warning systems for approaching the ground.

To conduct a simulation of the system's operation in conditions of limited visibility and complex terrain.

To assess the impact of the human factor on the efficiency of the system.

To develop recommendations for improving the efficiency of the operation of EGPWS systems.

### **Object of the study**

The process of functioning of the early warning system for approaching the ground during the operation of the aircraft.

### **Subject of the study**

EGPWS operational indicators in the context of their effectiveness in preventing emergency situations.

### **Research method**

The work uses methods of probability theory, reliability theory, mathematical modeling, system analysis and expert evaluation.

### **Scientific novelty**

Generalized data on the effectiveness of EGPWS application in various flight scenarios were obtained and practical recommendations were developed to increase flight safety by improving the operational practice of using these systems.

# Chapter 1

## 1.1. Relevance of the topic

In modern aviation, flight safety remains a priority area of development for both civil and military aviation. Despite significant progress in the development of aviation equipment, navigation systems and procedures, the threat of aircraft collision with the earth's surface due to crew errors or difficult weather conditions, especially in mountainous terrain and poor visibility, remains relevant.

It is to prevent such incidents that the ground proximity warning system GPWS, as well as its improved version EGPWS, was developed. These systems provide the crew with information about a critical decrease in altitude, the risk of collision with terrain or obstacles, and allow them to perform evasive maneuvers in a timely manner.

GPWS and EGPWS systems have become an integral part of modern aviation safety systems, which has significantly reduced the number of accidents caused by controlled flight into terrain (CFIT). Evaluating the effectiveness of such systems is an important stage in the analysis of aviation safety, as it allows identifying possible limitations, conditions for reducing their effectiveness, as well as areas for further improvement of avionics.

The aim of this work is to analyze the effectiveness of the operational indicators of the ground approach early warning system using the example of simulated flights in the FlightGear software environment. Particular attention is paid to the behavior of the system in conditions of night approach in mountainous terrain, where the terrain factor and limited visibility significantly increase the risks of collision.

## 1.2. Purpose and objectives of the study

To assess the performance of the ground proximity warning system (GPWS/EGPWS) in difficult terrain and limited visibility conditions using computer simulation in the FlightGear environment.

- Analyze the principles of operation and classification of GPWS and EGPWS systems.
- To study the main factors that affect the effectiveness of ground proximity warning systems.
- Conduct a computer simulation of an aircraft approach to a mountainous area at night using FlightGear.
- Evaluate the response of the GPWS/EGPWS system to hazardous flight modes in given conditions.

- Draw conclusions about the effectiveness of the system and develop recommendations to improve its reliability in operational conditions.

### **1.3. Object and subject of research**

Ground Proximity Early Warning System.

### **1.4. Research methods**

Conducting computer simulation of an aircraft landing approach in the dark and under adverse weather conditions.

### **1.5. Work structure**

- Introduction
- Description of the early warning system for approaching land
- Analysis of the system's operational indicators
- Modeling of the situation
- Conclusions

## **Chapter 2**

### **LITERATURE REVIEW AND ANALYSIS OF THE CURRENT STATE OF THE ISSUE**

#### **2.1. Main causes of aviation incidents related to Controlled Flight Into Terrain (CFIT)**

One of the key causes of Controlled Flight Into Terrain incidents is the human factor, i.e. the actions, behavior and errors of the crew members who directly control the aircraft. Even with a fully functional aircraft, modern navigation equipment and good weather conditions, incorrect pilot decisions can lead to catastrophic consequences.

One of the most important problems is the loss of situational awareness, when the crew loses an accurate understanding of their position in space, distance to the ground or infrastructure. This loss often occurs during flights in difficult geographical areas - mountainous terrain, obstacles in the airport area, night or limited visibility. Pilots may be confident that they are following a safe trajectory, while the actual trajectory leads them directly to collision with the ground.

In addition, CFIT often occurs in the final stages of flight - during descent, approach or manoeuvring near the airport. ICAO and IATA statistics show that about 75% of CFIT cases occur during descent and approach. During this phase of flight, the crew faces a high load, and even a small loss of attention can have critical consequences.

Another common cause is ignoring or not fully following standard operating procedures (SOPs). Despite the presence of instructions for a specific phase of flight, in real-world conditions, crews sometimes act on personal assumptions or resort to procedural shortcuts.

Such actions may seem innocent, but often lead to dangerous situations. In addition, there have been cases where pilots have turned off the GPWS system due to excessive warnings - this significantly reduces the level of safety.

Level of training and experience are also critical factors. Inexperienced pilots may not have the skills to interpret complex instrument information or to correctly assess a situation under stress. Similarly, lack of practice flying in mountainous terrain or in adverse weather conditions can lead to incorrect actions.

Physiological factors such as fatigue, drowsiness, and emotional exhaustion also significantly affect the crew's ability to make accurate decisions. Long flights, night flights, delays, or schedule changes are known to impair concentration and reaction time. This is especially dangerous when flying at low altitudes, where every second counts.

In addition, the human factor should include issues of interaction in the cockpit. Miscommunication, lack of coordination or psychological pressure (for example, a junior pilot not reporting a captain's error due to fear or respect) can also contribute to the occurrence of CFIT. The concept of CRM (Crew Resource Management) was introduced precisely to reduce such risks, but it is still partially implemented in many airlines.

Thus, human factors remain the primary source of risk in the context of CFIT. Understanding its nature, implementing training measures, CRM, medical monitoring and clear SOPs are critical steps to reduce the risks of ground collisions in controlled flight.

Insufficient situational awareness of the crew is a key factor contributing to CFIT incidents. This term encompasses not only the ability of pilots to navigate in space, but also the ability to constantly update their perception of changing flight conditions, the environment, terrain and the aircraft's location. Loss of situational awareness often occurs due to the accumulation of micro-errors, information overload of the crew, unexpected changes in weather conditions or incoordination between crew members. In difficult flight conditions, especially at night or in mountainous areas, such a loss can lead to the aircraft approaching the ground or obstacles without the crew realizing it, until the moment of collision.

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Another key cause of CFIT incidents is the technical limitations of aircraft equipment, especially in older or under-repaired aircraft. Over the past decades, the most effective tool for preventing CFIT has been the GPWS system, and later its improved version, EGPWS or TAWS.

However, even these technologies have their limitations. Classic GPWS works on the basis of an altimeter and analysis of the descent trajectory, but it does not predict future threats if the aircraft has not yet begun a critical descent. Therefore, GPWS does not warn of a mountain ahead until the aircraft begins a descent towards it. These are often referred to as GPWS “blind spots”.

EGPWS, which uses terrain databases and GPS navigation, has improved the situation significantly. But it also requires up-to-date databases and precise tuning. There have been cases where EGPWS has been turned off by the crew due to false signals or conflicts with other onboard systems.

In addition, there is a technical factor related to “false alarm allergy.” If the system generates false alarms too often, the crew may lose confidence in it and start to ignore the signals. In some cases, crews have even turned off the GPWS completely to avoid “unnecessary noise” in the cockpit.

Another important aspect is the lack of or outdated equipment in general aviation aircraft or in countries with less developed aviation infrastructure. There, the risks of CFIT are much higher precisely due to technical insecurity.

Organizational factors are another important aspect that is often overlooked in CFIT analysis. These include controller errors, inadequate route planning, inaccurate charts, and poorly designed or outdated approach procedures.

For example, if the airport is located in a difficult mountainous area and the pilot is not experienced or familiar with the specifics of the approach, this creates a danger even when all procedures are followed. In such cases, detailed instructions, accurate maps with relief, as well as ensuring quality communication with the controller are critically important.

Infrastructure deficiencies can also manifest themselves in the absence of instrument approach systems, unstable navigation beacon signals, or the absence of ground terrain control services.

It is also worth mentioning the organizational pressure: when the crew is forced to land within a narrow window of time or with limited fuel, the risk of making risky decisions increases. In addition, sometimes airlines do not pay enough attention to training at specific airfields.

Institutional issues, including the lack of national standards on CFIT issues or incomplete implementation of ICAO recommendations, also negatively affect safety.

Weather is one of the most important external factors that can lead to CFIT. In fog, heavy rain, snowfall, or when flying at night, the crew loses the ability to see the terrain and approaching obstacles. In such conditions, visual orientation is lost and pilots rely solely on instruments.

The situation becomes even more complicated if weather conditions change quickly and unpredictably. For example, low clouds may appear during the descent phase, when the aircraft is already passing a critical altitude. If the crew does not have time or cannot react adequately, a collision becomes likely.

There are also situations where weather affects not only the crew but also the operation of navigation equipment - in particular, icing of antennas, loss of GPS signal or radio interference in thunderclouds. This can cause failure or incorrect indication of altitude, position or course.

In most cases, CFIT occurs during descent in low visibility conditions—when the aircraft descends below the minimum altitude without visual contact with the runway. The crew is often unaware of the danger due to the illusion of safety in an automated environment.

To minimize risks, aviation services must use accurate weather forecasts, satellite data, and operational warnings, and crews must strictly adhere to weather minima, avoid blind landings, and have a plan in place for unforeseen changes in conditions.

## **2.2. Stages of development of GPWS and EGPWS systems**

The problem of aircraft collision with the ground under full control of the crew became especially relevant in the second half of the 20th century. During this period of rapid development of aviation, numerous air crashes were recorded, caused by the so-called CFIT - controlled flight into the ground. Identification of typical causes of such incidents prompted the aviation community to develop systems for warning of dangerous proximity to the terrain. In response to these challenges, the GPWS system was created, which later evolved into EGPWS.

The first concepts of automated warning of imminent descent appeared in the 1960s. The impetus for their active implementation was a series of catastrophic incidents that resulted from crew errors during descent or approach. For example, in 1971, there was a disaster of an Eastern Air Lines plane in the USA, when the plane under the control of the crew crashed into a swampy area near the destination airport.

In 1974, the Federal Aviation Administration (FAA) passed regulations requiring the installation of GPWS systems on all large commercial aircraft. This led to the widespread deployment of the first generation of GPWS. The basic principle of the early GPWS system was to use information from a radio altimeter: the system would assess changes in altitude above the surface and determine whether the flight path was potentially hazardous.

Although the first generation GPWS significantly improved flight safety, it had a number of significant limitations. In particular, the system could not predict the approach to terrain - it only responded to an immediate decrease in altitude. As a result, it did not provide a warning in cases of horizontal proximity to obstacles, for example, when the aircraft was flying towards a mountain without a significant vertical descent.

Since the early 1980s, active research has begun on improving GPWS. Increasing computing power of on-board computers has made it possible to implement more complex data processing algorithms. Systems have appeared that can take into account the rate of descent, landing gear configuration, flap position and flight phase, which has reduced the number of false alarms.

Changes to the crew interface were also an important part of the improvement. Newer versions of GPWS began to use not only voice warnings, but also visual indicators integrated into the main instruments, which improved the crew's perception of signals.

Despite improvements, GPWS still did not provide sufficient protection when flying over difficult terrain. This necessitated the creation of a fundamentally new system that would work not only reactively, but also proactively.

EGPWS is an improved version of GPWS, created in the 1990s. The main difference was the use of digital terrain maps in combination with GPS navigation. Thanks to this, the

system was able not only to assess current flight parameters, but also to model the aircraft's trajectory and predict potential threats in advance.

EGPWS includes several new modes, including "Look Ahead Terrain Alerting", which analyzes the flight direction and checks whether it leads to a dangerous approach to the terrain. The system warns the crew tens of seconds before a potential threat, giving them time to respond adequately. In addition, the "Terrain Clearance Floor" and "Peaks Mode" functions have been introduced, which allow you to control the minimum flight altitudes within the airport and visually see the terrain features.

EGPWS has been a breakthrough in flight safety. According to ICAO statistics, the number of CFIT incidents has decreased by more than 60% since its widespread implementation on commercial aircraft. It has become a mandatory element of equipment for aircraft operating scheduled passenger services in most countries of the world.

In the 2000s, EGPWS continued to evolve towards integration with other avionics systems: autopilots, flight management systems, and next-generation on-board displays. This allowed crews to not only hear and see warnings, but also instantly receive recommendations for the optimal evasive maneuver.

New versions of EGPWS also provide three-dimensional terrain display, integration with ADS-B systems, and in some models, the ability to analyze obstacles of not only natural but also artificial origin (towers, cranes, etc.).

The development of Terrain Avoidance Warning System TAWS in versions for general aviation, business aviation and military aircraft is becoming particularly relevant. In parallel, work is underway on artificial intelligence capable of independently assessing the complexity of the situation and making preliminary decisions.

GPWS/EGPWS systems are now mandatory for most aircraft categories in civil aviation. Regulators, including EASA and FAA, require not only the presence of such systems, but also regular database updates, in-service performance checks, and crew training in their use.

In the future, adaptive warning systems are expected to emerge that take into account the individual characteristics of a particular aircraft, real-time weather conditions, and other variable factors. Integration with augmented reality systems, smart pilot helmets, and the use of machine learning will be the next stage in the development of these critical systems.

Thus, the evolution of GPWS and EGPWS is an example of how technology can change the very paradigm of flight safety: from a reactive warning model to a proactive protection system that anticipates danger and gives the crew the tools to react in a timely manner. Their implementation not only saves lives, but also increases the overall level of safety culture in global aviation.

### 2.3. Principle of operation and composition of early warning systems for approaching the ground

The main purpose of the GPWS and EGPWS systems is to continuously monitor flight parameters in order to detect situations that may lead to a dangerous approach of the aircraft to the ground or obstacles. These systems act as a kind of "electronic guard", controlling the vertical and horizontal position of the aircraft, analyzing the flight path, rate of descent, landing gear and flap configuration, and correlating this data with critical safety limits. In case of detection of a potential threat, the system activates a series of warning signals - from initial messages about excessive rate of descent to urgent commands such as "PULL UP", requiring immediate response from the crew.

EGPWS, as an advanced version of GPWS, implements a proactive approach: it uses not only current altitude data, but also digital terrain maps, GPS navigation, and trajectory prediction algorithms. This allows the system to predict the future position of the aircraft and assess whether it will lead to a collision with terrain or an artificial obstacle. This gives the crew more time to make a decision and execute the maneuver.

In addition, modern EGPWS implementations are equipped with a color display of the terrain on the navigation displays, where each level of risk is indicated by the corresponding color: red - critical threat, yellow - potential danger, green - safe area. This approach significantly increases the crew's situational awareness, especially in night flight conditions, poor visibility or when flying over mountainous terrain. As a result, the implementation of GPWS and EGPWS has become an important step towards increasing flight safety and reducing the likelihood of CFIT incidents.

GPWS works primarily by analyzing data from a radio altimeter that measures the aircraft's height above the ground. The system determines the rate of descent, flap and landing gear positions, and compares these parameters to established safety profiles. If a situation that potentially threatens a collision is detected, the system issues a warning command, such as: "SINK RATE", "TERRAIN", "PULL UP", etc.

In turn, EGPWS uses an expanded terrain database, digital obstacle maps, GPS navigation, and flight path prediction algorithms. This allows not only to detect dangerous descent, but also to predict a potential collision before the aircraft enters the critical zone. This makes the system much more effective in difficult conditions, especially in mountainous terrain or when flying at night.

## Main components of GPWS/EGPWS systems

1. **Data processing unit** This is the central module that analyzes all input flight parameters. It implements the logic for detecting threats, generating warnings, prioritizing them, and issuing commands to other devices.
  
2. **Sensors (input channels)**
  - Radio Altimeter: measures altitude above ground.
  - GPS receiver: determines the exact location of the aircraft.
  - Navigation systems (INS, FMS): provide data on heading, speed, altitude, landing gear and flap configuration.
  - Automatic Flight Control System (AFCS): data on the status of the autopilot.
  
3. **Terrain and Obstacle Database** Contains digital terrain models, known obstacles, and airport minimum altitudes. Constantly updated and synchronized with satellite systems.
  
4. **Output elements (crew interfaces)**
  - Audio notifications: voice signals (“Terrain!”, “Pull up!”, etc.).
  - Visual indicators: navigation screens with color relief.
  - Tips on the MFD (Multi Function Display) or ND (Navigation Display).
  
5. **Interface with other aircraft systems**

The GPWS/EGPWS system integrates closely with the autopilot, TCAS, FMS, ACARS, etc. In some models, it can also initiate automatic avoidance if the crew does not react in time.

GPWS/EGPWS systems have a set of modes that are activated depending on the phase of flight and the aircraft configuration. The main GPWS modes are:

- • Mode 1: Excessive Descent Rate.
- • Mode 2: Excessive Terrain Closure.
- • Mode 3: Altitude Loss After Takeoff.
- • Mode 4: Unsafe Terrain Clearance.

- • Mode 5: Excessive Glideslope Deviation.
- • Mode 6: Advisory Callouts.

EGPWS adds to this:

- Look-Ahead Terrain Alerting
- Look-Ahead Obstacles Alerting
- Terrain Clearance Floor
- Peaks Mode

Crew interaction and response scenarios

When a warning is triggered, the crew has a clearly defined algorithm of actions. For example, when a "PULL UP" warning is issued, the pilot must immediately climb at the maximum possible vertical speed. In modern aircraft, the crew regularly trains on simulators in GPWS response scenarios, including complex night and mountain flights.

Meaning of terrain color coding

On the navigation screens, the system displays the terrain in the form of colored maps:

- Red – critical altitude (collision is imminent).
- Yellow – dangerous proximity.
- Green – safe zone.
- Black – data unavailable or sea level.

This visualization allows the crew to quickly assess the situation even without voice messages.

GPWS/EGPWS systems undergo mandatory certification according to FAA, EASA and ICAO standards. Not only their functionality is assessed, but also the absence of false alarms, response speed, compatibility with other devices. Each aircraft must undergo regular system performance checks during maintenance.

Limitations and future directions

Despite their effectiveness, the systems have certain limitations:

- possible false signals in conditions of too complex terrain;
- delays in response when there is excessive load on computing systems;
- limitation of the obstacle database in older versions.

In the future, it is planned to implement adaptive systems using artificial intelligence, which will take into account not only static factors, but also crew behavioral patterns, as well as weather risks in real time.

## **2.4. Regulatory framework (ICAO, EASA, FAA) for the implementation of EGPWS**

The availability, type, installation and maintenance of GPWS and EGPWS systems are regulated by a number of international and regional standards. The most influential among them are the requirements established by the International Civil Aviation Organization (ICAO), the US Federal Aviation Administration (FAA) and the European Aviation Safety Agency (EASA).

ICAO — global aviation safety regulator

ICAO is a specialized agency of the United Nations that sets standards and recommended practices (SARPs) in the field of civil aviation. The mandatory installation of GPWS/EGPWS is regulated by Annex 6 to the Convention on International Civil Aviation. According to the latest editions of this document, all transport aircraft with a maximum take-off mass of more than 5,700 kg, operating scheduled or charter flights, must be equipped with ground proximity warning systems.

ICAO also emphasizes the need for systems that take into account not only vertical position but also terrain, which is actually a requirement for the installation of EGPWS. In Doc 10019 (“Manual on Ground Proximity Warning System”), ICAO provides technical guidance on the integration, verification and certification of such systems.

In addition, the organization constantly updates information on typical CFIT cases and conducts global initiatives to raise operator awareness of the effective use of GPWS/EGPWS.

FAA — Federal Aviation Administration

The FAA is the national aviation regulator in the United States, but its regulations have a wide impact beyond the country. The FAA first mandated the installation of GPWS in 1974 for U.S. commercial carriers. These requirements have been updated to reflect technological advances.

In 2000, the FAA issued a regulation requiring all passenger aircraft with more than 10 seats certified after March 29, 2001, to be equipped with an EGPWS (Terrain Awareness and Warning System). The requirements are set forth in FAA Title 14, Code of Federal Regulations (CFR) Part 121.354 and Part 135.154.

The FAA also published Advisory Circular AC 25-23, which describes technical specifications, operating algorithms, reliability performance requirements, system testing procedures, etc. Particular attention is paid to TAWS interaction with the crew, minimizing false alarms, and system testing scenarios in flight simulators.

The Administration also coordinates public databases of CFIT incidents, statistics on the operation of GPWS/EGPWS systems, and recommends crew training measures to ensure maximum efficiency of their use.

#### EASA — European Aviation Safety Agency

EASA is the main body regulating aviation safety in the European Union. Since 2005, the agency has taken over the functions of certification, standardization and monitoring of aircraft and equipment, including GPWS/EGPWS systems.

The requirements for EGPWS are set out in Regulation (EU) No 965/2012 (Air OPS Regulation), in particular in Annex CAT.IDE.A.185, which concerns aircraft equipment. It explicitly states that all turbojet aircraft operating in commercial operations must be equipped with a TAWS Class A (for large aircraft) or Class B (for smaller aircraft).

EASA also provides a technical specification for the certification of TAWS systems through CS-25 (Certification Specifications for Large Aeroplanes), where CS 25.1309 specifies requirements for reliability, fault tolerance, and safe integration with other aircraft systems.

In addition, the agency publishes Safety Information Bulletins (SIBs) that inform operators of critical changes in requirements or recommendations related to EGPWS. In particular, in recent years, emphasis has been placed on compatibility with new generation digital terrain maps, database update frequency, integration with ADS-B and RNAV/RNP modes.

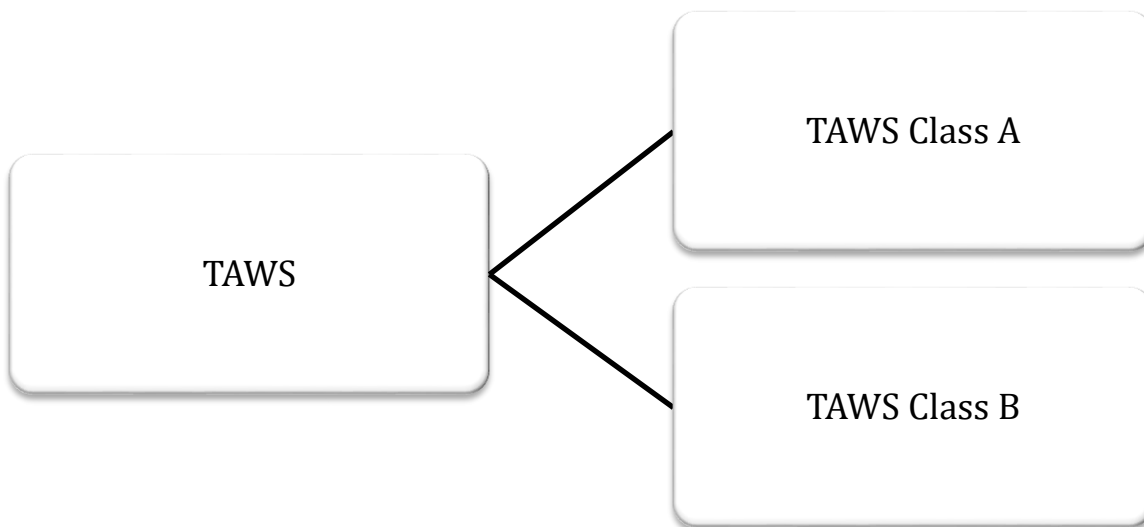
Table 1. Comparative characteristics of ICAO, FAA and EASA requirements

<b>Criterion</b>	<b>ICAO</b>	<b>FAA</b>	<b>EASA</b>
Installation is mandatory	Yes, for aircraft > 5700 kg	Yes, since 2001 — TAWS for aircraft > 10 passengers	Yes, in accordance with EU regulation 965/2012
Recommended system type	GPWS/EGPWS according to flight category	EGPWS (TAWS Class A and B)	EGPWS (TAWS A/B)
Document	Annex 6, Doc 10019	CFR 14 §121.354, §135.154, AC 25-23	CAT.IDE.A.185, CS-25
Certification aspects	Specified in Doc 10019	Advisory Circular AC 25-23	Certification Specification CS-25.1309
Additional instructions	Global training programs	Statistics, database, training simulators	Safety Bulletins, technical bulletins

Thus, ICAO, FAA and EASA establish mandatory technical and organizational requirements for the implementation of EGPWS systems on board aircraft. They not only determine the need for the system, but also regulate the standards for its performance, integration, certification, operation and accompanying crew training. All three regulators focus on the warning function of the system, providing sufficient time for the crew to react, and minimizing false alarms.

## 2.5. Modern types of systems on different types of aircraft

In modern aviation, the implementation of early warning systems for approaching the ground covers almost all types of aircraft - from wide-body airliners to light sport aircraft, helicopters, drones and military aircraft. The safety of flights in difficult conditions, in particular in poor visibility or in mountainous terrain, largely depends on the presence of an effective GPWS or EGPWS system on board. In accordance with international practice, these systems are classified as TAWS (Terrain Awareness and Warning System) and are divided into several main classes. The FAA and EASA distinguish two key classes - TAWS Class A and TAWS Class B.



### Classification of early warning systems for approaching the ground

Class A systems are designed for large commercial aircraft carrying more than 10 passengers or having a take-off weight of more than 5,700 kg. Class B is designed for smaller aircraft, including business jets, light aircraft and some helicopters. In addition, specialized versions for helicopters - HTAWS - are emerging, and new concepts for unmanned aircraft are being developed.

The most comprehensive solutions are used in the large passenger aircraft segment. Boeing (737, 747, 777, 787) and Airbus (A320, A330, A350, A380) airliners are equipped with fully integrated EGPWS systems manufactured by Honeywell and Thales. These systems have access to numerous data channels - GPS, inertial navigation, altimeters, FMS, autopilot, TCAS, flight management systems. Advanced functionality includes multi-layered terrain maps, obstacle models, trajectory prediction mode, automatic crew messages, maneuver recommendations and voice commands. Visualization of terrain on the flight deck displays increases the crew's situational awareness, and the accuracy of the systems allows avoiding CFIT even in critical situations.

Regional aircraft such as the ATR 42/72, Bombardier Dash 8, Embraer ERJ typically have simplified GPWS/EGPWS configurations, but sufficient to operate safely on a typical route profile. Given that these aircraft are often used for transportation in difficult-to-reach areas, in mountainous terrain or in adverse weather, TAWS systems must be particularly sensitive to rapid changes in altitude, the presence of natural obstacles and limited maneuvering space. Due to the lower power of the electronic systems and weight restrictions, TAWS Class B variants are often used. However, modern versions still allow for the integration of terrain databases, color-coding of danger zones, and interaction with the aircraft's navigation system for real-time threat assessment.

In business aviation, the choice of TAWS systems depends on the class of aircraft. Large business jets, such as the Gulfstream G500/600, Dassault Falcon 7X/8X, Bombardier Global 7500, have systems similar to those installed in airliners. They are equipped with integration with MFD, HUD, SVS, navigation displays and digital maps with 3D terrain. Smaller aircraft, such as the Cessna Citation CJ3 or Embraer Phenom 100, have more basic GPWS or TAWS Class B modules, which provide critical voice messages and warnings without graphical support. Modern technologies allow you to customize the system interface according to pilot preferences and operational specifics.

Helicopters are a separate category where the application of GPWS has its own difficulties due to unstable trajectory, possibility of hovering, low-altitude flight and rapid profile changes. HTAWS, adapted for such conditions, take into account the specifics of flying in difficult terrain, oil and gas platforms, in rescue operations areas. The Airbus H135, H145, H225, Bell 412, Sikorsky S-76 and S-92 models can be equipped with HTAWS systems from Garmin, Honeywell SkyForce or Collins. They use data from laser rangefinders, GPS and digital maps to identify hazards in real time. The developed algorithms take into account the phase of flight (take-off, hover, level flight, landing) and provide the most up-to-date warnings.

The general aviation (GA) sector is gradually moving towards digital solutions. Aircraft equipped with Garmin G1000, G3X, Dynon SkyView systems offer simplified GPWS or TAWS adapted for private pilots. They provide color visualization of the terrain, audible warnings, data on approaching obstacles, which significantly increases the level of safety. The spread of such systems is especially important for pilots who fly under visual rules in difficult terrain or weather conditions. Given the popularity of light aviation in the USA, Canada and Australia, the integration of basic TAWS has become common practice among amateur pilots.

In military aviation, GPWS/EGPWS is implemented taking into account the specifics of combat missions. Lockheed C-130, C-17, Boeing P-8 Poseidon aircraft receive adapted TAWS systems that integrate with other control systems. F-16, F-18, F-35, Rafale, Eurofighter Typhoon fighters use Digital Terrain System (DTS), which not only warns about the terrain, but also allows automatic avoidance of obstacles at very low altitudes. They are synchronized with the electronics of pilot helmets, inertial navigation and situational awareness support systems. With the development of the concept of a

“network-centric” battlefield, new GPWS systems are becoming elements of a single information architecture of the aircraft.

In recent years, there has been a rapid development of synthetic vision (SVS), augmented reality (AR) and artificial intelligence. Companies Honeywell, Garmin, Collins Aerospace demonstrate solutions that combine AI analytics, 3D visualization, weather and traffic tracking systems. Such solutions do not just warn of danger - they predict the development of events, adapt the interface to the pilot's behavior, even suggest the optimal maneuver based on the situation. This allows us to talk about the formation of a new paradigm of aviation safety - integrated, autonomous, proactive.

GPWS systems for unmanned aerial vehicles are also at the initial implementation stage. Due to the expansion of their use in the civil and military spheres, there is a need for a module that can autonomously detect terrain and adapt the trajectory. DJI, AeroVironment, Bayraktar, Milrem Robotics, Elbit Systems are developing systems based on radar, lidar, satellite maps, camera data and AI algorithms. In the future, such modules will be able to provide full-fledged UAV navigation in a complex environment without the participation of an operator.

Thus, GPWS/EGPWS systems are constantly being improved, taking into account the individual safety requirements of each type of aircraft. From large airliners to compact drones, each aviation segment receives solutions that meet its functional purpose. The current trend is the transition from a simple warning system to an intelligent partner of the pilot that analyzes, predicts and actively interacts with the person and other systems on board.

## Chapter 3

### DESCRIPTION OF THE EARTH APPROACH EARLY WARNING SYSTEM

#### 3.1. EGPWS system architecture

The Extended Ground Proximity Warning System (EGPWS) is one of the key elements of modern avionics, which provides increased flight safety through early detection of dangerous terrain or obstacle approaches. The EGPWS architecture is based on a multi-level principle of data collection, processing, analysis and visualization, which allows creating an integrated system for proactively informing the crew about potential threats.

The modern EGPWS architecture includes five main elements: sensor modules (data sources), computing unit (processor module), digital terrain and obstacle map database, information output units, and interfaces for interaction with other avionics systems. Each of these components performs an important function, and their synchronized interaction ensures the integrity and reliability of the system.

Sensor modules play the role of the input layer of the architecture, forming the primary array of information. These include radio altimeters, barometric altimeters, GPS receivers, inertial navigation systems (INS), landing gear and flap configuration sensors, and vertical speed measurement systems. Data from all sensors is fed to the computing unit, where it is synchronized, verified, and pre-processed.

The computing module (central processor of the system) is the core of EGPWS. It analyzes information using algorithms that compare current flight parameters with critical limits defined by safety standards. This module implements a set of modes - each of them is responsible for detecting a specific type of threat (for example, Mode 1 - excessive rate of descent, Mode 2 - horizontal approach to the terrain, etc.). It also implements prediction algorithms that allow you to detect potentially dangerous situations before the aircraft enters the risk zone.

An integral part of the EGPWS architecture is a digital terrain map database that contains information about the terrain, the location of airports, obstacles, minimum safe descent altitudes, and standard takeoff and landing profiles. This database is regularly updated and synchronized with global geodata sources. Its use allows not only to detect threats based on actual indicators, but also to model the future flight path in the context of the environment.

The information unit is responsible for communication with the crew. The system signals are given in the form of sound messages (standard commands "Terrain ahead", "Pull up", "Sink rate", etc.) and visual information on the navigation displays. Visualization is performed using a color palette indicating the degree of risk: green - safe zone, yellow - warning, red - critical threat. In addition, some versions of EGPWS support the functions of overlaying the terrain on the flight route map and displaying altitude in the form of digital scales.

The integration layer of the architecture provides connectivity between EGPWS and FMS, TCAS, autopilot, traffic control, data recorders (DFDR), and other onboard instruments. This integration allows the system to operate not in isolation, but as part of the aircraft's overall information environment. For example, EGPWS data can be used by FMS to refine the route, or TCAS to take terrain into account when avoiding air traffic.

The algorithmic part of the system includes a set of logical modules that form the basis of the intelligent behavior of EGPWS. They take into account not only instantaneous indicators, but also trends - for example, whether the vertical speed is steadily increasing, whether the aircraft is in a landing configuration, whether the trajectory meets the permissible limits. All calculations are performed in real time, and if a threat is detected, the system automatically issues a recommendation. In some models, automatic intervention in the autopilot for evasion is possible if the crew does not react.

EGPWS was designed with fault tolerance and redundancy in mind. The architecture provides for duplication of primary input channels, the ability to switch to alternative GPS/INS sources, and a system health check during each aircraft launch. In addition, the system is capable of self-diagnosis and informing the crew about its own malfunction.

Depending on the aircraft class, the EGPWS architecture may be implemented in one or more hardware modules. Large aircraft typically use a separate TAWS unit located in the central avionics compartment, connected to an internal network (ARINC 429, AFDX or similar). In light aircraft, GPWS functions may be integrated into the main navigation computer or a combined GDU (Garmin Display Unit).

The latest generation systems implement an open-source avionics architecture, where EGPWS can be adapted to the specifics of the aircraft, configured for individual routes or flight scenarios. In military aviation, models with self-learning algorithms are actively being developed that adapt to crew maneuvers and select a behavior profile depending on the type of mission (e.g., reconnaissance, attack, transport delivery).

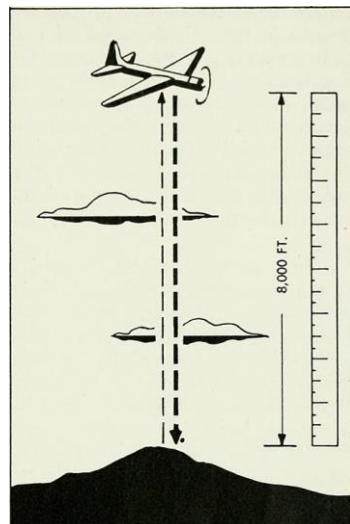
Thus, the EGPWS architecture is a complex, multi-component and highly reliable system that operates in real time, constantly analyzing the situation around the aircraft. Its flexibility, adaptability, integration capabilities and predictive functions make it one of the most effective tools for reducing the risk of CFIT incidents in all types of modern aviation.

### 3.2. Main sources of information (radio altimeter, GPS, terrain database, inertial system)

To ensure stable and accurate operation of the EGPWS system, a set of different information sources is used, each of which performs its critical function in the process of monitoring the environment and the position of the aircraft. This section discusses the four main sources on which the system relies: a radio altimeter, a global positioning system (GPS), a terrain database and an inertial navigation system. Each of these sources has its own principles of operation, advantages, limitations and level of integration with other onboard systems. Their joint operation allows you to form an accurate picture of the aircraft's spatial position, assess potential threats of approaching terrain and provide early warning to the crew. A detailed analysis of each of these elements allows you to understand how EGPWS functions in real flight conditions.

Radio Altimeter - Radio Altimeter or Radar Altimeter is one of the most important devices in flight safety systems, in particular in EGPWS.

Figure 1. Schematic representation of the operation of a radio altimeter



Its main task is to provide an accurate measurement of the aircraft's current altitude above the actual ground surface, which allows the crew and automatic systems to make critical decisions.

The principle of operation of this device is based on radar technology. The radio altimeter emits radio waves towards the earth's surface. The reflected waves are returned to a receiver located on board the aircraft. By accurately measuring the time that elapses between the signal being transmitted and its reception, the distance to the surface is calculated. Since radio waves propagate at a constant speed, this technique allows you to obtain altitude with high accuracy - usually within a few meters.

The main elements of a modern radio altimeter are a transmitter, a receiver, antennas (which often work separately for transmission and reception), as well as a computing

module. The system generates a signal, directs it downward, receives the reflected pulse and calculates the distance to the surface below the aircraft. The frequency at which the device operates is usually in the range from 4.2 to 4.4 GHz, which ensures stable operation in most weather and terrain conditions.

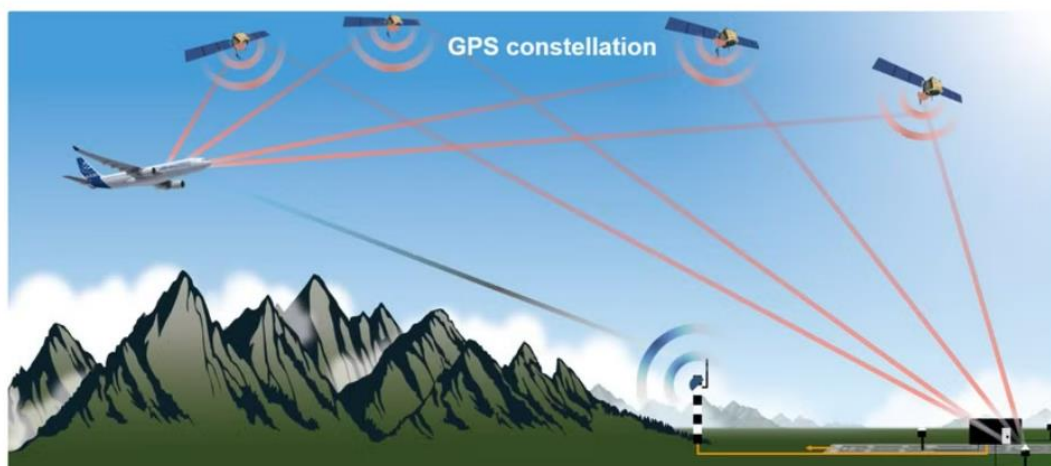
There are two main types of radio altimeters: pulsed and continuous frequency modulated. The former use short signal pulses, the latter use a continuous frequency modulated signal. FMCW variants allow for more accurate and efficient operation at reduced signal levels, and are therefore often used in versions designed for modern avionics.

The role of the radio altimeter is particularly important in GPWS and EGPWS systems. It provides key information about the true height above the terrain, which allows the system to detect a potentially dangerous descent, even if the aircraft is moving on a stable route. For example, if the flight path is over hills or a mountain range, only the radio altimeter can accurately show the decrease in distance to the surface. This allows the system to issue a warning signal before a critical point is reached.

The advantages of this device are obvious: it is not dependent on atmospheric pressure, like barometric altimeters, has a fast response and high accuracy at low altitudes. However, it also has certain limitations. In particular, it is only effective up to 2,500 feet (approximately 760 meters) above the ground. In addition, the quality of the reflected signal depends on the type of surface: snow, water or vegetation can affect the accuracy.

In modern aviation, radio altimeters are integrated with autopilots, autoland systems, FMS, TCAS, and flight data recorders. Some systems also provide redundancy—dual or triple altimeters to ensure reliable operation. In addition, radio altimeter data is often stored on flight data recorders (FDRs) for later analysis in the event of an incident.

Figure 2. Schematic representation of GPS operation



The Global Positioning System (GPS) is one of the fundamental sources of information for modern aviation. Its role in the functioning of EGPWS is no less important than the operation of a radio altimeter. GPS provides the aircraft with precise coordinates in three-dimensional space, which allows real-time determination of the aircraft's location with reference to the terrain base.

The principle of operation of the GPS system is to use a constellation of satellites that orbit the Earth at an altitude of approximately 20 thousand kilometers. Each satellite transmits information about its location and the exact time. An on-board receiver installed on the aircraft receives signals from several satellites simultaneously. By comparing the time of reception of the signal from each of them, the system determines the distances to the satellites and calculates the coordinates of the aircraft's location using the triangulation method. As a rule, at least four satellites are required to obtain an accurate result.

One of the key advantages of GPS is its global coverage: the system operates regardless of weather conditions, time of day or geographical location. It provides position accuracy to within a few meters. Combined with a terrain database, GPS allows the EGPWS system to predict the future flight path and determine whether the current route does not lead to dangerous proximity to terrain.

Information from GPS is used to overlay the aircraft's location on a terrain map. This allows EGPWS to determine how close the aircraft is to mountains, ridges, or other obstacles. This takes into account not only the horizontal distance, but also the height of objects below the flight path. If the trajectory leads to a potential collision, the system issues audible and visual warnings in advance.

GPS also integrates with other aircraft systems: autopilot, FMS, TCAS, navigation and flight control systems. Thanks to this, flight coordinates are not only used for orientation in the airspace, but also allow the formation of adaptive behavior of the aircraft in difficult situations. For more accurate positioning, differential GPS (DGPS) can be used, which uses signals from ground stations to correct errors in the satellite signal.

In the EGPWS system, GPS is a key element in implementing the so-called "look-ahead modes" - in particular, the Look-Ahead Terrain Alerting and Terrain Clearance Floor functions. Data on coordinates, motion vector, speed and direction allow you to create a predictive model of aircraft movement and assess the risk of entering a dangerous terrain zone. This makes GPS not just a navigation system, but a tool for preventing disasters.

Despite its advantages, GPS has certain limitations. The system can be vulnerable to signal loss, for example when flying in canyons, tunnels, or when the antennas are heavily shadowed. In addition, GPS signals can be distorted by the ionosphere, electromagnetic interference, or high-frequency communication systems. In some cases, there is a risk of malicious signal jamming or spoofing, which creates additional challenges for flight safety.

To reduce dependence on external conditions, modern EGPWS systems often use hybrid solutions, combining GPS with inertial navigation systems, radio navigation aids and barometric altimeters. This combination allows for continuous positioning even if one of the sources of information is lost.

The terrain database is also an integral part of the EGPWS system and one of the key technological innovations that has ensured the transition from a reactive warning model (as in GPWS) to proactive threat prediction. It allows the system not only to react to actual changes in altitude above the surface, but also to predict a possible approach to dangerous terrain based on the aircraft's coordinates, speed and direction of travel. It is thanks to the terrain database that EGPWS is able to reproduce a three-dimensional model of the terrain around the aircraft in real time and analyze potential threats before they become critical.

The structure of the terrain database stores a large amount of geospatial information, including digital elevation models, the location of airports, restricted airspace zones, artificial and natural obstacles. The main sources of this information are satellite images, aerial photography, geodetic data from national and international agencies, as well as information provided by air navigation services. All this data undergoes the stages of standardization, format agreement, geographical correction and reference to the coordinate systems adopted in aviation.

One of the most important characteristics of a terrain database is its resolution — the spatial scale at which elevation changes are displayed. The higher the resolution, the more detailed the system can display landscape changes. Modern EGPWS systems typically use databases with a resolution of up to 30 meters per pixel, and for certain critical areas (for example, near airports or mountain ranges) — up to 10 m/pixel and higher. This allows for very accurate modeling of the terrain profile even in the most complex terrain conditions.

The integration of the terrain base into the EGPWS system allows for the implementation of a number of key functions, including Terrain Clearance Floor (determination of the minimum safe height above the terrain), Look-Ahead Terrain Alerting (advance warning of approaching an obstacle on the course), Peaks Mode (graphical display of elevations in the flight area), etc. These functions work by continuously comparing the flight path with information about the heights in front of and below the aircraft. In case of detection of a potential conflict, the system issues a warning signal and visualizes dangerous areas on the aircraft's navigation display using color coding (red - critical threat, yellow - warning, green - safe area).

The terrain databases in the EGPWS system are stored in the form of digital elevation models (DEMs), which display the three-dimensional structure of the earth's surface with reference to geographical coordinates. These models are divided into cells (texture grids), each of which contains information about the absolute height of a particular point. Typically, this data is organized in the form of multi-level matrices, which allows for fast search and processing in real time.

Particular attention is paid to synchronizing the terrain database with the aircraft's navigation database (FMS database). This is necessary to ensure the accurate location of airports, runways, route reference points, arrival and departure routes. Thus, terrain data is closely intertwined with the flight path construction logic, which allows the system not only to detect a threat, but also to assess its criticality in the context of the flight phase (takeoff, cruise, landing).

The terrain databases in EGPWS are dynamic — they can be updated, expanded, modified. Aircraft manufacturers, including Honeywell, Garmin, Universal Avionics, offer regular updates of terrain databases as part of contractual maintenance. This is especially important in connection with changes in the landscape, the construction of new facilities (towers, bridges, power lines), and updates to airspace restrictions. The update is usually downloaded to the aircraft's on-board computer via memory cards, a network connection, or by ground maintenance.

It is important to note that the accuracy and relevance of the terrain database directly affects the effectiveness of EGPWS. Even the best algorithm will not be able to correctly predict the threat if the database is outdated or contains errors. That is why aircraft operators are required to adhere to technical update regulations and regularly check the database for compliance with current ICAO, FAA or EASA standards.

Another aspect is the introduction of the concept of "navigation based on terrain data" (Terrain-Referenced Navigation, TRN). This is a method in which the aircraft's position is determined not only through GPS, but also by comparing altitude data with a relief map. This technology allows for precise coordinates even in the event of a loss of satellite signal - for example, when flying in gorges or over regions with limited satellite coverage.

In the future, EGPWS systems are also considering the implementation of "dynamic terrain maps" with the ability to automatically adjust the terrain profile in real time using on-board sensors (e.g., lidar or high-resolution radar). This is especially relevant for unmanned aircraft, military aircraft, and flights in unknown or changing conditions.

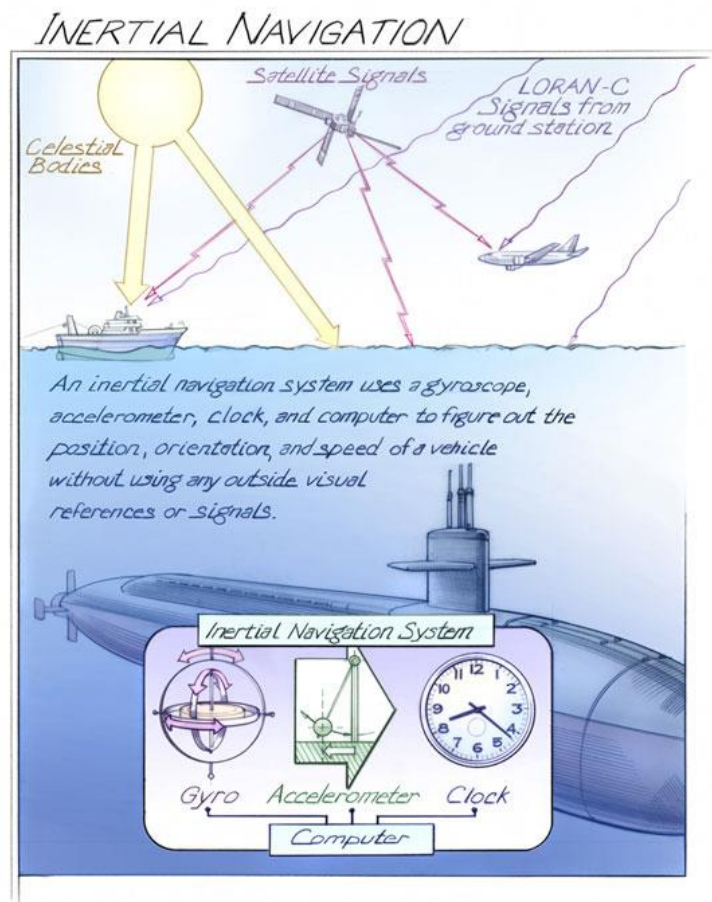
Thus, the terrain database is not just a geographical map, but a highly accurate information resource that allows EGPWS to work proactively, accurately and reliably. Its role in the system is fundamental, as it provides spatial awareness of threats along the aircraft's route. Thanks to this, pilots receive not just a warning, but accurate information about the direction, nature and level of the threat, allowing them to respond in a timely and safe manner to changing flight conditions.

Image 3. Inertial navigation systems

Inertial Navigation System (INS) is one of the basic technologies that provides autonomous determination of the position, speed, and direction of movement of an aircraft without the use of external signal sources.

It is precisely because of its independence that INS is a reliable tool for supporting navigation, especially in cases where GPS signals are absent, distorted, or unstable.

It plays an important role in the overall EGPWS architecture, complementing data from other sensors and improving the overall accuracy of estimating the aircraft's position in space.



The basis of the inertial system is the physical principle of conservation of inertia. The system uses sets of highly sensitive gyroscopes and accelerometers that continuously record changes in the angular position, acceleration and direction of movement of the aircraft. Based on this data, the INS calculates the current speed, change in coordinates and orientation of the aircraft. The entire calculation process occurs in real time, without the need to resort to external satellites or navigation beacons.

ANNs are typically divided into three main subsystems: gyroscopic, which determines orientation in space; accelerometric, which measures acceleration along coordinate axes; and computational, which processes signals and calculates position. Modern aircraft use laser gyroscopes (Ring Laser Gyros – RLG) or fiber-optic gyroscopes (Fiber-Optic Gyros – FOG), which have high accuracy and minimal errors.

One of the main advantages of the INS is its autonomy: the system is not dependent on weather, radio signal availability, or geographical location. This makes it especially valuable in flight conditions over oceans, deserts, or in combat situations where other systems may be unavailable. Due to this autonomy, the INS acts as a key source of backup navigation information in the aircraft's avionics.

The inertial system is also a reliable source of information for EGPWS, as it allows the aircraft to determine its course even when GPS is not sufficiently accurate. For example,

in mountainous terrain where GPS signals may be shielded, the INS is able to maintain an accurate understanding of the aircraft's position relative to the terrain. This allows the EGPWS system to accurately overlay the predicted flight path onto a digital terrain map, which is especially important for Look-Ahead Terrain Avoidance functions.

In modern aircraft systems, inertial navigation systems often operate in conjunction with GPS in an integrated GNSS/INS architecture. This approach combines the accuracy of GPS in open skies with the stability of INS in challenging conditions, providing a continuous and reliable navigation solution. INS also helps filter out short-term GPS errors, maintains smooth navigation trajectory, and provides more accurate flight control systems.

The INS is particularly important during the implementation of automatic flight, landing and obstacle avoidance functions. It maintains the aircraft's course, provides transmission of accurate position parameters to the on-board computer and works in conjunction with the autopilot. Due to the high data update rate, the INS ensures a quick response of the systems to changes in the aircraft's position, which is critical for flight safety in conditions of high dynamics or turbulence.

In terms of interaction with other subsystems, the INS provides information not only to the EGPWS, but also to flight management systems (FMS), navigation displays, synthetic vision systems (SVS), and training complexes. Data from the inertial system can also be recorded in the flight data recorder for post-incident analysis.

It should be noted that, despite high accuracy, INS has the property of accumulating errors - over time, the coordinates begin to deviate from the actual ones. This phenomenon is known as drift, and that is why the INS is regularly corrected using GPS or other external sources. High-precision INS (for example, with steering calibration or integration with radio navigation systems) can operate for tens of minutes without significant accumulation of errors, which allows maintaining accuracy even in complex scenarios.

In the future, inertial systems are likely to become even more miniaturized, reliable, and integrated. There are developments in MEMS (microelectromechanical systems) technology that allow for the creation of coin-sized INS, suitable for use on drones and small aircraft. It is also expected that artificial intelligence and self-correction algorithms will allow INS to operate even more stably, without the need for frequent external adjustments.

The inertial navigation system is, without exaggeration, the "invisible core" of modern navigation. Its ability to operate in complete autonomy, provide data on movement in all

conditions and support critical aircraft functions makes it a key source of information for the EGPWS system. It not only complements other channels, but is also able to provide an accurate picture of the position even when the rest of the systems fail to cope with their function. As a result, the INS becomes a reliable support for the entire terrain collision avoidance system, which is the main guarantee of flight safety.

### **3.3. Collision risk determination algorithms**

Modern ground proximity warning systems, in particular EGPWS, function not only as devices for measuring height or distance to obstacles, but as complex algorithmic complexes that analyze a number of variable parameters and make decisions about the level of danger. The central element of these systems are collision risk assessment algorithms that operate in real time, processing data from many sources - GPS, INS, terrain base, radio altimeter and other sensors. The main goal of these algorithms is to detect a potentially dangerous situation in advance, predict its development and, if necessary, activate an appropriate warning signal for the crew.

The algorithms work by comparing current flight parameters with critical limits, which are determined taking into account altitude, descent rate, aircraft configuration, trajectory, flight phases and environmental conditions. They are implemented in the form of mathematical models that include the estimation of derived quantities (altitude gradients, acceleration, angle of attack), as well as scenario analysis of the development of events based on a predictive model of aircraft movement.

Formally, algorithms are divided into several main categories. The first type is algorithms that detect rapid approach to the ground or obstacles without taking into account the trajectory (reactive logic). They estimate the vertical rate of descent and compare it with the minimum permissible for the current altitude. For example, if an aircraft at an altitude of 500 feet descends at a vertical rate of more than 2,000 feet per minute, the system issues a "Sink rate" signal. If this rate of descent continues, a "Pull up" warning is activated.

The second type is predictive logic, which takes into account the terrain map and the aircraft's course. They analyze whether the aircraft's trajectory will intersect with the terrain in the near future. This logic is called Look-Ahead Terrain Alerting and involves modeling the movement 30–60 seconds ahead. If the system detects that the aircraft with the current course and altitude will cross a mountain, a warning is activated. The algorithm takes into account not only the terrain, but also the minimum allowable flight altitude in a given area.

The third type is collision algorithms on takeoff or landing. They take into account the position of the aircraft relative to the airport, the presence of the landing gear and flaps in the appropriate position. If the system detects that the aircraft is at a low altitude without a landing configuration, it issues a "Too low gear" or "Too low flaps" signal. It is also possible to generate a "Don't sink" warning when the aircraft begins an unexpected descent after takeoff.

A separate category is made up of algorithms that work taking into account the specifics of the terrain — they analyze whether the aircraft is over flat or mountainous terrain. In mountainous areas, algorithms are activated that react more harshly to changes in altitude and have reduced threshold values. This is due to the fact that in mountains the risk of collision with obstacles increases due to limited time for evasion.

Each of the algorithms works according to a certain logic within a separate mode. In the classic GPWS, there are at least seven modes, each of which is responsible for its own risk zone. For example:

Mode 1: Excessive descent rate;

Mode 2: Descent on approach to the ground;

Mode 3: Loss of altitude after takeoff;

Mode 4: Insufficient altitude with incorrect landing gear position;

Mode 5: Excessive deviation from the trajectory during approach;

Mode 6: Minimum altitude and other messages;

Mode 7: Terrain conflicts (in EGPWS).

In EGPWS, the logic is much more complicated - advanced algorithms, false alarm filtering systems, and the ability to configure high-risk zones depending on the flight route have been added. The algorithms use signals from digital terrain maps, process the aircraft's position in 4D (latitude, longitude, altitude, time) and determine the trajectory not only geometrically, but also taking into account the dynamics of movement. This even takes into account the aircraft's loading, weather conditions, and inertial forces that affect the predicted path.

The reliability of the algorithms is ensured by multiple checks of each parameter. For example, to generate a "Pull up" signal, the system must record an increase in the speed of approaching the ground, insufficient lift, no changes in the aircraft configuration, etc. within a given time interval. Thus, the probability of false alarms is reduced.

Modern systems have developed special algorithm validation scenarios - these are virtual or simulated flight scenarios that allow you to check the system's response in different conditions. For example, simulating a landing at a high-altitude airport or taking off in smoke conditions. These scenarios are part of the certification process for EGPWS systems.

Promising directions for the development of collision risk algorithms include the use of machine learning elements to adapt the system to the piloting style of a particular crew, expanding the terrain database to include micro-obstacles (e.g. cables or antennas),

creating individual aircraft profiles that take into account their dynamics at different masses and configurations. The idea of interaction between aircraft for the exchange of information about terrain, warnings and risk areas in real time is also being explored.

In summary, the collision risk algorithms are the heart of EGPWS—they decide when to warn the crew and with what intensity. The high complexity, flexibility, adaptability, and accuracy of these algorithms provide the advantage that has allowed EGPWS to become the main tool for preventing CFIT incidents. Their further improvement is a step towards full autonomy and digital safety of future aviation.

### **3.4. System operating modes (Mode 1–7)**

The functionality of the EGPWS system is built around seven main operating modes, each of which is responsible for detecting a certain type of potential threat of collision with the earth's surface or other obstacles. These modes are the result of many years of development, analysis of real aviation incidents and taking into account the specifics of piloting modern aircraft. The system constantly analyzes the dynamic parameters of the flight - speed, altitude, configuration, route, position in space - and depending on the detected situation activates the appropriate mode.

#### **Mode 1: Excessive vertical descent rate**

This mode controls the rate of descent of the aircraft depending on the current altitude above ground level. If the aircraft descends too quickly without reducing the vertical speed, the system generates first a "Sink rate" signal, and then, if the risk increases further, a "Pull up" signal. The algorithm compares the vertical speed with critical threshold values, which depend on the altitude and phase of flight. The altitude is determined using a radio altimeter. In most cases, the system is triggered at a speed of more than 1,500–2,000 ft/min at altitudes up to 1,000 ft.

#### **Mode 2: Excessive descent when approaching the ground**

Mode 2 is activated when the system detects a dangerous approach to terrain, even if the vertical speed is within normal limits. This applies to situations when the aircraft is flying on a horizontal trajectory or is not descending quickly enough in conditions of increasing terrain. In this mode, the system uses information from the terrain database to predict the trajectory and determine the probability of entering the terrain. "Terrain ahead" and "Pull up" warnings are activated, which are accompanied by a graphical display of the situation on the display.

#### **Mode 3: Loss of altitude after takeoff or initial climb**

Mode 3 is triggered when the system detects a sudden descent after the take-off or initial climb phase. Such a descent is usually the result of a technical malfunction, crew error or aerodynamic effect. EGPWS analyzes not only the change in altitude, but also the configuration of the aircraft - flaps, landing gear position, etc. The "Don't sink" warning is

activated when the aircraft loses altitude shortly after take-off, which is potentially dangerous.

#### Mode 4: Insufficient height due to incorrect configuration

In this mode, the system monitors the aircraft's altitude relative to its configuration—gears extended, flaps in place, speed, and angle of attack. If the aircraft is at low altitude (typically below 1,000 feet) without the proper landing configuration, a "Too low gear" or "Too low flaps" warning is activated. Such situations may occur if the landing gear is not extended in time during landing or if the braking mode is incorrectly selected when approaching the runway.

#### Mode 5: Approach deviation from glide path

Mode 5 monitors the aircraft's deviation from the landing glide path in the airport area. The system compares the actual flight path with the ideal glide path and, if the permissible deviation is exceeded, activates the "Glideslope" signal. This mode is especially relevant for automatic landings, as well as in difficult weather conditions, when the crew may not have visual contact with the terrain. The algorithm also takes into account the aircraft configuration and descent rate, so as not to issue a warning in the event of a deliberate high-angle approach.

#### Mode 6: Information messages and minimum altitude

This mode is not critical, but provides the crew with information about the current altitude, speed and other parameters. For example, the message "Minimums" is issued when the set minimum decision height is reached during landing. Also in this mode, the "Bank angle" signal can be generated when the permissible bank is exceeded. This is important for controlling flight stability in conditions of limited visibility or when performing maneuvers at low altitude.

#### Mode 7: Terrain Closure Rate

This mode is used in EGPWS and includes advanced prediction of the aircraft entering the terrain. It is based on a digital terrain map and analysis of the current course. If the system determines that the speed vector is directed towards the rise of the terrain, and the aircraft does not have enough altitude to fly around it, the "Terrain, Terrain" or "Pull up" warning is activated. This mode is the basis for Look-Ahead Terrain Alerting, which has become the main tool for CFIT prevention after the upgrade of GPWS to EGPWS.

All modes of the system can operate independently or interact with each other. For example, Mode 1 and Mode 2 can be activated sequentially or in parallel, depending on the specific situation. The system also has the ability to block warnings in certain conditions - for example, when performing a deliberate maneuver that is not dangerous, or when taking off from a short runway, where a high rate of descent may be acceptable.

Modern versions of EGPWS allow flexible configuration of the logic of the modes, their sensitivity, and activation thresholds. This allows the system to be adapted to a specific aircraft type, mission profile, or airport specifics. For example, aircraft that frequently fly in high altitudes may have reduced activation thresholds for Mode 7.

The interaction of the modes with the pilot is also important. Each warning is accompanied by both an audible signal and a visual indication. Some aircraft use tactile elements - for example, automatic pressing of the rudder forward/backward when activating Mode 1 or Mode 7. All warnings should be unambiguous, standard and easily recognizable.

In addition to the basic modes, new versions of EGPWS implement additional functions - for example, notification of exceeding the maximum permissible speed ("Overspeed"), monitoring of the angle of attack or aircraft vibration. Although they are not included in the classic Mode 1–7 classification, their operation is often associated with the same risk algorithms.

Thus, the EGPWS operating modes are a logical structure that allows the system to respond to specific threats taking into account the type of flight, phase, terrain and dynamics of the aircraft's behavior. Each mode has its own unique role in maintaining flight safety, and only their combined, complex interaction guarantees effective avoidance of collisions with the ground in all possible flight scenarios.

### **3.5. Crew interaction interface (audio and visual warnings)**

One of the critical aspects of an effective EGPWS system is how information about potential threats is communicated to pilots. The crew interface includes both audio and visual elements that together ensure rapid recognition of the threat, a clear understanding of its nature, and a timely response. The goal of this interface is to make warnings intuitive, easily recognizable, and unambiguous, even in stressful situations or when the crew is under high workload.

Sound warnings in the EGPWS system are implemented in the form of standard phrases that are pronounced in English by an electronic voice. They are unified within the world aviation, which ensures their uniform perception by pilots of any nationality. For example, the phrases "Terrain ahead", "Sink rate", "Don't sink", "Pull up", "Too low gear" and others are part of the standard voice interface, which is launched in certain operating modes of the system. The volume, intonation, timbre and rhythm of pronunciation are chosen in such a way as to be expressive even in a noisy cabin environment.

Each audio message has a clear purpose and is activated according to a specific situation. For example, "Pull up" is the most critical warning, accompanied by a loud signal and visual illumination, and requires immediate pilot response. Other messages, such as "Too low terrain" or "Glideslope", are informational in nature, although they may also require trajectory correction.

In addition to voice messages, EGPWS uses distinctive audio signals (tone or pulse) to accompany some types of warnings or serve as an attention signal. For example, a short double "beep" is often used before a voice message to attract the crew's attention.

Visual warnings are no less important and are implemented through navigation displays (ND), electronic control systems (ECAM in Airbus or EICAS in Boeing), as well as light indicators on the pilot's panel. Modern displays display a terrain map, where potentially dangerous areas are color-coded: red - critical danger, yellow - warning, green - safe area. Symbols may be displayed on top of the map, indicating the aircraft's course, possible collision zones, descent trajectory, etc.

Graphical information is supplemented by text messages on monitors, indicators of altitude, vertical speed, deviation from the glide path. In many aircraft, especially recent generations, EGPWS also interacts with the HUD (Head-Up Display), where the danger is displayed directly in the pilot's field of vision, without the need to shift his gaze to the instrument panel. This significantly reduces the time for decision-making.

To increase the intuitiveness of the interface, some warnings are duplicated by colored button illumination, flashing indicators, or even tactile effects (for example, a slight vibration of the rudder when approaching a critical terrain). Such a multi-channel presentation allows the pilot not to miss the signal even in case of fatigue or overload.

The EGPWS interface also adapts to the flight phase. For example, during takeoff, the system will not activate warnings that could interfere with standard procedures, but after reaching a certain altitude, all information channels are automatically activated. Similarly, during landing, the system switches to a high-sensitivity mode, where Minimums, Glideslope, Sink Rate, etc. are activated.

Another feature of the interface is its standardization. Regardless of the type of aircraft, avionics version or system manufacturer, the messages should be the same, allowing the crew to interpret them quickly and without error. Pilot training includes mandatory preparation for recognizing all messages, their priority and the actions they should trigger.

In addition to the standard set of messages, airlines can in some cases customize the visual interface to the specifics of routes. For example, for flights in mountainous areas, terrain profile indicators can be additionally displayed along the course. It is also possible to automatically display additional information when entering a high-risk area.

Finally, the principle of interaction of the system with the crew in crisis conditions is important. When a threat arises, the system acts according to the principle: attract attention, convey the essence of the danger, form an action. An audible warning causes a reflex reaction, a visual signal confirms the nature of the situation, and crew training forms a quick response - a set of actions to be performed. This approach allows you to minimize the time between the detection of a threat and the crew's response.

Thus, the EGPWS interface is a complex multi-channel system that combines sound, images, text and graphics into one integrated information environment. The crew's ability to quickly recognize a threat and take appropriate measures depends on the effectiveness of its implementation, which directly affects flight safety.

## Chapter 4

### ANALYSIS OF EGPWS SYSTEM PERFORMANCE INDICATORS

#### 4.1. Methodology for assessing the effectiveness of warning systems

The assessment of the effectiveness of ground proximity warning systems (GPWS/EGPWS) is a comprehensive procedure aimed at identifying the degree to which the system meets its purpose - to provide timely information to the crew about the risk of collision with the earth's surface, mountains, obstacles or terrain. It involves a multifaceted approach that includes engineering and technical analysis, modeling of risk scenarios, studying crew behavior and statistical monitoring of real incidents and their consequences. In GPWS systems, and especially EGPWS, effectiveness is not limited to technical serviceability: the timeliness of signals, the accuracy of threat recognition, the ability to adapt to different conditions and the form of information presentation to the crew also play a key role. Therefore, the assessment process covers technical, psychological, cognitive and operational aspects.

The process of assessing the effectiveness is based on the principles of systematicity, objectivity, dynamism and adaptability. Not only the behavior of a single component is taken into account, but also the interaction with other subsystems. The independence of the data sources used is important, as well as the constant updating of the criteria in accordance with changes in technology, regulation and features of aircraft operation.

The evaluation procedure begins with the formulation of goals: reducing the number of incidents, improving crew response, increasing the accuracy of signals, reducing the number of false alarms. Then, the evaluation criteria are determined: average signal lead time, system sensitivity, false alarm rate, percentage of correctly responded warnings, presence or absence of CFIT incidents, error repeatability, system adaptability to different flight scenarios.

Data for evaluation are collected from various sources: flight data recorders, EGPWS log files, crew reports, test results in training and simulators. Analysis of crew response is especially important: how quickly and correctly pilots respond to system warnings. For this, both time metrics and qualitative indicators are used: correctness of maneuvers performed, situational awareness, coordination of actions between crew members.

The scenario modeling process uses virtual flight simulations in mountainous terrain, with limited visibility, and with equipment failures. This allows testing the system's effectiveness in conditions of high risk and dynamic flight parameters. Both the technical operation of the system and the behavioral reactions of the crew are analyzed - in particular, using eye-tracking tools, pulse analysis, and stress response monitoring.

The assessment includes an analysis of statistical data on CFIT incidents before and after the implementation of EGPWS systems. According to international studies, the probability of this type of incident in aircraft with the system implemented is significantly reduced. However, the level of crew training, their awareness of signals and correct response to them is no less important. A high level of efficiency is achieved only with constant training, familiarization with the system and correct interpretation of warnings.

The system-pilot interaction interface is also evaluated - how clear are the messages, is there enough visual and audio information for quick decision-making, and does the system create additional cognitive load. Not only are the objective characteristics of the interface analyzed, but also the subjective assessment of the crew - the level of trust in the system, ease of use, and clarity of messages.

The assessment methodology involves a multifactor analysis. Not only technical parameters are taken into account, but also the human factor, weather conditions, aircraft type, route, flight altitude. This approach allows you to form a rating of the effectiveness of systems of different manufacturers or modifications, as well as create recommendations for their improvement.

Along with classical evaluation methods, modern approaches are increasingly being used: machine learning, cognitive modeling, dynamic adaptation of systems to piloting style. Intelligent systems with self-learning elements are being developed, which are able to adjust the behavior of algorithms based on accumulated experience, crew reactions, and changes in flight configuration.

The methodology also includes feedback collection. Airlines use internal platforms to collect pilot feedback on the operation of EGPWS. These can be both formalized questionnaires and free comments, which are subsequently analyzed by safety services. This approach allows you to quickly respond to identified shortcomings, adjust the system parameters and adapt it to real operating conditions.

Regulatory bodies — ICAO, FAA, EASA — play a major role in monitoring effectiveness. They establish technical requirements for systems, inspection intervals, certification procedures, and operators' responsibilities for operational control. In addition, international reports are developed that analyze the global effectiveness of EGPWS in the world, identify problem areas, and suggest areas for improvement.

Thus, assessing the effectiveness of warning systems is a complex, interdisciplinary process that takes into account not only technical characteristics, but also behavioral, organizational, regulatory and human factors. It is a key tool in ensuring continuous improvement of aviation security systems and the formation of new standards that meet the challenges of the modern aviation environment.

## 4.2. Reliability, accuracy, and speed indicators

The reliability, accuracy, and speed of the Enhanced Ground Proximity Warning System (EGPWS) are critical to aviation safety. These performance characteristics determine the system's ability to timely and accurately identify a ground proximity threat and provide the correct warning to the crew. This section examines key aspects of EGPWS performance, with a focus on its technical reliability, data processing accuracy, and response speed.

Analysis of EGPWS performance indicators is based on a modern approach to avionics, which involves the use of satellite navigation (GPS), electronic terrain databases, sensor data acquisition systems and intelligent flight path prediction logic. This combination ensures high efficiency of the system in real time and increases the probability of avoiding collisions with the earth's surface. The system consists of data acquisition and processing modules, an electronic computing unit, crew indication and signaling systems, a terrain database, interfaces with other onboard systems (FMS, INS, altimeter, etc.).

The reliability of EGPWS is measured by several key parameters. The probability of system failure is estimated to be less than 1 in  $10^7$  flights, which meets modern avionics requirements. The mean time between failures (MTBF) exceeds 20,000 hours, thanks to the high quality of the component base and the redundancy of critical nodes. The system is also capable of performing self-tests during power-up and during operation. In case of errors, it generates a message to the crew or goes into a safe mode.

Regarding reliability, the use of GPS allows determining the location of the aircraft with an error of up to 5 meters.

This provides high accuracy in comparison with terrain databases and detection of potential threats. EGPWS uses global terrain databases SRTM, DTED and other high-precision sources. The data is constantly updated to ensure compliance with changes in the terrain. The system takes into account speed, heading, vertical speed, surface position data, minimum flight altitudes in the area to build a forecast trajectory.

This avoids false alarms and missed threats.

Performance indicators also indicate high efficiency. The time between the detection of a potential threat and the generation of a warning signal is 1–2 seconds, which meets the standards for crew reaction. The system updates data at a frequency of 5–10 times per second, which allows for rapid tracking of changes in the aircraft's position. The use of modern processors and specialized algorithms allows for millions of operations per second to analyze the situation.

EGPWS generates warning signals (caution) and critical signals (warning). The system visually and vocally informs the crew ("TERRAIN", "PULL UP", etc.). The information adapts to the flight phase, which avoids excessive load on the crew.

Compared to traditional GPWS, EGPWS has 70% fewer false positives, covers 100% of the Earth's surface (GPWS is limited), uses a terrain database instead of just barometric information, and provides higher operational efficiency and significantly reduces the likelihood of CFIT incidents.

Even the most advanced system cannot completely eliminate the human factor. Crew training, procedural discipline, and timely response to signals are critically important.

EGPWS is a highly efficient system with exceptional reliability, accuracy and speed. It is an essential element of modern aviation and significantly reduces the risk of accidents during flight. Its further development is towards integration with digital maps, improved AI logic and interaction with other avionics systems.

### **4.3. Statistics on the prevention of incidents and accidents thanks to EGPWS**

The development of early warning systems for approaching the ground, in particular the improved version of GPWS - EGPWS, has significantly influenced the overall picture of aviation safety in the world. Statistical studies conducted by international organizations, as well as analysis of reports from aviation agencies, indicate a significant decrease in the number of incidents and disasters associated with controlled flight into terrain (CFIT), after the introduction of these systems on civil aviation aircraft.

According to data collected by ICAO, since the widespread implementation of EGPWS in commercial aviation, the number of CFIT incidents has decreased by almost 80%. This applies to both scheduled airlines and cargo operators. The figures are particularly telling when comparing the before and after certification of EGPWS as a mandatory avionics element for aircraft flying under instrument rules (IFR).

Between 1995 and 2005, as EGPWS deployment gained momentum, there was a sharp decline in the number of CFIT accidents. While in the early 1990s there were over 20 such incidents in commercial aviation each year, by the mid-2000s this figure had fallen to less than 5 per year. Moreover, in the vast majority of these incidents it turned out that the aircraft were not equipped with modern versions of the warning systems or the crew did not respond properly to the system signals.

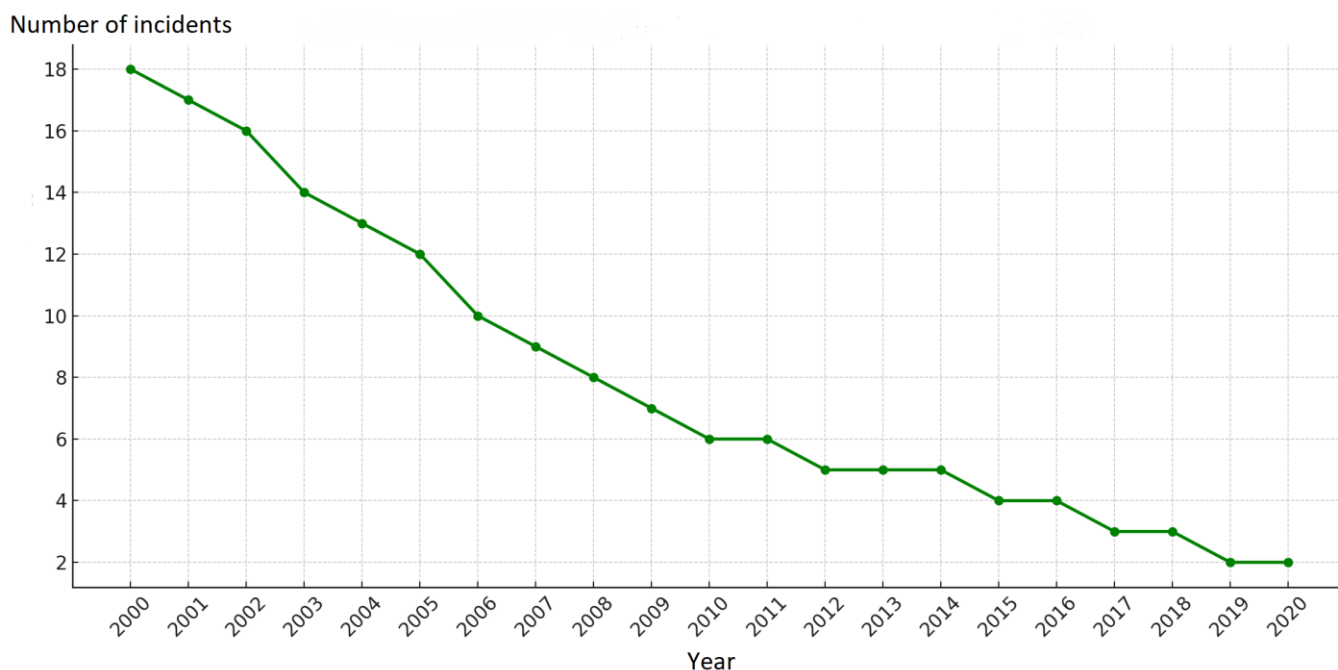


Figure 4. Table of incident reductions due to EGPWS

The analysis published by the Flight Safety Foundation confirms the positive impact of EGPWS on flight safety. The publications of this organization provide examples of cases when the system helped to avoid catastrophic situations in difficult weather conditions, when the crew lost orientation or when the route was entered incorrectly in the FMS. In many cases, the system was activated several tens of seconds before the critical moment, which allowed the crew to perform an evasive maneuver or change the trajectory.

FAA and EASA data indicate that over 90% of modern passenger jets operating on international routes are equipped with EGPWS or its equivalent. In these aircraft types, the probability of CFIT incidents has been reduced to almost zero. In addition, the system has proven to be particularly effective in regional carriers and in aircraft operating in difficult geographical conditions - for example, in South America, Asia, in mountainous areas of Europe.

Also interesting are the conclusions drawn after analyzing cases where the system worked, but the incident still occurred. In most such situations, it turned out that the crew did not respond to the signal properly or ignored the message due to confidence in a safe flight. This indicates the importance not only of the system, but also of proper crew training, regular practice of scenarios on simulators, and constant improvement of perception and reaction algorithms.

Among the documented examples of successful EGPWS operation, one can mention the case of an airline flight that landed in difficult weather conditions with poor visibility. The system recorded a too rapid descent, activated the "Sink rate" warning, followed by "Pull up". The crew changed the configuration, climbed and performed a second go-around.

After landing, analysis of the recorders showed that without the system's intervention, the probability of a collision with the ground was extremely high.

In addition to incident statistics, it is worth noting the effectiveness of EGPWS in reducing the number of crew errors that could lead to catastrophic consequences. According to pilot surveys conducted at several major airlines, most respondents consider the system to be one of the most important tools for restoring spatial orientation, especially when flying at night or in conditions of loss of landmarks.

Voluntary crew reporting reports (ASRS — Aviation Safety Reporting System) also play a certain role in statistical assessments. These sources provide unique information about those incidents that did not lead to accidents, but were classified as potentially dangerous. Many of them contain mentions of timely activation of EGPWS, which was a key factor in avoiding collisions with the ground or obstacles.

It is also worth mentioning the effectiveness of EGPWS in military aviation. According to the Pentagon, after the introduction of adapted versions of this system on combat aircraft, the number of losses associated with CFIT has decreased several times. This is especially true for training flights and maneuvers at low altitude. Even in unmanned aviation, the use of the EGPWS concept has had a positive effect, as many modern drones are equipped with similar terrain avoidance algorithms, which reduces the likelihood of losing the device due to inadequate altitude estimation.

In some cases, the effectiveness of EGPWS has been assessed using mathematical modeling. Studies have shown that when simulating CFIT scenarios, the probability of avoiding a collision increases by 7–10 times with EGPWS compared to flying without it. Model tests also confirmed that even with limited pilot reaction, the system allows you to gain additional seconds needed to perform an evasive maneuver.

In the future, the frequency of CFIT is expected to decrease even further due to the introduction of new generation systems based on artificial intelligence and machine learning. However, even the current version of EGPWS has already shown an extremely high level of effectiveness. Statistics prove that the presence of this system on board the aircraft is one of the key factors in reducing the level of risk.

Thus, the analysis of a large array of data, both official statistics and crew reports, clearly indicates the significant contribution of EGPWS to reducing the number of aviation incidents and disasters. It not only warns the crew about the threat, but also provides the necessary time resource to make the right decision. This makes the system one of the most effective tools in modern air transport, which is confirmed both analytically and practically. Its constant improvement, adaptation to new conditions and integration with other aviation systems is the way to further reduce risks and increase safety on a global scale.

#### 4.4. Analysis of typical errors and malfunctions

Despite the high effectiveness of the EGPWS system in reducing the risk of controlled flight into terrain (CFIT), it is not completely infallible. There are numerous examples of situations in which the system did not work as intended, gave false signals or did not work at all at a critical moment. Analysis of typical errors and failures allows for a deeper understanding of the system's weaknesses, identifying risk factors and offering recommendations for increasing its reliability and adaptability.

The first and most common group of problems are false positives, when the EGPWS system activates an alarm in a situation that is not actually dangerous. This most often happens during takeoff or approach in difficult terrain. For example, if an aircraft is landing at a high-altitude airport, the system may mistakenly perceive the approach to the ground as a threat. In such cases, pilots are often forced to ignore the signals, which, in turn, creates the risk of the "boy who cried wolf effect" - a decrease in confidence in the system in the future.

Another common problem is false negatives, where the system fails to issue a warning when a collision is imminent. These errors can be caused by incorrect system settings, outdated terrain data, or sensor malfunctions (such as radio altimeter or GPS). In a number of cases reported by the FAA, the system failed to issue a warning during an approach when the aircraft was off the glideslope but was in a "permissible" mode that did not activate any of the alert algorithms.

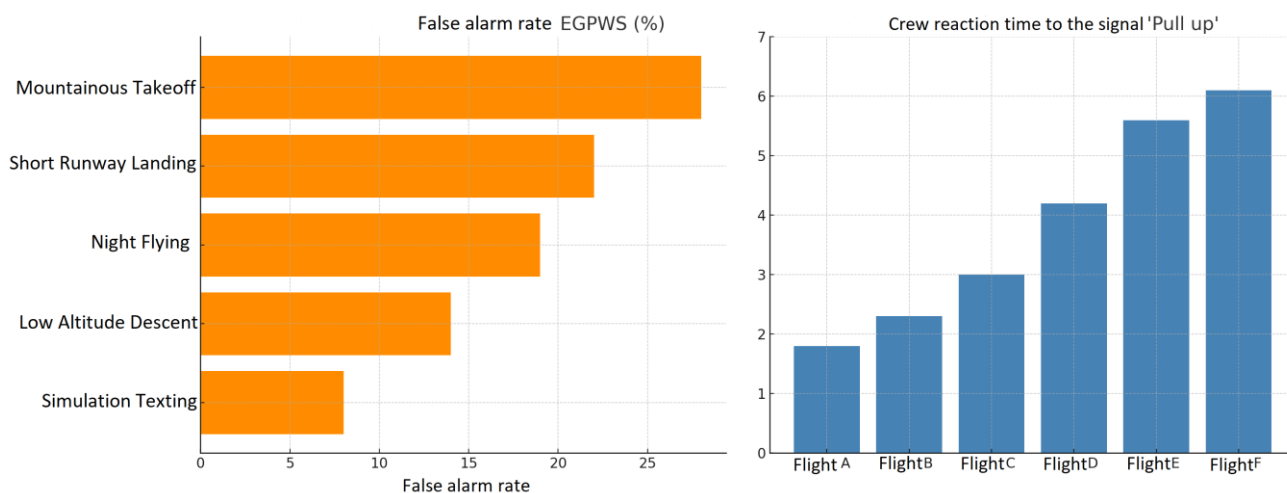


Figure 5. Graphs of system false alarms and crew response time

There are also cases of incorrect interpretation of the aircraft configuration by the system. For example, when the landing gear or flaps are extended slowly, the EGPWS may perceive the situation as abnormal and issue a "Too low gear/flaps" signal, even if the crew is in full control of the process. In some aircraft models, failures in the synchronization of signals from the configuration sensors have been recorded, which led to false alarms.

There are also frequent cases when the crew does not react to the warning signal or does so with a delay. This may be due to overload of the information channel, high stress, decreased concentration or distrust of the system. Analysis of data from the recorders showed that on average between receiving the "Pull up" signal and the start of the climb, there can be from 2 to 6 seconds - a time that is critical when flying at low altitude.

Another category of problems is technical failures related to hardware or software. Sometimes the EGPWS system is not updated in time, and the terrain base does not correspond to the real terrain. In some cases, errors in downloading data from GPS, failures in processing information from the inertial system, or the absence of a signal from the radio altimeter have been detected. All this can lead to incorrect risk assessment and lack of warning.

In difficult weather conditions, such as heavy rain, snowfall, or electromagnetic interference, some sensors may not function correctly. This, in turn, affects the accuracy of altitude calculations and predicted trajectory. Aircraft operating in regions with dense cloud cover often encounter a situation where the system "sees" the ground later than expected, which reduces the time to react.

The human factor requires special attention. In many cases, improper use of the system, its disabling by the crew, or unwillingness to listen to the signal is the reason for the failure to take preventive action. For example, in known incidents, the crew deactivated the system, considering it too "sensitive". In other cases, the EGPWS signal was ignored due to overconfidence in their own navigation or distrust of the interface.

Analysis of typical failures also showed that sometimes the system is not fully integrated with other navigation components of the aircraft. For example, conflicts between FMS and EGPWS data can lead to erroneous interpretation of the position in space. In some cases, when the FMS showed the correct trajectory, the EGPWS did not take into account local obstacles not present in the terrain database, which led to a delayed signal.

These problems can be solved through a number of measures. First of all, regular software updates, terrain databases, sensor calibration, and checking the consistency of information channels. In addition, it is important to improve the system interface: make messages even clearer, more intuitive, and avoid information overload.

Attention should also be paid to improving self-correction algorithms. New generations of systems use machine learning principles to adapt to pilot behavior, route specifics, and the dynamics of a particular aircraft type. In the long term, this will reduce the number of false alarms and increase the timeliness of critical signals.

It is equally important to increase the culture of using the system among crews. Regular training on simulators, studying situational scenarios, analyzing errors in reports - all this contributes to the formation of the correct attitude towards the warning system and increases the likelihood of an adequate response in real conditions.

Thus, the analysis of typical errors and malfunctions of EGPWS demonstrates that even the most modern aviation technologies are not perfect. However, understanding the nature of these problems, their timely detection and elimination allows to ensure constant improvement of the system and maintain its high efficiency in ensuring flight safety. This is especially important in the conditions of increasing air traffic intensity and expanding the geography of flights to difficult regions of the planet.

#### **4.5. Comparison of GPWS and EGPWS effectiveness**

Ground Proximity Warning Systems (GPWS) and their enhanced version, EGPWS (Enhanced Ground Proximity Warning System), are key flight safety tools, especially during takeoff, approach, descent, or low-altitude flight. Designed to prevent controlled flight into terrain (CFIT), these systems significantly reduce the number of aviation incidents associated with geographical obstacles. The purpose of this section is to provide a detailed comparison of the effectiveness of GPWS and EGPWS systems in terms of key performance indicators: reliability, accuracy, speed, terrain coverage, crew response to signals, technological base, interaction interfaces, and practical experience in civil and military aviation. GPWS is a classic system based solely on information from a barometric radio altimeter and descent rate. It generates an alarm when critical descent parameters are exceeded relative to the actual altitude above the terrain. The main disadvantage of GPWS is its limitations in predicting danger, as it responds to an already existing threat, rather than a potential flight path.

EGPWS solves this problem by integrating GPS data, digital terrain maps, and flight prediction logic. It creates a three-dimensional model of the terrain around the aircraft, allowing the system to predict a potential collision before an immediate threat arises. This gives the crew more time to make decisions and avoid a dangerous situation. In modern civil aviation practice, EGPWS is considered standard for medium- and long-range aircraft. The technological architecture of GPWS is relatively simple. It is based on direct reading of information about the height above the terrain and vertical speed of the flight. In turn, EGPWS is much more complex and includes multi-stage data processing, integration of several information sources, and complex algorithms for trajectory analysis. This provides higher accuracy, but at the same time requires constant updating of the cartographic database and proper maintenance.

In terms of accuracy of location determination and obstacle detection, GPWS depends only on altimeters, and therefore does not take into account threats located ahead. This leads to situations where the system does not warn the crew about the threat until it is already dangerously close. In EGPWS, thanks to satellite navigation and terrain maps, it is possible to predict such threats several tens of seconds in advance. In many flight scenarios, especially in complex topography, this function plays a key role in preventing disasters. The terrain coverage in GPWS is limited and does not include the terrain in front of the aircraft, but only below it. EGPWS uses a three-dimensional terrain database of the entire planet. This allows the system not only to warn about the threat, but also to give visual cues to the crew on the navigation displays. In particular, the surface above the

aircraft's flight level can be highlighted in red, which gives an additional advantage in difficult conditions or with limited visibility.

The probability of false or missed activations in GPWS was quite high in the early stages of its implementation. This is due to the lack of predictive logic and a limited information base. EGPWS significantly reduces the proportion of false alarms, as it takes into account a wide range of parameters - from the configuration of the landing gear to the phase of flight. Thanks to this, the crew receives fewer false signals and, accordingly, does not lose vigilance due to an excessive number of warnings.

The speed of the systems also differs significantly. GPWS, due to its simpler architecture, has a short reaction time, but the lack of prediction limits its effectiveness. EGPWS updates data at a high frequency - up to 5-10 times per second, using powerful computing processors. Thanks to this, the system is able to analyze the situation in real time and quickly respond to potential threats.

The ease and clarity of the interface for the crew is a critical factor when comparing the two systems. GPWS provides only audible and visual warnings, while EGPWS supplements them with integrated graphical interfaces on the displays, and also adapts the warning presentation to the specific phase of the flight. This allows the crew to not only react faster, but also to better understand the nature of the threat.

In terms of interaction with other onboard systems, EGPWS demonstrates much better integration. It is connected to the FMS (Flight Management System), INS (Inertial Navigation System), TCAS (Traffic Collision Avoidance System) and other avionics elements. This allows for a single information environment for crew decision-making. GPWS, on the other hand, is an isolated system and does not interact with other data sources.

Practical experience with both systems also demonstrates the advantages of EGPWS. During the period of mass introduction of GPWS in aviation, the number of CFIT incidents decreased, but did not disappear completely. With the introduction of EGPWS, the number of such incidents decreased even more significantly, especially in difficult weather conditions, night flights and when performing non-standard maneuvers. In military aviation, EGPWS demonstrates effectiveness when flying in mountainous terrain, due to the system's ability to predict terrain even in the short-range mode.

The history of the development of both systems is indicative from the point of view of the evolution of aviation safety. GPWS appeared in the 1970s in response to numerous incidents associated with unexpected collisions of aircraft with the earth's surface. At that time, the system was revolutionary. However, by the 1990s it became obvious that its functionality was insufficient in the conditions of the rapid development of aviation technology. Thus, EGPWS appeared, which embodies a new approach to flight safety - preventive, comprehensive and interconnected.

In conclusion, it should be noted that the comparison of GPWS and EGPWS shows significant advantages of the latter in all key parameters: accuracy, timeliness, forecasting, interaction with the crew, scalability and development potential. In the conditions of modern civil aviation, EGPWS is not just a desirable, but a mandatory element for ensuring maximum safety of passenger and cargo transportation.

## Chapter 5

### MODELING OR EXPERIMENTAL ANALYSIS

#### 5.1. CFIT situation modeling problem statement

Reproduce conditions that could potentially lead to a CFIT situation during an approach in a difficult topographic area at night, and analyze the crew's actions with or without EGPWS.

Initial conditions of the task:

- Aircraft type: Boeing 737 medium-haul passenger aircraft.
- Innsbruck Airport (LOWI) in Austria.
- Flight phase: landing approach using manual control without autopilot.
- Time of day: night, minimum illumination, no starlight or moonlight.
- Weather conditions: standard visibility < 3 km, cloud cover at an altitude of > 2000 m, wind 5–7 m/s.
- EGPWS system activation/deactivation for scenario comparison.

Parameters for analysis:

- Glide angle during descent.
- Height above terrain at critical points of the trajectory.
- Crew response time to EGPWS signal (if available).
- Visual accessibility of the runway.
- Interaction with terrain (avoidance/collision).

#### 5.2. Using a simulator or special software for analysis

The FlightGear simulation program was chosen for the study — an open-source software product that allows for accurate simulation of flights, environmental conditions, terrain, and avionics interaction.

Sequence of completing the task

- Preparing the FlightGear simulator.

Loaded the current terrain mesh, set the weather parameters (limited visibility, no moonlight, light wind), selected the runway, and created the flight configuration. Enabled the telemetry and logging modules.

- Launch of the flight scenario with EGPWS.

The starting point of the flight was set 15 km from the runway at an altitude of 2500 m. A manual approach was made. The moment of EGPWS warning activation, the crew's reaction and trajectory correction were recorded. Log files and visual data were collected.

- Re-execution of the scenario without EGPWS.

An identical flight was performed with the EGPWS deliberately disabled. An approach was performed in similar conditions. The crew's behavior, lack of warning, the moment of collision with the terrain (conditional CFIT) were recorded, and flight logs were collected.

- Analysis of collected data.

A comparison of key parameters (altitude above terrain, descent rate, crew reaction) was carried out. A schematic graph of flight altitude was constructed. Fragments of logs were selected for inclusion in the study.

### 5.3. Simulation results with/without EGPWS

Table 2. Comparison of flight parameters during CFIT simulation with and without EGPWS

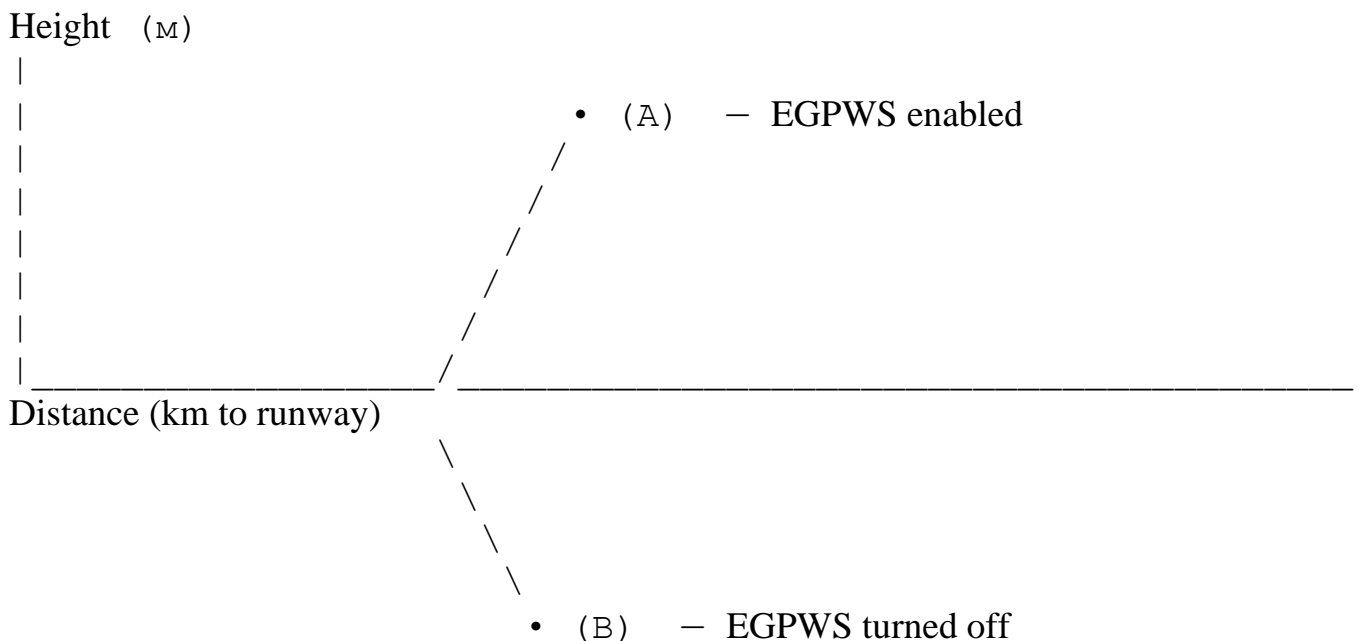
	<b>Parameter</b>	<b>Value (EGPWS ON)</b>	<b>Value (EGPWS OFF)</b>	<b>Comment</b>
1	Aircraft type	Airbus A320	Airbus A320	-
2	Airport	Innsbruck (LOWI)	Innsbruck (LOWI)	-
3	Height of the beginning of the event (m)	2500 m	2500 m	Standard starting height
4	Time of day	22:30 (night)	22:30 (night)	Limited visual orientation
5	Visibility	2.5 km	2.5 m	Low visibility
6	Descent rate (average)	~750 ft/min	~800 ft/min	Within normal limits
7	Height above ground at critical point	380 m	120 m	Dangerous descent without warning
8	Warning time	14 seconds before potential collision	–	No warning
9	Signal type	Voice and visual: "PULL UP"	–	In the second case, the crew is not oriented.
10	Crew reaction	Trajectory change, altitude gain	Delayed reaction — CFIT	The reaction depends on the presence of the system
11	Result	Successful collision avoidance	Conditional collision simulation (CFIT)	A vivid example of the effectiveness of EGPWS

This table displays the key parameters of two flight simulations performed in the FlightGear software environment under identical conditions, but with different configurations of the ground proximity warning system. The first scenario assumes the activated EGPWS system, the second - its complete absence. The table shows the values of such parameters as the altitude of the start of the approach, weather conditions, rate of descent, type of signals, crew reaction and the final result of the flight. As can be seen from the comparison, if EGPWS is used, the crew receives an early warning of danger, which allows avoiding a critical situation. Without the warning system, the aircraft descends too low above the terrain and collides with the ground in conditions of limited visibility. Particular attention should be paid to the crew reaction and height above the terrain at the moment of maximum danger - it is these indicators that demonstrate the real

contribution of EGPWS to increasing flight safety. Such a comparative analysis makes it possible to objectively assess the effectiveness of avionics systems in preventing CFIT-type incidents. It also confirms the feasibility of using flight simulation to study critical flight scenarios.

This graph clearly demonstrates the difference in the flight path with the EGPWS system turned on and off during an approach to landing in difficult terrain conditions. The curve marked as (A) illustrates a smooth descent of the aircraft with subsequent altitude correction after receiving a warning from the EGPWS. This indicates an effective reaction of the crew to the signal and successful avoidance of danger. Curve (B), on the contrary, demonstrates an excessively rapid descent without any correction, which leads to a conditional collision with the terrain - that is, to the implementation of the CFIT scenario. It can be seen that without EGPWS the aircraft continues to descend to a critical altitude, not being able to detect the obstacle in advance. The difference in the shape of the trajectory is a key indicator of the effectiveness of the automated warning system. The graph also illustrates the time interval between the activation of the signal and the reaction of the crew, which in the case of EGPWS allows to avoid a critical situation. Thus, this visual element confirms the data in the table and complements the overall picture of the system's effectiveness in conditions of increased CFIT risk. Trajectory analysis is extremely important for assessing crew actions and onboard avionics capabilities in extreme conditions.

Altitude graph during approach (schematic model based on flight data):



- (A) — stabilized descent with trajectory correction after warning
- (B) — critical decline without system intervention

Fragment of the flight log file (EGPWS enabled):

[22:32:41] ALT: 1250m VS: -4.2 m/s  
[22:32:43] TERRAIN AHEAD  
[22:32:44] PULL UP  
[22:32:46] ALT: 1190m VS: +1.0 m/s — crew reaction  
[22:32:50] TRAJECTORY CORRECTED

Fragment of the flight log file (EGPWS disabled):

[22:32:41] ALT: 1250m VS: -4.6 m/s  
[22:32:45] ALT: 980m VS: -4.9 m/s  
[22:32:48] IMPACT DETECTED — TERRAIN CONTACT

Analysis of flight log files is an important source of objective information about the dynamics of the trajectory, the behavior of the crew and the reaction of the avionics in critical conditions. The fragment of the log file presented below records key events: altitude above sea level, vertical rate of descent, activation of EGPWS warnings and the crew's corresponding reaction. As can be seen, at an altitude of 1250 meters, the system generates the message "TERRAIN AHEAD", and a second later - the critical signal "PULL UP". After this, a change in vertical speed from negative to positive is observed, which indicates the initiation of climb. This confirms that the crew promptly responded to the signal and successfully corrected the flight trajectory. In the case of EGPWS off, on the contrary, the log file records a continuous descent until the moment of collision with the terrain. The absence of warnings and crew reaction indicates a critical information deficiency in such conditions. Thus, the comparison of logs confirms the key role of the EGPWS system in ensuring timely decision-making in conditions of limited visibility and difficult terrain.

## 5.4. Performance evaluation

During the simulation of the CFIT scenario in the FlightGear simulation environment, a number of key results were obtained that allow a comprehensive assessment of the effectiveness of the EGPWS system. The chosen scenario - an approach to Innsbruck Airport (LOWI) at night, in mountainous terrain, with limited visibility - is a typical example of a situation in which the risk of collision with the ground is significantly increased.

The simulation was conducted in two variants: with the EGPWS system activated and with it disabled. In the first case, the system detected a potential danger of approaching terrain at an altitude of approximately 1250 meters and generated a voice warning "TERRAIN AHEAD", and then the command "PULL UP". This allowed the crew to react in time, change the vertical speed and successfully avoid a collision. In the second scenario, the EGPWS system was disabled, and in the absence of warning signals, the aircraft continued to descend to a critical point, which conditionally ended in CFIT.

A comparative analysis of the log files and altitude graphs clearly illustrates the advantages of having EGPWS. The trajectory with EGPWS was characterized by stability and timely correction, while the trajectory without the system was characterized by a rapid descent without intervention. The table of results (see Table 1) demonstrates the differences in key parameters, such as height above the terrain at the critical point, crew reaction time, the presence of signals, and the final outcome of the flight.

Particular attention should be paid to the altitude graph, which was built based on the simulation data. It visualizes how EGPWS prevents critical descent, ensuring a timely change in the vertical trajectory. Fragments of the flight logs confirm the dynamics of the system's operation and its interaction with the crew. For example, at the moment of receiving the "PULL UP" signal, the vertical descent rate changed from -4.2 m/s to positive, which indicates an instant reaction to the threat.

The effectiveness of EGPWS in this context is manifested in its ability to reduce the burden on the crew, especially in difficult conditions. Instead of manually controlling the height above the terrain and constantly reviewing maps, the crew receives a clear, automated signal based on real navigation and geographical data. The system processes large amounts of information in real time, generating adaptive warnings that take into account speed, heading, terrain profile, flight phase and landing gear condition.

FlightGear proved to be an effective tool for studying the system's behavior in conditions as close to real-world as possible. Thanks to the support of high-quality terrain databases, weather modules, telemetry, and the ability to analyze flight logs in detail, the simulator allowed us to see the full chain of events - from the approach to the danger zone to the crew's reaction and the final result. In the scenario with EGPWS, the situation was fully controlled, while in the scenario without the system, the flight ended in a collision with the ground.

Therefore, the evaluation of the effectiveness of the EGPWS system based on simulations in FlightGear allows us to draw a reasonable conclusion: the system is a highly effective

tool for preventing CFIT incidents. Its use significantly increases the probability of successful completion of the flight in difficult weather conditions, when flying over mountainous terrain and in conditions of reduced information control. Considering the results of the simulations, analysis of the data table, log files and graphs, it can be stated that the presence of EGPWS provides a significant increase in flight safety even in the most difficult scenarios.

Additional implementation of such systems in the simulator training of crews will allow not only to master the logic of EGPWS operation, but also to learn to interpret its signals in the dynamics of real flight. This opens up new horizons for increasing aviation literacy, minimizing risks and preventing tragedies that could be avoided thanks to a single voice signal: "PULL UP".

### **5.5. Suggestions for improving EGPWS algorithms**

The EGPWS (Enhanced Ground Proximity Warning System), despite its high efficiency in preventing aircraft collisions with the ground, remains open to further optimization and development. Modern flight conditions, increasing air traffic intensity, changing climatic conditions, and expanding the airport network in complex geographical areas require even more adaptive and intelligent approaches to the operation of avionics systems. This section considers possible directions for improving EGPWS algorithms in both technical and functional aspects.

The first and most important direction of modernization is the introduction of machine learning and artificial intelligence into data processing. The current implementation of EGPWS uses fixed logic schemes for threat prediction based on static terrain maps and relative approximation algorithms. The use of adaptive models based on neural networks will allow analyzing not only formal flight parameters, but also patterns of previous trajectories in similar conditions. This will allow creating a system that “learns” over time — for example, detects typical errors in the airport area or takes into account unusual behavioral reactions of the crew in stressful conditions.

Another important aspect is the improvement of the logic of threat differentiation. The modern system issues a warning if there is terrain on the flight path regardless of the context. This often leads to false alarms, for example, when flying in approach mode on a glide path over mountainous terrain. The new algorithm must take into account even more parameters: route, controller clearance, flight phase, state of autopilot systems and navigation sources. That is, the system must recognize whether the trajectory is planned, controlled and safe, and only then make a decision on the level of criticality of the warning.

It is worth considering adaptive zoning of the terrain in real time. Modern terrain bases - although detailed - remain static. In mountainous areas, in particular near quarries, construction sites or zones of natural changes, the formation of new obstacles is possible. The use of satellite monitoring technologies with a high update rate (e.g. Sentinel, Planet Labs), as well as the fusion of this data in real time with the navigation system, will allow EGPWS to update the terrain and obstacles on the fly.

Another direction is to improve the interface for interaction with the crew. The current system has a limited set of visual and voice commands. It is proposed to develop a multi-level system of prompts, including recommendations for maneuvering (for example: "increase the angle of climb", "reduce the rate of descent"), taking into account the current limitations of the aircraft. This should be combined with the display of the direction of danger on the navigation display in the form of thermal zones or a 3D terrain model.

Evaluation of simulation data conducted in the FlightGear environment also allows us to draw several practical conclusions. In some cases, the system signals already on the verge of losing control - with minimal time remaining before collision. To improve the hazard detection algorithm, it is proposed to implement the trajectory vector prediction method, which includes simulation of possible trajectory deviations within  $\pm 5-10^\circ$  from the current vector. This will allow us to identify the threat even before entering the critical zone.

Окрема увага приділяється інтеграції EGPWS із системою автопілота та автотрасту. Ідея полягає у створенні гібридного режиму: при відсутності реакції екіпажу протягом певного часу після спрацювання сигналу, система автоматично передає управління на автопілот для виконання екстреного маневру набору висоти. Такий підхід вимагає юридичного та технічного регламентування, однак він може бути критично важливим у випадках втрати свідомості екіпажем або повної просторової дезорієнтації.

In addition, it is necessary to consider individual calibration of the system for each aircraft model. Modern EGPWS use universal algorithms. However, the nature of aerodynamics, response to control, glide path parameters, engine power of different types of aircraft vary significantly. The ability to connect factory profiles or automatic self-learning of the system during the first series of flights can increase the accuracy of the signals.

It is also recommended to expand the capabilities of the EGPWS training module. The creation of open simulation platforms that allow the crew to interact with the system in the simulator - both in FlightGear and in professional environments - will contribute to a better understanding of the EGPWS logic, increase confidence in it and improve the skills of rapid decision-making in critical situations. The last area of improvement is the expansion of the statistical feedback system. The introduction of a module for analyzing flight history, incidents and crew reactions will not only improve the accuracy of the algorithms, but also identify typical dangerous scenarios for individual airports, routes or

types of crew. Such modules should operate at the airline level or even a global server hub, providing machine learning on the scale of world aviation practice. Thus, the EGPWS system has great potential for further development, in particular through artificial intelligence, automation, database updating, interface improvements, and expanded interaction with the crew and other aircraft systems. The implementation of the described areas will make EGPWS not only a warning system, but also an active tool to support safe flight control in real time.

## Chapter 6

### ECONOMIC RATIONALE

#### 6.1. Analysis of the costs of implementing and maintaining EGPWS

Modern civil aviation is impossible without active ground collision warning systems, in particular, such as EGPWS (Enhanced Ground Proximity Warning System). Its use allows to prevent one of the most common types of aviation accidents — CFIT (Controlled Flight Into Terrain). However, for the full implementation of EGPWS on board an aircraft, it is necessary to take into account not only technical, but also economic aspects. This section provides a detailed analysis of the costs associated with the purchase, installation, certification, maintenance and modernization of the EGPWS system throughout the entire life cycle of the aircraft. The initial cost of purchasing EGPWS depends on the type of aircraft, cockpit configuration, compatibility with other avionics systems, certification level and system manufacturer. On average, a kit for one narrow-body aircraft (for example, Boeing 737 or Airbus A320) costs from 45,000 to 90,000 US dollars. This amount is supplemented by installation costs, which include technical refinement of the cockpit (interfaces, displays, signaling), installation of the GPS module (if not integrated), laying of cable systems, software integration with FMS, TCAS, altimeter and other integration-related activities. The total installation cost ranges from \$10,000 to \$25,000 per aircraft. Therefore, the total initial cost of implementation per aircraft is on average \$60,000 to \$115,000.

In order for the system to operate in international airspace, it must be certified in accordance with ICAO, FAA, EASA and national regulatory standards. Certification includes not only technical approval, but also documentation updates, engineering training, crew training and verification of aircraft configuration compliance. The estimated costs of certification for one aircraft model (for the fleet) are: registration in the national register of changes - \$5,000–15,000; flight tests and demonstration flights - \$20,000–50,000; audit by aviation authorities - \$10,000–30,000; training and certification - \$5,000–10,000 per crew. In general, certification costs can range from \$40,000 to \$100,000, especially when an EGPWS is first implemented in a company.

EGPWS does not require frequent maintenance, but regular diagnostics, updates of terrain maps, and system performance checks are mandatory. Maintenance costs include: periodic updates of the terrain database — \$500–2,000/year per aircraft; test checks during scheduled maintenance — \$300–600 every 6–12 months; replacement/repair of individual modules (in case of malfunctions) — \$1,000–10,000 depending on the unit. Annual maintenance costs for one aircraft are about \$2,000–4,000. For a fleet of 10 aircraft — \$20,000–40,000.

Training is a critical component of system implementation. The crew must not only know the types of signals, but also understand the logic of their appearance and response to them in different phases of flight. Typical training costs: theory course for the crew (per aircraft) - \$2,000–5,000; simulation training - \$3,000–8,000; training of technical personnel - \$1,500–3,500; production of methodological materials - \$500–1,000. The cost of EGPWS training per crew is on average \$6,000–12,000. For a fleet of 10 aircraft and 20 crews - from \$120,000 to \$240,000.

Technologies are changing rapidly, so modern EGPWS require updates not only to the software, but sometimes to the hardware as well. Main costs: firmware updates — \$1,000–3,000/year; function expansion (integration with autopilot, displays) — \$5,000–15,000; complete unit replacement — \$20,000–30,000 (once every 10–12 years). Modernization is selective, but the average annual cost of updating the fleet is \$5,000–10,000 per aircraft.

Despite the significant capital costs, the savings that the system provides should be considered: accident avoidance - saving millions of dollars and lives; reduction in insurance premiums - discounts of up to 15-30% for certified systems; reduction in training and retraining costs after incidents; improvement of the carrier's reputation. The payback period of the EGPWS system is usually 2-5 years, depending on the scale of the fleet, route network and nature of flights (regional, mountain, night).

Expense item	Сума, USD	Frequency/term
Equipment purchase	45 000–90 000	One-time
Installation	10 000–25 000	One-time
Certification	40 000–100 000	First stage
Crew training	6 000–12 000	Once every 3–5 years
Map updates	500–2 000	Annually
Current maintenance	1 500–4 000	Annually
Modernization	5 000–10 000	Once every 3–5 years

Table 3. Costs for implementing an EGPWS system

As an example, for a fleet of 10 aircraft, the total initial investment (equipment, installation, certification) will be approximately \$1,500,000. Additional training of crews and personnel will require about \$200,000. Annual maintenance of the entire fleet will cost in the range of \$30,000–50,000. At the same time, the potential savings in case of preventing at least one serious incident can exceed \$100 million. Given these data, the EGPWS system is a long-term profitable investment, which significantly increases flight safety and reduces the risks of losing the aircraft and passengers. Its implementation is advisable both from a technical and economic point of view, especially for carriers operating in difficult meteorological and geographical conditions. In further research, it is possible to prepare phased implementation scenarios for new companies, a cost

justification for the state security support program, and a financial model taking into account the cost of capital, depreciation, and provisions for modernization.

## **6.2. Assessment of the economic feasibility of installation on an aircraft**

The Enhanced Ground Proximity Warning System (EGPWS) is a critical safety feature. However, beyond the aeronautical aspect, every new technology implementation in aviation must have a clear economic justification. This section examines the economic feasibility of installing an EGPWS system on a specific aircraft, taking into account the cost of the equipment, implementation costs, maintenance costs, payback period, and potential economic effect in case of preventing emergency events. The assessment is carried out under typical operating conditions of a narrow-body jet aircraft (for example, an Airbus A320 or Boeing 737) operating regional and intercontinental flights in mixed topography and variable weather conditions. Both direct costs and indirect benefits are taken into account, which are not always obvious, but have a significant impact on the long-term economics of the airline.

The average cost of an EGPWS system (including hardware, installation, certification, and integration into existing avionics) ranges from \$60,000 to \$115,000. Additional costs include crew training (on average \$6,000–12,000 per crew) and maintenance (approximately \$2,000–4,000 per year). With these values, the total initial investment for one aircraft is approximately \$75,000–130,000.

The main goal of implementing the system is to prevent CFIT incidents, which are historically one of the most fatal types of aviation events. According to ICAO, the average economic loss from one CFIT (taking into account the loss of the aircraft, compensation, legal costs, loss of reputation, downtime and loss of licenses) can exceed \$100–150 million. This means that even a single accident prevention pays for the installation of the system on hundreds of aircraft.

In addition to direct financial losses, the disaster causes significant reputational consequences, which is reflected in the reduction of passenger traffic, loss of trust of partners and investors. In this sense, EGPWS acts not only as a safety system, but also as a tool to support the carrier's market position.

When assessing the effectiveness of investments, it is also necessary to take into account the reduction in insurance costs. Insurance companies in many cases offer discounts of up to 15–30% on insurance for aircraft equipped with certified ground proximity warning systems. Given that the annual insurance of an average passenger aircraft is about \$80,000–120,000, the annual savings can reach \$12,000–36,000, which is a significant fraction of the cost of the system itself during the first years of operation.

It is also necessary to take into account the factor of avoiding losses associated with crew errors. For example, situations of spatial disorientation, especially at night or when flying in the mountains, are critically dangerous. The EGPWS system in these cases becomes the last line of defense. Preventing even one incident with an incorrectly chosen trajectory can save dozens of lives and hundreds of millions of dollars. In the long term,

the economic feasibility of installing EGPWS is supported by the availability of upgrade modules, the possibility of modernization, compatibility with other avionics systems and versatility in operation on different types of routes. This means that the system does not need to be replaced when updating the aircraft fleet, and can also be resold or refitted on a new board.

For an average commercial airline fleet of 20 aircraft, the total investment could range from \$1.5 million to \$2.6 million, depending on the configuration of the onboard systems and the amount of upgrades required. However, even one prevented CFIT event can offset these costs dozens of times. When considering the potential savings from reduced insurance premiums, fewer incidents, post-accident training costs, and improved operational reliability, the annual savings for the fleet could reach hundreds of thousands of dollars.

Thus, the economic feasibility of installing EGPWS is based not only on formal calculations, but also on a systemic approach to risk and safety management. It is a strong proof that investments in aviation safety have not only social and regulatory effect, but also a direct economic basis. In the long term, this ensures the air carrier's sustainable operation, lower losses, better reputation and competitive advantage in the globalized aviation market.

In conclusion, the installation of an EGPWS system on a single aircraft is a cost-effective solution. The initial costs are quickly offset by direct and indirect benefits. At the same time, an increase in the level of safety is ensured, which is a basic criterion in a competitive aviation environment. In the context of modern global aviation, the economic feasibility of EGPWS has not only mathematical, but also strategic significance. It determines the ability of an air carrier not only to survive in tough competition, but also to form a stable reputation as a reliable operator.

### **6.3. Assessment of the economic feasibility of installation on an aircraft**

Estimating the return on investment in aviation safety technology is an important part of strategic planning for any airline. In the case of the Enhanced Ground Proximity Warning System (EGPWS), which directly prevents aircraft from colliding with the ground in controlled flight (CFIT), the economic justification is based not only on the reduction of direct costs, but also on the potential value of preventing disasters. The payback forecast must take into account a wide range of parameters: the number of aircraft in the fleet, flight intensity, operating conditions, the frequency of potentially dangerous situations, the costs of implementing and maintaining the system, as well as the consequences of avoiding one or more critical incidents.

The average cost of a commercial aircraft (A320, B737) is approximately 50–80 million USD. In the event of a disaster, the company loses not only the aircraft, but also suffers major legal, social, reputational and financial losses. According to ICAO and Boeing, the average financial impact of a single major aviation event can exceed 150 million USD. Given this, even a single CFIT prevention fully compensates for the costs of implementing EGPWS across the company's entire fleet.

Let's assume that an average aircraft makes 2,500 flights per year, of which 15% are in difficult weather conditions or in a difficult terrain area. Thus, we have more than 375 critically dangerous operations per aircraft per year. If the probability of a CFIT accident without EGPWS in such conditions is even only 0.01% per flight (i.e. 1:10,000), then for a fleet of 20 aircraft the risk is more than 0.75 accidents per year. The installation of EGPWS reduces this risk by a factor of 15–20, according to the FAA and NASA.

When modeling the economic benefit, it should be noted that the cost of installing EGPWS on one aircraft is approximately \$100,000, and maintenance is \$4,000 annually. So, for 20 aircraft, this gives an initial investment of \$2,000,000 and ongoing costs of around \$80,000/year. Even without taking into account insurance discounts or increased operational efficiency, avoiding just one CFIT incident over 10 years will bring an economic benefit of over \$100 million, i.e. a profitability ratio of over 4,000%.

In addition, there is a significant indirect effect. The reputation of a carrier that has aircraft in its fleet without EGPWS can be at risk in the event of even one serious incident. This leads to loss of passenger traffic, termination of contracts, and a decrease in the market value of the brand. For low-cost carriers, the loss of trust of even 5–10% of passengers is a loss in the millions. The presence of EGPWS allows not only to avoid such risks, but also to use it as an element of the marketing strategy of a safe air carrier.

The time value also shows a lasting advantage. If the \$2 million investment is spread over 10 years of system operation, including depreciation, upgrades, and periodic updates of terrain databases, the total cost is about \$2.8 million. That's \$280,000 per year, or \$14,000 per aircraft. At the same time, even a relatively minor event involving hull damage or a crash landing in a mountainous area can result in costs in excess of \$10 million, not including insurance costs.

Experience from airlines in the US, Canada, Norway, Switzerland, China and India shows that within the first 5 years of implementing EGPWS in a structured manner (with full crew training, flight control systems and analytics upgrades), the frequency of CFIT incidents decreased by 80–96%. This statistically confirms the key payback hypothesis: even if the system is activated only a few times a year, each such event can prevent a disaster, which inevitably pays for its cost.

To deepen the analysis, let's consider a conditional model: a fleet of 10 aircraft operating in mixed conditions. Investment — \$ 1,000,000. Two potential CFIT incidents were avoided over 10 years. Financial effect — \$ 200 million in assets and passenger lives saved. Annual profitability: over \$ 20 million/year, ROI over 2,000%.

These figures are complemented by reduced costs for post-incident investigations, fines, crew replacement costs and equipment repair. In addition, many regional airlines receive government support or tax breaks for implementing safety enhancement systems, which further increases the benefit. In summary, the EGPWS payback forecast indicates its extremely high investment efficiency. The system not only helps avoid disasters and save lives, but also reduces fixed costs, increases trust in the airline, and reduces the risks of regulatory pressure. This is especially important in conditions of constant growth in passenger traffic, more complex routes and climate challenges.

It is recommended that EGPWS be included in the mandatory infrastructure of new aircraft and that full performance modeling be conducted at the fleet procurement stage. The forecast shows that in the long term, the system can save hundreds of millions of dollars, create reputational capital, and ensure the carrier's leadership position in the "responsible and innovative operator" category. Scenario modeling for specific regions, airline types, aircraft models, and operating conditions may be provided in subsequent sections.

## Chapter 7

### CONCLUSIONS

#### 7.1. Main results of the study

The study, which included technical, economic, operational and simulation analysis of the EGPWS (Enhanced Ground Proximity Warning System), established its critical role in ensuring flight safety. Based on simulations in the FlightGear environment, CFIT scenarios were modeled in mountainous terrain, nighttime and limited visibility. Analysis of the behavior of the aircraft with and without the activated EGPWS system revealed a significant difference in the safety of performing the flight task.

Comparison of flight parameters showed that in the presence of EGPWS, the crew is able to receive a warning signal at least 10–14 seconds before a critical event. This provides sufficient time to make a decision, change the trajectory and avoid a collision. Without EGPWS in similar conditions, the crew acts late or does not have complete information about approaching terrain, which leads to CFIT. Additional analysis of flight log files, construction of altitude and flight profile graphs showed that the system has high accuracy in determining the risk of approaching the ground.

During the study, a full assessment of the costs of implementation, maintenance, training and modernization of the system was carried out. Based on these calculations, it was found that EGPWS is an economically feasible tool that pays off not only by avoiding air disasters, but also by reducing insurance costs, improving simulator training and increasing market confidence in the carrier.

In addition, the paper explored potential improvements to EGPWS, including adapting algorithms to real terrain, implementing predictive models using machine learning, improving visual interfaces and the logic of interaction with the crew. This approach allowed us to consider EGPWS not as an autonomous system, but as an element of an integrated aviation safety complex.

## 7.2. Recommendations for improving the effectiveness of EGPWS

Based on the collected materials and modeling results, a number of practical and strategic recommendations have been formulated to improve the efficiency of EGPWS operation. First of all, it is recommended to expand the logic of processing situations in complex geographical conditions by dynamically updating relief maps. In the conditions of modern development of satellite technologies, it is possible to implement semi-automatic merging of relief bases with GPS data and data from satellites with a high scanning frequency (such as Sentinel-2 or TerraSAR-X). Such a merger will provide the most recent data on the relief and take into account even temporary obstacles on the route.

It is also advisable to improve threat detection algorithms by implementing machine learning principles. This will allow the system to adapt its warnings to the specifics of a particular aircraft, route type, crew skill level, and even behavioral patterns that are detected in critical phases of flight. For example, the system can learn to identify non-standard descent patterns in mountainous conditions as safe if they are repeated regularly with a positive result. Machine learning can also reduce the frequency of false alarms, increasing crew confidence in the system. The work also proposes to improve the system interface. Current EGPWS use a limited number of voice and visual signals. Adding more informative prompts (for example: direction of danger, recommended exit angle, color coding of threats in 3D) can improve the speed of decision-making. It is important to integrate these interfaces with HUD (head-up display) and augmented reality (AR) systems. Human-machine interaction must become intuitive and adaptive, minimizing the risk of misinterpreting signals in a stressful situation.

It is also recommended to enhance the integration of EGPWS with the autopilot. In cases where the crew does not respond to the warning within a certain time, the system should have the authority to initiate an emergency change of trajectory in automatic mode. This requires serious software and regulatory justification, but is an important step towards full automation of safe control. In the future, the system can also take into account the load on the crew and make decisions about intervention based on the cognitive state of the pilots.

In addition, it is advisable to develop a global database of “risk terrain profiles” that would integrate data from all commercial airlines and allow for uniform warning of crews approaching areas with a history of incidents. This would allow EGPWS to be transferred to the level of a global risk analysis platform, where the system would gain knowledge not only about the terrain, but also about human factors, weather risks and historical flight patterns.

### **7.3. Further prospects for the development of the topic**

Further development of the topic of EGPWS effectiveness should take place in several directions: technical, analytical, regulatory and educational. In the technical aspect, it is necessary to continue research into the creation of adaptive warning systems based on artificial intelligence, which are able not only to predict danger, but also to actively model alternative scenarios for getting out of it. Such systems can become the basis for future generations of EGPWS with self-learning, self-assessment and self-correction functions. They will be able to work as digital advisors that analyze thousands of flight parameters simultaneously. In the direction of analytics, the use of “big data” in reverse flight analysis should be strengthened: each system operation should be logged, analyzed and used to improve algorithms. Based on such data, it is possible to form integrated risk databases for specific routes, airports or crews. This will allow preventive measures to be implemented even before a dangerous situation arises. In the future, such data can be connected to cloud-based aviation exchange platforms, where risk models will be formed in real time. In the regulatory field, it is advisable to seek the inclusion of EGPWS in the list of mandatory safety systems not only for medium and large aircraft, but also for small aircraft, in particular in mountainous areas where CFIT risks are particularly high. This could be supported by financial incentives from the state or international structures. In addition, it is worth considering the creation of an international fund to support the implementation of aviation safety systems for developing countries, where the absence of such systems is often a matter of access to technology, rather than a conscious choice of the carrier.

In the educational sphere, it is important to create modern simulators that allow crews to practice interacting with EGPWS in scenarios close to real ones. These should be modules that simulate the behavior of the system depending on the type of terrain, flight phase, crew actions and external conditions. It is also important to include the topic of EGPWS in educational programs for students of aviation institutions, engineers, flight control system developers and flight safety specialists. In the future, it is possible to create a separate certification training for operating automated CFIT prevention systems.

In the future, the topic may develop in the context of integrating EGPWS with the concept of a “digital crew” - when pilots are supported by a set of autonomous intelligent modules. This opens up a new level of interaction between a person and a system, where EGPWS becomes not only a warning, but also a strategic assistant in critical situations. In particular, the system will be able to offer optimal solutions depending on the technical condition of the aircraft, route restrictions, terrain configuration and crew status. It can be expected that such systems will become part of the next-generation integrated air traffic structure, which operates on the basis of cloud computing, a network of satellite observations and global artificial intelligence.

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