APPLIED TECHNOLOGIES OF FMCW RADIO ALTIMETERS FOR NEXT-GENERATION AVIATION AND AUTOMOTIVE SYSTEMS

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Title:

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Abstract

The field of Frequency Modulated Continuous Wave (FMCW) radar represents a significant area of modern intelligent transportation systems. Owing to their ability to simultaneously determine the distance and relative velocity of objects through the exploitation of the Doppler effect, FMCW radars have found widespread application, particularly in automotive Advanced Driver Assistance Systems (ADAS) and autonomous driving technologies. Building upon these technological advances, the presented monograph extends their application to aviation by investigating the use of onboard FMCW radio altimeters as cost-effective terrain collision avoidance systems for small aircraft and helicopters. The monograph provides a comprehensive theoretical and experimental analysis of the Doppler component contained in the beat signal for predicting the time to terrain collision, experimentally validates the proposed concepts under real flight conditions, and introduces novel methods for improving measurement accuracy. The proposed solutions extend the functionality of existing radio altimeters by incorporating active Controlled Flight Into Terrain (CFIT) warning capabilities without the need for expensive onboard terrain awareness systems, thereby contributing significantly to the enhancement of flight safety.

Keywords:

FMCW radio altimeter, Doppler effect, Terrain collision avoidance, Controlled Flight into Terrain (CFIT), Helicopter flight safety, Radio altimeter signal processing, Mathematical modelling, Terrain awareness, Low-altitude helicopter operations

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Preface

The presented monograph aims to address the need for cost-effective terrain collision avoidance systems for small aircraft and helicopters. The rapid advancement of aviation technology and the increasing volume of air traffic have highlighted the necessity for affordable anti-collision systems for these aircraft, which are not required by current regulations to be equipped with complex systems such as TCAS/ACAS or EGPWS. Building upon the monograph Applied Technologies for the Use of FMCW Radio Altimeter, this work explores the possibilities of extending the functionality of onboard low-range frequency-modulated continuous wave (FMCW) radio altimeters to create simple terrain collision avoidance and warning systems. The monograph provides a comprehensive theoretical and experimental analysis of FMCW altimeter operation, with a special focus on utilizing the Doppler component in the difference frequency signal. Through mathematical modeling, error analysis, and stabilization of the altimeter constant, the authors demonstrate that the existing altimeter hardware can be effectively used not only for precise altitude measurement but also for predicting the time to potential collision with rising terrain. The monograph experimentally verifies the Doppler effect during flights over ascending terrain, presents dual-channel altimeter configurations, and introduces a patented measurement method using a depolarization plate, which significantly improves the resolution of methodological errors. It proposes supplementary solutions based on the research, which generate timely warnings of approaching terrain based on the ratio of altitude to vertical velocity, and integrates altimeter outputs with aircraft dynamic models to enhance the crew's situational awareness. The proposed solutions offer a practical and economically accessible way to improve flight safety for small aircraft and helicopters, particularly in operations where expensive advanced systems are not available. They may also help reduce the risk of controlled flight into terrain (CFIT).

LIST OF USED SYMBOLS AND ABBREVIATIONS

a	- terrain approach angle
c	- propagation speed of light (electromagnetic waves)
Δf	- frequency deviation
Δh	- absolute height measurement error
ΔH	- methodological error of the frequency method
ΔHS	- measurement error due to aircraft pitch or bank angle
ΔU	- error signal voltage
S0	- elementary reflecting surface of the Earth's surface
ρ	- random error
f_v	- frequency of the transmitted signal
f_0	- mean value of the carrier signal frequency
f_p	- instantaneous frequency of the received signal
f_M	- modulation frequency
f_D	- Doppler frequency
f_{rD}	- difference frequency including the Doppler effect
f_r	- difference frequency
f_{r0}	- difference frequency corresponding to the oblique (slant) distance
φ(t)	- phase of the low-frequency difference signal
φ_0	- initial phase of the difference signal
φ_M	- variable phase of the difference signal,
G_0	- energy spectrum of the signal reflected from an elementary surface
G	- energy spectrum of the composite (summary) signal
γ	- aircraft bank angle
H	- flight altitude
H_{abs}	- absolute height
H_{et}	- standard (reference) height
H_m	- flight altitude measurement result
H_{min}	- minimum measured flight altitude

H_n	- measured altitude during aircraft pitch or roll
H_{rel}	- relative height
H_a	- actual (true) flight altitude
IPS	- direct signal current
iC	- mean value of the integrating capacitor current
C	- radio altimeter constant
λ	- wavelength
ν	- systematic error
RA	- radio altimeter
T_M	- modulation frequency period
T_i	- measured part of the modulation frequency period
τ	- time delay of the reflected signal
τ_{ref}	- time delay of the reference coaxial line
U_{ref}	- reference voltage
U_v	- amplitude of the transmitted signal
U_p	- amplitude of the received signal
U_{dif}	- voltage proportional to the difference frequency
U_f	- difference frequency signal
ξ	- coaxial cable shortening (velocity) factor
ζ	- relative height measurement error
FMCW	- Frequency Modulated Continuous Wave
HAGL	- Height Above Ground Level
ACAS	- Airborne Collision Avoidance System
TCAS	- Traffic Collision Avoidance System
TAWS	- Terrain Awareness and Warning System
EGPWS	- Enhanced Ground Proximity Warning System
GPWS	- Ground Proximity Warning System
CFIT	- Controlled Flight Into Terrain
ADS-B	- Automatic Dependent Surveillance–Broadcast
UAS	- Unmanned Aerial System
UAV	- Unmanned Aerial Vehicle

EASA	- European Union Aviation Safety Agency
FAA	- Federal Aviation Administration
ICAO	- International Civil Aviation Organization
VFR	- Visual Flight Rules
IFR	- Instrument Flight Rules
GPS	- Global Positioning System
FFT	- Fast Fourier Transform
DAQ	- Data Acquisition
AFCS	- Automatic Flight Control System
AGL	- Above Ground Level
QNH	- altimeter setting to indicate altitude above mean sea level
QFE	- altimeter setting to indicate altitude above a specified datum
RWY	- runway
FDR	- Flight Data Recorder
HEMS	- Helicopter Emergency Medical Service
CTR	- Control Zone

1 INTRODUCTION

The rapid development of aviation and rocket technology continuously imposes increasingly demanding requirements on control and navigation systems. Modern systems must deliver a high degree of autonomy, accuracy at the meter level, reliability, and fault tolerance. Key components include autonomous radio-technical sensors that measure essential motion parameters such as true altitude above terrain (Height Above Terrain), vertical speed, true airspeed, drift angle, and distance traveled. Accurate measurement of true altitude above the ground has been critical since the early days of aviation, particularly for safe flights in mountainous and hilly terrain and during landing maneuvers. Historical development progressed from optical methods (dependent on visibility and weather) and acoustic methods (limited by the speed of sound) to electrical principles. While capacitive methods remained largely theoretical, early pulse-based radio altimeters faced technological barriers in generating nanosecond pulses. Phase-based methods proved too complex for practical deployment at the time. Contemporary avionics employs a wide range of physical principles for altitude measurement and terrain collision protection:

- Radiometric and laser methods (RADAR, LIDAR) – based on measuring the propagation time of electromagnetic waves.
- Barometric systems – measurement of static air pressure.
- Inertial systems (IMU) – double integration of vertical acceleration using accelerometers and gyroscopes.
- Specialized methods such as radioisotope or corona discharge techniques (used in specific historical applications).

The current trend in avionics is toward multi-sensor fusion, integrating data from multiple sources (radar, GPS, IMU, and digital terrain databases) to eliminate the weaknesses of individual methods. This approach is particularly important for small aircraft and helicopters, where legislation (e.g., FAA/EASA) has not strictly required advanced TAWS/EGPWS systems until recently. However, increasing air traffic density and accident statistics now demand their adoption.

Significant examples of technologies combining two principles include:

1. Radar-Inertial Fusion in Terrain Awareness and Warning Systems (TAWS/EGPWS). Modern systems (e.g., Honeywell) combine data from radio altimeters (direct measurement above the terrain) with inertial measurement units (IMU) and GPS. While the radio altimeter provides precise instantaneous height, the inertial system enables trajectory prediction and filters out noise caused by terrain irregularities.
2. Dual-principle signal processing in low-altitude radio altimeters (FMCW + Doppler). This monograph focuses on utilizing aircraft radio altimeters not only as distance-measuring devices but also as active collision-avoidance elements. It employs Frequency Modulated Continuous Wave (FMCW) for altitude measurement and exploits the Doppler shift present in the beat frequency to provide immediate information about the rate of closure to obstacles. This transforms a passive sensor into an active warning system. The growth in air traffic volume requires the introduction of collision-avoidance systems even into categories of aircraft and helicopters where they were not previously mandatory. This monograph analyzes and classifies existing warning and anti-collision systems and proposes operating modes optimized for the specific flight characteristics of helicopters. The main contribution lies in exploring practical applications of available technologies—specifically, using a radio altimeter as a simple yet effective collision-avoidance system. By utilizing the Doppler component in the radio altimeter signal, early detection of dangerous proximity to the ground or obstacles can be achieved. This is critical for safe operations at low altitudes and during search-and-rescue missions.

Flights into mountainous and hilly areas rank among the highest-risk operations in aviation. Even with a fully functional aircraft and pilot in control, unintentional collision with terrain (CFIT) can occur, historically causing thousands of fatalities. CFIT accidents frequently happen in conditions of reduced visibility (IMC), at night, or during approach and departure, when pilots underestimate rising terrain or misinterpret barometric altitude readings. Helicopters and general aviation aircraft engaged in search-and-rescue, firefighting, or VFR flights in mountainous regions face elevated risk due to low flight levels, turbulence, and rapidly changing terrain, where traditional barometric altimeters are often insufficient. Statistics show that the introduction of GPWS in 1974 and later TAWS/EGPWS dramatically reduced CFIT accidents in commercial air transport (nearly eliminating them among large jets in the USA). However, in general aviation and helicopter operations, CFIT still accounts for a significant proportion of fatal accidents. Key contributing factors include loss of situational awareness, incorrect altimeter settings, pilot fatigue, and the absence of look-ahead terrain warning functions in older systems. These highlight the need for Doppler-based detection and multi-sensor fusion even in smaller aircraft.