



Recommendation ITU-R M.2059-0
(02/2014)

**Operational and technical characteristics
and protection criteria of radio altimeters
utilizing the band 4 200-4 400 MHz**

M Series
**Mobile, radiodetermination, amateur
and related satellite services**

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Note: This ITU-R Recommendation was approved in English under the procedure detailed in Resolution ITU-R 1.

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RECOMMENDATION ITU-R M.2059-0

Operational and technical characteristics and protection criteria of radio altimeters utilizing the band 4 200-4 400 MHz

(2014)

Scope

This Recommendation describes the technical and operational characteristics, and protection criteria of radio altimeters used in the aeronautical radionavigation service.

The ITU Radiocommunication Assembly,

considering

- a) that radio altimeters are an essential component of aeronautical safety-of-life systems, including precision approach, landing, ground proximity and collision avoidance systems;
- b) that radio altimeter systems operate in the aeronautical radionavigation service;
- c) that radio altimeters have been fitted for decades to all types of aircraft;
- d) that radio altimeters are operational during and must operate without harmful interference for the entire flight;
- e) that a radio altimeter system on a single aircraft consists of up to three identical radio altimeters;
- f) that there is a need to document the spectrum usage characteristics and deployment of radio altimeter systems on a worldwide basis;
- g) that coexistence between radio altimeters located on the same aircraft is achieved by technical and operational mitigation methods,

recognizing

- a) that the aeronautical radionavigation service is a safety service;
- b) that radio altimeter systems operate in the frequency band 4 200-4 400 MHz on a worldwide basis;
- c) that representative technical and operational characteristics and protection criteria of radio altimeter systems are required for spectrum management and deployment planning;
- d) that the airworthiness certification of radio altimeters is a lengthy and costly process;
- e) that radio altimeters require a bandwidth of 196 MHz,

noting

- a) that, in accordance with RR No. **4.10**, the safety aspects of radionavigation and other safety services require special measures to ensure their freedom from harmful interference;
- b) that regulatory requirements for radio altimeters are specified by the International Civil Aviation Organization (ICAO);
- c) that Recommendation ITU-R M.1461 is used as a guideline in analysing the compatibility between radars (including radio altimeters) operating in the radiodetermination service with systems in other services,

recommends

- 1 that operational and technical characteristics of the radio altimeters described in Annex 1 and Annex 2 should be considered representative of those systems operating in the frequency band 4 200-4 400 MHz and should be used when conducting compatibility studies;
- 2 that the protection criteria provided in Annex 3 should be used for protection of radio altimeters operation.

Annex 1

Operational characteristics

1 Introduction

The band 4 200-4 400 MHz is currently allocated to the aeronautical radionavigation service (ARNS) and is reserved exclusively for radio altimeters installed onboard aircraft and for the associated transponders on the ground by Radio Regulations footnote No. **5.438**.

The basic function of a radio altimeter is to provide accurate height measurements above the Earth surface with a high degree of accuracy and integrity during the approach, landing, and climb phases of aircraft operation representing a wide variety of reflectivity. Such information is used for many purposes and the high degree of accuracy and integrity of those measurements must be achieved regardless of the Earth surface, such as during final approach and flare guidance in the last stages of automated approach to land. It is also used to determine the particular altitude in which the aircraft can safely land and as an input to the terrain awareness warning system (TAWS), which gives a “pull up” warning at a predetermined altitude and closure rate; and as an input to the collision avoidance equipment and weather radar (predictive wind shear system), auto-throttle (navigation), and flight controls (autopilot).

Radio altimeter systems are designed to operate for the entire life of the aircraft in which they are installed. The installed life can exceed 30 years, resulting in a wide range of equipment age, performance and tolerance.

2 Altimeters

There are two types of radio altimeters in use today. One type utilizes Frequency Modulated Continuous Wave (FMCW) modulation, the second utilizes pulsed modulation. The following sections provide information regarding these types of radio altimeters.

2.1 Frequency Modulated Carrier Wave Altimeters

2.1.1 Operational description

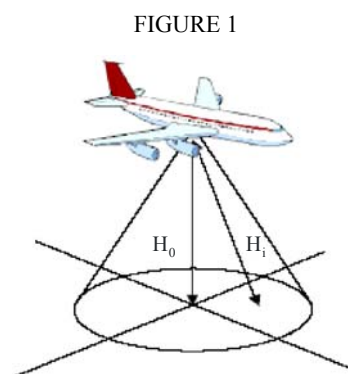
The purpose of a radio altimeter is to provide the aircraft with an accurate, independent and absolute measurement of the minimum distance to the Earth surface below that aircraft. Typically, radio altimeters have a measurement range from –6 metres to 6 000 metres (–20 feet to 19 685 feet). However, there are exceptions where some altimeters have a measurement range greater than 15 000 metres (49 213 feet). Radio altimeters are an essential component of aeronautical

safety-of-life systems, including precision approach, landing, ground proximity and collision avoidance systems. Radio altimeters are essential for landing on autopilot and in low-visibility conditions. Additionally, radio altimeters are employed when landing manually to help alert a pilot when to or automatically engage in a manoeuvre known as a “flare”, which is performed just before touchdown to lessen the force upon landing with the ground. A radio altimeter also functions as part of an aircraft’s terrain avoidance warning system providing predictive forward-looking capability on the flight deck, and if necessary a warning, when an aircraft descends beneath a certain altitude or too close to the ground.

Because of the importance of radio altimeters to the safe operation of an aircraft, they are included in the minimum equipment list on aircraft certified for passenger service. Furthermore, they must be certified at a safety criticality rating or Design Assurance Level (DAL) of “A”, “Where a software/hardware failure would cause and/or contribute to a catastrophic failure of the aircraft flight control systems” for all transport aircraft and a DAL of “B”, “Where a software/hardware failure would cause and/or contribute to a hazardous/severe failure condition in the flight control systems” for business and regional aircraft. Design assurance level is a safety criticality rating from level A to E, with level A/B being the most critical and requiring the most stringent certification process.

Radio altimeter systems on a single aircraft consist of up to three identical radio altimeter transceiver (Tx/Rx) units with their associated equipment. All Tx/Rx units operate simultaneously and independently from one another. The radio altitude is computed from the time interval a signal, originating from the aircraft, is reflected from the ground. Radio altimeters designed for use in automated landing systems are required to achieve an accuracy of 0.9 metres (3 feet). Several methods utilized either individually or in combination are used to avoid altimeter to altimeter mutual interference. First, the centre frequency of each altimeter can be offset. Second, transmissions can be offset in time. Third, transmissions can be offset by frequency bandwidth and/or modulation period. Using one or a combination of these options will cause the occupied bandwidth on a single aircraft to be greater than the required bandwidth of any single radio altimeter.

Figure 1 shows the location and direction of transmissions of the radio altimeter signal.



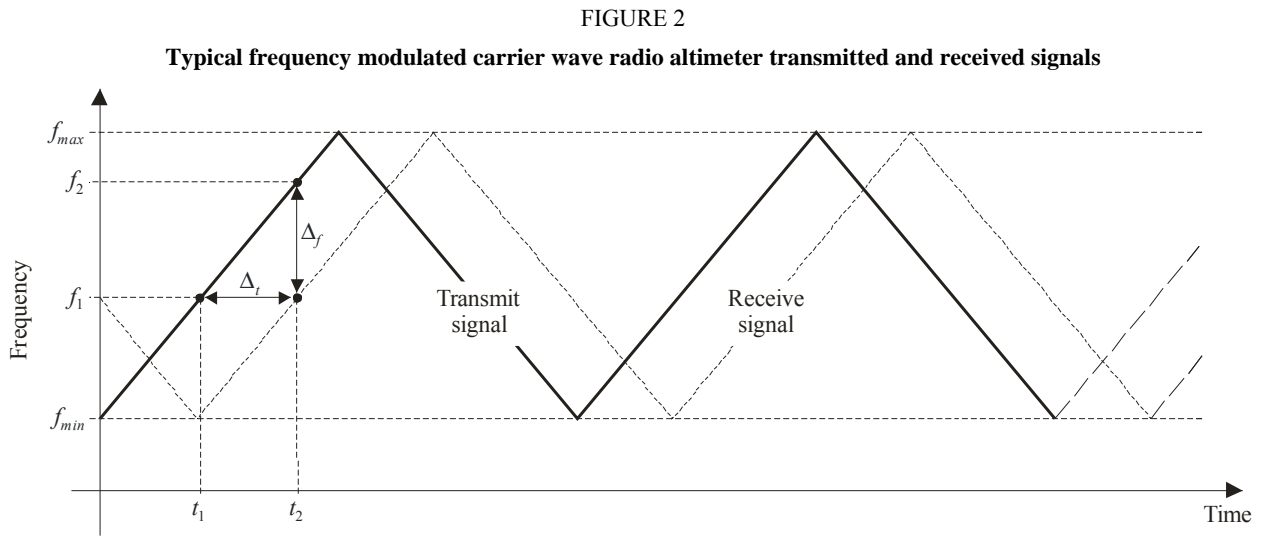
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2.1.2 Principles of operation

FMCW radio altimeters operate by a Tx/Rx working in conjunction with separate transmit/receive antennas. Operation requires a signal from the transmit antenna to be directed to the ground. When the signal hits the ground it is reflected back to the receive antenna. The system then performs a time calculation to determine the distance between the aircraft and ground, as the altitude of the aircraft is proportional to the time required for the transmitted signal to make the round trip.

The frequency modulated (FM) signal produced by the Tx/Rx is not tunable from the flight deck. The calculation is based upon the stipulation that a signal transmitted in the 4 200-4 400 MHz band will return at the same frequency. However, during the time it takes for the signal to travel to the ground and return, the transmitter frequency has changed. The difference between the transmit and receive frequencies (Δf) is directly proportional to the height of the aircraft above the ground and depends on the exact slope of the FMCW modulation (span vs. period) as shown in Fig. 2.

As illustrated by Fig. 2, an altitude is calculated by determining the difference between the frequency f_1 of the reflected signal and the frequency f_2 of the signal being transmitted at the instant t_2 the reflected signal is received. This difference frequency Δf is directly proportional to the time Δt required for the reflected signal to traverse the distance from the aircraft to the terrain and back to the aircraft.



M.2059-02

The period of the triangle FMCW waveform could be variable depending upon the altitude. At every instant, a beat signal is obtained by mixing the transmitted wave (with frequency f_2) and the received wave (with frequency f_1). The frequency Δf of this signal is equal to:

$$\Delta f = f_2 - f_1 \quad (1)$$

Knowing either Δt or Δf , the height above terrain can be calculated using the following formula:

$$H_0 = \frac{c\Delta t}{2} = \frac{c\Delta f}{2(df/dt)} \quad (2)$$

where:

- H_0 : height above the terrain (m)
- c : speed of light (m/s)
- Δt : measured time difference (s)
- Δf : measured difference in frequency (Hz)
- df/dt : transmitters frequency shift per unit time (Hz/s).

2.2 Pulsed altimeters

2.2.1 Operational description

Similar to FMCW, pulsed altimeters provide the aircraft with accurate, independent and absolute measurement of the minimum distance to the Earth surface below that aircraft. Typical pulsed radio altimeters have a range of reported altitude from –6 metres to 2 500 metres (–20 feet to 8 200 feet) and an operational altitude of 12 km (39 360 feet).

Any analysis of the aggregate effects of potential interferers must be computed at the Operational Altitude, where the altimeters continue to search for the ground and are vulnerable to interference that may result in a false altitude track. Functions of pulsed radio altimeters also include precision approach, landing, ground proximity and collision avoidance systems that are essential for landing on autopilot, and in low-visibility conditions, function as part of an aircraft's terrain avoidance warning system providing predictive forward-looking capability on the flight deck, and if necessary a warning, when an aircraft descends beneath a certain altitude or too close to the ground.

2.2.2 Pulsed altimeter principles of operation

The pulsed-type radio altimeter uses a pulse of radio-frequency energy transmitted towards the earth to measure the absolute height above the terrain immediately underneath the aircraft. The time difference between the transmitted pulse and the received pulse is measured. Where the velocity of propagations of electromagnetic energy is known and is a constant, the time is proportional to the height of the aircraft.

The function of the pulsed radar altimeter is to provide terrain clearance or altitude between the ground and the bottom of the aircraft. The pulsed altimeter may also provide vertical rate of climb or descent and selectable low altitude warning. Performance characteristics are designed to match particular applications where altitude tracking at high vertical rates may be necessary. Pulsed radar altimeters are also designed to support automatic landing and also auto-hover function on helicopters.

2.3 Application

Radio altimeters designed for use in automated landing systems are required to achieve an accuracy of 0.9 metres (3 feet) or more. Such elevation readings are transmitted to a pilot's visual display and to several automatic safety components. Radio altimeters provide an essential informational component of the automatic flight control system¹ for approach and landing, ground proximity warning system², terrain awareness and warning system³, flight management guidance computer, flight control systems, electronic centralized aircraft monitoring⁴ and engine-indicating and

¹ A system which includes all equipment to control automatically the flight of an aircraft to a path or altitude described by references internal or external to the aircraft.

² This system alerts the flight crew when certain thresholds are exceeded, such as excessive descent rate, between 50 and 2 450 feet radio altitude.

³ This is an enhanced version of the ground proximity warning system.

⁴ A system that monitors aircraft functions and relays them to the pilots. The system displays corrective action to be taken by the pilot, as well as system limitations after the failures.

crew-alerting system⁵. In addition, elevation information from radio altimeters is transmitted to the traffic collision-avoidance system and automatic dependent surveillance-broadcast system, which are used to monitor the airspace around an aircraft and to warn pilots of any threat of a mid-air collision.

Information from radio altimeters is especially critical in low-visibility conditions, but is always imperative. Generally, if a system's check before take-off indicates that the radio altimeters are non-functioning, a flight must be suspended. If the signal from the radio altimeters is lost during flight, the collision-avoidance and other safety systems listed above are significantly impaired. If the radio altimeters are not functioning properly when an aircraft is approaching and landing, autopilot systems would be unable to function properly. Under the best situation, a crew would manually fly the approach or divert to another airport. However, this increases crew workload and degrades the approach capability, which can result in a "go around" missed approach. Such repeated landing attempts can significantly impact already congested landing patterns, increase air traffic control workload and create safety concerns. In addition, for certain category airports and weather conditions, loss of the radio altimeter system would prevent the authorized landing of the aircraft. Thereby forcing the aircraft to either fly a holding pattern until weather improves or divert to another airport. Because of the importance of radio altimeter functions, the spectrum allocated and used by these devices must be protected from harmful interference and be sufficient to meet accuracy requirements.

2.3.1 Operational scenarios

Aircraft approach and landing

Analysing a typical landing profile from 18.5 km (10 nm) to the runway threshold for an aircraft, the avionic system components predominantly in use are the instrument/microwave landing systems, distance measurement equipment, satellite navigation systems radio altimeters, inertial reference systems and the air data computers providing barometric altitude and airspeed. The flight-management and flight-control computers continuously monitor sensor data input and correlate this data to ensure they are within specific parameter limits, particularly that the radio altimeter height readings between the sensors are correlated to be within tolerance. Auto-throttle is engaged; a stabilized approach with controlled descent rate and speed is maintained. At a pre-established height, the glide-path vertical information sensor data is phased out of the equation by the flight-management computer and the vertical height above the runway surface is provided by the radio altimeter with aural annunciation in feet to initiate flare of the aircraft to touchdown. The flare phase is controlled by the autopilot system using information from the radio altimeter. This flight profile can be achieved in normal or low-visibility conditions.

If an aircraft loses or receives erroneous radio altimeter data, several consequences can occur depending upon the aircraft type, airport landing requirements or classification, and weather. Loss of radio altimeter data will disable the autopilot resulting in the pilot and co-pilot manually flying and landing the aircraft. Some airport categories or certain weather conditions would prohibit the landing of some types of aircraft without altimeter data. If only one radio altimeter is operational, then the height above ground when the decision to land the aircraft is made must be adjusted to a higher altitude. If visibility is poor, then the aircraft might be forced to wait until the weather gets better or land at a different airport. If the radio altimeter signal receives harmful interference during the final stages of landing, then a hazardous or catastrophic situation could

⁵ A system used in modern aircraft to provide aircraft crew with engines' and other systems' instrumentation. The system displays corrective action to be taken by the pilot in the form of a "checklist".

occur. At best, the flight crew workload increases significantly; at worst the aircraft, crew and passengers are placed in a catastrophic situation.

Terrain avoidance and ground proximity warning systems

A ground proximity warning system (GPWS) onboard an aircraft provides an automatic and very distinctive aural warning to a flight crew when the aircraft is in close proximity to ground below the aircraft. Another type of ground proximity warning system is known as the terrain avoidance warning system (TAWS) which also provides distinctive aural warnings based on the level of ground proximity threat in front of the aircraft.

The design and intention of GPWS and TAWS is to prevent controlled flight into terrain (CFIT). Radio altimeters are integrated into the aircraft flight management computer systems and provide critical data, such as effective aircraft height above terrain to the GPWS and TAWS. Working together, the radio altimeter, TAWS and GPWS enable safe operations when flying close to terrain, typically during low visibility operations and precision approach and landings or in mountainous areas.

In accordance with ICAO Annex 6 – Part 1 Chapter 6, the GPWS provides time-critical alerts when flight conditions are hazardous. The TAWS with GPWS functions are required to provide the flight crew with immediate situational awareness of the aircraft's height above the ground.

GPWS alerts are radio altitude based, and derived from the inputs provided to the system and are available from 10 to 1 538 metres (30 to 5 000 feet). The aural annunciation modes are:

- Mode 1 Excessive descent rate and severe descent rate
- Mode 2 Excessive terrain closure rate
- Mode 3 Negative climb rate or altitude loss after take-off or go around
- Mode 4 Unsafe terrain clearance when not in the landing configuration
- Mode 5 Excessive deviation below an ILS glideslope
- Mode 6 Bank Angle callouts

All of these modes rely on the height above ground information provided by the radio altimeter in order to provide appropriate crew alerting (caution and warning) to avoid collisions, to avoid an aircraft landing with an incorrect aircraft configuration (gears or flaps in an incorrect position), and to provide the crew with information regarding the relative height of the aircraft with respect to the ground along its approach path. The expected accuracy on the height is in the range of 0.3 to 0.9 metres (1 to 3 feet).

Most of those modes are based on protection envelopes being defined in particular with the actual height provided by the radio altimeter.

By comparison, TAWS provides predictive and timely forward-looking alerts for potentially hazardous flight conditions involving terrain proximity and the potential for impact with the ground. Similar to the GPWS, the radio altimeter provides vertical data relative to the height of the aircraft above ground.

TAWS is mandated on all turbine-engine aircraft with a maximum certificated take-off weight over 5 700 kg, or authorized to carry more than nine passengers, and also on helicopters.

Failure in providing a correct height will most likely result in a hazardous or catastrophic situation by failing to alert the crew in a timely manner enabling them to take appropriate action to prevent ground collisions.

3 ICAO requirements

ICAO Annex 6 Part 1 Chapter 6 specifies the mandatory carriage of GPWS and TAWS with forward-looking terrain functions for certain aircraft weight categories. In addition to these requirements, many Administrations' aviation regulations and airworthiness requirements mandate the carriage of such equipment as it is directly related to airworthiness and certification dispatch requirements of an aircraft.

ICAO Annex 6 Part 1 Chapter 6 states:

“All turbine-engine aeroplanes of a maximum certificated take-off mass in excess of 15 000 kg or authorized to carry more than 30 passengers shall be equipped with a ground proximity warning system which has a forward looking terrain avoidance function. (other paragraphs have similar provisions for different weight categories of aircraft.)”

Annex 2

Technical characteristics

1 Technical description

1.1 Radio altimeter modulation and receiver sensitivity

Radio altimeters in use today utilize two types of radar waveform modulation methods known as linear frequency modulation – continuous wave or LFMCW or FMCW and pulsed modulation. The FM/LFMCW modulation waveform is used as the least complex way to provide exceptionally accurate altitude measurements at the critical altitudes before touchdown. This accuracy is required to provide smooth continuous data to the flight controls and autopilot for automated landings in conditions of limited visibility. This data is particularly critical when the pilot's view of the runway is restricted.

Radar altimeters have sensitive receivers with minimum detection thresholds as shown in Tables 1 and 2. The basic FMCW radio altimeter consists of a “homodyne” system that samples a fraction of the currently transmitted waveform and supplies it as a reference to the receiver mixer. This configuration directly down converts all received signals to a baseband receiver. While the signal processing bandwidth of the typical radar altimeter may be less than 100 Hz per altitude range bin, the overall receiver bandwidth can be several MHz wide depending on the chosen frequency modulation rate and the altitude delay time. More recent radio altimeter implementations apply digital signal processing of the down-converted and digitized signal. This post-processing of the received signal is usually done in the frequency domain. For that purpose the received and down-converted signal is applied to a fast Fourier transformation (FFT). After this transformation stage decision algorithms (generally proprietary) extract the height information from the signal. FMCW radars with a fixed duration of the triangle FMCW waveform measure range to a target via a linear relationship of the spectral frequency of the target in the wide band receiver bandwidth. The higher the spectral frequency of a detected target the greater the range to the target and the lower the spectral frequency of a target in the receiver passband, the shorter the range. FMCW radars with variable duration of the triangle FMCW waveform, measure range to a target via the duration of the period of the triangle waveform.

All FMCW radio altimeters determine altitude via spectral analysis or duration of the triangle FMCW waveform. Some radio altimeters use a method of “counting zero crossings” as a means of computing the dominant signal frequency while other radio altimeters use the digital processing technique of FFT and subsequently applied algorithms extracting the height information from the received signal.

It should be understood then that any interference that is unpredictable and that can mix with the linear FM waveform, thereby causing the radio altimeter to mistake the mixed signal as terrain has the potential to cause a radio altimeter to report a false altitude.

In those cases where the interfering modulation is spread across many megahertz of bandwidth as it mixes with the linear FM reference in the receiver mixer, the effect is to raise the noise floor of the FMCW radar receiver incrementally by the contribution of each received radiator. It is crucial to understand that the linearly varying frequency modulation causes a relatively narrow-band carrier that falls within or nearby to the edge of the altimeter modulation to be swept through some fraction of the radio altimeter receiver passband.

There are several pulsed radar altimeter examples in Tables 1 and 2. The pulse altimeter system includes a receiver-transmitter, integrated or remote height indicators, and various antenna options.

Aircraft altitude is determined by a pulsed altimeter by measuring the time delay between the transmitted and received pulse, reflected from the Earth’s surface. Some variations of pulsed altimeters have the advantage that they can use one antenna for transmit and receive. The antenna beam width of a dedicated radar altimeter antenna must be wide enough to accommodate normal roll and pitch angles of the aircraft, resulting in a significant variation in return delay. To provide the range to the nearest return within the bounds of the antenna beam, many pulsed radar altimeters incorporate a leading edge range tracker servo loop. The tracker functions to position the gate in a pulse modulated radar over the leading edge of the return.

For a pulsed altimeter, the height is given by half the product of the elapsed time and the speed of light ($h = (c \cdot t)/2$ where h is the aircraft altitude, c is the speed of light and t is the elapsed time between transmission and reception). A time reference signal is fed from the transmitter to initiate a precision ramp generator. The ramp voltage is compared with the range voltage which is proportional to the indicated height.

It is critical to note that any evaluation of the aggregate effects of potential interferers using the altimeter band must use the “Operational Altitude” stipulated in Tables 1 and 2 and not the “Range of Reported Altitude”. Use of the “Operational Altitude” is justified because all radio altimeters continue to operate in an altitude search mode the entire time they are flown beyond their “Reported Altitude Range”. As a result, during altitude search mode radio altimeters are vulnerable to detection of interferers as false altitudes that would in turn cause inappropriate reactions among radio altitude dependent systems such as Ground Proximity Warning, Weather Radar, TCAS, Flight Controls and other critical systems.

1.2 Radio altimeter antenna pattern

All radio altimeters use an antenna design that provides 8 to 13 dBi of gain and between 35 and 60 degrees of coverage to the 3 dB point (half power) of the antenna pattern. These wide antenna beams are made necessary by the wide range of pitch and roll angles that can be performed by an aircraft in flight. The antenna pattern is essentially cone shaped and is linearly, horizontally polarized. However the actual orientation of the H polarized radiation in terms of pointing N, S, E, W depends entirely on the flight vector of the aircraft. Cross-polarization isolation to vertically polarized signals is not specified in any production radio altimeter antenna and cannot be depended

on to provide any measure of protection to the altimeter from interference by choosing a vertically polarized transmission.

The fact that all radio altimeter antennas are necessarily pointed at the Earth's surface makes the system vulnerable to all possible interference sources illuminated during approach. The altimeter antennas, due to their location on an aircraft, do not have the benefit of being shielded or screened from many of the possible interference sources on the Earth's surface. Instead it can virtually "see" all possible radiation sources as they escape buildings and via direct transmission from devices operating outside of any structure.

The peak gain, as provided in Tables 1 and 2, of the radio altimeter antenna should be used if propagation paths are within $\pm 30^\circ$ of a vector orthogonal to the bottom of the aircraft. Sharing and compatibility studies shall take into account the fact that aircraft angle position can reach $\pm 45^\circ$ in roll and $\pm 20^\circ$ in pitch. Outside this angle range, the gain of the radio altimeter should be based on antenna characteristics (see Tables 1 and 2).

1.3 Measurement accuracy

Absolute measurement accuracy requirements are specified in RTCA DO-155 "Minimum Performance Standards – Airborne Low-Range Radar Altimeters" as well as EUROCAE ED30 which specify measurement accuracy to be within 0.9 metres (3 feet) at altitudes below 46 metres (150 feet). ARINC 707 requires a measurement accuracy, when measured in accordance with RTCA DO-155, be within 0.45 metres (1.5 feet) or 2%, whichever is greater, at the indicated altitude throughout the range of -6.1 to 762 meters (-20 to 2 500 feet) altitude. Such accuracy requirements within the bandwidth available are achieved utilizing data processing techniques of the signal. However, such techniques are only possible with exceptionally high signal-to-noise ratios and over the flat surface of the runway at low altitudes. For specific bandwidth usage, see Tables 1 and 2.

1.4 Unit-to-unit interference prevention – Frequency offset

Some aircraft employ up to three radio altimeters simultaneously. Multiple altimeters are required to provide protection against the probability of false altitude data being accepted by the autopilot or flight control system of less than 1×10^{-9} (1 in 1 billion) occurrences. In order to allow three simultaneous radio altimeters to coexist with their antennas installed within a few feet of each other, many radio altimeter systems operate with an offset centre frequency to decrease the probability of mutual interference. Generally, the frequency offset is approximately 5 MHz. Therefore, if two altimeter systems are installed on a single aircraft, an additional 5 MHz is required while for aircraft with three altimeter systems, an additional 10 MHz is required.

1.5 Frequency stability of radio altimeters

A vast number of radio altimeters in operation are based on "open loop" linear frequency modulation of a voltage controlled oscillator (VCO) that operates at a centre frequency of approximately 4 300 MHz with frequency stability of typically up to ± 25 MHz over a temperature variation of -55° to $+70^\circ\text{C}$.

2 Total required radio altimeter bandwidth

In order to determine the bandwidth utilized by an aircraft's radio altimeter system, several factors must be considered. First, the chirp bandwidth must be combined with the frequency stability of the radio altimeter. Given the criticality of the radio altimeter system to the safety-of-life and property,

it is recommended that the -40 dB drop-off bandwidth be utilized to determine the transmission signal bandwidth. Third, an operational or installation factor must be included. On a large aircraft two or three altimeter systems are employed and these systems could utilize a frequency offset of 5 MHz to 10 MHz. Note also that the reception bandwidth should, at a minimum, include the emitter bandwidth in all operating conditions; and in particular the drift due to temperature range.

If an aircraft has more than one radio altimeter installed onboard, the centre frequency cannot always be 4 300 MHz. On an aircraft with two or three radio altimeters, the altimeters can operate with two or three centre frequencies offset from 4 300 MHz to avoid interfering with each other. Altimeter systems can also offset the timing, period or span. In this manner, the utilized bandwidth on each aircraft is greater than the bandwidth of any single radio altimeter.

Pulsed radar altimeters use spread spectrum techniques to achieve the required accuracy and signal integrity which may use the full 200 MHz bandwidth available in the frequency band 4 200-4 400 MHz.

Furthermore, radio altimeters operate in wide bandwidths to achieve the necessary accuracy levels, which are especially important for the automatic flight control system used for the approach and landing of aircraft. Reducing the available frequency bandwidth proportionately reduces the accuracy of radio altimeters.

FMCW radar altimeters receivers employ a bandpass filter which is meant to reject high intensity radiated field (HIRF) transmissions outside the operating band from degrading or damaging the radio altimeter performance. However, the bandpass filter has limited ability to reject transmissions close to the desired band. As a result, altimeter performance may be affected by signals at the edge of the band.

Tables 1 and 2 provide technical characteristics for representative analogue and digital FMCW radio altimeters.

TABLE 1 (continued)

	Radio altimeter A1	Radio altimeter A2	Radio altimeter A3	Radio altimeter A4	Radio altimeter A5	Radio altimeter A6	Units
Centre frequency offset between individual radio altimeter systems	5	5	0	Not applicable	Not applicable	Not applicable	MHz
Waveform repetition frequency	49 to 51 Hz	150 Hz	12 Hz to 1 623 Hz	10 000 pps	20 000 pps	6 000 pps	Hz or pps (pulse per second)
Pulse width	Not applicable	Not applicable	Not applicable	130	200	75	ns
3 dB emission bandwidth	110	162.8	171	8	7	15	MHz
20 dB emission bandwidth	120	170	181	44	29	51	MHz
40 dB emission bandwidth	180	180	191	130	108	131	MHz
Receiver							
Sensitivity*	-120	< -113	≤ -120	-95	-95	-95	dBm
Noise Figure	10	6	6	10	10	10	dB
$P_{T,RF}$ Input Power Threshold Receiver Overload	-30	-53	-56	-40	-40	-40	dBm
-3 dB Intermediate Frequency (IF) bandwidth	2	0.25	0.025 to 2	9.2	6.0	16	MHz

TABLE 1 (*end*)

	Radio altimeter A1	Radio altimeter A2	Radio altimeter A3	Radio altimeter A4	Radio altimeter A5	Radio altimeter A6	Units
Antenna							
Antenna gain	10	10 typical, 9.5 minimum	10 typical, but different antenna could be used	13	11	11	dBi
Cable loss (single path)	6	6	2 to 7	6	6	6	dB
-3 dB beam width	40 to 60	55	45 to 60	35	45	45	degrees

* For some of the radio altimeters listed above, the receiver noise power level, calculated based upon IF bandwidth and noise figure, is higher than the receiver sensitivity level. In these cases, the detector bandwidth of the radio altimeter, which is generally lower than the IF bandwidth, determines the receiver sensitivity level.

TABLE 2
Digital radio altimeters

	Radio altimeter D1	Radio altimeter D2	Radio altimeter D3	Radio altimeter D4	Units
Transmitter					
Nominal centre frequency	4 300	4 300	4 300	4 300	MHz
Transmitted power (peak)	0.400	0.100	0.1 to 1	5	W (peak)
Modulation	FMCW	FMCW	FMCW	Pulsed	
Chirp bandwidth excluding temperature drift	150	176.8	133	Not applicable	MHz
Range of reported altitude	-6 to +1 676 (-20 to +5 500)	-6 to +1 737 (-20 to +5 700)	-6 to 6 000 (-20 to +19 685)	-6 to 2 424 (-20 to +8 000)	Metres/(feet)
Operational altitude	12	12	20	12	km
Temperature range	-40 to +70	-40 to +70	-40 to + 71	-40 to + 71	Celsius
Frequency stability	±50	±30	±5	Not applicable	ppm
Maximum frequency drift over the operational temperature range	±0.22	±0.129	±0.22	Not applicable	MHz
Typical number of systems fitted	2 or 3	2 or 3	1 or 2	1 or 2	Per aircraft

TABLE 2 (continued)

	Radio altimeter D1	Radio altimeter D2	Radio altimeter D3	Radio altimeter D4	Units
Sharing principle for dual and triplex radio altimeter installations	Frequency span set according to installed SDI (offset -2.5, 0, or +2.5 MHz). Waveform timing adjusted on receipt of interference. Signal processing used to mitigate effect of cross over IF pulse.	System installation number (1,2,3) determines a frequency offset of -5 MHz, 0 MHz or +5 MHz. Each system number selects a linear frequency hop pattern to avoid mutual interference among aircraft	Not applicable	Not applicable	
Pulse width	Not applicable	Not applicable	Not applicable	30 or 225	ns
Waveform repetition frequency	143 Hz Fixed	1 000 Hz Fixed	100 Hz to 4 700 Hz	25 000 pps	Hz or pps (pulses per second)
3 dB emission bandwidth	150	177	175	5 or 31	MHz
20 dB emission bandwidth	153	180	185	26 or 105	MHz
40 dB emission bandwidth	180	190	196	106 or 195	MHz
Receiver					
Sensitivity*	< -114	< -125	≤ -120	-95	dBm
Noise figure	8	9	8 to 12	10	dB
$P_{T,RF}$ Input Power Threshold Receiver Overload	-30	-43	-53	-40	dBm

TABLE 2 (*end*)

	Radio altimeter D1	Radio altimeter D2	Radio altimeter D3	Radio altimeter D4	Units
–3 dB Intermediate Frequency (IF) bandwidth	0.312 MHz (LPF – Single sided)	1.95 MHz	0.1 to 2.0	30	MHz
Antenna					
Antenna gain	11	10	8 to 11	13	dBi
Cable loss (single path)	6 (10 max)	0	2 to 7	0 to 2	dB
–3 dB beam width	40 to 60	45 to 60	45 to 60	45	degrees

* For some of the radio altimeters listed above, the receiver noise power level, calculated based upon IF bandwidth and noise figure, is higher than the receiver sensitivity level. In these cases, the detector bandwidth of the radio altimeter, which is generally lower than the IF bandwidth, determines the receiver sensitivity level.

Annex 3

Protection criteria and its application in sharing and compatibility

1 Introduction

The protection requirements and criteria described below will protect radio altimeters from harmful interference effects that can cause loss of altitude accuracy or cause false altitude measurements. Interference can occur from out-of-band and in-band interference sources. Both types of sources can create many deleterious effects including receiver desensitization, overload, false altitude reports, and general failure; depending on the duration and characterization of the interference. To this end, a number of interference-induced failure modes are described and analysed, and protection criteria established.

Perhaps the most deleterious effect to a radio altimeter due to harmful interference occurs when the interference signal is interpreted by the radio altimeter as a false ground signal, thereby giving an incorrect altitude reading. This case can only be handled on a case-by-case basis with each representative radio altimeter and each type of potential interference source because the effect is highly dependent on the combination of the interferer and the radio altimeter characteristics.

An interfering transmitter may cause harmful interference by introducing unwanted emissions within the intermediate frequency (IF) bandwidth that will be measured as invalid altitudes by the radio altimeter. Interference can also result in an increase in the noise floor, thereby creating a loss of receiver sensitivity and subsequent ability to determine the correct altitude.

2 Protection criteria

Any compatibility analysis between radio altimeters and other systems must utilize protection criteria for the maximum acceptable degradation for a radio altimeter. There are three primary electromagnetic interference coupling mechanisms between radio altimeters and interfering signals from other transmitters: receiver overload, desensitization, and false altitude generation. Also, both out-of-band and in-band interference can affect a radio altimeter performance. While one or more types of impact are more likely to occur with an in-band vs. out-of band interference source, there are no clear demarcations to determine which type of impact will occur. Therefore, all factors must be accommodated when conducting sharing studies.

2.1 Receiver front-end overload

Receiver front-end overload occurs when sufficient power from an interfering signal saturates the front-end of a radio altimeter receiver causing the inherent effects of non-linear behaviour; for example, harmonic distortion or intermodulation. A radio altimeter front-end generally has modest selectivity (gradual RF-filter roll-off). Therefore a radio altimeter is susceptible to interference both within its operational swept bandwidth as well as from outside this bandwidth.

The potential interference to the radio altimeter front-end will exist whenever:

$$I_{RF} \geq P_{T,RF} \quad (3)$$

where:

$$I_{RF} = \sum_i (I_{i,RF} * FDR_{i,RF}) \quad (4)$$

- I_{RF} : Total peak interference signal power at receiver input (the sum of all individual interference contributors at the antenna output after considering the cable loss and the frequency dependent rejection (FDR) factor (mW)
- $P_{T,RF}$: Input power threshold at which receiver front-end overload occurs (mW)
- $I_{i,RF}$: Power of the i^{th} interference source at the input to the receiver after considering cable loss (mW)
- $FDR_{i,RF}$: Receiver front-end FDR factor given by the filter characteristics shown in Table 3 below, representing the attenuation to be applied to the i^{th} interference signal (see Recommendation ITU-R SM.337).

TABLE 3

RF selectivity for radio altimeters

Interference frequency (MHz)	RF filter attenuation (dB)
$\leq 4\ 200$	Attenuated at 24 dB per octave to a maximum of 40 dB
4 200	0
4 300	0
4 400	0
$\geq 4\ 400$	Attenuated at 24 dB per octave to a maximum of 40 dB

Note that $P_{T,RF}$ is generally the receiver 1 dB compression point, as referenced to the receiver input port (as opposed to the low noise amplifier (LNA) output). This quantity is a model-dependent property that must be identified uniquely for each altimeter type from its data sheet; the values for candidate altimeters are given in Tables 1 and 2.

2.2 Receiver desensitization

The desensitization effect is related to the intensity of the interfering signal that falls into the IF bandwidth of the radio altimeter. What complicates the issue of desensitization of a radio altimeter is that the RF spectrum related to the IF bandwidth by mixing is not constant in time, because radio altimeters operate in a homodyne configuration using a linear frequency-modulated signal. Thus, the impact of interference toward desensitization of a radio altimeter receiver is time dependent according to the technical characteristics of the specific radio altimeter.

The effect on a radio altimeter from in-band interference sources is related to the power of the interfering signals in the receiver IF bandwidth.

When considering I , the interference power within IF bandwidth (after mixing the received interference signal with the linear FM chirp), the radio altimeter performance is considered degraded when the interfering signal causes a noise floor increase within the RA receiver of 1 dB.

This corresponds to an I/N of -6 dB where the effective receiver thermal noise power, that should be considered to conduct the protection analysis within the IF bandwidth of the radio altimeter, is given by:

$$N = -114 \frac{\text{dBm}}{\text{MHz}} + 10 \log(B_{R,IF}) + N_F \tag{5}$$

with:

$B_{R,IF}$: IF bandwidth of the radio altimeter (MHz)

N_F : Noise figure at receiver input (dB).

In determining compatibility based on desensitization within the IF bandwidth, the interference power threshold $I_{T,IF}$ at which the radio altimeter performance starts to degrade is defined as:

$$I_{T,IF} \geq N - 6 \text{ dB} \quad (6)$$

The Interference Duty Cycle is the ratio of I (the interference power within the IF bandwidth) to I_{RF} (the total interference power received). It describes the effect of mixing a fixed-frequency interference signal with a linear FM waveform followed by subsequent IF low pass filtering.

To define the Interference Duty Cycle, several additional parameters have to be defined:

f_1 : Lowest swept frequency of the radio altimeter (MHz)

f_2 : Highest swept frequency of the radio altimeter (MHz)⁶

B_S : Chirp bandwidth

f_{ci} : Centre frequency of an interference source (MHz).

For fixed-frequency interference sources, the Interference Duty Cycle is defined by:

$$R_s = \frac{2B_{R,IF}}{B_S} \quad (7)$$

provided that:

$$f_1 < f_{ci} < f_2$$

The minimum and maximum sweep frequency, f_1 and f_2 respectively, can be located anywhere in the band 4 200 to 4 400 MHz, provided that the sweep bandwidth and adjacent band protection criteria are not violated.

The amount of interference signal power that is captured by the IF of the receiver is proportional to R_s (the Interference Duty Cycle). Thus the relation between $I_{T,RF}$ and the RF-referred interference threshold $I_{T,IF}$ is then defined by:

$$I_{T,RF} = I_{T,IF} - 10 \log(R_s) \quad (8)$$

Should the calculated aggregated interference exceed the threshold at which desensitization of the receiver occurs ($I_{T,RF}$) then harmful interference would occur.

In cases where the interference is not continuously transmitted or where the interference frequency changes with time, the transmitted interference should be treated as if it was a continuously transmitting source because interference generated by any variable waveform has the opportunity to cause either the loss of any single altitude measurement (due to degraded performance) or cause a false altitude computation to occur for any single measurement that in turn is included in the overall estimate of the altitude. Altitude measurements made inaccurate via increases in noise level or false altitudes generate “out of bounds” values that seriously offset an altitude measurement that would otherwise have been accurate.

⁶ Note that $f_1 = 4.3\text{GHz} - 0.5*B_S - \text{Max Frequency Drift}$, $f_2 = 4.3\text{GHz} + 0.5*B_S + \text{Max Frequency Drift}$, where Chirp Bandwidth (B_S) and Max Frequency Drift are defined in Tables 1 and 2.

2.3 False altitude reports

A false altitude report is a serious radio altimeter error that may cause critical aircraft systems such as ground proximity warning, weather radar, traffic collision avoidance system (TCAS), flight controls and other critical systems to respond inappropriately.

In the case of FMCW-based radio altimeters, false altitude reports occur when interference signals are detected as frequency components during spectral frequency analysis of the overall IF bandwidth.

The FMCW altimeter local oscillator (LO) signal provided to the receiver mixer is swept from f_1 to f_2 as defined in equation (7) above. The receiver mixer will subtract the LO instantaneous frequency from the incoming interference signal f_{ci} . When the absolute value of the difference between the swept LO frequency and the interferer frequency f_{ci} falls between 0 Hz and the IF bandwidth ($B_{R,IF}$) potential false altitudes will be generated in the spectral frequency analysis.

The magnitude of the spectral components and the bandwidth of the resulting interfering signal spectra will be dependent on the strength of the received interference level and the fraction of time the resulting difference signals remain within the IF bandwidth.

Thus the received interference power must be adjusted by the amount of time the interference signal is present in the final signal processing bandwidth, which is the detector bandwidth. The resulting interference power at the detector stage is then given by:

$$I_D = I_{RF} - 10 \log \left(\frac{2 * 100 \text{ Hz}}{B_S} \right) \quad (9)$$

Where a 100 Hz detection bandwidth is considered representative:

I_D : Interference power at the detector

B_S : Chirp bandwidth.

If the magnitude of the spectral components caused by the interference signal rises above the detection threshold of the altimeter ($I_{T,FA}$), then they may falsely be regarded as valid altitudes by the altimeter and there will be no means to exclude them from the altitude calculation.

In practice, I_D (the interference power at the detector) would cause false target spectral components within the FMCW receiver signal processing chain if it exceeds the protection threshold $I_{T,FA}$

$$I_{T,FA} = -143 \text{ dBm considering } 100 \text{ Hz detector bandwidth following the instantaneous altimeter LO frequency.}$$

Formally:

If $I_D < I_{T,FA}$ then no spectral components and no false targets would exist.

If $I_D > I_{T,FA}$ then spectral components would exist causing false altitudes.

Potential spectral components of the interferer lie within the overall IF bandwidth $B_{R,IF}$ and hence may be processed in the detector when:

$$|f_{ci} - f_{LOi}| < B_{R,IF} \quad (10)$$

where:

f_{ci} : Centre frequency of the potential interference source (MHz)

f_{LOi} : Any instantaneous frequency between f_1 and f_2 defined in § 2.2 above.

In addition, in no case shall the power spectral density of the Interferer (I_{PSD}) be greater than the P1dB Power Spectral Density limit of the FMCW Receiver (P_{1dBSD}):

$$I_{PSD} < P_{1dBSD} \quad (11)$$

with:

$$I_{PSD} = P_{RI} - 10 \log(B_i)$$

where:

P_{RI} : received interference power at f_{ci} (dBm)

B_i : the –40 dB bandwidth of the interferer (Hz)

$$P_{IdBSD} = P_{T,RF} - 10 \log(B_{R,IF}) \quad (12)$$

where:

$P_{T,RF}$: Input Threshold Receiver Overload (see Tables 1 and 2).

3 Compatibility study considerations and summary of protection criteria

Radio altimeters are operational during all phases of flight, including ground manoeuvres. Thus, when considering sharing scenarios, it is important that all the possible interference sources are aggregated appropriately. Various scenarios from ground level up to 12 km should be considered in sharing studies. The total interference to the radio altimeter will depend on the number and the spectrum characteristics of interference sources, their spatial distribution, and their relative antenna gains. Due to the altitude above ground at which aircraft fly, the impact of aggregated interference located on the ground could be substantial and could create harmful interference to the radio altimeter.

The peak gain, as provided in Tables 1 and 2 of the radio altimeter antenna should be used if propagation paths are within $\pm 30^\circ$ of a vector orthogonal to the bottom of the aircraft. Sharing studies shall also take into account the fact that aircraft altitudes can reach $\pm 45^\circ$ in roll and $\pm 20^\circ$ in pitch. Outside of this range, the gain of the radio altimeter antenna should be based on the antenna characteristics (see Tables 1 and 2). In determining the propagation path loss with terrestrial systems, direct line-of-sight propagation must be used due to the unobstructed path between the ground and an aircraft flying overhead. If the calculated worst aggregate interference exceeds any of the protection criteria defined below for desensitization, front-end overload, false altitudes or power spectral density, then harmful interference will be present in the radio altimeter.

Due to the fact that radio altimeters provide a safety-of-life service, harmful interference needs to be avoided when the aircraft is in operation. In order to avoid harmful interference the following protection criteria have to be fulfilled in flight critical operating scenarios:

Desensitization: $I/N = -6$ dB

Front End Overload: $I_{RF} \leq P_{T,RF}$ as defined in Tables 1 and 2

False Altitudes (for FMCW Altimeters only):

$$I_D < I_{T,FA}, \text{ where } I_{T,FA} = -143 \text{ dBm/100 Hz following the instantaneous altimeter local oscillator}$$

Due to the critical safety-of-life function performed by radio altimeters, an additional safety margin added to the protection criteria may be necessary as a means to maintain the high reliability requirements of this application. The level of the safety margin, if any, to be applied to radio altimeters operating in the band 4 200-4 400 MHz, is to be established on the basis of further study.