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TNO report

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Engineering Assessment of Effects on TACAN at Florennes AFB due to Wind Farm Walcourt 2

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Contents

1 Introduction

The performance of a TACtical Air Navigation (TACAN) system, might be negatively influenced by wind turbines in the vicinity. Luminus has requested TNO to perform an Engineering Assessment to investigate the influence of a new wind farm Walcourt 2 on the Florennes Air Force Base (AFB) TACAN system.

In Chapter 2 the relevant input parameters of the wind turbines and TACAN system are given.

Chapters 3 and 4 serve as a reference to the working principles of a TACAN system and the calculation of the radio wave reflections from wind turbines and the direct and indirect propagation paths that are relevant for this assessment.

The results of the assessment are shown as follows:
- Chapter 5: Line-of-sight analysis
- Chapter 6: DME range measurement errors
- Chapter 7: Bearing measurement errors

The main conclusions are given in Chapter 8.

2 Input Parameters

2.1 Wind turbines

The engineering assessment is carried out for the wind turbines shown in Figure 2.1. The orange marked dots WT1, WT2, WT3, and WT4 indicate the wind turbines of the windfarm Walcourt 2 under investigation. The green dots represent the locations of the 10 wind turbines of the Walcourt 1 wind farm (W1-1 to W1-6) which serve as the reference situation within this engineering assessment.

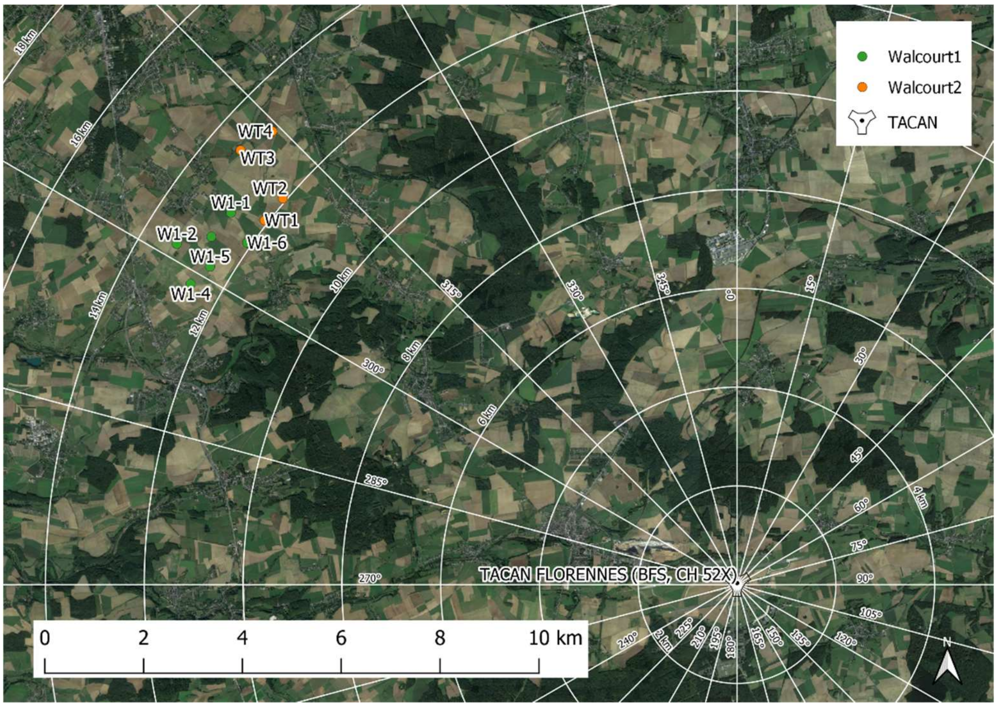


Figure 2.1 The locations of a newly planned windfarm Walcourt 2 (orange) as well as the locations of the wind turbines of the Walcourt 1 windfarm (green). Background image is taken from Google Earth.

The positions and dimensions of the newly planned wind turbines (WT1 to WT4) are presented in Table 2.1. The information has been provided by Luminus. The wind turbines will have a maximum tip height of 150 m above ground level (AGL). A maximum rotor diameter of 119 m has been taken into account.

The positions and dimensions of the existing and granted wind turbines of Walcourt 1 are presented in Table 2.2. This information has been provided by Luminus.

Table 2.1 Overview of the positions of the four newly planned wind turbines. The X, Y coordinates have been provided by Luminus. The longitude and latitude have been derived from the Lambert72 coordinates. The terrain height, reference to EGM96, has been derived from the SRTM1 altitude database.

Nr.	ID	Lambert'72 X [m]	Lambert'72 Y [m]	Terrain Height EGM96 Z [m]	Lat. WGS84 [°]	Lon. WGS84 [°]	Hub Height AGL [m]	Tip Height AGL [m]
1	WT1	160731	110787	234	50.30799	4.51939	91.5	150.0
2	WT2	161100	111231	228	50.31197	4.52458	91.5	150.0
3	WT3	160244	112207	198	50.32076	4.51259	91.5	150.0
4	WT4	160890	112590	207	50.32419	4.52167	91.5	150.0

Table 2.2 Overview of the positions, type and tip heights of the existing wind turbines within a 20 km distance from the four newly planned wind turbines which have been provide by Luminus. The longitude and latitude have been derived from the Lambert72 coordinates provided by Luminus, and the hub height from the type and tip height. The terrain height has been derived from the SRTM1 altitude database.

Nr.	ID	Lambert'72 X [m]	Lambert'72 Y [m]	Terrain Height EGM96 Z [m]	Lat. WGS84 [°]	Lon. WGS84 [°]	Hub Height AGL [m]	Tip Height AGL [m]
1	W1-1	160049	110940	229	50.30937	4.50982	85	123.5
2	W1-2	158955	110308	239	50.30371	4.49444	85	123.5
3	W1-3	159652	110455	241	50.30502	4.50423	85	123.5
4	W1-4	159234	109503	231	50.29647	4.49834	85	123.5
5	W1-5	159629	109850	237	50.29958	4.50389	85	123.5
6	W1-6	160379	110335	238	50.30393	4.51443	85	123.5

2.2 TACAN System Florennes

The analysis is done for the TACAN navigation system at Florennes AFB. The system parameters that are relevant for this study are presented in Table 2.3. This information has been taken from the eAIP of Belgium and Luxembourg [1]. According the the eAIP the TACAN uses channel 52X, which implies transmission at 1013 MHz while it receives interrogation signals at 1076 MHz.

Table 2.3 Relevant system parameters of the TACAN Florennes taken from eAIP Belgium and Luxembourg [1].

Parameter	Value
ID	BFS
Frequency	CH 52X
Latitude (WGS84)	50°14'29.1" N
Longitude (WGS84)	4°39'11.7" E
Elevation	952 ft

In Lambert'72 coordinates the location of the TACAN is converted as shown in Table 2.4.

Table 2.4. TACAN location converted from WGS84 to Lambert'72 coordinates.

Parameter	Value
Lambert'72 X [m]	170295
Lambert'72 Y [m]	103409
Height EGM96 Z [m]	290

Figure 2.2 shows the location of the TACAN at the Florennes AFB as well as a zoomed image.

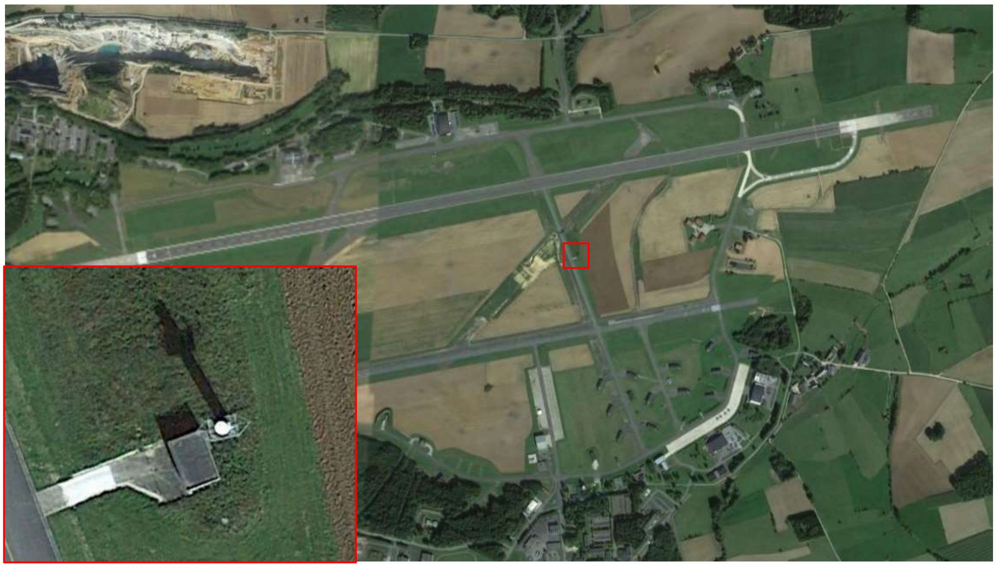


Figure 2.2. Location of the Florennes TACAN. Imagery is taken from Google Earth.

2.3 Terrain data model

For consistency reasons the terrain elevation data as used in TNO's simulation environment is based on the validated US Shuttle Radar Topography Mission[1] (SRTM1) with 1 arc-second resolution. The elevations might deviate from a locally published terrain elevation map.

[1] For the line-of-sight analysis the data from the Shuttle Radar Topography Mission (SRTM1) is used. This database contains terrain altitude information with respect to the EGM96 geoid. The database was determined by NASA using high-resolution radar carried on the Space Shuttle. The SRTM1 data has a resolution of 1 arcseconds, which corresponds to a horizontal resolution of about ~20 m at 51 degrees latitude.

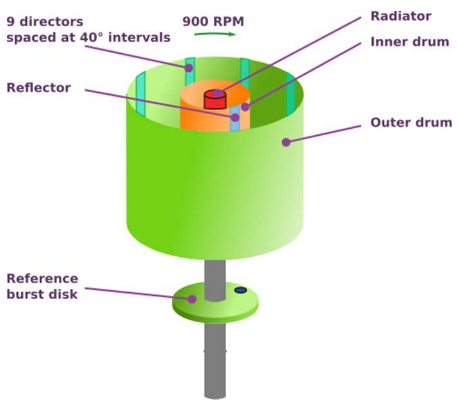
3 TACAN

This chapter provides an easy to read explanation of TACAN. It is largely an amalgamation of [2], [3], and [4].

TACAN stands for Tactical Air Navigation System and is a navigation system for military use. The TACAN is a military radio navigation aid to determine aircraft relative range and bearing. Bearing and distance signals require only a single transceiver on the ground and on the aircraft. They also use the same UHF frequency.

The TACAN shape is (has been for a long time) a vertical cylinder, see Figure 3.1a.

a. A US Air Force TACAN antenna, from [4]



b. Rotating parasitic elements in TACAN antenna, from Reference [2].

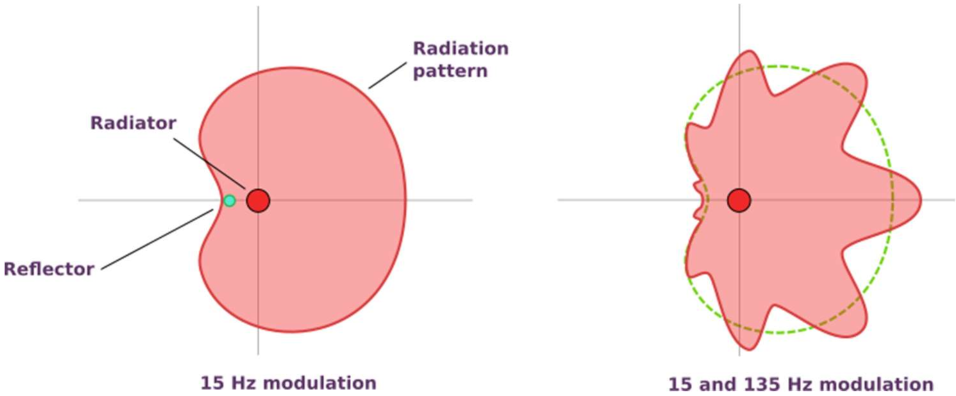
Figure 3.1 The TACAN antenna.

A rotating drum with a reflector electrically adjusts the radiation pattern, adding a signal dip (low gain) that rotates at 900 RPM, which is equivalent to a 15 Hz amplitude modulation. The radiation pattern in the horizontal plane takes the shape of a cardioid, as is shown in Figure 3.2a. Another drum with a set of 9 directors, mechanically linked to the first one, creates a 135 Hz (9x15) additional amplitude ripple over the 15 Hz modulation, as is shown in Figure 3.2b.

The TACAN does not transmit a signal continuously, but the signal is keyed (transmitter switched on/off) by bursts of information. There are five different burst types:

- Main Reference Burst (MRB)
- Auxiliary Reference Burst (ARB)
- Responses to DME interrogations
- Burst for identification of the TACAN
- Squitter bursts

For TACAN systems with X channels all burst types contain one or more pulse pairs with a pulse repetition interval of 12 μs as shown in Figure 3.3.



a. A US Air Force TACAN antenna, from [2]. b. Rotating parasitic elements in TACAN antenna, from [2].

Figure 3.2 TACAN 15 Hz and 135 amplitude modulation patterns.

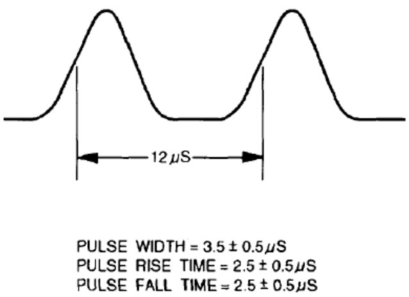


Figure 3.3 TACAN interrogation pulse pair, from [5].

3.1 Main Reference Burst

While the antenna drums rotate, the ground station transmits a Main Reference Burst (MRB) that informs receivers that the antenna faces the reference direction, usually the magnetic north. For an X channel TACAN the MRB contains 12 pulse pairs with 12 μs spacing between the pairs. This burst is transmitted at a rate of 15 Hz (i.e. at every antenna rotation).

By comparison of the phase of the 15 Hz modulated signal during reception of the MRB, the aircraft is able to determine its own bearing relative to the station. For example if the receiver senses that the received signal is weakest during reception of the MRB, it knows that it is located south of the TACAN.

3.2 Auxiliary Reference Burst

To be able to refine the bearing estimation, the TACAN also transmits Auxiliary Reference Bursts (ARB) at a rate of 135 Hz at the magnetic directions 040°, 080°, 120°, 160°, 200°, 240°, 280°, and 320°. For an X channel TACAN the ARB contains 6 pulse pairs with 24 μs spacing between the pairs. Therefore the ARB can be distinguished from the MRB.

By comparison of the phase of the 135 Hz modulated signal during reception of the ARB, the aircraft is able to determine its own bearing relative to the station within a 40° sector as is already known from the bearing estimation on the 15 Hz signal.

Figure 3.4 shows the 15 Hz and 135 Hz modulations and the phase of these modulations during the reception of the reference bursts.

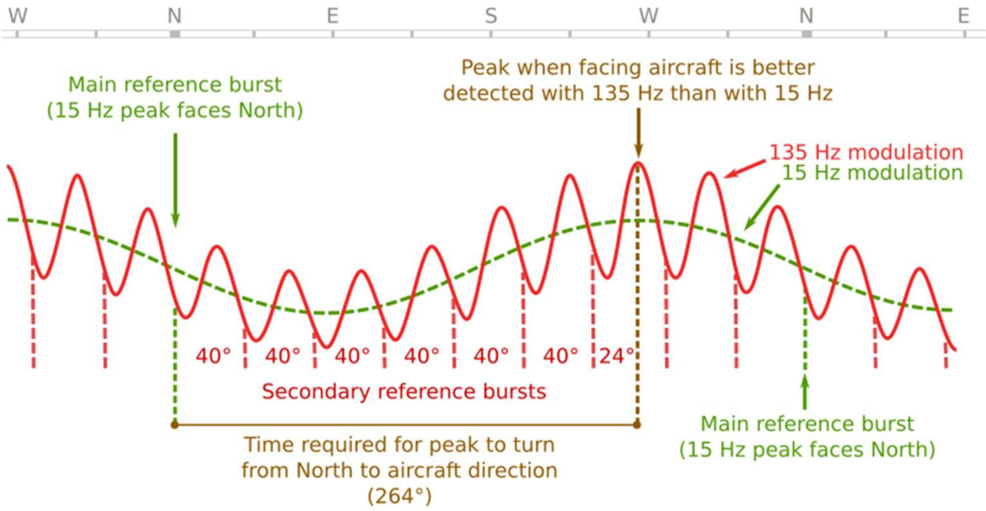


Figure 3.4 Transmitted signal, with reference signals, in a given direction. From [2].

3.3 Responses to DME interrogations

Distance is measured by determining the time delay between an interrogation transmission and the received response. The aircraft transmits an interrogation signal (pulse pair). In response, the TACAN retransmits this signal with a predefined delay of 50 μs (see Figure 3.5). This is described in more detail in [5].

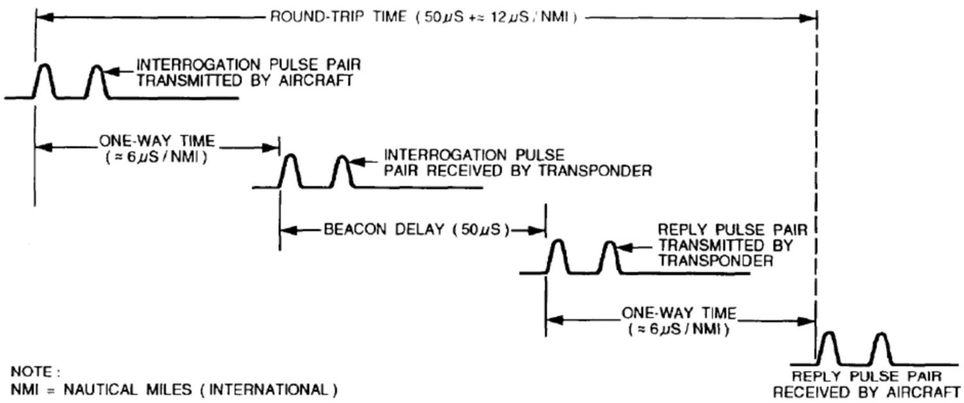


Figure 3.5 Distance measuring round trip travel time, from [5]

In order not to reply to interrogations as received by multipath, a dead time after reception of the first pulse pair is implemented during which the TACAN does not react to any interrogations.

3.4 Identification bursts

Before bearing and distance information can be used, first an aircraft has to identify the TACAN. Only after positive identification the aircraft knows that the signals of the correct TACAN is received. The identification is based on Morse code of the 3 letter designator of the TACAN. About every 30 seconds all distance and bearing transmissions are stopped to send the identification burst.

The duration of a Morse dot is 100 to 125 ms, and for a dash 300 to 370 ms. During transmission of a Morse dot or dash, repeatedly two 12 µs-pulse pairs with 100 µs spacing are transmitted with a rate of 1350 Hz. It can be observed that the total length of an identification burst can take about 2 to 4 seconds. After completion of the burst, the TACAN again starts transmitting the reference bursts and interrogation replies.

3.5 Squitter bursts

In order for the aircraft to receive sufficient pulses to determine the phase of the amplitude modulated signal, the TACAN system is designed to transmit 2700 to 3600 pulse pairs per seconds, i.e. 300 to 400 pulse pairs per antenna rotation. In the case that there are only few interrogation requests, the number of transmitted replies is supplemented by randomly spaced squitter bursts.

4 Wind turbine RCS and multipath

The wind turbine consist of three parts, each having their own contribution to the overall wind turbine RCS:

- The wind turbine blades
- The tower or mast
- The nacelle

Moreover, for TACAN one is interested in the so called bistatic RCS, this is the radar cross section the object has if the direction of the incident wave does not coincide with the direction of the reflected wave. (Note: with radar, one needs the monostatic RCS, the reflection back to the radar, hence incident wave direction = reflected wave direction).

Where in this document the acronym RCS is used, the bistatic RCS is meant. The monostatic RCS will be explicitly mentioned, if applicable.

The radar cross section σ_w models used for pole, nacelle, and blade are the ones also applied in the TNO model PERSEUS.

4.1 Blade RCS

The RCS differs strongly in accordance to the angles of incident and reflected wave, as depicted in a general way for a section of the blade in Figure 4.1.

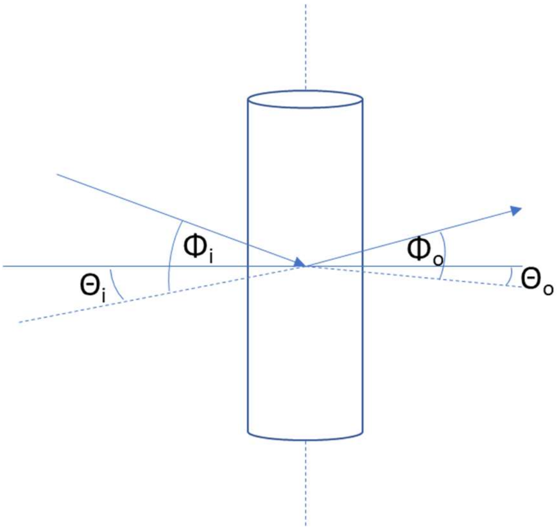


Figure 4.1 Blade with incident and reflected wave direction.

The blades rotate and moreover the nacelle is turned towards the wind. As a result, the blades can have any position, including that providing maximum RCS. In this document this maximum RCS is taken into account. One should note however that, due to the rotation of the blade, this condition is only valid for a short time.

In the condition of a stationary rotor, the optimum would only occur for a specific direction. The aircraft can be in this direction, however only for a short moment, due to the movement of the aircraft.

The bistatic RCS of the blade is modelled as an elongated ellipsoid with defined blade length *a*, width *b*, and thickness *c*. The bistatic RCS can be calculated as:

$$\sigma = \pi \frac{a^2 b^2}{c^2} \frac{4}{(1+\cos\beta) + \frac{b^2}{c^2}(1 - \cos\beta)}$$

The angle β is the angle between the line of incidence and the line of reflection.

4.2 Tower RCS

The RCS of the tower is modest, except if the incident angle equals the reflection angle. For cylindrical poles, with the TACAN transmitter close to the horizon, incident and reflected wave are both perpendicular to the pole, so the high RCS is only discerned at very low elevation angles.

For cone-shaped poles, the reflection is discernible at low angles, see Figure 4.2. Note that the angles are exaggerated. A typical value for β is 2°. The horizontally travelling TACAN signal is reflected in a cone of β from horizontal.

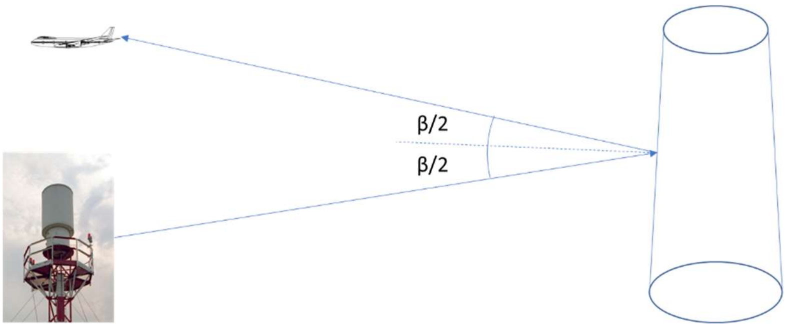


Figure 4.2 Tower RCS

Note that due to the Earth’s curvature, only a part of the cone is illuminated by the TACAN system.

Since for the vast majority of possible aircraft locations the pole RCS is small compared to the maximum attainable RCS of the wind turbine’s blade, the pole RCS is not taken into account separately.

4.3 Nacelle RCS

The RCS of the nacelle is small compared to the RCS of blade and pole and is neglected in the study.

4.4 Multipath

The pulses that are transmitted by either the TACAN or the aircraft, travel via a direct path to the aircraft or TACAN respectively. The presence of a wind turbine also causes an indirect path by reflecting part of the pulse. This phenomenon is called multipath. The relative geometry of TACAN, aircraft and wind turbine is shown in Figure 4.3. In this graph, ϕ is the angle between the line TACAN-aircraft and TACAN-wind turbine. Θ is the elevation angle of the aircraft as seen from the TACAN.

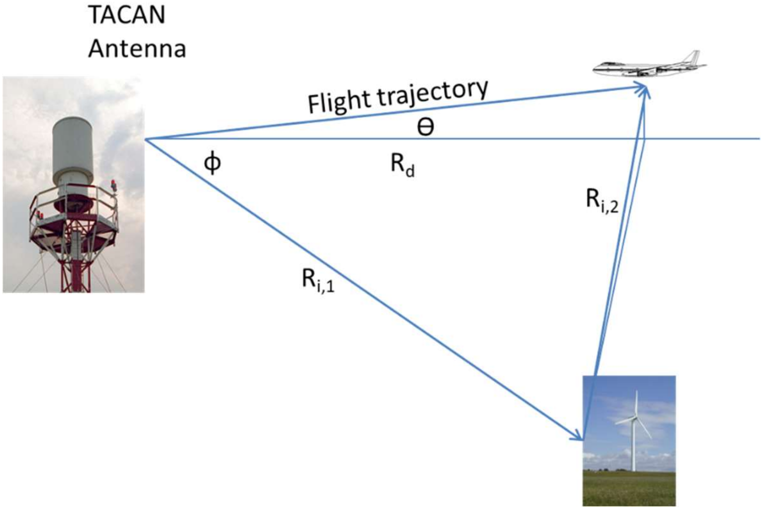


Figure 4.3 Geometry of TACAN, aircraft and wind turbine.

For the power of the direct path (P_d) without reflection at the wind turbine, the radio equation yields:

$$P_d = \frac{P\ G_t}{4\pi\ R_d^2} \cdot \frac{A_{eff}}{L_d} = \frac{P\ G_t\ G_r\ \lambda^2}{(4\pi)^2\ R_d^2\ L_d}$$

P is transmit power, G_t is transmit antenna gain, A_{eff} is the area of the effective antenna aperture (on receive), R_d is the length of the direct path, L_d represents losses along that path, λ is wavelength, G_r is the receive gain.

The indirect power, which includes the reflection at the wind turbine, is given by:

$$P_i = \frac{PG_t}{4\pi R_{i,1}^2} \cdot \frac{\sigma_w}{4\pi R_{i,2}^2} \cdot \frac{A_{eff}}{L_i} = \frac{PG_tG_r\lambda^2\sigma_w}{(4\pi)^3 R_{i,1}^2 R_{i,2}^2 L_i}$$

in which σ_w denotes the bistatic radar cross section (RCS) and L_i denotes losses along the indirect path. Assuming losses are equal along both paths, the power ratio is given by:

$$\frac{P_i}{P_d} = \frac{\sigma_w R_d^2}{4\pi R_{i,1}^2 R_{i,2}^2}$$

The radar cross section σ_w of the wind turbine is modelled in the same way as it is modelled in PERSEUS. The power ratio is used in the next chapter to determine the distance and bearing accuracy.

5 Line of Sight Analysis

Using the input parameter information of Chapter 2, a line-of-sight analysis has been carried out. In Figure 3.1 the terrain profile is shown in the area containing the wind turbines and TACAN. The terrain profile has been obtained from the SRTM1 database. The lines in the figure connect the TACAN to the planned wind turbines. By studying the terrain profile along this line, it can be determined whether the TACAN will have line-of-sight to the windfarm.

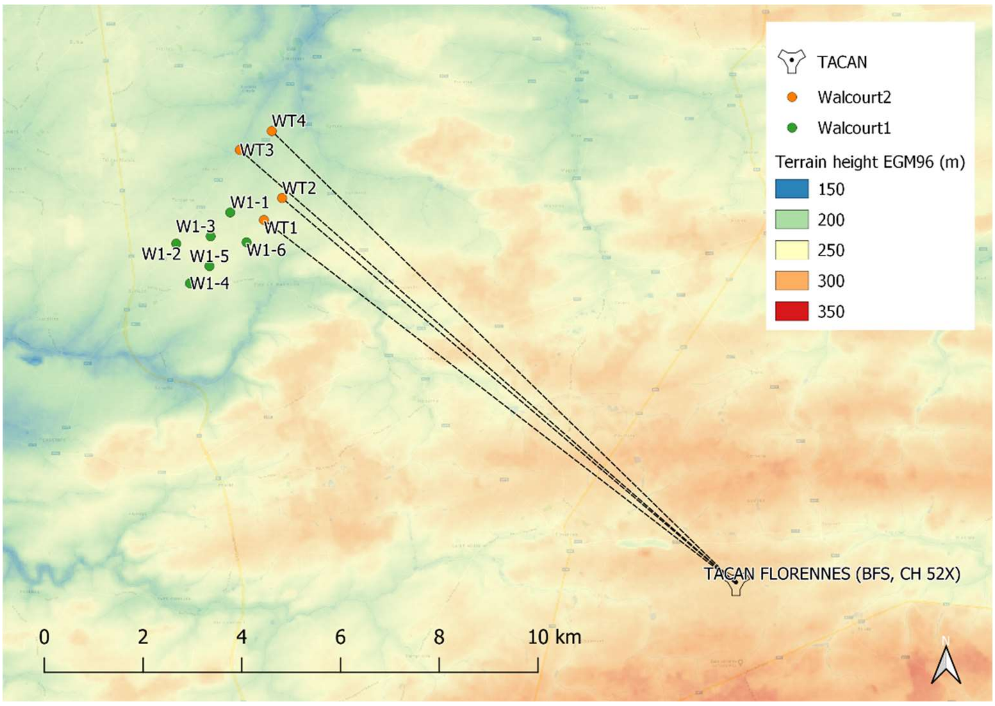


Figure 5.1 The altitude of the terrain between TACAN and wind turbines taken from the SRTM1 database. The altitude in this image varies from +150 m (blue) to +350 m (red) AMSL. The line-of-sight analysis is performed by studying the terrain profile on the line connecting the TACAN and each wind turbine.

So-called 'standard propagation' is assumed when determining the line-of-sight. This is modelled by multiplying the earth radius by a factor of 4/3 (the "k-factor").

In the subsequent figures the blue ellipses show the first Fresnel zone from the TACAN to the tip height of the wind turbine. The red ellipses show the first Fresnel zone to the wind turbine's hub. These ellipses are referred to as the ¼ λ Fresnel zone, where λ refers to the TACAN wavelength. Signals travelling between the terminals within the blue ellipses are at most 90° out of phase with respect to the signal that takes the shortest path. The black lines show the profile of the ground level between the TACAN and wind turbine as derived from the SRTM database.

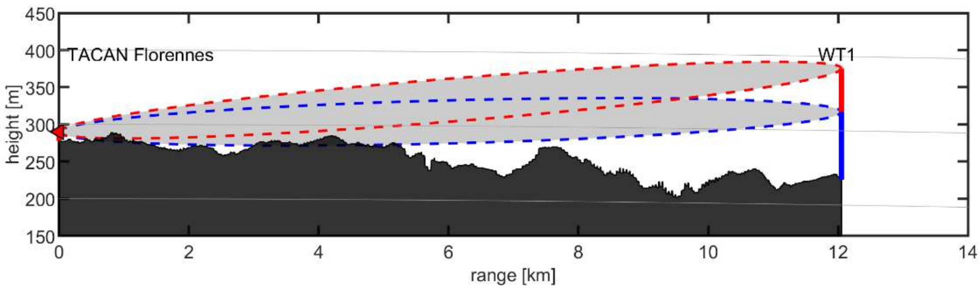


Figure 5.2 to Figure 5.5 show line-of-sight diagrams between the location of the TACAN and the newly planned wind turbine locations. The x-axis shows range over ground in kilometres calculated using Vincenty's formulae. The turbines are located between approximately 12.0 and 13.4 km from the TACAN. As an illustration of the line-of-sight between the TACAN and existing turbines, Figure 5.6 shows the line-of-sight diagram for existing wind turbine WT1-6 of Walcourt 1 which is closest in range.

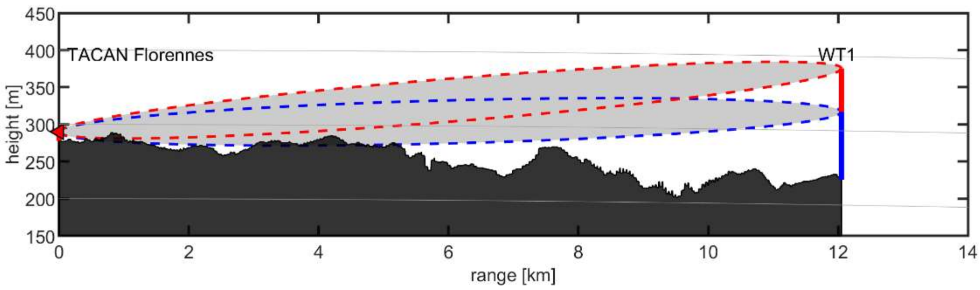


Figure 5.2 Line-of-sight between the TACAN (antenna height: 290 m, ground level: 278 m) and wind turbine WT1 (tip height: 384 m, hub height: 325.5 m, ground level: 234 m). The ground range from the TACAN to the wind turbine is 12.05 km.

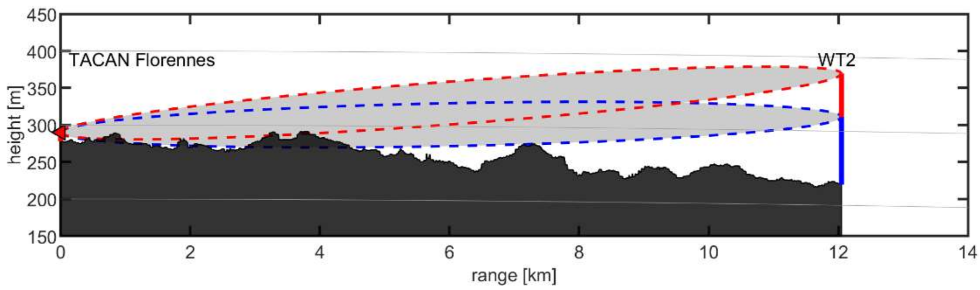


Figure 5.3 Line-of-sight between the TACAN (antenna height: 290 m, ground level: 278 m) and wind turbine WT2 (tip height: 378 m, hub height: 319.5, ground level: 228 m). The ground range from the TACAN to the wind turbine is 12.05 km.

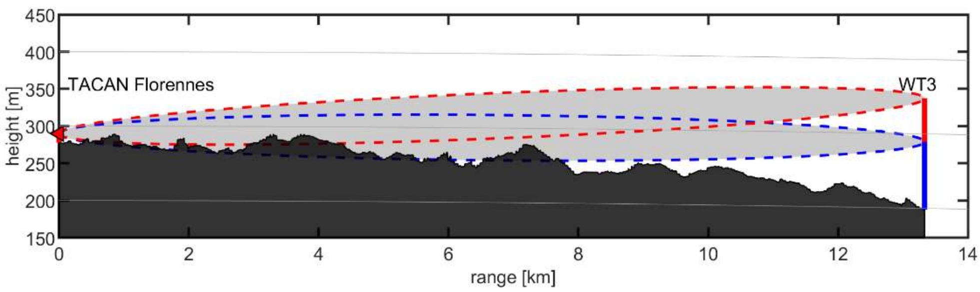


Figure 5.4 Line-of-sight between the TACAN (antenna height: 290 m, ground level: 278 m) and wind turbine WT3 (tip height: 348 m, hub height: 289.5 m, ground level: 198 m). The ground range from the TACAN to the wind turbine is 13.3 km.

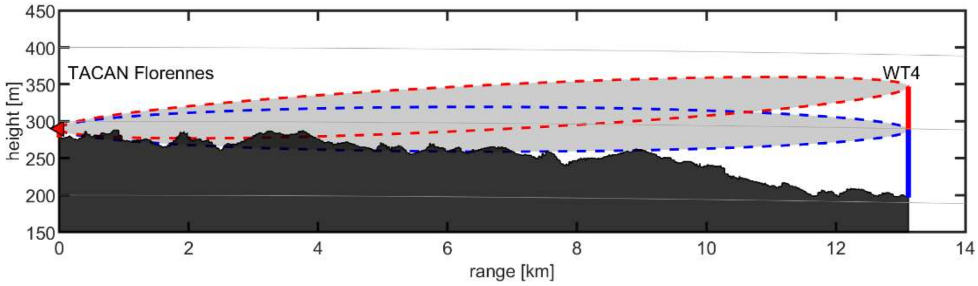


Figure 5.5 Line-of-sight between the TACAN (antenna height: 290 m, ground level: 278 m) and wind turbine WT4 (tip height: 357 m, hub height: 298.5 m, ground level: 207 m). The ground range from the TACAN to the wind turbine is 13.1 km.

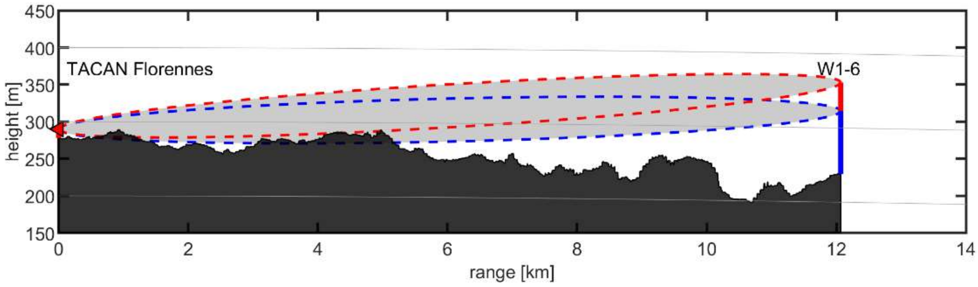


Figure 5.6 Line-of-sight between the TACAN (antenna height: 13 m, ground level: 51 m) and wind turbine W1-6 (tip height: 361.5 m, hub height: 323 m, ground level: 238 m). The ground range from the TACAN to the wind turbine is 12.07 km.

For the wind turbines WT1 to WT4 the (red) Fresnel zones between the TACAN and the highest tip of the blade are not significantly obstructed by the terrain profile. This means that the TACAN has line-of-sight to these wind turbines. For WT1 also the turbine’s hub is not obstructed. For WT2 to WT4 there is significant obstruction due to the elevation profile. This means that the towers of these wind turbines have limited line-of-sight as seen from the TACAN.

The reference wind turbines W1-1 to W1-6 of the existing windfarm Walcourt 1 all show similar behaviour with unobstructed line-of-sight from TACAN to the turbines’ blades.

6 DME distance accuracy

To determine the DME distance measurement accuracy, it is assumed that a blade is in a position providing maximum reflection towards the aircraft (worst case assumption).

In this chapter the following sets of simulations have been made for:
- Reference wind turbine W1-6. This existing wind turbine of Walcourt 1 is closest to the TACAN with respect to all other reference wind turbines.
- Wind turbines WT1, WT2, WT3, and WT4.

6.1 Propagation

DME is based on the travelling of radio waves in both directions between an aircraft (interrogator) and TACAN (transponder). The DME analysis is done for the propagation channel, from TACAN antenna to aircraft antenna. This channel is reciprocal, which means the channel has the same characteristics, irrespective of the signal direction. It is assumed that TACAN behaviour is equal for both directions.

6.2 Error mechanism

In order for a reflected pulse pair to elicit a second TACAN response, two conditions have to be met that are explained more in detail in the sections that follow:
- The delay between the two pulse pairs needs to be more than the “dead time”;
- The signal strength shall be above the TACAN receiver threshold.

6.2.1 Dead time

As can be seen from Figure 4.3, there will be a difference in path length between the direct and indirect path:

$$\Delta R = (R_{i,1} + R_{i,2}) - R_d$$

The TACAN receiver needs to be able to separate the direct interrogation pulse pair from the indirect/reflected interrogation pulse pair. In theory, given that the pulses in a pulse pair are 12 μs apart (see Figure 3.3), the second interrogation pulse pair needs to be delayed by about 24 μs in order to be detected as a separate pulse pair.

The dead time, the time the TACAN system does not respond to a second interrogation, is much larger than 24 μs. The dead time is a mechanism that is used to prevent the TACAN system to react to multipath. The specification [8] states “The dead time shall not normally exceed 60 μsec”, a minimum value however is not specified. Literature [6] indicates the dead time is “about 60 μsec”. In this report, the dead time is considered to be relatively short, 50 μs, which is a worst case assumption. This implies that, to trigger a second TACAN response, the difference in path length would be at least:

$$\Delta R = 50\ \mu s \times c = 15\ \text{km}$$

Where *c* is the speed of light (300.000 km/s).

In case the interrogation pulse pair is delayed by more than 50 μs, it can trigger the TACAN transponder to transmit a second response to the same, but delayed interrogation request. If the delay is less, triggering will not occur due to the dead time of the transponder.

6.2.2 *Sensitivity*

TACAN sensitivity is not specified in [8]. In [5] it is indicated that the maximum measuring distance can be as large as 200 Nautical Mile or 370 km. Assuming a margin of 6 dB in receiver sensitivity, responses can be triggered up to 740 km under favourable conditions. Other literature [6] is more exact and claims -92 dBm receiver sensitivity.

In this report a receiver threshold is assumed which allows the TACAN system at a distance of 370 km reliably being received with 6 dB margin.

6.3 Reference analysis W1-6

As a reference, the existing wind turbine W1-6 of Walcourt 1 is taken to be able to compare the results of wind turbines WT1 to WT4. As explained before, the TACAN transponder may be triggered via the indirect path if both the dead time of 50 μs (15 km) is exceeded and the signal power as indirectly received is sufficiently high.

To determine whether it is possible to erroneously trigger the TACAN transponder via the indirect path, the relative signal strength of the indirect interrogation pulse pair (reflected at the wind turbine) is calculated for a number of flight trajectories at a flight altitude of 305 m AGL (1000 ft) with reference to the terrain elevation at the TACAN. This low altitude is chosen since the effects on the DME distance accuracy are large at low altitudes. At larger altitudes, these adverse effects are smaller. For the angle ϕ, values of 0°, 8°, 16°, and 24° are taken.

For an aircraft passing overhead the wind turbine W1-6 (ϕ = 0°), Figure 6.1 shows the relative signal strength as the ratio between the received signal strengths of the direct and the indirect path. Close to the closest point of approach of the aircraft to W1-6 (at a distance of 14 km from the TACAN), the relative signal strength is maximally -17 dB. The other line shows the path length difference (in km) between the direct and indirect path. Since the power ratio is sufficiently low at the range where the path length difference exceeds 15 km, this flight trajectory does not trigger DME responses due to multipath.

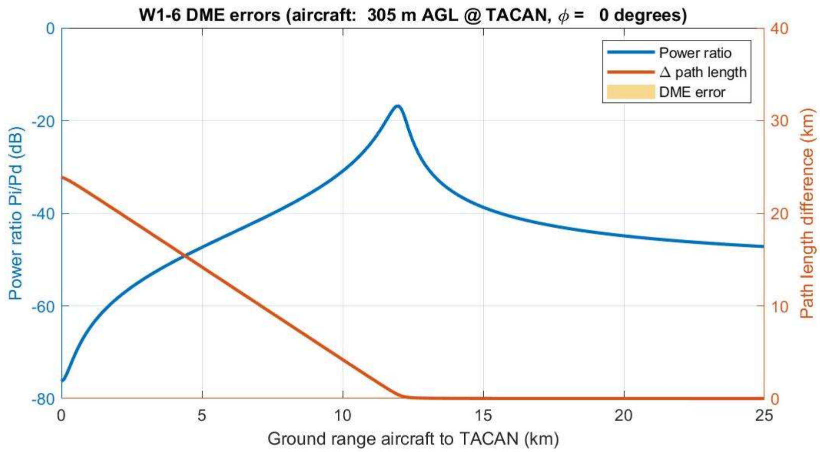


Figure 6.1 Relative signal strength and path length difference along flight trajectory at 305 m AGL with angle ϕ = 0°.

Note that an error of zero implies that no erroneous response can be evoked, irrespective of the actual position of the wind turbine blades. Even the most unfavourable position of the wind turbine blade, as is assumed in this analysis, will not evoke any erroneous responses.

The same diagram is given for ϕ = 8°, ϕ = 16° and ϕ = 24°. See Figure 6.2, Figure 6.3 and Figure 6.4. The graphs all show no error due to erroneously triggering the DME response caused by multipath.

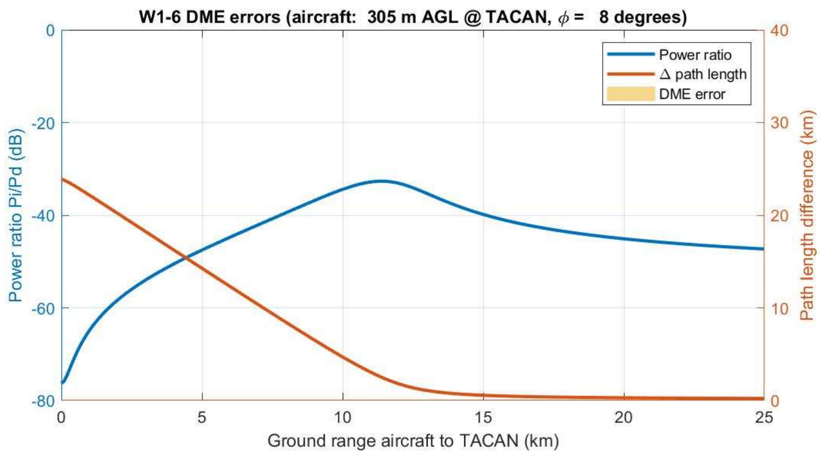


Figure 6.2 Relative signal strength and path length difference along flight trajectory at 305 m AGL with angle ϕ = 8°.

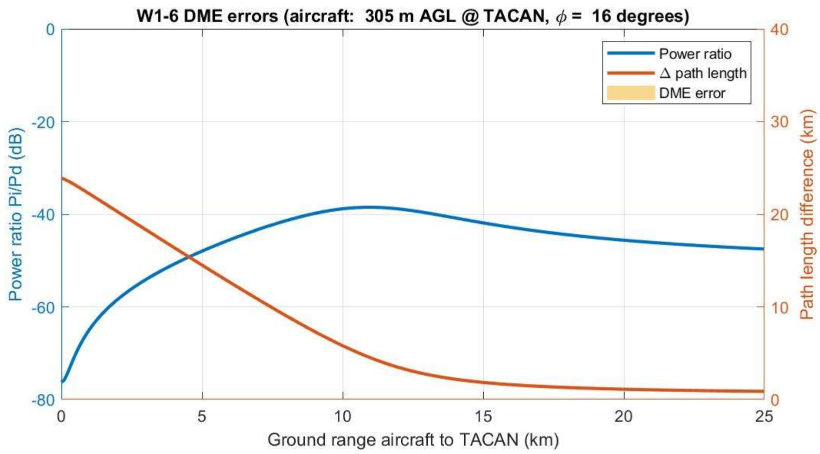


Figure 6.3 Relative signal strength and path length difference along flight trajectory at 305 m AGL with angle ϕ = 16°.

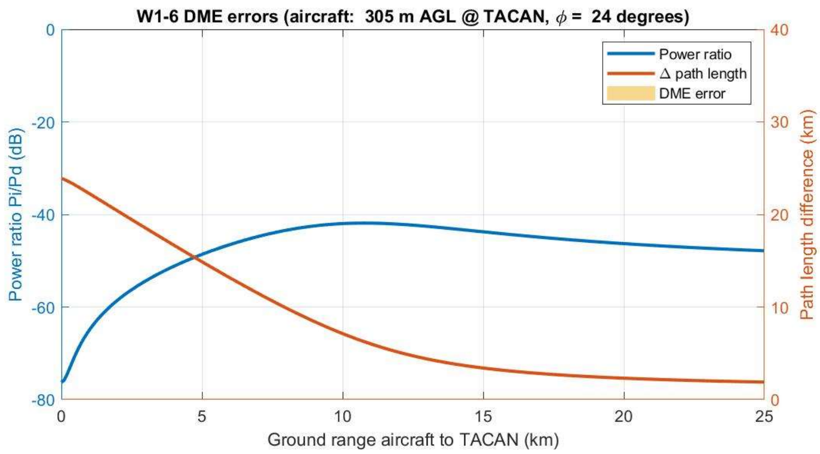


Figure 6.4 Relative signal strength and path length difference along flight trajectory at 305 m AGL with angle ϕ = 24°.

As can be concluded from Figure 6.1 to Figure 6.4, the TACAN does not erroneously trigger a second DME reply for this wind turbine since there is no region in which both the power of the indirect path is large enough compared to the direct path and with a minimum difference in path length between the direct and indirect paths of 15 km.

The TACAN behaves without any observed error areas due to double replies that would be triggered by any of the Walcourt1 wind turbines.

The combined effect of the wind turbines is neglected, because:
- There is virtually no chance that more than one wind turbine is in the most unfavourable position.
- Even if more than one wind turbine has a blade in the most unfavourable position, then the signals only sum up to a limited extend, due to the fact the phase relationship between the signals is random.
- For other positions than the most unfavourable position, the RCS of the wind turbine blades rapidly decays.

6.4 Analysis WT1

For WT1 the relative signal strength of the indirect interrogation pulse pair (reflected at the wind turbine) has been calculated. The results are shown in Figure 6.5, Figure 6.6, Figure 6.7, and Figure 6.8 for an altitude of 305 m AGL (1000 ft) and for ϕ = 0°, ϕ = 8°, ϕ = 16°, and ϕ = 24° respectively.

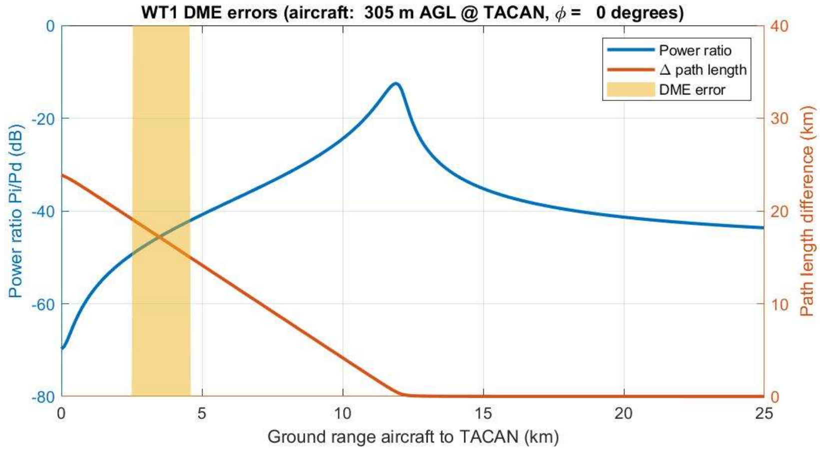


Figure 6.5 Relative signal strength and path length difference along flight trajectory. Flight trajectory altitude is 305 m AGL and angle ϕ = 0°. This is a trajectory passing the wind turbine overhead.

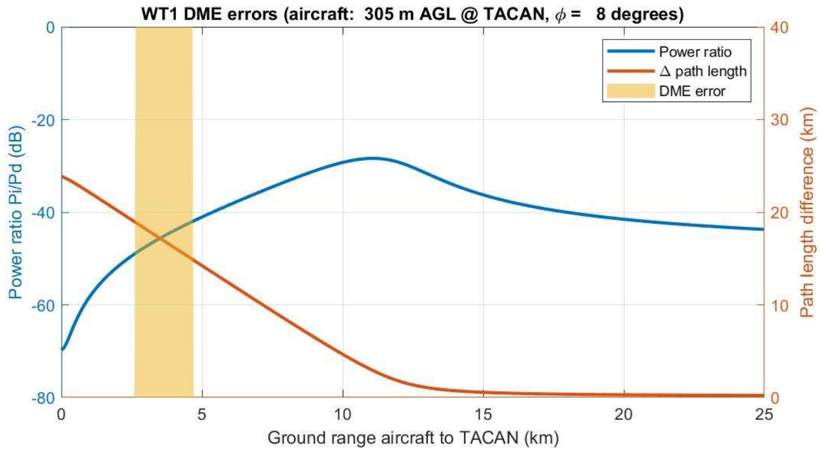


Figure 6.6 Relative signal strength and path length difference along flight trajectory. Flight trajectory altitude is 305 m AGL and angle ϕ = 8°.

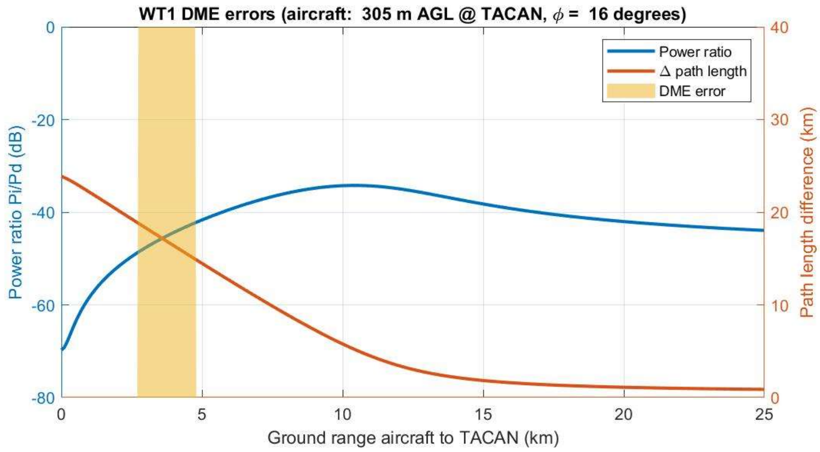


Figure 6.7 Relative signal strength and path length difference along flight trajectory. Flight trajectory altitude is 305 m AGL and angle ϕ = 16°.

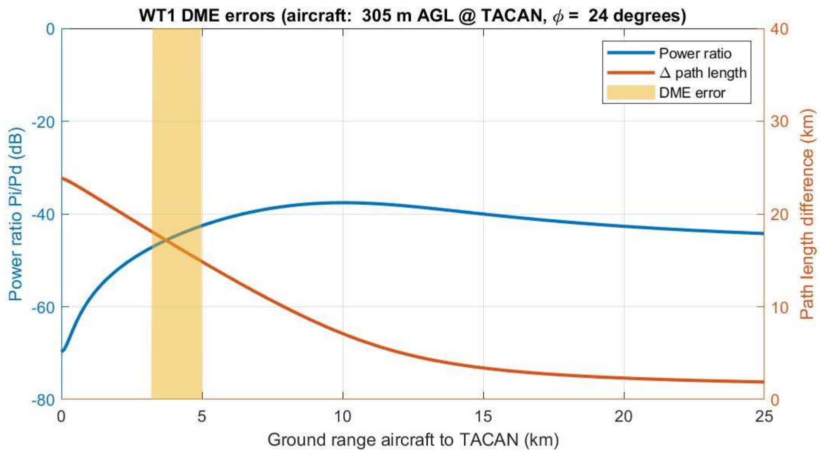


Figure 6.8 Relative signal strength and path length difference along flight trajectory. Flight trajectory altitude is 305 m AGL and angle ϕ = 24°.

The graphs show possible errors for all trajectories. For values up to ϕ = 31° errors might occur, as is shown in Figure 6.9. For values of ϕ = 32° and larger no errors occur.

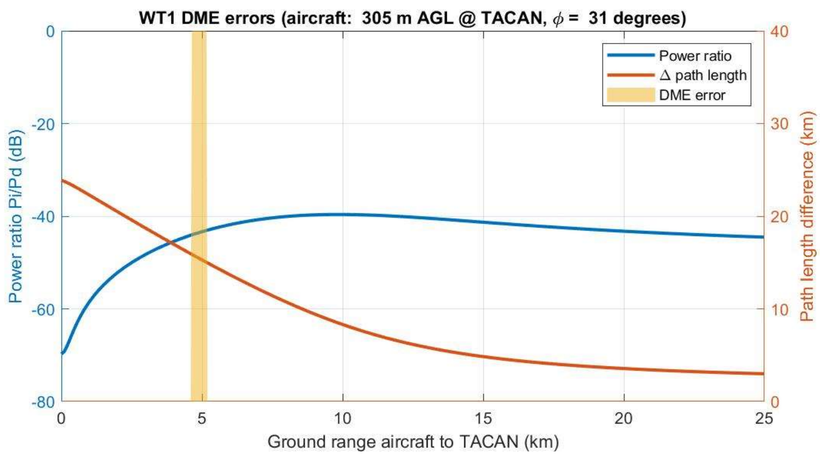


Figure 6.9 Relative signal strength and path length difference along flight trajectory. Flight trajectory altitude is 305 m AGL and angle ϕ = 31°.

For higher altitudes the DME errors are smaller compared to the lower altitudes. Therefore only the results that correspond to an aircraft altitude of 305 m AGL are shown.

As explained in Section 6.2, a DME “error” indicates that both:
- The path length difference is more than 15 km (or 50 μs delay)
- The relative signal strength is large enough to evoke a response of the TACAN system.

The error value is the distance error that might appear on the navigation display in the airplane.

This situation only occurs for the most unfavourable position of the wind turbine blade (worst case scenario). The probability of the blade being in this position is very low (in the order of 10^{-4}). Moreover, the wind turbine is rotating and the aircraft is moving, so this most unfavourable position lasts only for a second at most. Even in the unlikely event an erroneous response of the TACAN is evoked, this will only happen once. It should be noted that, should a TACAN death time of 60 μs be used, the probability of erroneous TACAN DME responses would be close to zero.

In addition, the receiver in the aircraft is equipped with an “echo cancellation”. The second TACAN DME response (which arrives with 50 μs delay or more) is neglected by the aircraft.

The area where erroneous TACAN DME responses might be evoked (and needs to be suppressed by the aircraft echo cancellation), is shown in Figure 6.10 for aircraft altitudes of 1000, 5000 and 8000 feet AGL (305 m, 1524 m, and 2438 m). This area extends to a height of about 2.5 km. Above this height, no erroneous TACAN DME responses are sent.

The shape of the contours can be explained by both observing the curved and the straight part. The curved part of the contour relates to the relative power ratio between the direct and indirect paths and is strongly dependent on the range to the wind turbine with higher ratios closer to the wind turbine. The straight part gives the line of 50 μs dead time. Closer to the TACAN the difference in path length exceeds the maximum dead time.

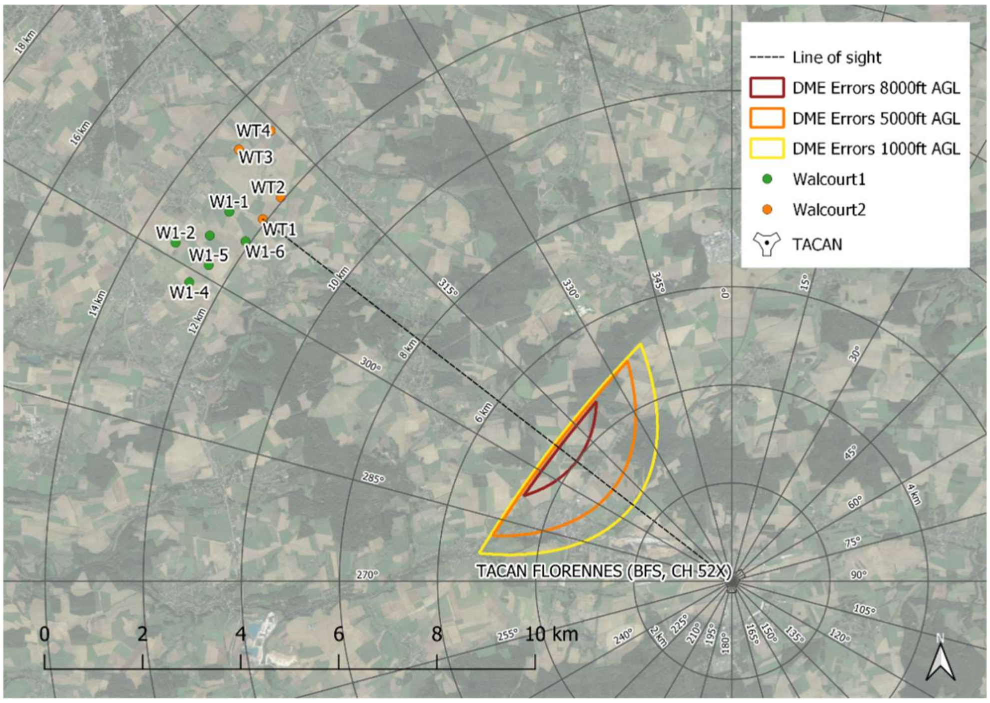


Figure 6.10 Area where echo cancellation is needed, shown in relation to TACAN and wind turbine WT1. The colours from yellow to red represent the contour at altitudes of 1000, 5000 and 8000 ft AGL.

As a concluding remark it is stated that although a volume exists in which DME measurements can be negatively affected, this error volume is not considered to hamper proper operation of the distance measuring part of the TACAN due to the presence of WT1. The volume is only related to a worst case geometry of the wind turbine blade. Moreover these volume are not overlapping with the extended centre lines of the runways at Florennes AFB.

6.5 Analysis WT2

For WT2 the relative signal strength of the indirect interrogation pulse pair (reflected at the wind turbine) has been calculated. The results are shown in Figure 6.5, Figure 6.6, Figure 6.7, and Figure 6.8 for an altitude of 305 m AGL (1000 ft) and for ϕ = 0°, ϕ = 8°, ϕ = 16°, and ϕ = 24° respectively.

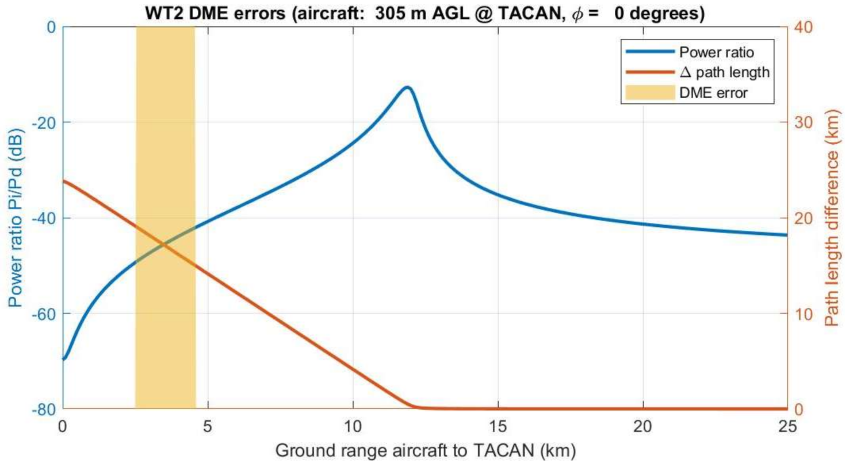


Figure 6.11 Relative signal strength and path length difference along flight trajectory. Flight trajectory altitude is 305 m AGL and angle ϕ = 0°. This is a trajectory passing the wind turbine overhead.

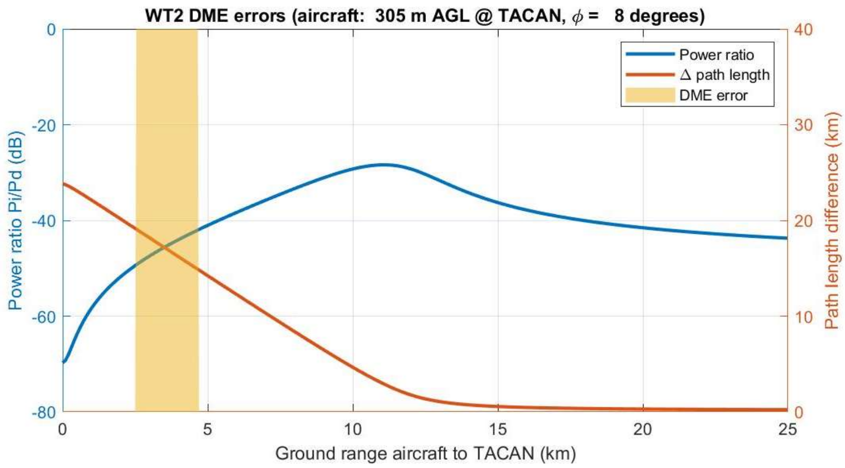


Figure 6.12 Relative signal strength and path length difference along flight trajectory. Flight trajectory altitude is 305 m AGL and angle ϕ = 8°.

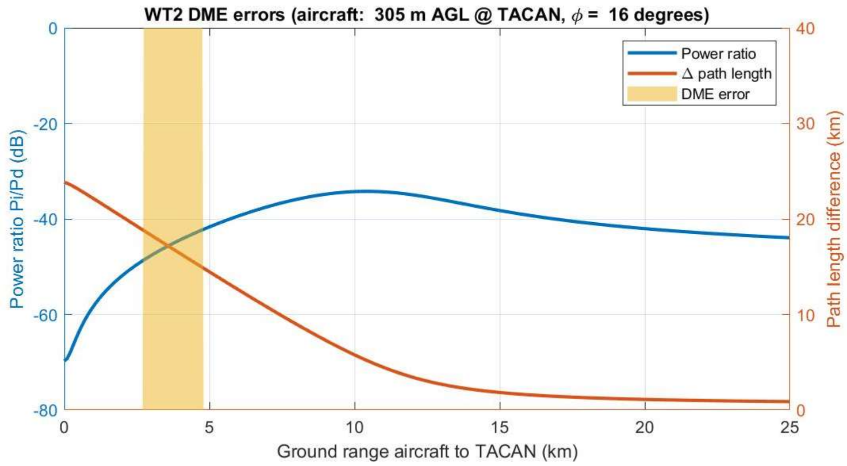


Figure 6.13 Relative signal strength and path length difference along flight trajectory. Flight trajectory altitude is 305 m AGL and angle ϕ = 16°.

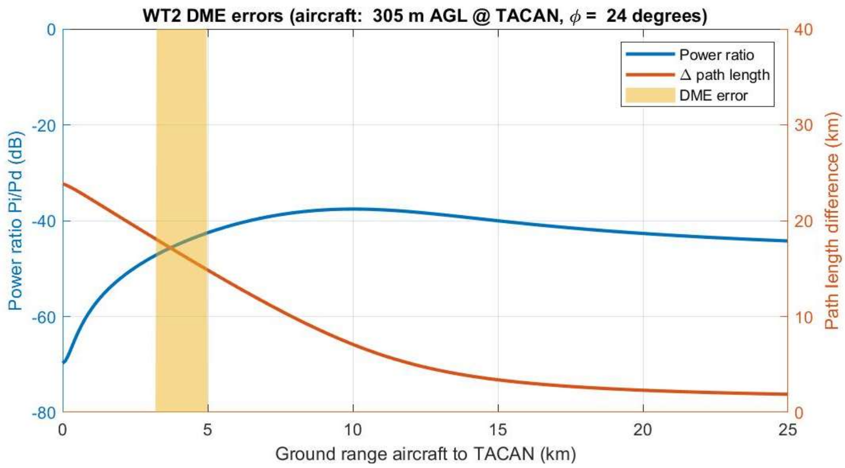


Figure 6.14 Relative signal strength and path length difference along flight trajectory. Flight trajectory altitude is 305 m AGL and angle ϕ = 24°.

The graphs show possible errors for all trajectories. For values up to ϕ = 31° errors might occur, as is shown in Figure 6.9. For values of ϕ = 32° and larger no errors occur.

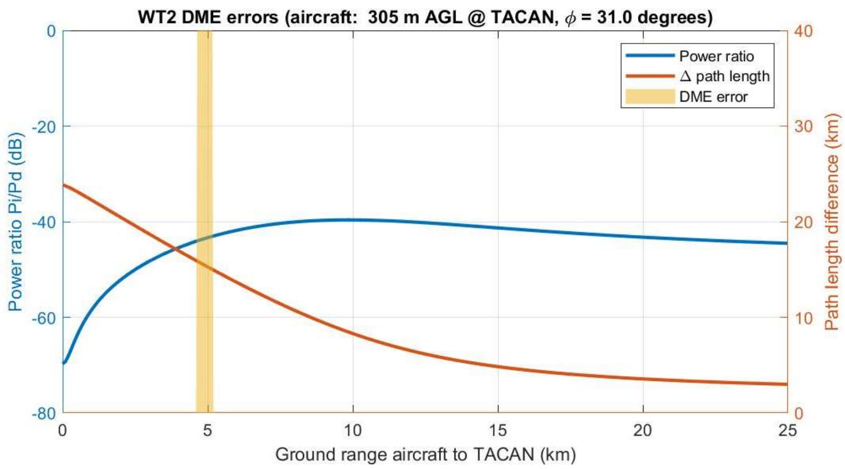


Figure 6.15 Relative signal strength and path length difference along flight trajectory. Flight trajectory altitude is 305 m AGL and angle ϕ = 31°.

For higher altitudes the DME errors are smaller compared to the lower altitudes. Therefore only the results that correspond to an aircraft altitude of 305 m AGL are shown.

As explained in Section 6.2, a DME “error” indicates that both:
- The path length difference is more than 15 km (or 50 μs delay)
- The relative signal strength is large enough to evoke a response of the TACAN system.

The error value is the distance error that might appear on the navigation display in the airplane.

This situation only occurs for the most unfavourable position of the wind turbine blade (worst case scenario). The probability of the blade being in this position is very low (in the order of 10^{-4}). Moreover, the wind turbine is rotating and the aircraft is moving, so this most unfavourable position lasts only for a second at most. Even in the unlikely event an erroneous response of the TACAN is evoked, this will only happen once. It should be noted that, should a TACAN death time of 60 μs be used, the probability of erroneous TACAN DME responses would be close to zero.

In addition, the receiver in the aircraft is equipped with an “echo cancellation”. The second TACAN DME response (which arrives with 50 μs delay or more) is neglected by the aircraft.

The area where erroneous TACAN DME responses might be evoked (and needs to be suppressed by the aircraft echo cancellation), is shown in Figure 6.10 for aircraft altitudes of 1000, 5000 and 8000 feet AGL (305 m, 1524 m, and 2438 m). This area extends to a height of about 2.5 km. Above this height, no erroneous TACAN DME responses are sent.

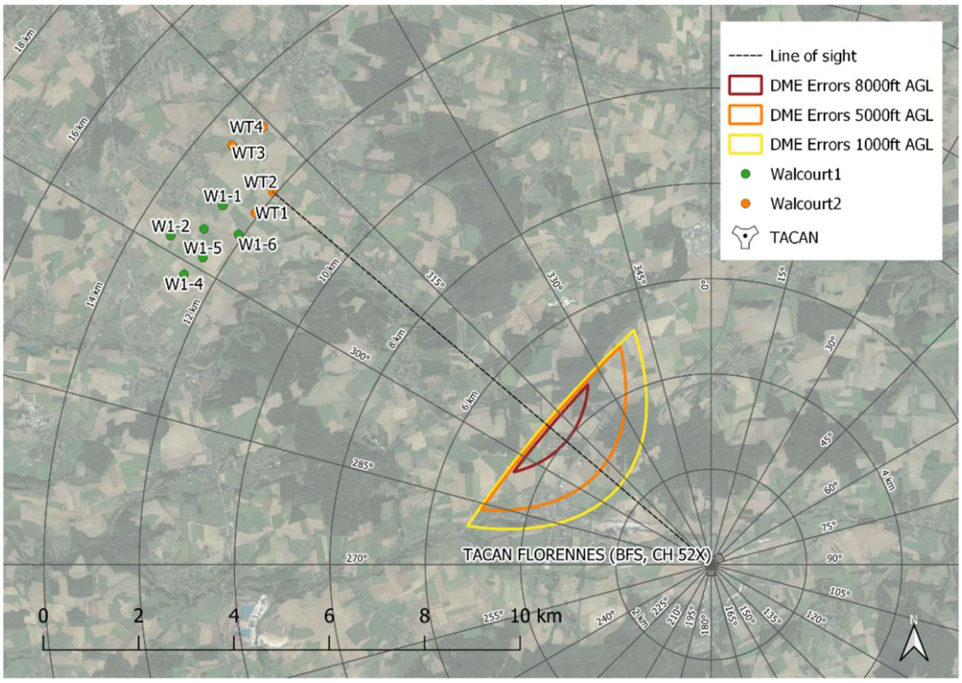


Figure 6.16 Area where echo cancellation is needed, shown in relation to TACAN and wind turbine WT2. The colours from yellow to red represent the contour at altitudes of 1000, 5000 and 8000 ft AGL.

The shape of the contours can be explained by both observing the curved and the straight part. The curved part of the contour relates to the relative power ratio between the direct and indirect paths and is strongly dependent on the range to the wind turbine with higher ratios closer to the wind turbine. The straight part gives the line of 50 µs dead time. Closer to the TACAN the difference in path length exceeds the maximum dead time.
As a concluding remark it is stated that although a volume exists in which DME measurements can be negatively affected, this error volume is not considered to hamper proper operation of the distance measuring part of the TACAN due to the presence of WT1. The volume is only related to a worst case geometry of the wind turbine blade. Moreover these volume are not overlapping with the extended centre lines of the runways at Florennes AFB.

6.6 Analysis WT3

For WT3 the relative signal strength of the indirect interrogation pulse pair (reflected at the wind turbine) has been calculated. The results are shown in Figure 6.5, Figure 6.6, Figure 6.7, and Figure 6.8 for an altitude of 305 m AGL (1000 ft) and for ϕ = 0°, ϕ = 8°, ϕ = 16°, and ϕ = 24° respectively.

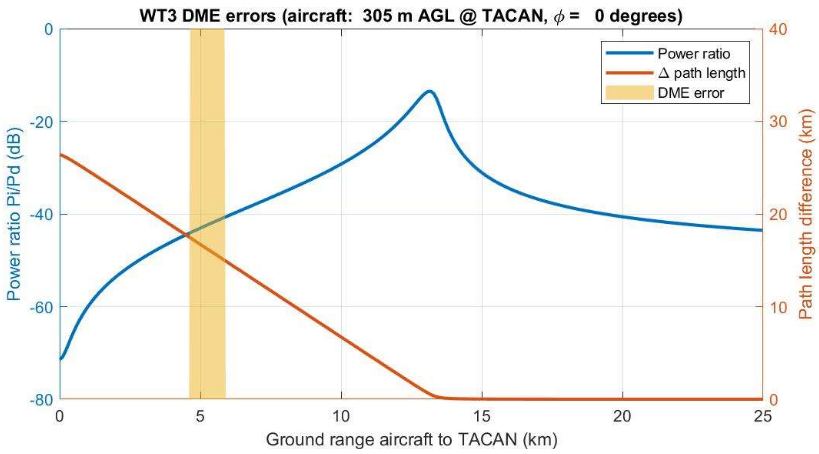


Figure 6.17 Relative signal strength and path length difference along flight trajectory. Flight trajectory altitude is 305 m AGL and angle ϕ = 0°. This is a trajectory passing the wind turbine overhead.

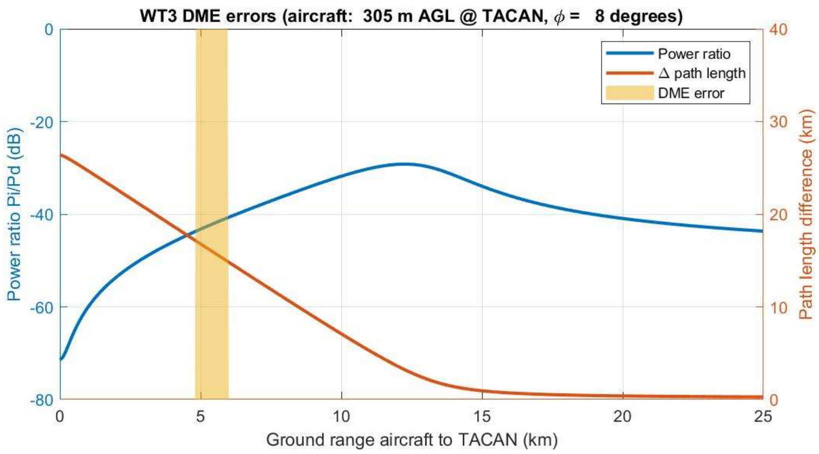


Figure 6.18 Relative signal strength and path length difference along flight trajectory. Flight trajectory altitude is 305 m AGL and angle ϕ = 8°.

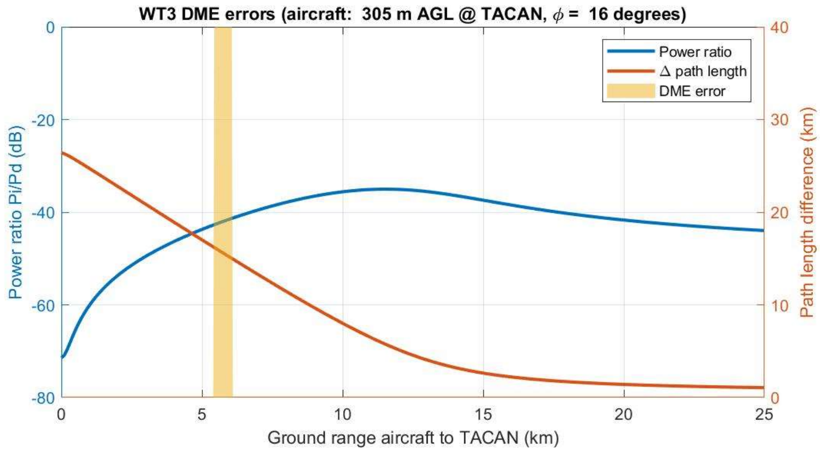


Figure 6.19 Relative signal strength and path length difference along flight trajectory. Flight trajectory altitude is 305 m AGL and angle ϕ = 16°.

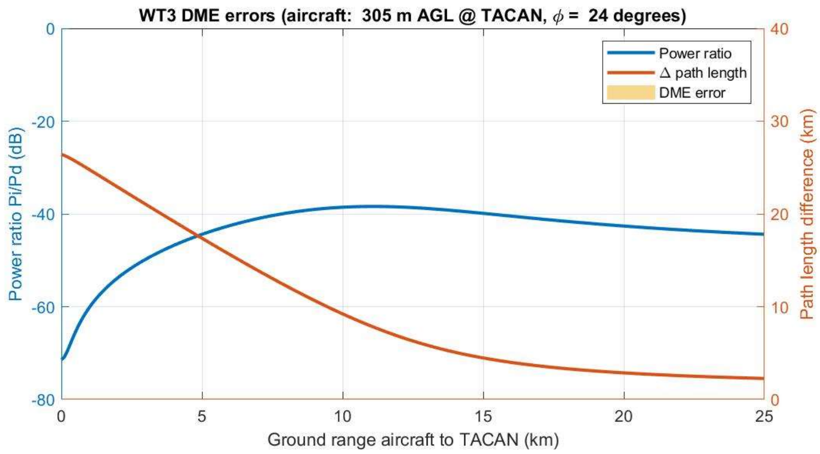


Figure 6.20 Relative signal strength and path length difference along flight trajectory. Flight trajectory altitude is 305 m AGL and angle ϕ = 24°.

The graphs show possible errors for all trajectories except for the trajectory at ϕ = 24°. For values up to ϕ = 19° errors might occur, as is shown in Figure 6.21. For values of ϕ = 20° and larger no errors occur.

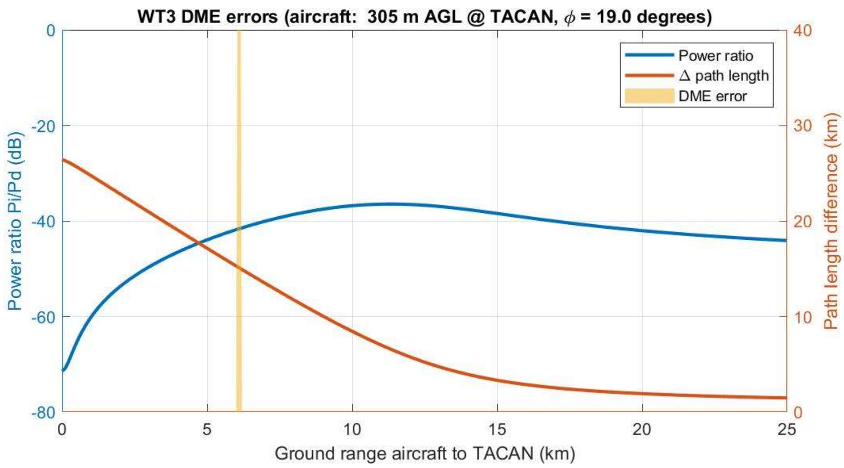


Figure 6.21 Relative signal strength and path length difference along flight trajectory. Flight trajectory altitude is 305 m AGL and angle ϕ = 19°.

For higher altitudes the DME errors are smaller compared to the lower altitudes. Therefore only the results that correspond to an aircraft altitude of 305 m AGL are shown.

As explained in Section 6.2, a DME “error” indicates that both:
- The path length difference is more than 15 km (or 50 µs delay)
- The relative signal strength is large enough to evoke a response of the TACAN system.

The error value is the distance error that might appear on the display in the airplane.

This situation only occurs for the most unfavourable position of the wind turbine blade (worst case scenario). The probability of the blade being in this position is very low (in the order of 10^{-4}). Moreover, the wind turbine is rotating and the aircraft is moving, so this most unfavourable position lasts only for a second at most. Even in the unlikely event an erroneous response of the TACAN is evoked, this will only happen once. It should be noted that, should a TACAN death time of 60 to 65 µs be used, the probability of erroneous TACAN responses would be close to zero.

In addition, the receiver in the aircraft is equipped with an “echo cancellation”. The second TACAN response (which arrives with 50 µs delay or more) is neglected by the aircraft.

The area where erroneous TACAN responses might be evoked (and needs to be suppressed by the aircraft echo cancellation), is shown in Figure 6.22 for aircraft altitudes of 1000, 5000 and 8000 feet AGL (305 m, 1524 m, and 2438 m). At 8000 ft AGL there is no region in which DME errors occur.

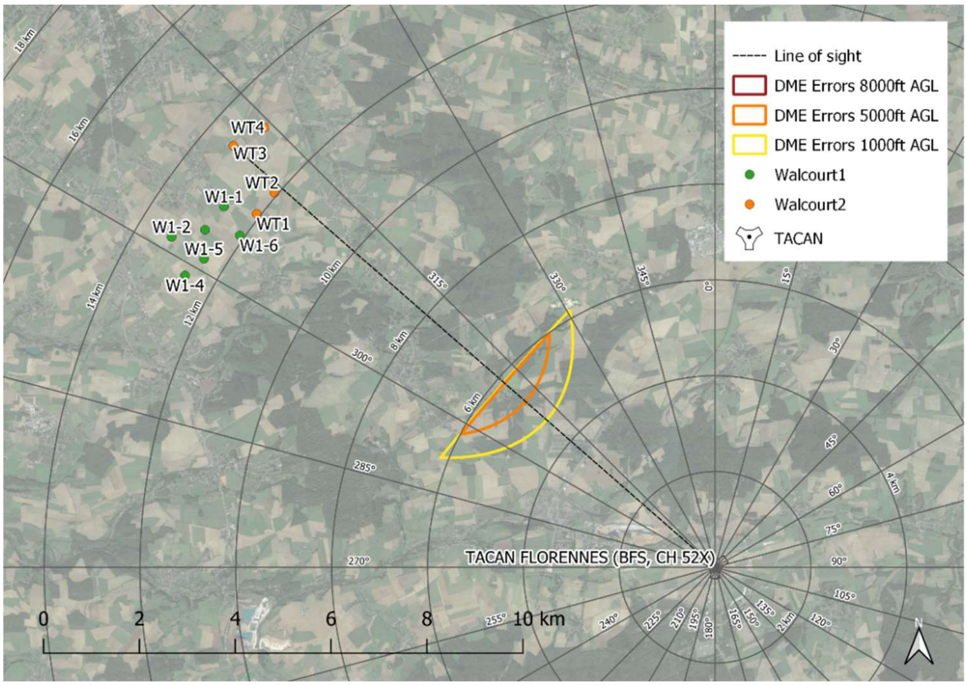


Figure 6.22 Area where echo cancellation is needed, shown in relation to TACAN and wind turbine WT3. The colours from yellow to red represent the contours at altitudes of 1000, 5000 and 8000 ft AGL (absent).

The shape of the contours can be explained by both observing the curved and the straight part. The curved part of the contour relates to the relative power ratio between the direct and indirect paths and is strongly dependent on the range to the wind turbine with higher ratios closer to the wind turbine. The straight part gives the line of 50 µs dead time. Closer to the TACAN the difference in path length exceeds the maximum dead time.
As a concluding remark it is stated that although a volume exists in which DME measurements can be negatively affected, this error volume is not considered to hamper proper operation of the distance measuring part of the TACAN due to the presence of WT1. The volume is only related to a worst case geometry of the wind turbine blade. Moreover these volume are not overlapping with the extended centre lines of the runways at Florennes AFB.

6.7 Analysis WT4

For WT4 the relative signal strength of the indirect interrogation pulse pair (reflected at the wind turbine) has been calculated. The results are shown in Figure 6.5, Figure 6.6, Figure 6.7, and Figure 6.8 for an altitude of 305 m AGL (1000 ft) and for ϕ = 0°, ϕ = 8°, ϕ = 16°, and ϕ = 24° respectively.

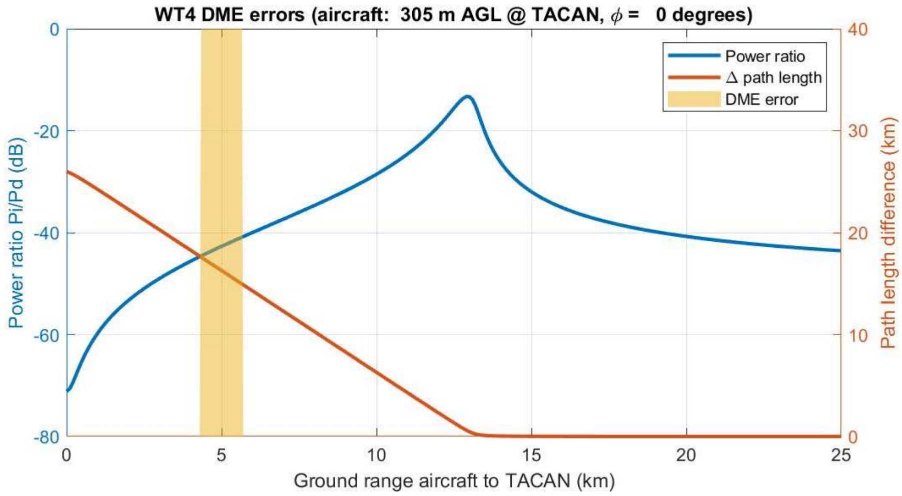


Figure 6.23 Relative signal strength and path length difference along flight trajectory. Flight trajectory altitude is 305 m AGL and angle ϕ = 0°. This is a trajectory passing the wind turbine overhead.

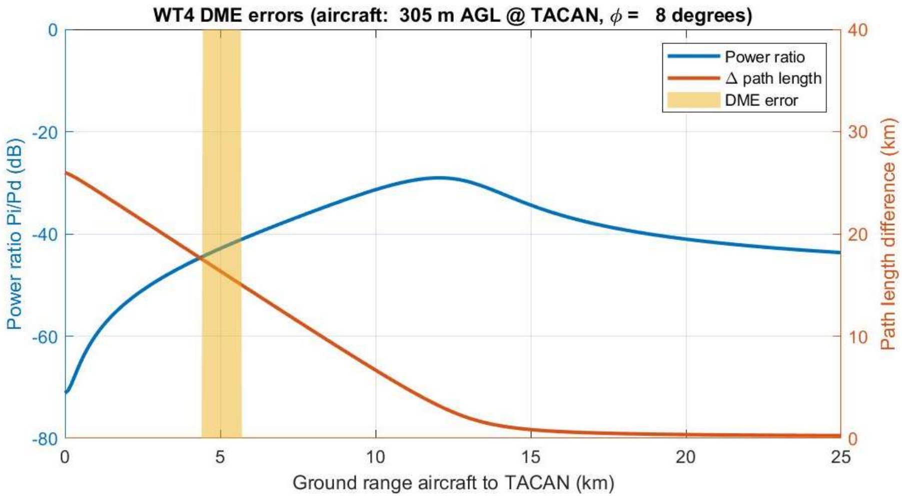


Figure 6.24 Relative signal strength and path length difference along flight trajectory. Flight trajectory altitude is 305 m AGL and angle ϕ = 8°.

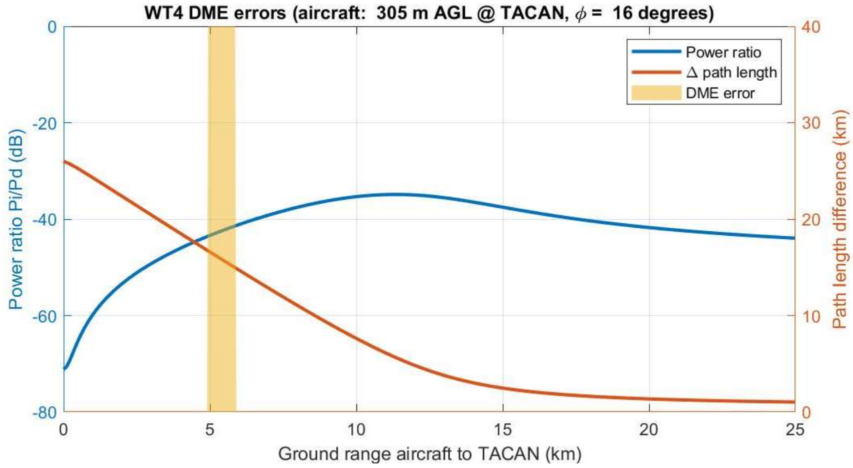


Figure 6.25 Relative signal strength and path length difference along flight trajectory. Flight trajectory altitude is 305 m AGL and angle ϕ = 16°.

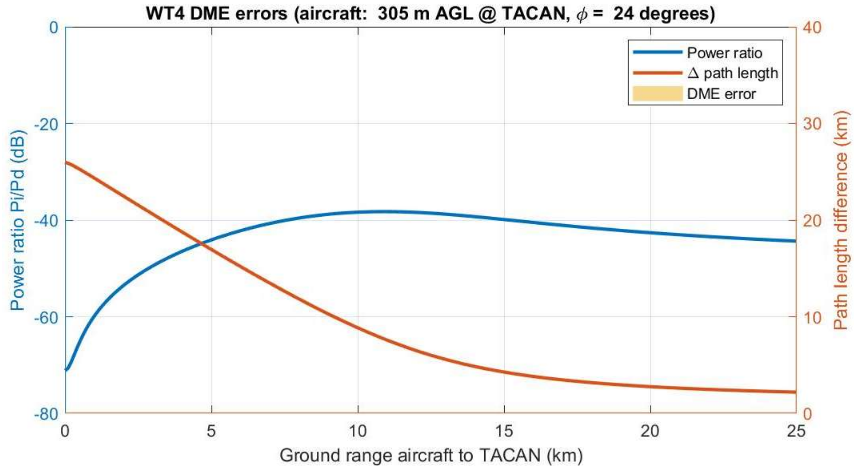


Figure 6.26 Relative signal strength and path length difference along flight trajectory. Flight trajectory altitude is 305 m AGL and angle ϕ = 24°.

The graphs show possible errors for all trajectories except for the trajectory at ϕ = 24°. For values up to ϕ = 20° errors might occur, as is shown in Figure 6.21. For values of ϕ = 21° and larger no errors occur.

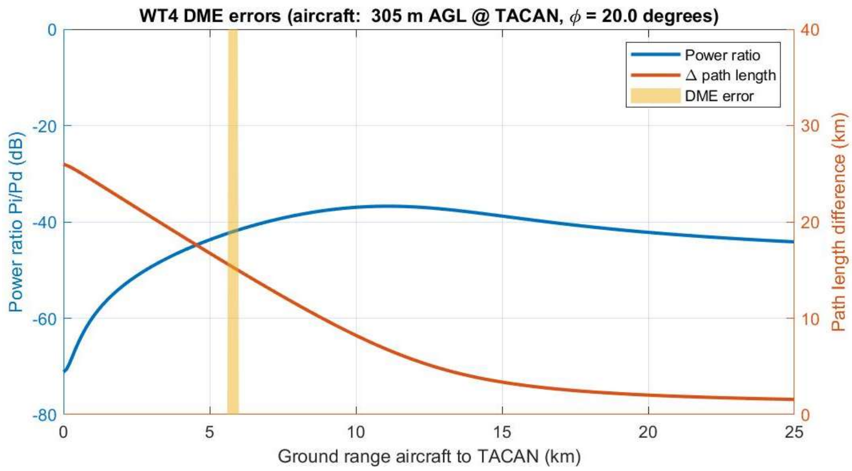


Figure 6.27 Relative signal strength and path length difference along flight trajectory. Flight trajectory altitude is 305 m AGL and angle ϕ = 20°.

For higher altitudes the DME errors are smaller compared to the lower altitudes. Therefore only the results that correspond to an aircraft altitude of 305 m AGL are shown.

As explained in Section 6.2, a DME "error" indicates that both:
- The path length difference is more than 15 km (or 50 µs delay)
- The relative signal strength is large enough to evoke a response of the TACAN system.

The error value is the distance error that might appear on the display in the airplane.

This situation only occurs for the most unfavourable position of the wind turbine blade (worst case scenario). The probability of the blade being in this position is very low (in the order of 10^{-4}). Moreover, the wind turbine is rotating and the aircraft is moving, so this most unfavourable position lasts only for a second at most. Even in the unlikely event an erroneous response of the TACAN is evoked, this will only happen once. It should be noted that, should a TACAN death time of 60 to 65 µs be used, the probability of erroneous TACAN responses would be close to zero.

In addition, the receiver in the aircraft is equipped with an "echo cancellation". The second TACAN response (which arrives with 50 µs delay or more) is neglected by the aircraft.

The area where erroneous TACAN responses might be evoked (and needs to be suppressed by the aircraft echo cancellation), is shown in Figure 6.22 for aircraft altitudes of 1000, 5000 and 8000 feet AGL (305 m, 1524 m, and 2438 m). At 8000 ft AGL there is no region in which DME errors occur.

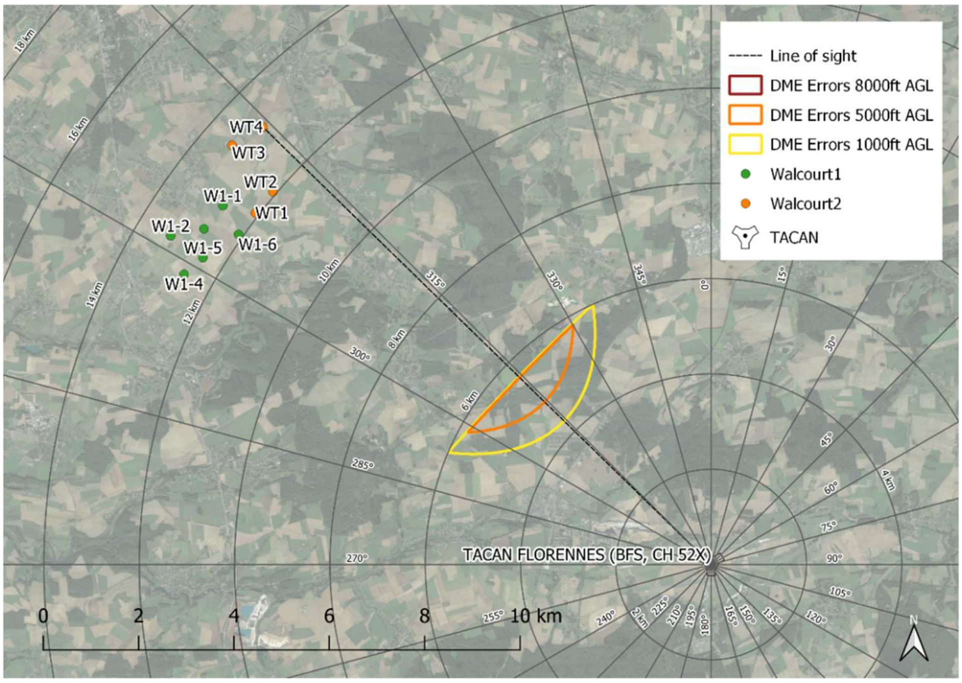


Figure 6.28 Area where echo cancellation is needed, shown in relation to TACAN and wind turbine WT3. The colours from yellow to red represent the contours at altitudes of 1000, 5000 and 8000 ft AGL (absent).

The shape of the contours can be explained by both observing the curved and the straight part. The curved part of the contour relates to the relative power ratio between the direct and indirect paths and is strongly dependent on the range to the wind turbine with higher ratios closer to the wind turbine. The straight part gives the line of 50 μs dead time. Closer to the TACAN the difference in path length exceeds the maximum dead time.
As a concluding remark it is stated that although a volume exists in which DME measurements can be negatively affected, this error volume is not considered to hamper proper operation of the distance measuring part of the TACAN due to the presence of WT4. The volume is only related to a worst case geometry of the wind turbine blade. Moreover these volume are not overlapping with the extended centre lines of the runways at Florennes AFB.

6.8 Consequences for TACAN DME accuracy

The analysis shows that the DME measurement accuracy is not affected by the reference wind turbines W1-1 to W1-6, even though a stringent scenario is used with an aircraft at low altitude and a turbine blade in a most unfavourable position.

The assessed wind turbines WT1, WT2, WT3, and WT4 might in the most unfavourable position of the wind turbine blade evoke erroneous TACAN DME transmissions.

Note that the analysis given here is based on the worst case scenario, a wind turbine blade in the most unfavourable position. This condition will only be present for a short time, due to both rotation of the wind turbine rotor and the movement of the aircraft.

As is argued, this transmission will be cancelled by the aircraft echo cancellation. Moreover the area where this effect may occur is small and not close to the extended centre lines of the runways at Florennes AFB.

Under nominal conditions, the performance degradation of the TACAN system will be much less than described here.

7 Bearing accuracy

7.1 Wind turbine RCS assumption

To determine the bearing accuracy, it is assumed a blade is in a position providing maximum reflection towards the plane. Simulations have been run for one for the existing wind turbines of Walcourt 1 at closest range, W1-6, and for the all of the new wind turbines WT1, WT2, WT3, and WT4.

7.2 Propagation

For bearing determination, radio waves travel only from TACAN to aircraft.

7.3 Error mechanism

The aircraft relies on three signals from the TACAN system (see Figure 3.4):

- The main and secondary reference bursts, transmitted omni-directional
- The 15 Hz signal transmitted by the rotating antenna
- The 135 Hz signal transmitted by the rotating antenna

These mechanisms are described in detail in the sections that follow.

7.3.1 Reference

The reference bursts can be affected in the same way as the DME signals (see Section 6.2). A reflected reference signal will arrive at the receiver with a delay as well as with an attenuation. If the signal strength is sufficient, it might give rise to a false reference (although most systems will have an echo cancellation function).

7.3.2 Bearing signal 15 Hz

As is explained in Chapter 3, the bearing signal is amplitude modulated. By measuring the phase of this amplitude modulated signal, the actual bearing to the TACAN is estimated. The signal transmitted in the direction of the wind turbine has a different phase than the direct signal transmitted towards the airplane. Hence also the reflected signal towards the airplane has this different phase, as is shown in Figure 7.1.

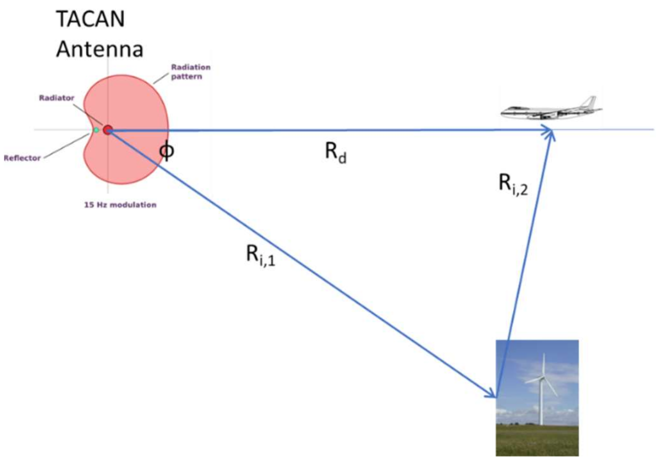


Figure 7.1 TACAN phase modulation of reflected signal.

The direct signal between TACAN and aircraft is modulated as

$$D = \sin(\omega t + \psi)$$

Where D is the direct received signal, ω is the angular frequency of 15 · 2π, t is time and ψ is the phase carrying the coarse (15 Hz) bearing information.

The reflected signal of the indirect path is

$$R = {}^{Pi}/_{Pd} \sin(\omega(t + \Delta t) + \psi + \phi)$$

Where R is the received reflected signal, ϕ is the angle between aircraft and wind turbine (as seen from the TACAN, see Figure 7.1) and Δt the time delay due to the path length difference. P_i / P_d is the power ratio calculated earlier in section 4.4.

The direct and reflected signals sum up at the airplane antenna, giving rise to a signal with a shifted phase:

$$D + R = \sin(\omega t + \psi) + {}^{Pi}/_{Pd} \sin(\omega(t + \Delta t) + \psi + \phi)$$

7.3.3 *Bearing signal 135 Hz*

For the 135 Hz modulation, the case is similar. Only the modulation is different, as is shown in Figure 7.2.

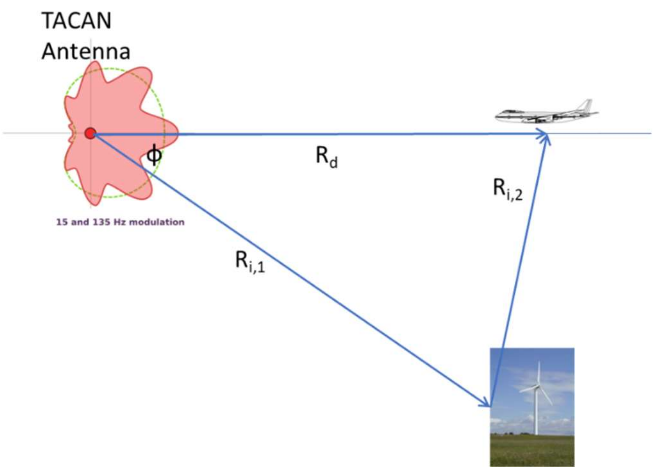


Figure 7.2 TACAN phase modulation of reflected signal.

The direct signal is modulated as

$$D = \sin(9\omega t + 9\psi)$$

Note that:

- ω is the same angular frequency of 15 · 2π, given the factor 9 in the formula.
- The phase angle in the 135 Hz signal is 9ψ, this phase angle carries the fine (135 Hz) bearing information.

The reflected signal is

$$R = {}^{Pi}/_{Pd} \sin(9\omega(t + \Delta t) + 9\psi + 9\phi)$$

The direct and reflected signals sum up at the airplane antenna, giving rise to a signal with a shifted phase:

$$D + R = \sin(9\omega t + 9\psi) + {}^{Pi}/_{Pd} \sin\left(9\omega(t + \Delta t) + 9\psi + 9\phi\right)$$

7.4 Reference analysis W1-6

For reference wind turbine W1-6, the maximum (worst-case) bearing errors that may occur, are analysed for the area that surrounds the TACAN and wind turbines as a function of the position of the aircraft. The bearing signal will be changed in phase and amplitude by the reflected signal. To determine the bearing error, the relative signal strength of the reflected signal and the resulting phase deviation of the combined (D+R) signal is calculated for each point on the grid.

7.4.1 Reference burst signal errors

The reference burst signals can be affected the same way the DME signals are. A reflected reference signal will arrive at the receiver with a delay as well as with a power level that are functions of the geometry of the TACAN, wind turbine, and aircraft and the RCS of the wind turbine's blade (ref. Chapter 4).

Figure 7.3 shows the maximum bearing errors that occur due to reception of the reflected reference burst signal. The maximum error is 0.16° at 7.6 km distance to the TACAN within the vertical plane defined by the line of sight from TACAN to wind turbine.

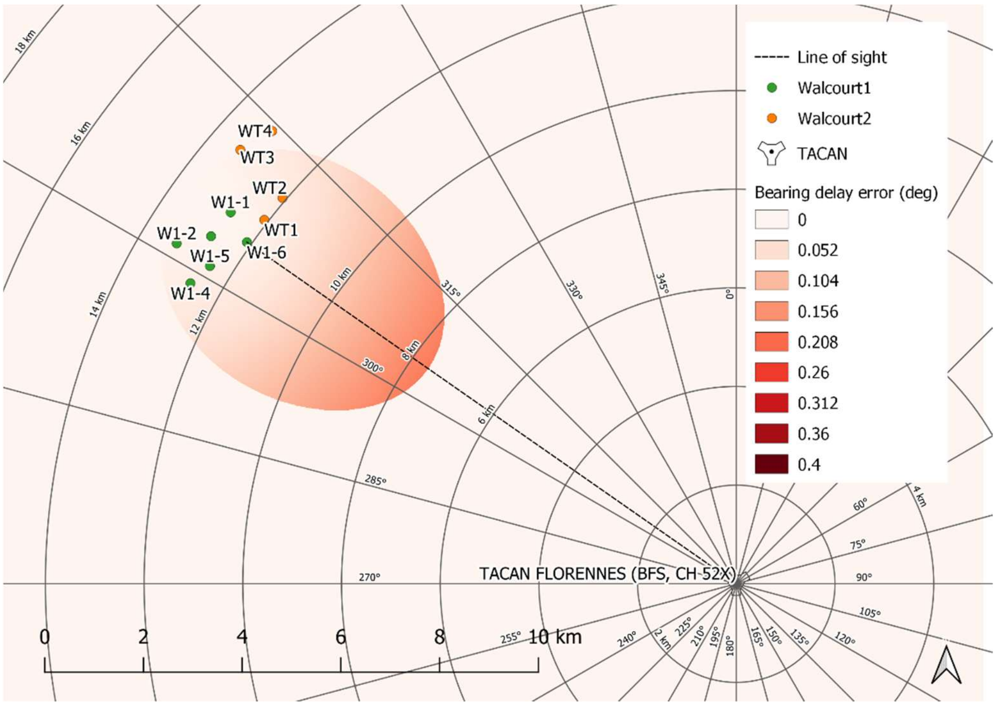


Figure 7.3 Maximum bearing measurement errors in degrees of the reference signal due to the presence of W1-6 only. Flight altitude is 305 m AGL. Maximum error is 0.16° at range to TACAN 7.6 km.

7.4.2 15 Hz and 135 Hz amplitude modulated signal errors

In Figure 7.4 and Figure 7.5 the maximum bearing errors due to the presence of W1-6 are shown for the 15 Hz and 135 Hz amplitude modulated signals. The largest errors occur close to the wind turbine, to the left and right of the line of sight from TACAN to wind turbine. At these locations the aforementioned power ratio between the indirect and direct path is large. The phase difference due to the rotation of the antenna is also significant at these locations. The additional phase difference due to the path delay is much smaller and plays only a marginal role. At

an altitude of 305 m AGL the maximum bearing error is 0.013° and 0.13° for the 15 Hz and 135 Hz modulations respectively.

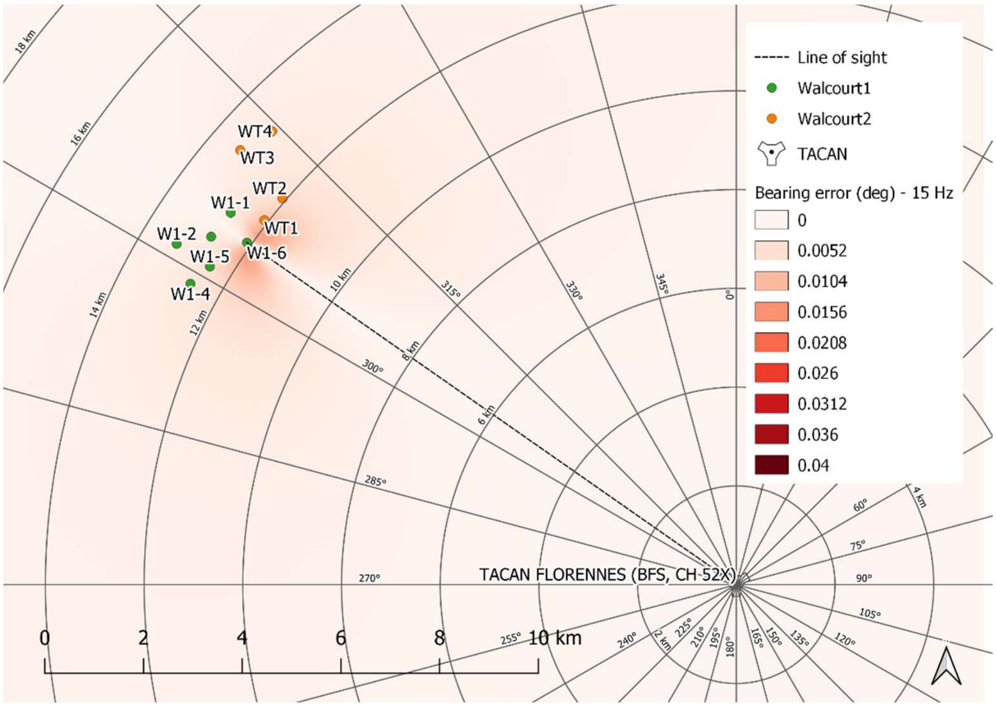


Figure 7.4 Maximum bearing measurement errors in degrees of the 15 Hz modulated signal due to the presence of W1-6 only. Flight altitude is 305 m AGL. Maximum error is 0.013° at range to TACAN 11.91 km, ϕ = 1.3°.

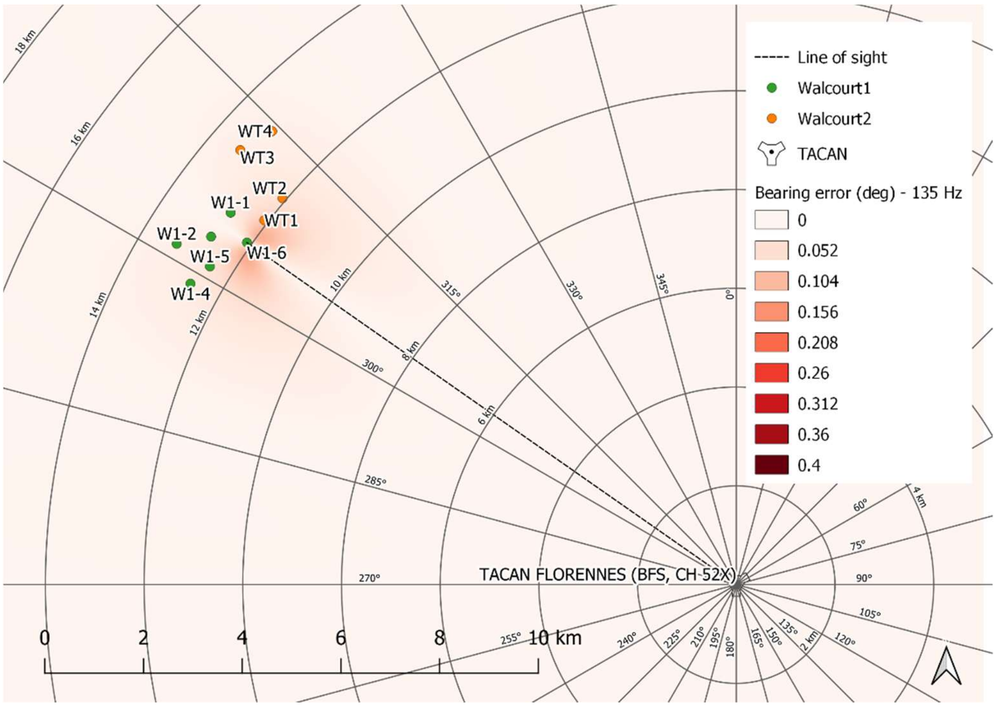


Figure 7.5 Maximum bearing measurement errors in degrees of the 135 Hz modulated signal due to the presence of W1-6 only. Flight altitude is 305 m AGL. Maximum error is 0.12° at range to TACAN 11.91 km, ϕ = 1.3°.

In Figure 7.6 the bearing error is shown both for the 15 Hz and 135 Hz signal, for an azimuth angle between aircraft and wind turbine of ϕ = 1.3°. At ϕ = 1.3° the bearing error is maximal at 0.13°.

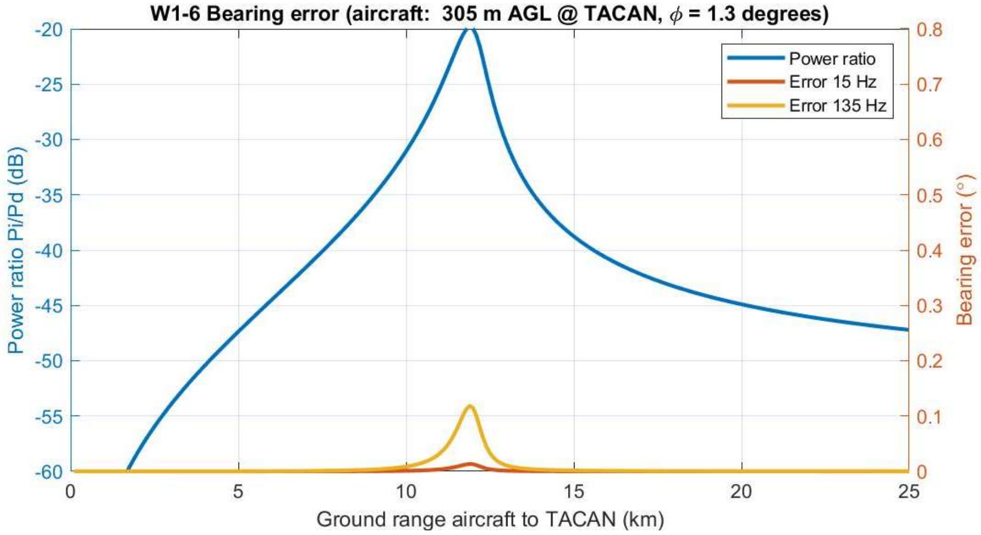


Figure 7.6 Bearing error in the 15 Hz and 135 Hz signal. Flight trajectory altitude is 305 m AGL and angle ϕ = 1.3°.

As is expected, the bearing error is proportional to the received signal strength. Also, the error is approximately 9 times as large in the 135 Hz signal as in the 15 Hz signal.

For ϕ = 40°, the 135 Hz reflected signal is in phase again with the direct signal, hence the remaining error in the 135 Hz signal is only due to the additional time delay Δt. This is shown in Figure 7.7. The bearing error in the 15 Hz signal is 0.001°. Note that the error in the 15 Hz signal is to a large extent irrelevant, it is only used to resolve the ambiguity in the 135 Hz signal.

Figure 7.7 Bearing error in the 15 Hz and 135 Hz signal. Flight trajectory altitude is 305 m AGL and angle ϕ = 40°.

Please note again that these errors do only occur in a worst case situation with the blade of the wind turbine in the most adverse attitude. This will occur only rarely and under normal ‘average’ conditions the errors are substantially smaller. For all the other existing wind turbines the maximum error is similar. The event that two or more blades are in their worst case attitude simultaneously is considered negligible and this situation would occur for a very short time period only.

7.5 Analysis WT1

For wind turbine WT1, the maximum (worst-case) bearing errors that may occur, are analysed for the area that surrounds the TACAN and wind turbines as a function of the position of the aircraft. The bearing signal will be changed in phase and amplitude by the reflected signal. To determine the bearing error, the relative signal strength of the reflected signal and the resulting phase deviation of the combined (D+R) signal is calculated for each point on the grid.

7.5.1 Reference burst signal errors

The reference burst signals can be affected the same way the DME signals are. A reflected reference signal will arrive at the receiver with a delay as well as with a power level that are functions of the geometry of the TACAN, wind turbine, and aircraft and the RCS of the wind turbine's blade (ref Chapter 4).

Figure 7.3 shows the maximum bearing errors that occur due to reception of the reflected reference burst signal. The maximum error is 0.34° at 2.6 km distance to the TACAN within the vertical plane defined by the line of sight from TACAN to wind turbine.

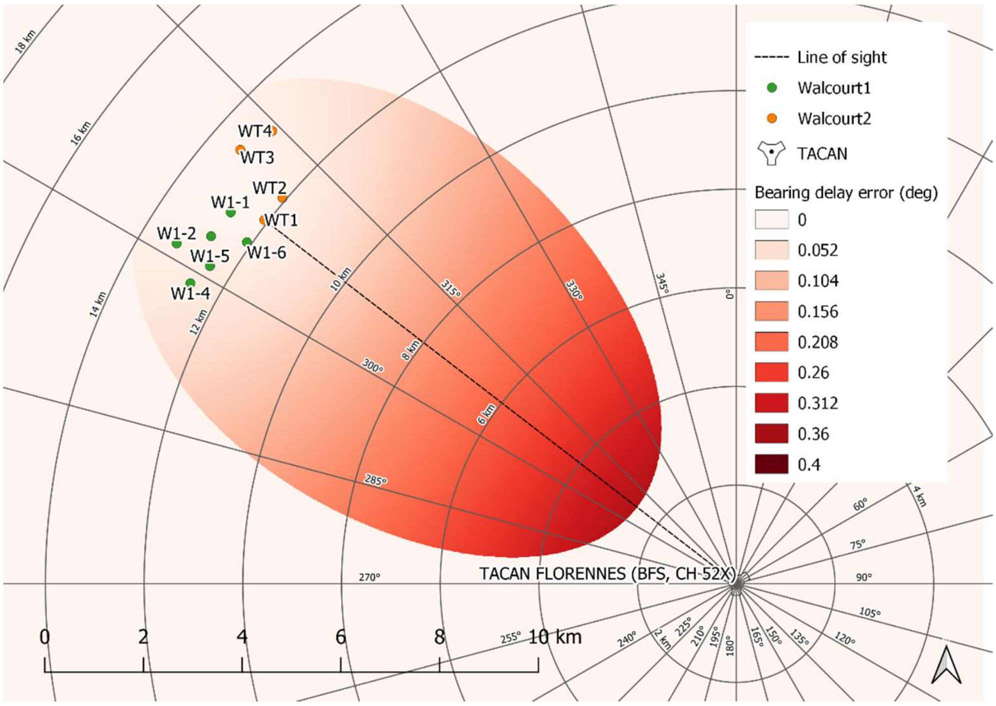


Figure 7.8 Maximum bearing measurement errors in degrees of the reference signal due to the presence of WT1 only. Flight altitude is 305 m AGL. Maximum error is 0.34° at range to TACAN 2.6 km.

7.5.2 15 Hz and 135 Hz amplitude modulated signal errors

In Figure 7.9 and Figure 7.10 the maximum bearing errors due to the presence of W1-6 are shown for the 15 Hz and 135 Hz amplitude modulated signals. The largest errors occur close to the wind turbine, to the left and right of the line of sight from TACAN to wind turbine. At these locations the aforementioned power ratio between the indirect and direct path is large. The phase difference due to the rotation of the antenna is also significant at these locations. The additional phase difference due to the path delay is much smaller and plays only a marginal role. At

an altitude of 305 m AGL the maximum bearing error is 0.013° and 0.13° for the 15 Hz and 135 Hz modulations respectively.

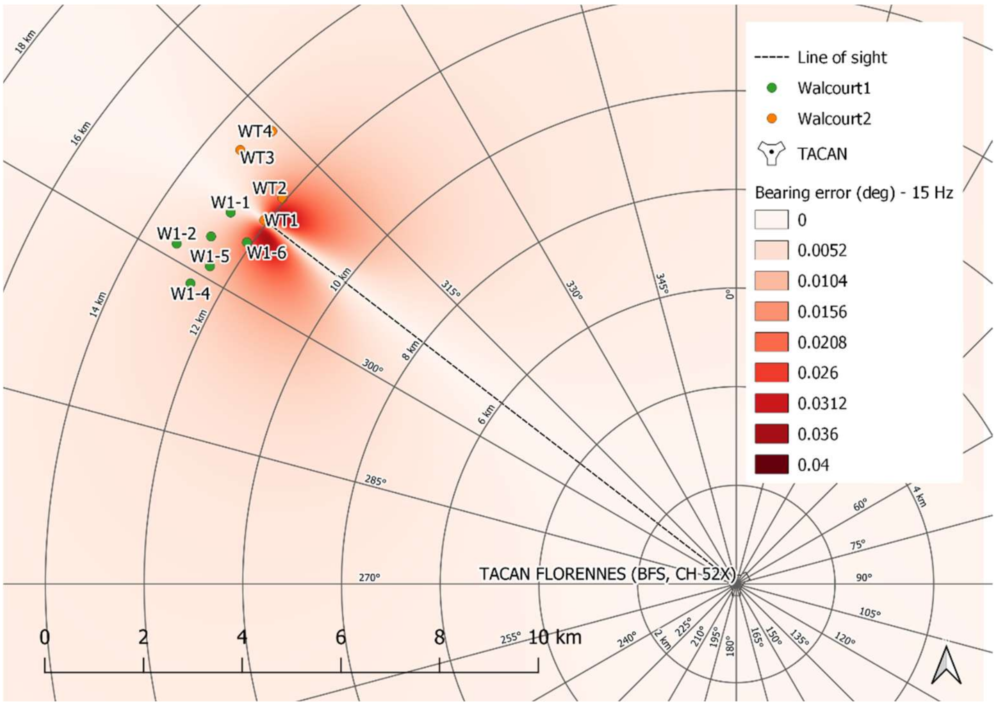


Figure 7.9 Maximum bearing measurement errors in degrees of the 15 Hz modulated signal due to the presence of WT1 only. Flight altitude is 305 m AGL. Maximum error is 0.036 degrees at range to TACAN 11.82 km, ϕ = 1.3°.

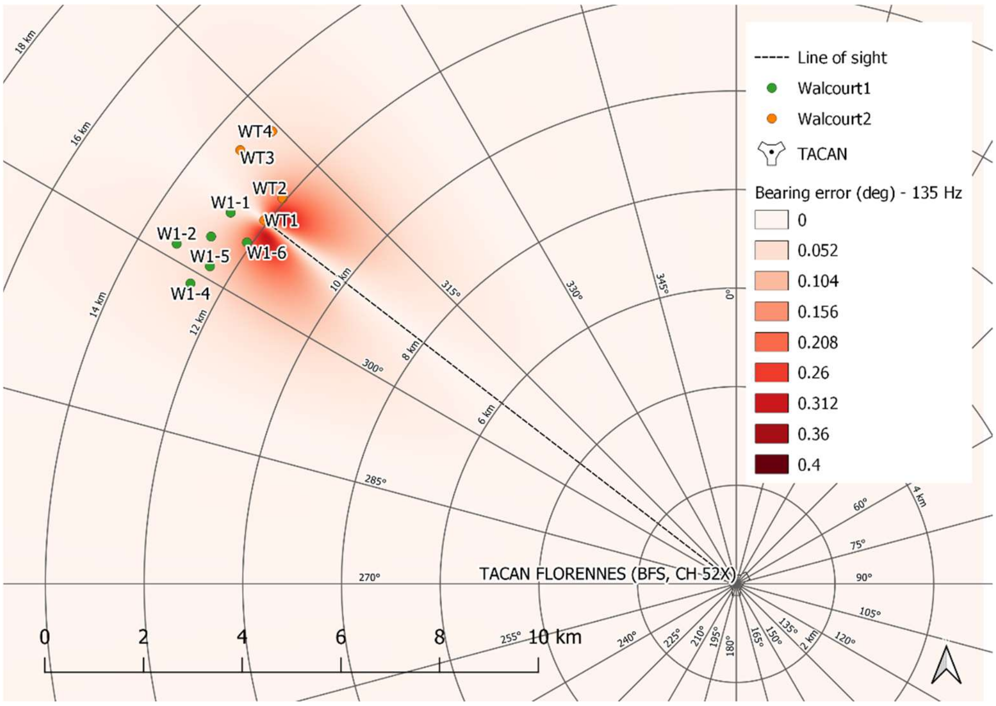


Figure 7.10 Maximum bearing measurement errors in degrees of the 135 Hz modulated signal due to the presence of WT1 only. Flight altitude is 305 m AGL. Maximum error is 0.32 degrees at range to TACAN 11.82 km, ϕ = 1.3°.

In Figure 7.11 the bearing error is shown both for the 15 Hz and 135 Hz signal, for an azimuth angle between aircraft and wind turbine of ϕ = 1.3°. At ϕ = 1.3° the bearing error is maximal at 0.32°.

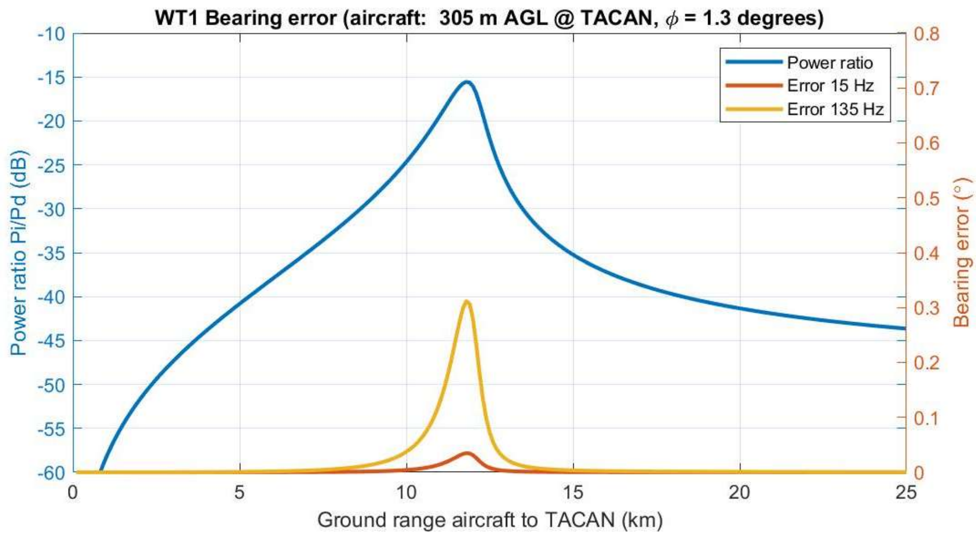


Figure 7.11 Bearing error in the 15 Hz and 135 Hz signal. Flight trajectory altitude is 305 m AGL and angle ϕ = 1.3°.

As is expected, the bearing error is proportional to the received signal strength. Also, the error is approximately 9 times as large in the 135 Hz signal as in the 15 Hz signal.

For ϕ = 40°, the 135 Hz reflected signal is in phase again with the direct signal, hence the remaining error in the 135 Hz signal is only due to the additional time delay Δt. This is shown in Figure 7.12. The bearing error in the 15 Hz signal is 0.003°. Note that the error in the 15 Hz signal is to a large extent irrelevant, it is only used to resolve the ambiguity in the 135 Hz signal.

Figure 7.12 Bearing error in the 15 Hz and 135 Hz signal. Flight trajectory altitude is 305 m AGL and angle ϕ = 40°.

Please note again that these errors do only occur in a worst case situation with the blade of the wind turbine in the most adverse attitude. This will occur only rarely and under normal ‘average’ conditions the errors are substantially smaller. The event that two or more blades are in their worst case attitude simultaneously is considered negligible and this situation would occur for a very short time period only.

7.6 Analysis WT2

For wind turbine WT2, the maximum (worst-case) bearing errors that may occur, are analysed for the area that surrounds the TACAN and wind turbines as a function of the position of the aircraft. The bearing signal will be changed in phase and amplitude by the reflected signal. To determine the bearing error, the relative signal strength of the reflected signal and the resulting phase deviation of the combined (D+R) signal is calculated for each point on the grid.

7.6.1 Reference burst signal errors

The reference burst signals can be affected the same way the DME signals are. A reflected reference signal will arrive at the receiver with a delay as well as with a power level that are functions of the geometry of the TACAN, wind turbine, and aircraft and the RCS of the wind turbine's blade (ref Chapter 4).

Figure 7.3 shows the maximum bearing errors that occur due to reception of the reflected reference burst signal. The maximum error is 0.34° at 2.6 km distance to the TACAN within the vertical plane defined by the line of sight from TACAN to wind turbine.

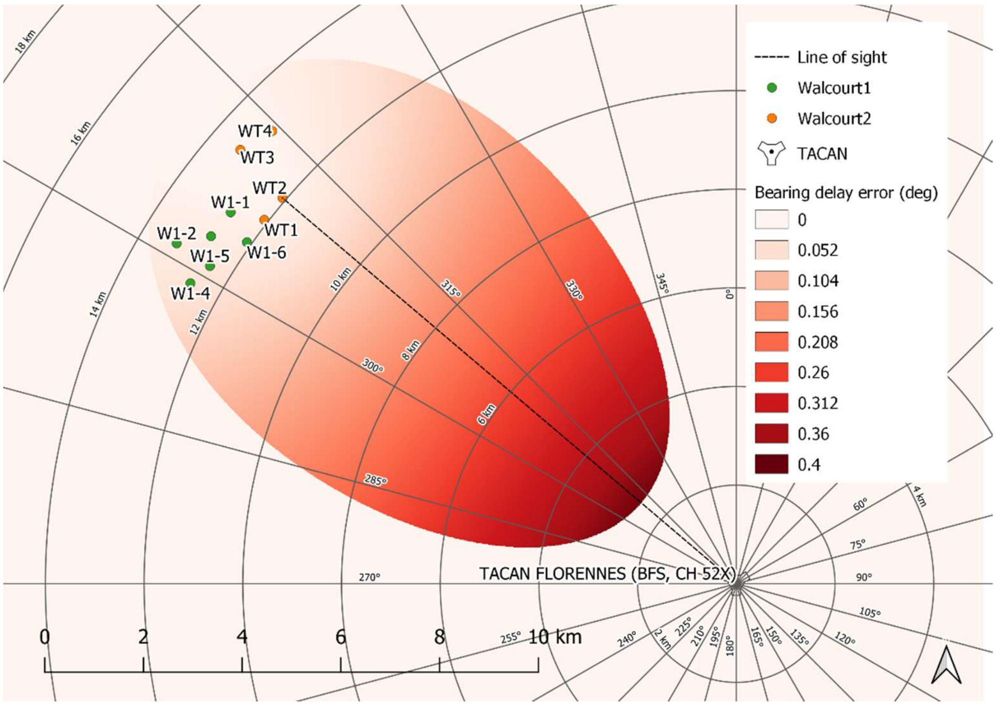


Figure 7.13 Maximum bearing measurement errors in degrees of the reference signal due to the presence of WT2 only. Flight altitude is 305 m AGL. Maximum error is 0.34° at range to TACAN 2.6 km.

7.6.2 15 Hz and 135 Hz amplitude modulated signal errors

In Figure 7.14 and Figure 7.15 the maximum bearing errors due to the presence of the wind turbine are shown for the 15 Hz and 135 Hz amplitude modulated signals. The largest errors occur close to the wind turbine, to the left and right of the line of sight from TACAN to wind turbine. At these locations the aforementioned power ratio between the indirect and direct path is large. The phase difference due to the rotation of the antenna is also significant at these locations. The additional phase difference due to the path delay is much smaller and plays only a marginal role. At

an altitude of 305 m AGL the maximum bearing error is 0.035° and 0.31° for the 15 Hz and 135 Hz modulations respectively.

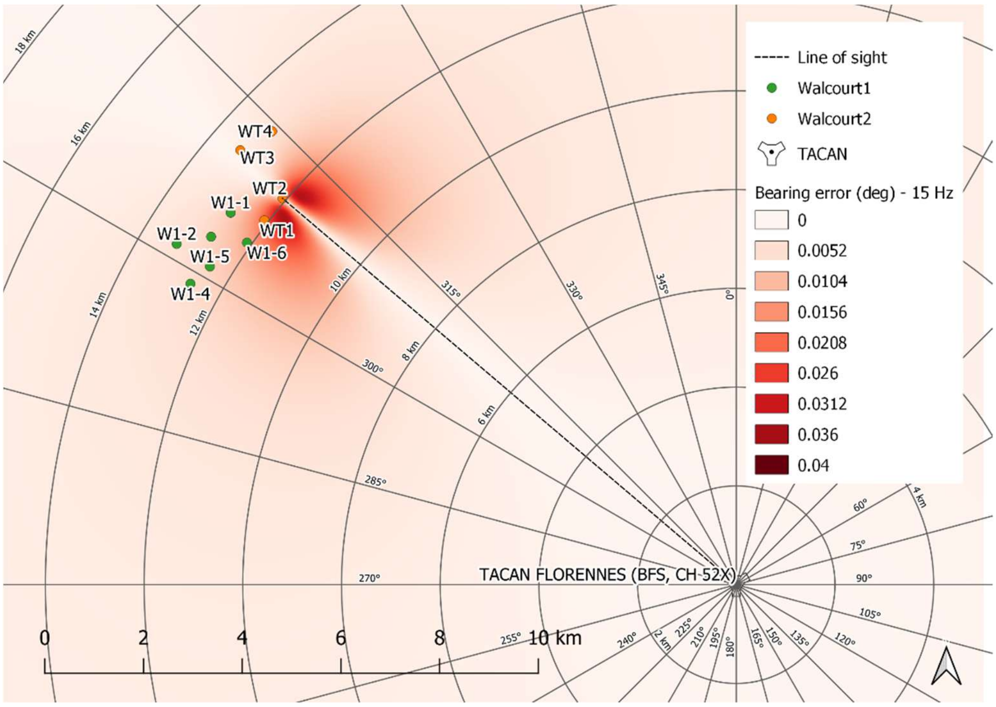


Figure 7.14 Maximum bearing measurement errors in degrees of the 15 Hz modulated signal due to the presence of WT2 only. Flight altitude is 305 m AGL. Maximum error is 0.035 degrees at range to TACAN 11.81 km, ϕ = 1.3°.

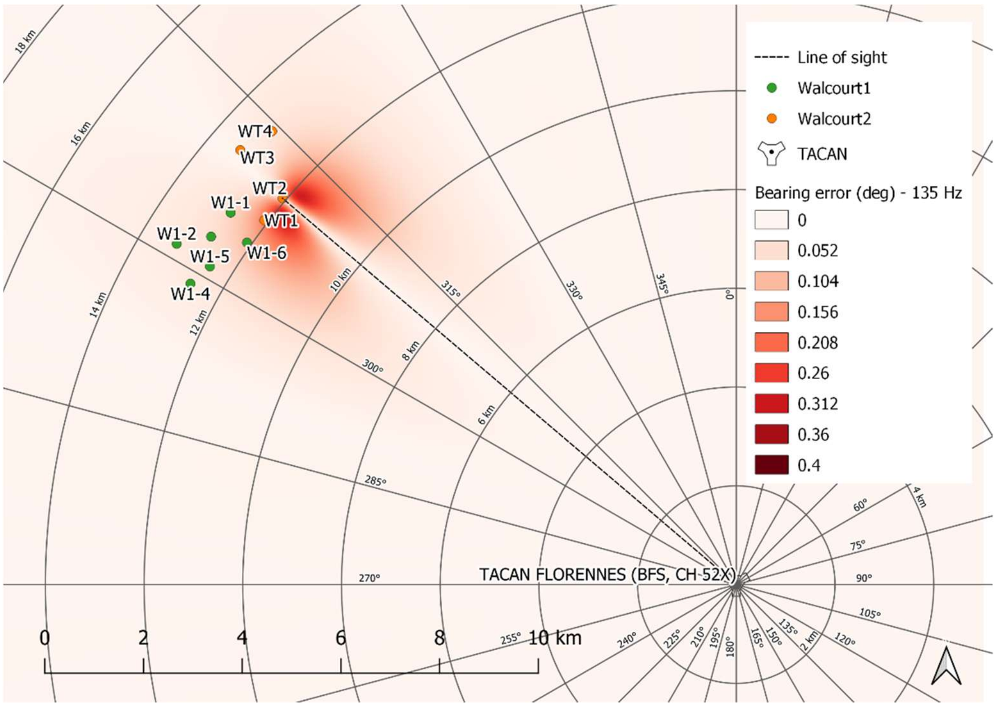


Figure 7.15 Maximum bearing measurement errors in degrees of the 135 Hz modulated signal due to the presence of WT2 only. Flight altitude is 305 m AGL. Maximum error is 0.31 degrees at range to TACAN 11.81 km, ϕ = 1.3°.

In Figure 7.16 the bearing error is shown both for the 15 Hz and 135 Hz signal, for an azimuth angle between aircraft and wind turbine of ϕ = 1.3°. At ϕ = 1.3° the bearing error is maximal at 0.31°.

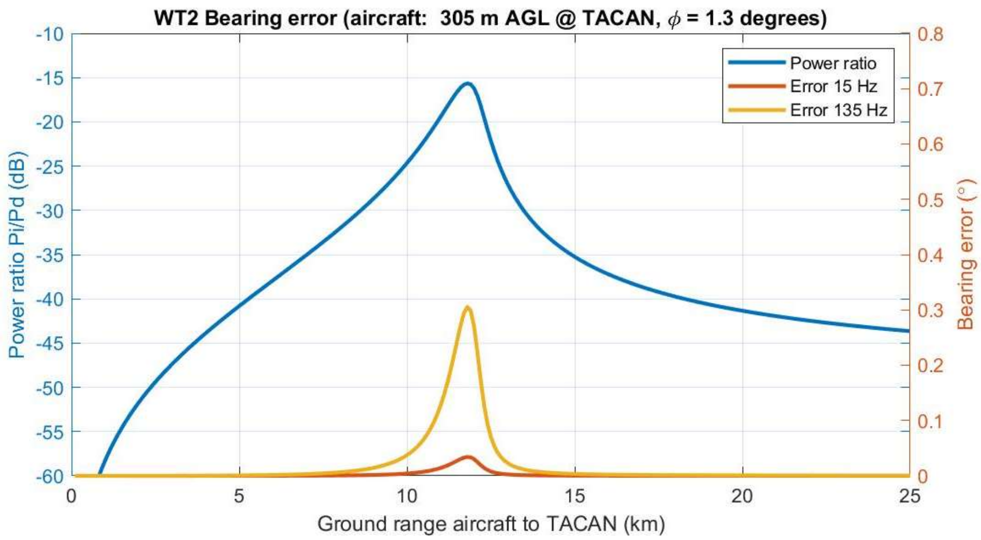


Figure 7.16 Bearing error in the 15 Hz and 135 Hz signal. Flight trajectory altitude is 305 m AGL and angle ϕ = 1.3°.

As is expected, the bearing error is proportional to the received signal strength. Also, the error is approximately 9 times as large in the 135 Hz signal as in the 15 Hz signal.

For ϕ = 40°, the 135 Hz reflected signal is in phase again with the direct signal, hence the remaining error in the 135 Hz signal is only due to the additional time delay Δt. This is shown in Figure 7.17. The bearing error in the 15 Hz signal is 0.003°. Note that the error in the 15 Hz signal is to a large extent irrelevant, it is only used to resolve the ambiguity in the 135 Hz signal.

Figure 7.17 Bearing error in the 15 Hz and 135 Hz signal. Flight trajectory altitude is 305 m AGL and angle ϕ = 40°.

Please note again that these errors do only occur in a worst case situation with the blade of the wind turbine in the most adverse attitude. This will occur only rarely and under normal ‘average’ conditions the errors are substantially smaller. The event that two or more blades are in their worst case attitude simultaneously is considered negligible and this situation would occur for a very short time period only.

7.7 Analysis WT3

For wind turbine WT3, the maximum (worst-case) bearing errors that may occur, are analysed for the area that surrounds the TACAN and wind turbines as a function of the position of the aircraft. The bearing signal will be changed in phase and amplitude by the reflected signal. To determine the bearing error, the relative signal strength of the reflected signal and the resulting phase deviation of the combined (D+R) signal is calculated for each point on the grid.

7.7.1 Reference burst signal errors

The reference burst signals can be affected the same way the DME signals are. A reflected reference signal will arrive at the receiver with a delay as well as with a power level that are functions of the geometry of the TACAN, wind turbine, and aircraft and the RCS of the wind turbine's blade (ref Chapter 4).

Figure 7.3 shows the maximum bearing errors that occur due to reception of the reflected reference burst signal. The maximum error is 0.31° at 4.7 km distance to the TACAN within the vertical plane defined by the line of sight from TACAN to wind turbine.

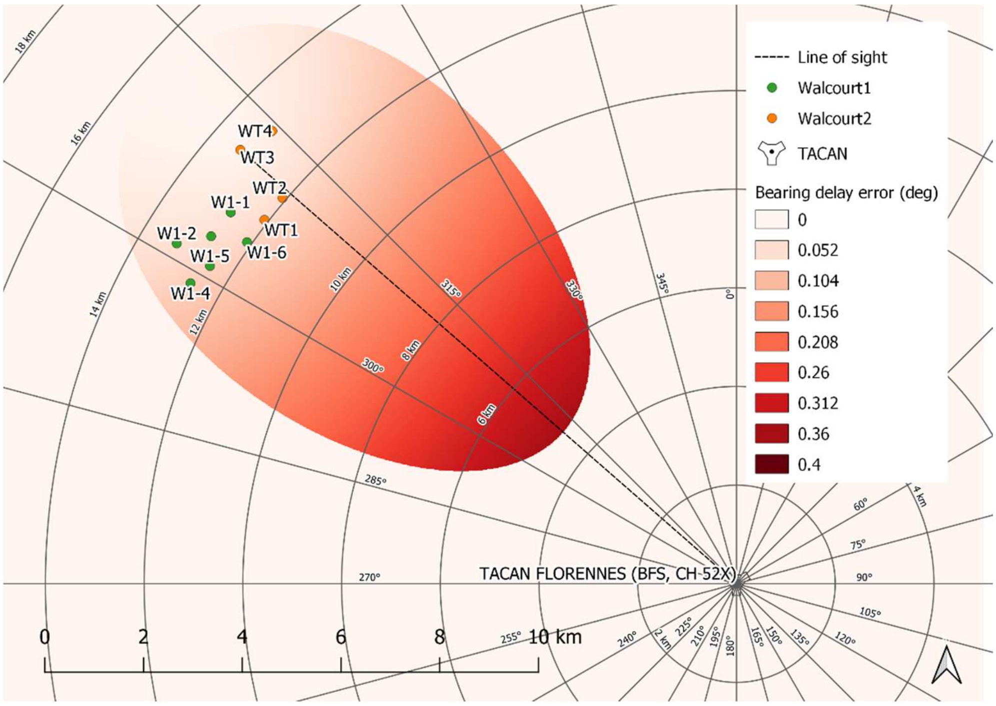


Figure 7.18 Maximum bearing measurement errors in degrees of the reference signal due to the presence of WT3 only. Flight altitude is 305 m AGL. Maximum error is 0.31° at range to TACAN 4.7 km.

7.7.2 15 Hz and 135 Hz amplitude modulated signal errors

In Figure 7.19 and Figure 7.20 the maximum bearing errors due to the presence of the wind turbine are shown for the 15 Hz and 135 Hz amplitude modulated signals. The largest errors occur close to the wind turbine, to the left and right of the line of sight from TACAN to wind turbine. At these locations the aforementioned power ratio between the indirect and direct path is large. The phase difference due to the rotation of the antenna is also significant at these locations. The additional phase difference due to the path delay is much smaller and plays only a marginal role. At

an altitude of 305 m AGL the maximum bearing error is 0.029° and 0.26° for the 15 Hz and 135 Hz modulations respectively.

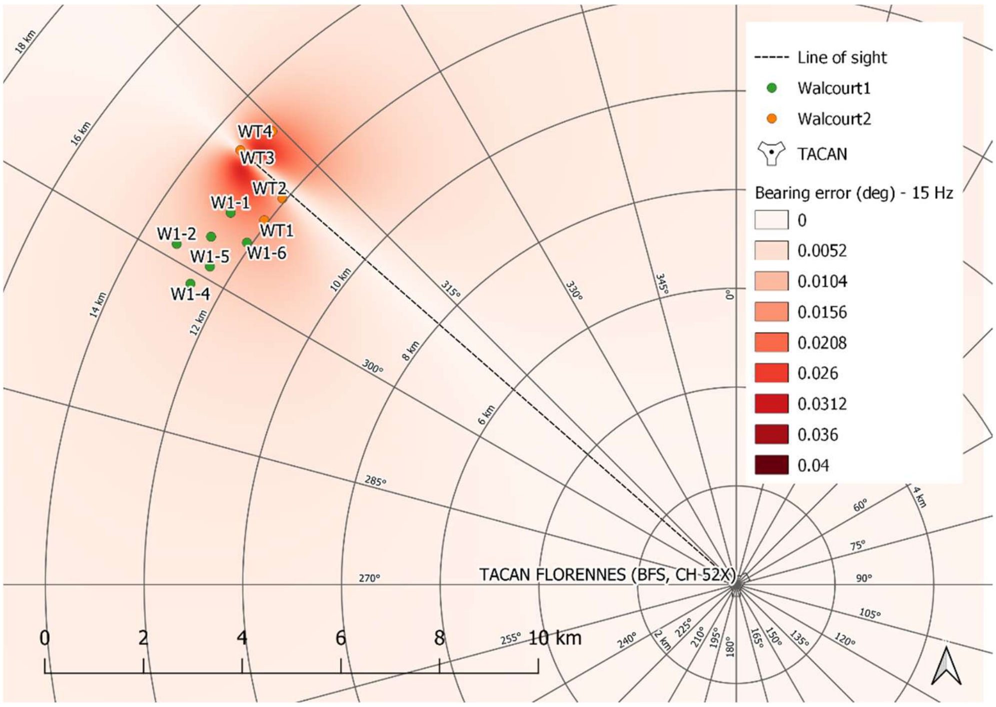


Figure 7.19 Maximum bearing measurement errors in degrees of the 15 Hz modulated signal due to the presence of WT3 only. Flight altitude is 305 m AGL. Maximum error is 0.029 degrees at range to TACAN 13.07 km, ϕ = 1.3°.

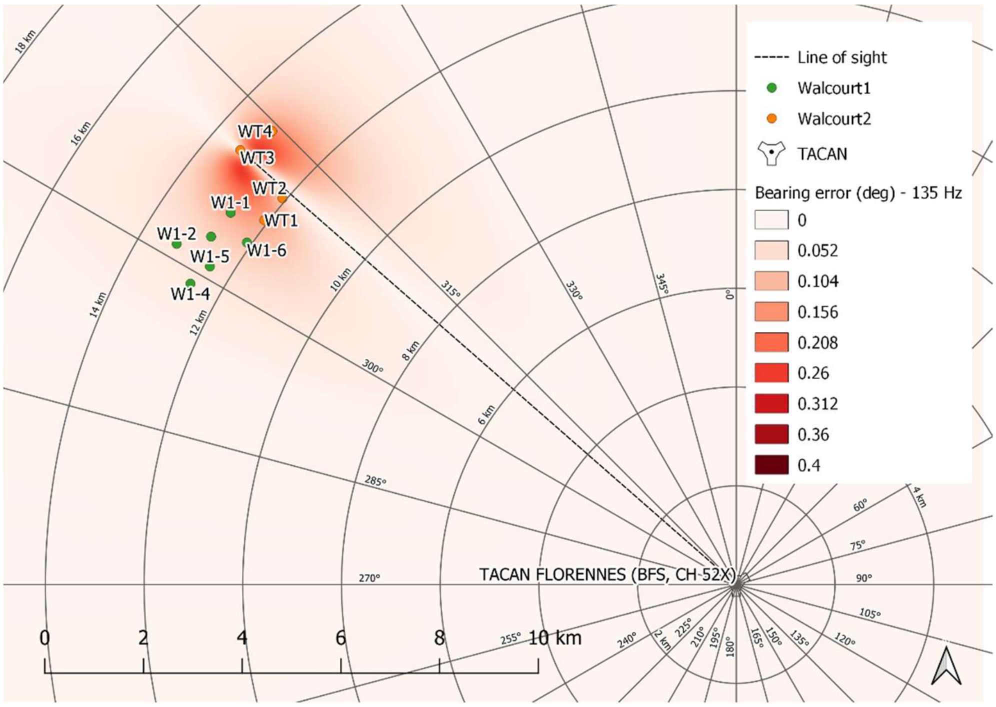


Figure 7.20 Maximum bearing measurement errors in degrees of the 135 Hz modulated signal due to the presence of WT3 only. Flight altitude is 305 m AGL. Maximum error is 0.26 degrees at range to TACAN 13.07 km, ϕ = 1.3°.

In Figure 7.21 the bearing error is shown both for the 15 Hz and 135 Hz signal, for an azimuth angle between aircraft and wind turbine of ϕ = 1.3°. At ϕ = 1.3° the bearing error is maximal at 0.26°.

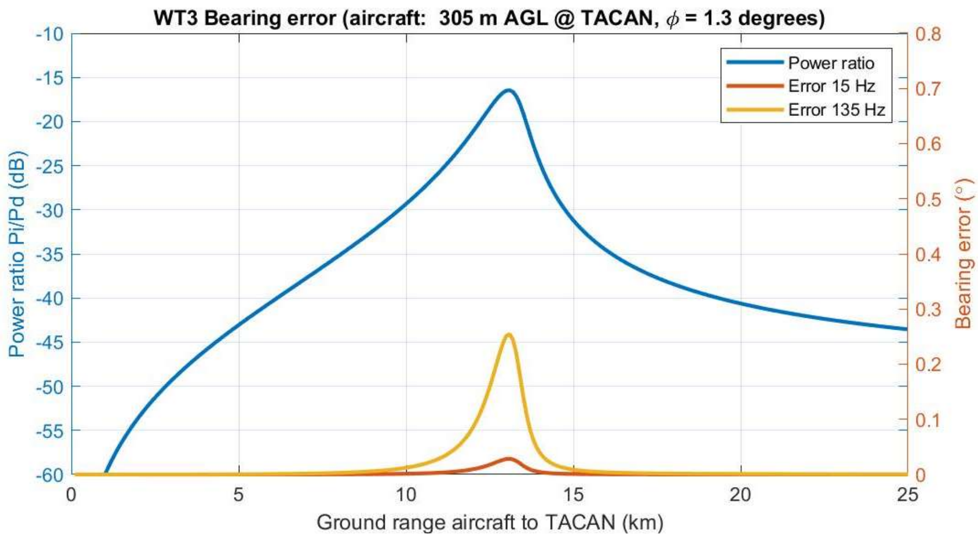


Figure 7.21 Bearing error in the 15 Hz and 135 Hz signal. Flight trajectory altitude is 305 m AGL and angle ϕ = 1.3°.

As is expected, the bearing error is proportional to the received signal strength. Also, the error is approximately 9 times as large in the 135 Hz signal as in the 15 Hz signal.

For ϕ = 40°, the 135 Hz reflected signal is in phase again with the direct signal, hence the remaining error in the 135 Hz signal is only due to the additional time delay Δt. This is shown in Figure 7.22. The bearing error in the 15 Hz signal is 0.002°. Note that the error in the 15 Hz signal is to a large extent irrelevant, it is only used to resolve the ambiguity in the 135 Hz signal.

Figure 7.22 Bearing error in the 15 Hz and 135 Hz signal. Flight trajectory altitude is 305 m AGL and angle ϕ = 40°.

Please note again that these errors do only occur in a worst case situation with the blade of the wind turbine in the most adverse attitude. This will occur only rarely and under normal ‘average’ conditions the errors are substantially smaller. The event that two or more blades are in their worst case attitude simultaneously is considered negligible and this situation would occur for a very short time period only.

7.8 Analysis WT4

For wind turbine WT4, the maximum (worst-case) bearing errors that may occur, are analysed for the area that surrounds the TACAN and wind turbines as a function of the position of the aircraft. The bearing signal will be changed in phase and amplitude by the reflected signal. To determine the bearing error, the relative signal strength of the reflected signal and the resulting phase deviation of the combined (D+R) signal is calculated for each point on the grid.

7.8.1 Reference burst signal errors

The reference burst signals can be affected the same way the DME signals are. A reflected reference signal will arrive at the receiver with a delay as well as with a power level that are functions of the geometry of the TACAN, wind turbine, and aircraft and the RCS of the wind turbine's blade (ref Chapter 4).

Figure 7.3 shows the maximum bearing errors that occur due to reception of the reflected reference burst signal. The maximum error is 0.32° at 4.3 km distance to the TACAN within the vertical plane defined by the line of sight from TACAN to wind turbine.

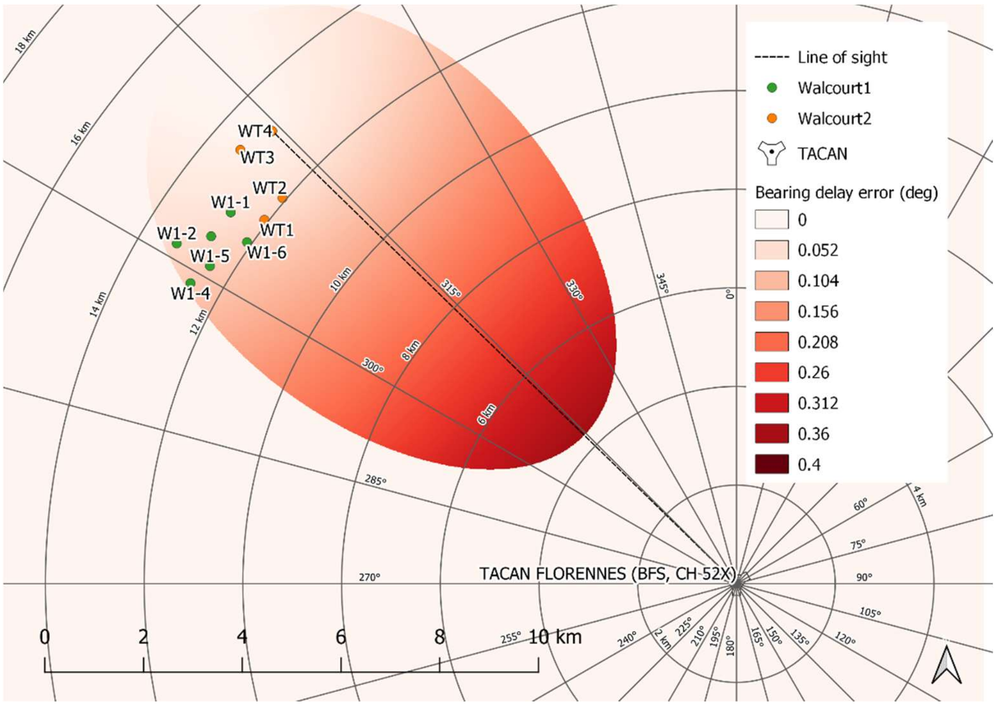


Figure 7.23 Maximum bearing measurement errors in degrees of the reference signal due to the presence of WT4 only. Flight altitude is 305 m AGL. Maximum error is 0.32° at range to TACAN 4.3 km.

7.8.2 15 Hz and 135 Hz amplitude modulated signal errors

In Figure 7.24 and Figure 7.25 the maximum bearing errors due to the presence of the wind turbine are shown for the 15 Hz and 135 Hz amplitude modulated signals. The largest errors occur close to the wind turbine, to the left and right of the line of sight from TACAN to wind turbine. At these locations the aforementioned power ratio between the indirect and direct path is large. The phase difference due to the rotation of the antenna is also significant at these locations. The additional phase difference due to the path delay is much smaller and plays only a marginal role. At

an altitude of 305 m AGL the maximum bearing error is 0.030° and 0.27° for the 15 Hz and 135 Hz modulations respectively.

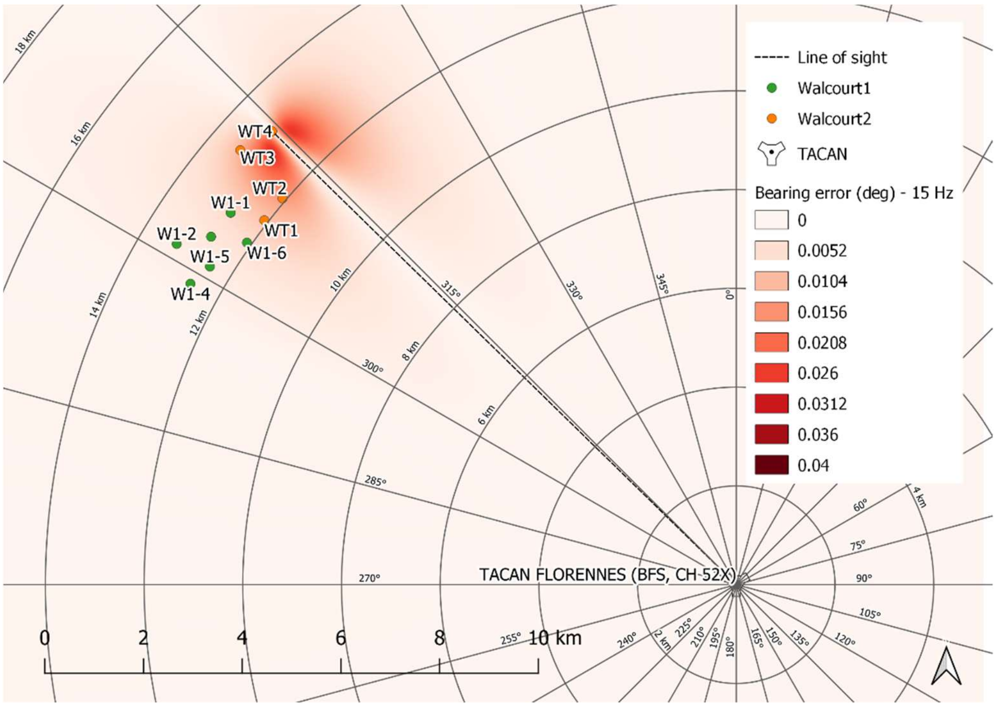


Figure 7.24 Maximum bearing measurement errors in degrees of the 15 Hz modulated signal due to the presence of WT4 only. Flight altitude is 305 m AGL. Maximum error is 0.030 degrees at range to TACAN 12.85 km, ϕ = 1.3°.

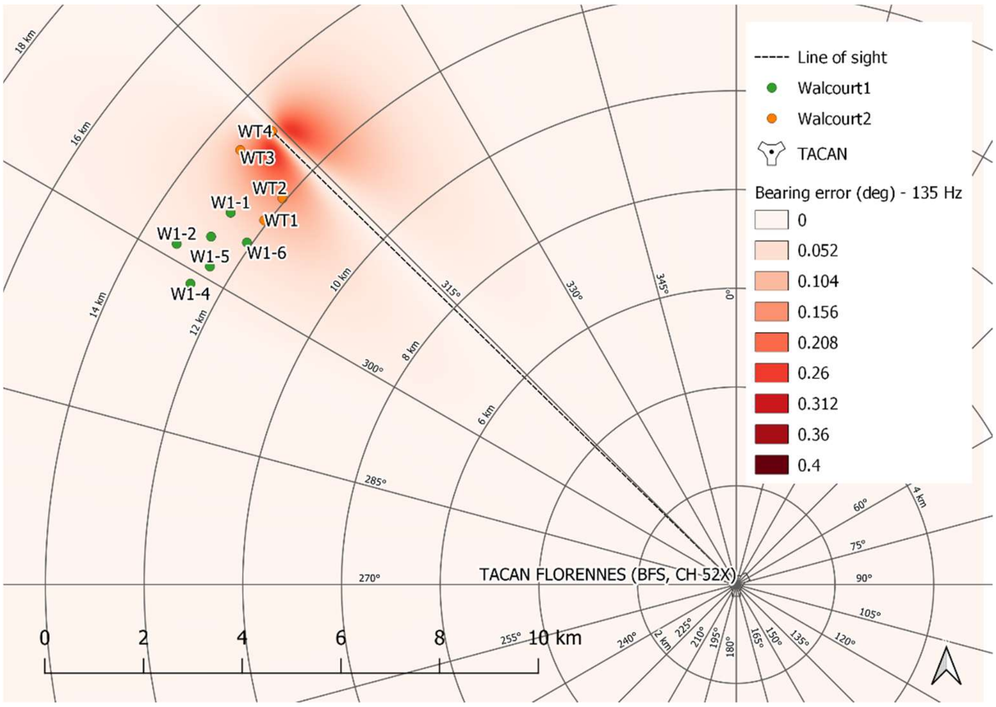


Figure 7.25 Maximum bearing measurement errors in degrees of the 135 Hz modulated signal due to the presence of WT4 only. Flight altitude is 305 m AGL. Maximum error is 0.27 degrees at range to TACAN 12.86 km, ϕ = 1.3°.

In Figure 7.26 the bearing error is shown both for the 15 Hz and 135 Hz signal, for an azimuth angle between aircraft and wind turbine of ϕ = 1.3°. At ϕ = 1.3° the bearing error is maximal at 0.27°.

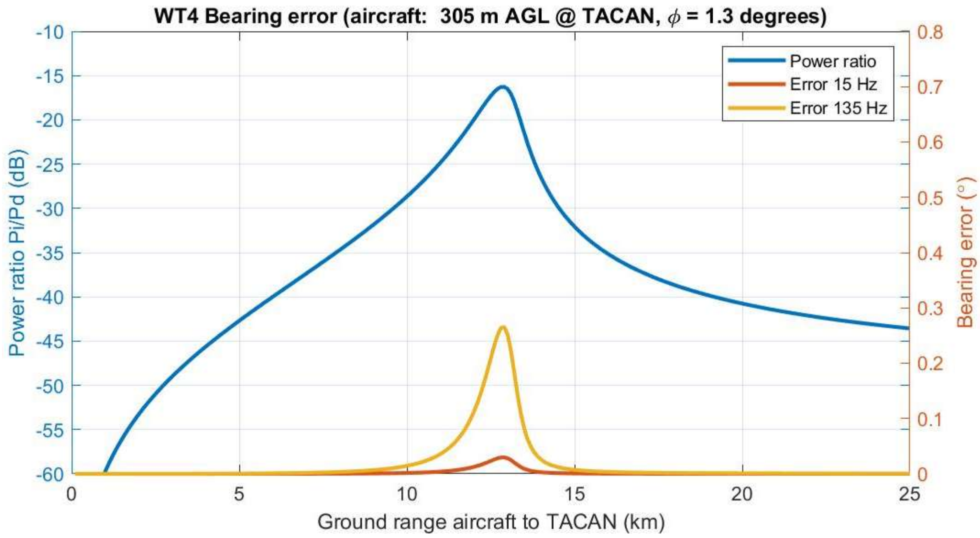


Figure 7.26 Bearing error in the 15 Hz and 135 Hz signal. Flight trajectory altitude is 305 m AGL and angle ϕ = 1.3°.

As is expected, the bearing error is proportional to the received signal strength. Also, the error is approximately 9 times as large in the 135 Hz signal as in the 15 Hz signal.

For ϕ = 40°, the 135 Hz reflected signal is in phase again with the direct signal, hence the remaining error in the 135 Hz signal is only due to the additional time delay Δt. This is shown in Figure 7.27. The bearing error in the 15 Hz signal is 0.002°. Note that the error in the 15 Hz signal is to a large extent irrelevant, it is only used to resolve the ambiguity in the 135 Hz signal.

Figure 7.27 Bearing error in the 15 Hz and 135 Hz signal. Flight trajectory altitude is 305 m AMSL and angle ϕ = 40°.

Please note again that these errors do only occur in a worst case situation with the blade of the wind turbine in the most adverse attitude. This will occur only rarely and under normal ‘average’ conditions the errors are substantially smaller. The event that two or more blades are in their worst case attitude simultaneously is considered negligible and this situation would occur for a very short time period only.

7.9 Consequences for TACAN bearing measurements

The analysis shows that the bearing accuracy of the 15 Hz and 135 Hz amplitude modulated signals is only marginally affected by the reference wind turbine W1-6 with bearing measurement errors of maximum 0.13°. For the new wind turbines WT1, WT2, WT3, and WT4 the maximum errors are 0.32°, 0.31°, 0.23°, and 0.27° respectively.

Equipment with poor echo cancellation might, under specific circumstances, show an additional error of maximum 0.34°, due to an error in the reception of the reference burst signals.

Both errors are small in comparison to the TACAN overall bearing error, which is claimed to be ± 1°, [4]

Note that the analysis given here is based on the worst case scenario, a wind turbine blade in the most unfavourable position. This condition will only be present for a short time, due to both rotation of the wind turbine rotor and the movement of the aircraft.

Figure 7.28 and Figure 7.29 show the aggregated maximum of the errors for all locations of an aircraft on the grid at an altitude of 305 m AGL for respectively the Walcourt 1 wind farm and for the new situation with Walcourt 2 included. Since it is highly unlikely that for multiple wind turbines these worst-case situations occur simultaneously, for all locations the maximum of the individual errors is taken. The main difference in magnitude of the errors for the two situations is due to the larger size of the wind turbines of the Walcourt 2 wind farm.

Under nominal conditions, the performance degradation of the TACAN system will be much less than described here.

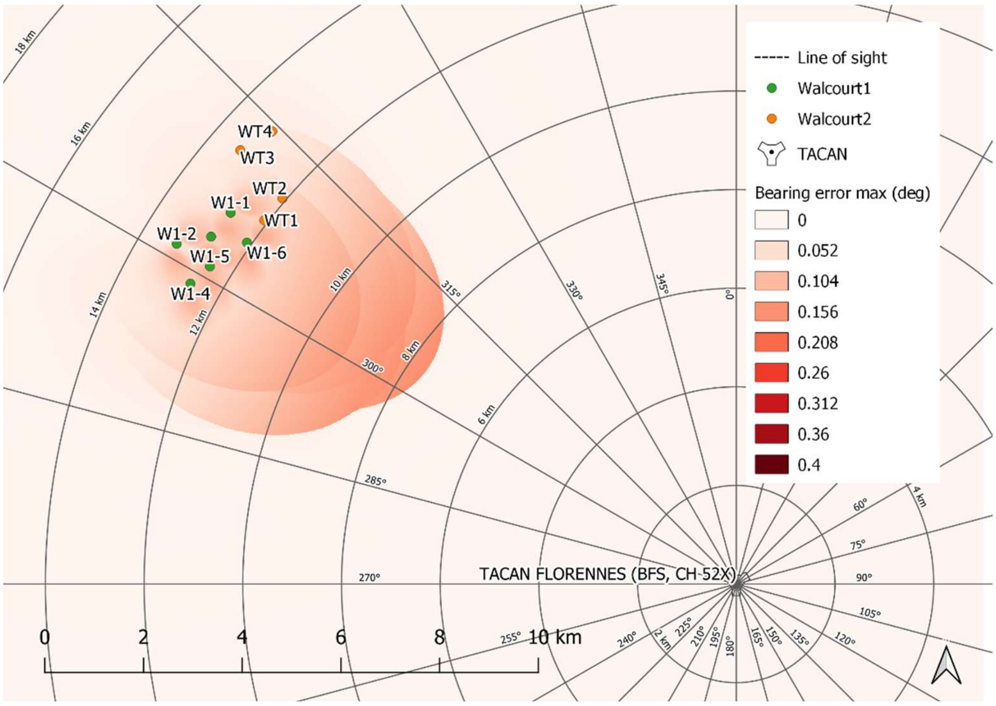


Figure 7.28 Current situation: Maximum aggregated bearing measurement errors in degrees of wind farm Walcourt 1. Flight altitude is 305 m AGL.

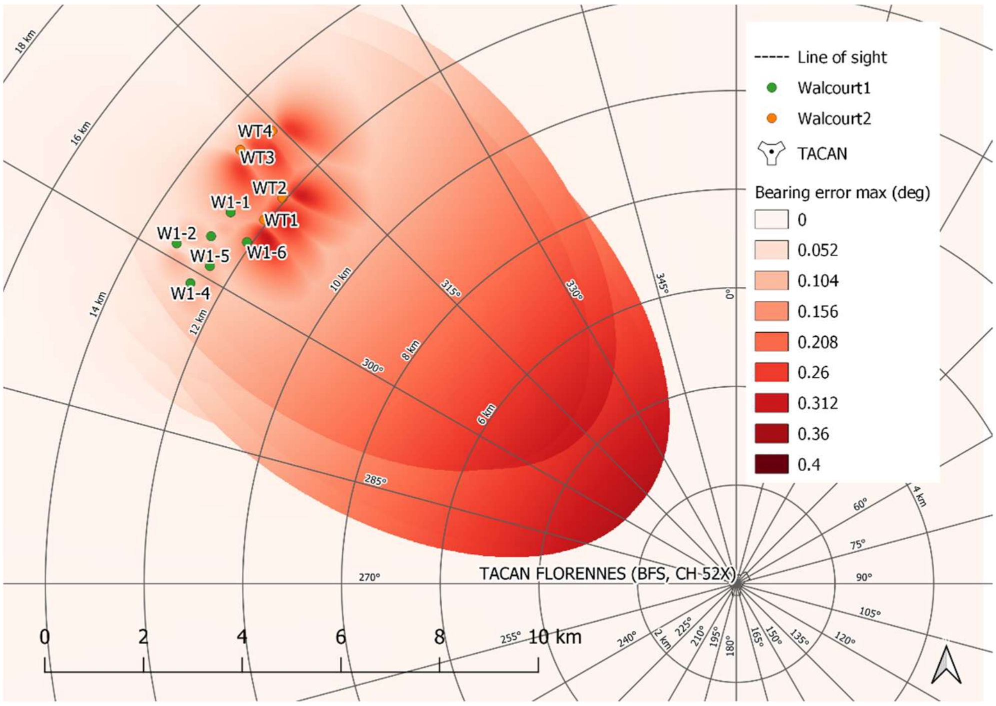


Figure 7.29 New situation: Maximum aggregated bearing measurement errors in degrees of wind farm Walcourt 1 and Walcourt 2. Flight altitude is 305 m AGL.

8 Conclusions

The main conclusion of this analysis are:

1. There is only a marginal negative influence of the wind turbine on the TACAN DME accuracy found based on a worst-case situation. In exceptional circumstances, and only at low altitudes in specific regions, the TACAN might erroneously be triggered to transmit a second reply on a single DME interrogation. Airborne DME-equipment is deemed to be sufficiently protected to these rare situations by means of ‘echo cancellation’.

2. The TACAN bearing error augments to maximally 0.32° in a worst-case situation. This is still small with respect to the overall claimed bearing error of ± 1°.

The above mentioned conclusions assume that the TACAN system works with properly implemented dead time and that aircraft navigation equipment have proper ‘echo cancellation’ functionality.

Please note that the conclusions are based on a worst case scenario. Under nominal conditions, the performance degradation of the TACAN system will be much less than stated above.

9 List of abbreviations

AFB	Air Force Base
AGL	Above Ground Level
AMSL	Above Mean Sea Level
ARB	Auxiliary Reference Burst
DME	Distance Measuring Equipment
EGM96	Earth Gravitational Model 1996
MRB	Main Reference Burst
RCS	Radar Cross Section
RPM	Revolutions Per Minute
SRTM	Shuttle Radar Topography Mission
TACAN	TACtical Air Navigation system
TNO	Netherlands Organisation for Applied Scientific Research
WGS84	World Geodetic System 1984
WT	Wind Turbine

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