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Master Thesis

Simulator of Pulsed Interference Environment of an Airborne GNSS Receiver

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Abstract

The US *Global Positioning System* (GPS) and the future European Galileo system are satellite-based navigation systems which commonly named as *Global Navigation Satellite System* (GNSS). GPS system broadcasts civil L5 signal within the 960-1215 MHz frequency band already used worldwide for *Aeronautical Radio Navigation Services* (ARNS) such as *Distance Measuring Equipment* (DME) and *Tactical Air Navigation* (TACAN). Galileo system will broadcast two civil signals E5a and E5b. E5a will be broadcast in the same ARNS band as GPS L5, and E5b will be broadcast in another ARNS band. The civil aviation community is looking forward to GPS L5 and Galileo E5a/E5b signals, for they are expected to improve accuracy, integrity, continuity and availability of the future GNSS.

Interfering environment of the 960-1215 MHz ARNS band is very heavy and will affect Galileo E5 and GPS L5 signals. One of the main threats comes from DME/TACAN system, which is one of the main *Radio Frequency Interference* (RFI) contributors within the Galileo E5 and GPS L5 bands. This pulsed interference caused by DME/TACAN ground based beacon signals is powerful, especially at high altitude. The main objective of this thesis is to simulate the pulsed DME/TACAN interference environment of an airborne GNSS receiver and assess the interference impact on the performance of GNSS receiver.

GNSS receiver performance functions, such as signal acquisition and tracking, depend on the signal to noise density ratio at the correlator output. Hence, on one hand we estimate the carrier to noise density ratio (C/N_0) degradation at the correlator output due to DME/TACAN only at a maximal en-route flight altitude of 40,000 feet. A worst case approach is chosen in the simulation. It implies the useful GNSS signals are assumed received at their minimum powers while interference are deemed received at their maximum levels. On the other hand, we determined the C/N_0 thresholds of acquisition and tracking of GNSS receiver by simulating DME/TACAN interference environment at different duty cycles.

The C/N_0 degradations at the correlator output for Galileo E5 and GPS L5 signals were estimated using the algorithm represented in [11]. Pulse blanker is considered in the GNSS receiver structure as a way to cope with strong pulsed interference. We will show that the blanker duty cycle and the degradation caused by DME/TACAN beacon signals are larger at a higher flight height. And DME/TACAN signals with large duty cycle would cause GNSS receiver losing track and acquisition failure.

KEYWORDS: Galileo E5a/E5b, GPS L5, GNSS receiver, DME/TACAN, $C/N_{0,eff}$ degradation, pulse blanker, acquisition threshold, tracking threshold

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1 Introduction

1.1 Motivation

Positioning and timing services provided by Global Navigation Satellite System (GNSS) have already given rise for various applications almost in all fields of our daily life. Safety-of-life GNSS applications with extremely high accuracy and reliability requirements are the significant performance improvements which are planed to be achieved by the coming European GNSS Galileo and the future modernized GPS.

One of the GNSS safety-of-life applications is the aircraft navigation during all flight phases including precise landing approaches. In order to provide spectrum protection of the GNSS signals used for safety-of-life applications, these signals are allocated within the frequency band of Aeronautical Radio Navigation Service (ARNS), 960-1215 MHz. This frequency band is also explored by *Distance Measuring Equipment* (DME) and *Tactical Air Navigation* (TACAN) systems, which are pulsed ranging systems being used currently as one of the primary means for aircraft navigation. Therefore, the safety-of-life GNSS aviation receiver has to cope with strong pulsed in-band radio interference caused by an air-borne and a number of ground DME/TACAN beacons. This pulsed interference becomes stronger with the flight height of the airplane since more signals of ground DME/TACAN beacons can be observed simultaneously.

The objective of this master thesis is to develop a software DME/TACAN signal simulator that can be used for testing the GNSS receiver performance under realistic pulsed DME/TACAN interference conditions.

1.2 Background

A great many of studies have been carried out on the impact of DME/TACAN pulses on the performance of the future GNSS receiver both in Europe and the U.S.. The U.S. RTCA develops minimum standards that form the basis for the *Federal Aviation Administration* (FAA) approval of equipment for using GPS as a primary means of civil aircraft navigation. The *European Organization for Civil Aviation Equipment* (EUROCAE) which is in charge of Galileo standardization for civil aviation in Europe, is studying the degradations and computing results over Europe where the DME/TACAN ground beacons density is very high at certain locations.

Radio Frequency Interference (RFI) sources in Galileo E5 and GPS L5 bands are listed in detail in [11]. Also [11] represents a theoretical algorithm for calculating the effective carrier to noise degradation due to RFI and pulse blanking. The algorithm for the degradation calculation caused by DME/TACAN only used in this master thesis is derived from [11].(Chap. 3.3.2)

In [1], it estimates the DME/TACAN impact on the future GNSS receivers by both simulation tool PULSAR and theoretical calculation. The derived degradations are compared with our simulation results at the end of this thesis.

Information of the DME/TACAN ground based beacons inside Europe is shown in [8]. Longitude, latitude, transmitting channel and height of the DME/TACAN beacons are listed in detail. And channel frequencies for DME/TACAN system are shown in [4].

1.3 Organization

The assessment of the impact of DME/TACAN signal on the future Galileo E5a/E5b and GPS L5 receivers constitutes the heart of this thesis. The structure of this thesis is as follows.

First of all, the future GNSS signals (Galileo E5 and GPS L5) are introduced in Chap. 2 as well as the receiver structure without going into details.

Chap. 3 presents the structure of DME/TACAN system and the impact of DME/TACAN interference signal on Galileo E5a/GPS L5 and E5b signals. The impact is assessed through the computation of the signal to noise density ratio at the correlator output. The algorithm for the degradation calculation is presented at the end of this chapter.

DME/TACAN pulsed interference environment of an airborne GNSS receiver at high altitude is simulated by MATLAB for both Galileo E5a/GPS L5 and E5b in Chap. 4. Two kinds of simulation modes are assumed in the simulation. One is "hot-spot" mode, which models the interference environment at the GNSS antenna port of an aircraft flying at high altitude over European hot-spot. Two kinds of front-end filters are used in the simulation and the simulation results are presented in Chap. 4.1.2.1 and Chap. 4.1.2.2. The other mode is "Duty Cycle Mode", which models the interference environment with different DME/TACAN duty cycles, regardless of DME/TACAN beacon information. Simulated C/N_0 degradations of this mode are shown in Chap. 4.2.2.1.

The next chapter, Chapter 5, we test the performance of the GNSS software receiver under the DME/TACAN pulsed interference environment. We determine the acquisition and tracking thresholds by changing DME/TACAN signal's duty cycle. In this chapter, we also show the influences of pulse blanker and DME/TACAN power level on the software receiver's performance.

Simulation results are analyzed in Chapter 6 and a summary is given in Chapter 7. Some improving suggestions are listed for future works.

2 Future GNSS Signal and Receiver Structure

The future GNSS signals (GPS L5 and Galileo E5a/E5b) are proposed for use as civilian *Safety-of-Life* (SoL) signals. They will be available worldwide to civil users and transmitted in the ARNS band. They will provide open service, commercial service, safety-of-life service, public regulated service and support to search-and-rescue service. An introduction of the future GNSS signals is given at the beginning of this chapter. In our simulation, we assume that the receiver structure of Galileo E5 is the same as GPS L5, which is presented at the end of this chapter.

2.1 Future GNSS signals

Both Galileo and GPS systems are satellite based navigation systems. The operating principle is simple: the satellites in the constellation are fitted with an atomic clock measuring time very accurately.The satellites emit personalized signals indicating the precise time that the signal leaves the satellite.The ground receiver, incorporated for example into a mobile phone, has in its memory the precise details of the orbits of all the satellites in the constellation. By reading the incoming signal, it can thus recognize the particular satellite, determine the time taken by the signal to arrive and calculate the distance from the satellite. Once the ground receiver receives the signals from at least four satellites simultaneously, it can calculate the exact position.

2.1.1 GPS L5 Signal

The GPS L5 signal is part and parcel of the GPS modernization program consisting to the introduction of two new civil signals (L5 and L2) after the original GPS L1 signal. As far as the civil aviation community is concerned, the main requirements for this signal are to provide a completely redundant signal to the L1 signal to improve signal diversity and, as a consequence, robustness in case of interference. Moreover, the capability for the users to perform dual frequency measurements and so apply a precise ionospheric delay correction is a key request so as to improve accuracy and availability of operations such as precision approaches. The use of a C/A code, as employed on GPS L1, would satisfy those requirements however the promoters of the GPS L5 signal have felt new characteristics should be proposed to improve global performance and level of service. Among the new features are an increased code rate (ten times faster than C/A code, 10.23 Mcps) to improve, for instance, resistance to multipaths and accuracy in noise. The transmitted signal is a QPSK modulation where there is a data-free carrier component called the *Pilot* component that allows carrier phase tracking at lower signal-to-noise ratio. The GPS L5 signal consists of QPSK modulation, although it is still based on the CDMA principle to distinguish the transmitting satellite vehicles. The transmitted signal is right-hand circularly polarized and each carrier is modulated by a specific bit train. The inphase train is generated by the modulo-2 addition of a *pseudo-random noise* (PRN) ranging code, a synchronization sequence, called the *Neuman-Hoffman* (NH) code and the navigation data message. The Quadraphase (or Pilot) train does not carry any navigation data and so is simply the modulo-2 sum of a different PRN code and a different NH synchronization sequence. The role of the NH synchronization sequence is first to improve the bit synchronization performance that is one of the weaker functions in the signal acquisition process and then to improve robustness to interference.

2.1.2 Galileo Signals

Galileo will provide 10 navigation signals in the frequency ranges 1164-1215MHz (E5a and E5b), 1260-1300MHz (E6) and 1559-1592 MHz (E2-L1-E1). E2-L1-E1 and E5a are common to GPS frequency bands for interoperability. All the Galileo satellites will share the same nominal frequency, making use of Code Division Multiple Access (CDMA) compatible with the GPS approach. Fig. 2.1 indicates the type of modulation, the chip rate and the data rate for each signal. [7]

From Fig. 2.1, we can see that Galileo offers four types of data (service), which are carried by the different radionavigation signals:

1. Open Services (OS): Mass-Market applications not requiring any guarantee. It is as accurate as conventional differential GPS but without requiring additional ground infrastructure.

2. Commercial Services (CS): it provides professional use and guaranteed service in return of a fee as well as system capabilities introduced to foster application with commercial interest.

3. Safety-of-life Services (SoL): it provides guaranteed service for Safety-of-life applications and integrity alerts.

4. Public Regulated Service (PRS): it would be used by police, coast guards, customs, strategic civil infrastructure and so on. It also provides high continuity of service. Signals are more robust to interference. It provides access to the service to government authorized-users only.

5. Search and Rescue Service (SAR): Relay of distress alarms to improve existing relief and rescue services. It is compatible with COSPAS-SARSAT.

The Galileo E5a frequency is exactly the same as GPS L5 (1176.45 MHz) and Galileo E5b frequency is 1207.14 MHz. Each signal has to carry two different spreading codes in phase quadrature with each other. In total four different ranging signals have to be transmitted in two separate frequency bands. Two proposed schemes were:

- Two BPSK signals generated coherently and transmitted on two separate channels: E5a and E5b. In this case, each signal is generated at the baseband, amplified separately and combined at RF before transmission by the satellite antenna. The disadvantage of that approach is that phase coherency may be difficult to keep in the RF circuitry.

- A single-carrier wideband signal following a modified *Binary Offset Carrier* (BOC) modulation with a subcarrier frequency of 15.345 MHz and a code rate of 10.23 Mcps. The central frequency of this signal is equally spaced between E5a and E5b and so equates 1191.8 MHz. The modified structure enables transmission of a signal having a constant envelope so as to avoid non-linear behavior of amplifiers on the satellite side. Because of a wider bandwidth, this signal is expected to increase positioning accuracy and resistance to multipaths. However one possible drawback is that more interfering signals will be allowed to enter to receiver since its bandwidth will be larger if the whole wideband signal is intended to be processed. Because there are a large number of DME/TACAN ground beacons transmitting in this band, especially

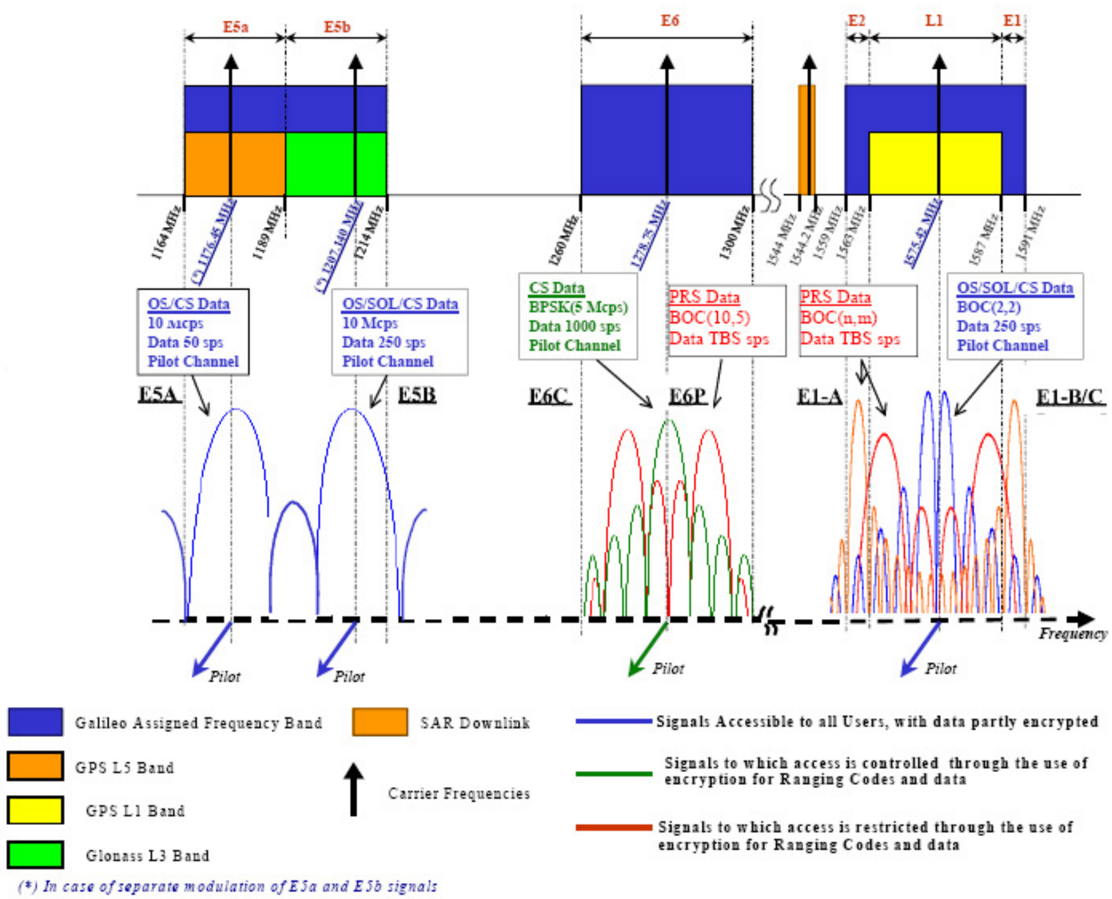

Figure 2.1: Galileo Frequency

for an aircraft flying at high altitude. However separated processing of either Galileo E5a or Galileo E5b will reduce the interference impact, but care must be taken in the receiver design so that the phase coherency of the generated signal is not lost in RF section of the receiver.

2.2 GNSS Receiver Structure

The received GNSS signal is woefully ill-suited for computer processing. First, the signal power must be increased by approximately ten orders of magnitude in power. Second, natural noise and man-made RFI must be removed to the possible extent. Third, the received carrier frequency is 1.5 billion cycles per second and most computers would have a difficult time coping with such a rapid variation. Finally, we must convert from an analog signal to a digital signal. Processing above is called signal conditioning.[10]

After conditioning, we must estimate the arrival time, τ, and the the Doppler shift, f_D. If we desire the ultimate in precision, the carrier phase, θ, must also be tracked. The estimation of our key triplet, τ, f_D, θ, proceeds in two stages. The first stage is a global search for approximate values of τ, f_D. This process is known as *signal acquisition*. The second stage is a local search for accurate estimate of τ, f_D that may include estimation of the carrier phase, θ. This process is called *signal tracking* because it is continuous and the estimates are updated as the receiver and satellites move. The signal acquisition and tracking processes suffer from interference if strong competing signals are present or the satellite signals are blocked. DME/TACAN signal falls in the GPS L5 and Galileo E5 radio spectrum, if DME/TACAN signal is much stronger, then the GNSS signal acquisition and tracking situation can quickly become bleak.

Assume the receiver for Galileo E5 signal has the same architecture with GPS L5 signal. The receiver scheme is shown in Fig. 2.2.[2]

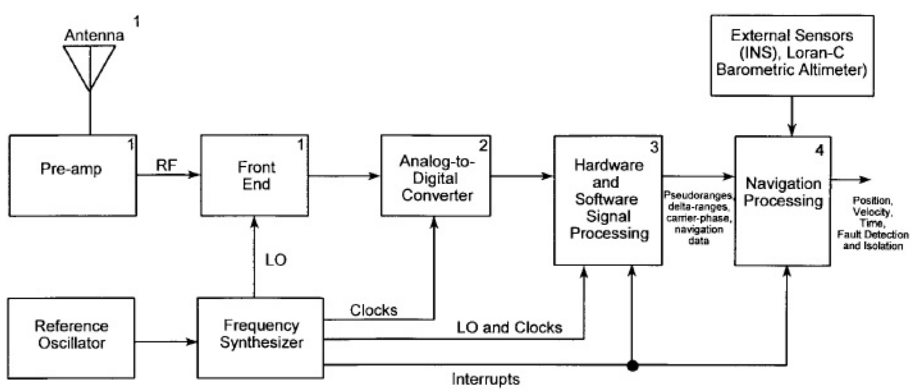

Figure 2.2: Classical GNSS signal-frequency receiver block diagram

2.2.1 Antenna

The gain pattern of receiver antenna should be a high and relatively constant gain for satellites above a given elevation. The gain at negative elevations should be low to reduce the impact of multipath of interference.

2.2.2 Preamplifier

Preamplifier provides burnout protection and unwanted interference filtering. It also composed of a LNA whose characteristics are set to achieve a desired system-level noise figure.

2.2.3 Front-end

Incoming signal down conversion from RF to IF is achieved by mixing the incoming amplified signal with local oscillator (LO). The filtering requirements of the applied successive filters are more stringent while limiting insertion loss. A mixer is followed by a bandpass filter to suppress the unwanted sideband, LO feed-through and harmonics.

2.2.4 ADC/AGC

AGC and a digital blanker are implemented within the ADC. The AGC is a variable gain amplifier which would adapt its gain to reduce quantization losses. Given the front-end filter bandwidth and the number of bits, there is an optimal gain. Depending on ADC bins distribution, AGC system can be analog or digital.

In our simulation, the AGC/ADC processes are not considered.

2.2.4.1 Digital Pulse Blanker

Pulse blanking is a technique that suppresses pulsed interference by having the ADC output zeros when a pulse is detected. For the received Galileo signals are buried below the thermal noise, detection of DME/TACAN strong pulses would be relatively simple.

Digital blanker can reduce the influence of DME/TACAN pulsed signals. Each individual quantized sample whose power is above the blanking threshold is zeroed. The blanking threshold is chosen as a compromise between the ability to detect pulses and SNR degradation in the absence of pulses. The blanker is also characterized by blanking duty cycle which is the percentage of time where the blanker is active so when the signal is set to zero. Blanking threshold and blanking duty cycle are important for final degradation of post-correlation carrier-to-noise density ratio($C/N_{0,eff}$).

2.2.5 Hardware and Software Signal Processing

The output signal from ADC is split into I and Q channels after mixing with two local carriers generated by carrier NCO. Then each channel is mixed with the Prompt, Early and Late local code replica of the Data (XI) and Pilot (XQ) components. The resulting signals are integrated over 1 ms and then dumped.The Neuman-Hoffman codes are removed by multiplying the 1 ms-Data and 1 ms-Pilot samples by the adequate NH code. Then the outputs are used by the code and carrier tracking loops to form discriminator functions that are then filtered by the loop filter. The filtered signals finally constitute the control values of the tracking processes.

2.2.6 Navigation Processing

The output data from Signal Processing unit will be computed and used for different applications.

In our MATLAB simulation, we assume only antenna, equivalent RF/IF front-end filter, digital pulse blanker and correlator are implemented in the GNSS receiver, when accessing the $C/N_{0,eff}$ degradations caused by the simulated DME/TACAN environments. For GNSS receiver acquisition and tracking thresholds determination, we use the software GPS receiver (available at DLR), which also includes ADC/AGC.

3 DME/TACAN Interference Environment for An Airborne Galileo E5a/E5b Receiver

The interfering environment of the 960-1215 MHz ARNS band is heavy and will affect the future Galileo E5 signals. The interference sources are more numerous and more powerful, especially at high altitude. Only the impact of the DME/TACAN ground beacon signal is simulated since it is one of the main RFI contributors at high altitude within the Galileo E5 and GPS L5 bands.

At the beginning of this chapter, interference in Galileo E5a and E5b bands is presented. Then it is followed by an introduction of the DME/TACAN system. At last, the impact of the DME/TACAN interference on GNSS receivers is evaluated through the theoretical analysis of the degradation of post-correlation carrier-to-noise density ratio $C/N_{0,eff}$.

3.1 Interference in Galileo E5 and GPS L5 Band

For civil aviation community, the Galileo E5a, E5b signals and GPS L5 signal are of great interest. They will be broadcast in the ARNS band and are expected to increase accuracy and availability of service. The Galileo E5a frequency is exactly the same as GPS L5 which is 1176.45 MHz, and Galileo E5b frequency is 1207.14 MHz. E5a and E5b signals are in the frequency ranges of 1164-1215 MHz.

Radio frequency interference (RFI) refers to man-made signals other than GNSS that exists in the GNSS portion of radio spectrum. The potential sources of RFI to the Galileo E5 and GPS L5 signals are vastly more complicated. Galileo E5 and GPS L5 signals must contend with RFI signals. If RFI is weak compared to the received natural noise, then it can be neglected. If the received RFI is strong, then its impact depends on whether it is pulsed or continuous in time. Pulsed interference is sometimes very well tolerated by properly designed GNSS receivers. This type of RFI is roughly categorized by the pulse duration and duty cycle. Pulse duration is the time width of an individual pulse of RFI. Duty cycle is the percentage of time that the interfering pulses are on. Very strong pulsed signals can cause problems even during their "off" state, since active components in GNSS receiver may require "recovery" time after a pulse to resume normal operation. All electronic amplifiers saturate when the input signal reaches some level. In-band pulses will typically saturate the last gain stage first. Interference sources at frequencies offset from the center of the receiver passband require progressively larger amplitudes to saturate the receiver front-end as that frequency offset increases. Strong pulses will also saturate the analog-to-digital (A/D) converter (ADC) in GNSS receiver. When ADC is being saturated by a pulse, the desired signal is completely suppressed. Weaker pulses may be viewed as adding to the receiver's noise floor[3].Continuous interference is generally more troublesome than pulsed RFI. It includes wideband RFI, narrowband RFI, and tone interference.[10]

The report [11] lists in great details all the potential sources of RFI to the GPS L5 signal and consequently to the Galileo E5a signals since they share the same frequency band. The Galileo E5b signal is allocated to the same ARNS band, the associated RFI environment may be easily inferred.

DME/TACAN systems constitute one of the main threats for an aircraft flying at high altitude. DME and TACAN systems are pulse-ranging navigation systems that operate in the 960-1215 MHz ARNS frequency band. DME system provides distance measurements from an aircraft to a ground beacon. TACAN is a military navigation system, provides both azimuth and distance information. Interference due to DME/TACAN ground-based sources increases with the altitude since more interfering signals are received. When the victim aircraft flying over $50°N$ $9°E$, 180 DME/TACAN ground beacons are in aircraft insight region at flight height of 40 kft, compared to 48 beacons at 10 kft. According to the database [8], in E5a-band with a bandwidth of 20 MHz, there are 23 DME/TACAN ground beacons in-range of an aircraft flying at 40 kft and at a lower flight altitude of 10 kft, there are only 7 DME ground beacons.

3.2 DME/TACAN System

3.2.1 DME/TACAN System Introduction

The *Distance Measuring Equipment* system is a pulsed ranging system which provides range measurements from an aircraft to a ground beacon. This system is internationally standardized and operates in the 960-1215MHz ARNS frequency band. The *Tactical Air Navigation* (TACAN) system was designed primarily as a military system providing both range measurement and azimuth measurements. The ranging function of this system is identical to that of DME and the azimuth information is retrieved thanks to a rotating antenna at 900 revolutions per minute. Both two systems are composed of an aircraft interrogator and a ground beacon. The DME/TACAN interrogator obtains a distance measurement by transmitting pulse pairs and waiting for reply pulse pairs from the beacon.

The aircraft interrogator transmits a signal composed of pulse pairs from an omnidirectional antenna. The beacon replies after a predetermined delay from the time of receipt of the interrogation. After the interrogator received replies from the beacon, it automatically compares the elapsed time between transmission and reception. Based on the propagation delay, the aircraft interrogator equipment calculates the distance from the beacon transponder to its current location.

DME/TACAN operates on four modes (X,Y,W and Z), and only the X-mode replies in the 1151-1213 MHz frequency band that overlaps the GNSS E5a/L5 and E5b bands

(1164-1215 MHz). The standard DME/TACAN channel plan is shown in Fig. 3.1. [11]

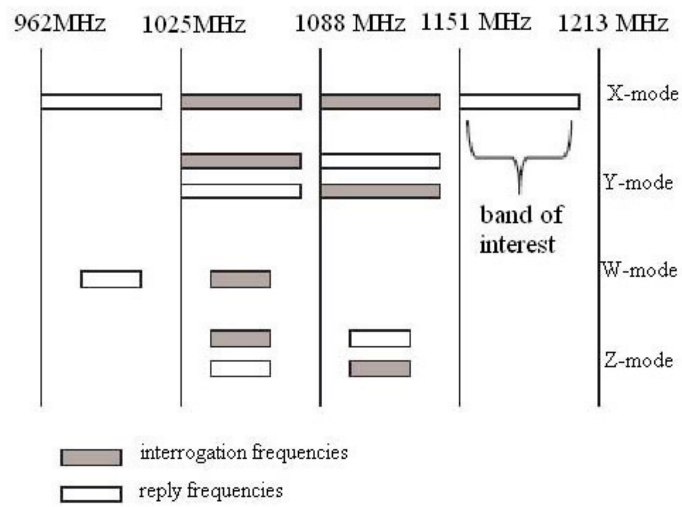

Figure 3.1: Standard DME/TACAN Channel Plan

3.2.2 DME/TACAN Interrogator

The DME/TACAN aircraft interrogator transmits pulse pairs on one of the 126 frequencies, each is spaced 1 MHz in the 1025 to 1150 MHz band. The pulse-repetition rate of the interrogators is deliberately made somehow unstable, and the interrogator is designed to recognize only those replies whose pulse-repetition rate and phase are exactly the same as their own. The transmitted pulse pairs follow a unique pattern thanks to random variations of the time interval between pairs. This phenomenon is called jitter and enables the aircraft to identify replies to its own answer. The round trip time is usually much less than the interval between transmitted pulse pairs; hence the interrogator will receive a response before it sends out the next pulse pair.

In the search mode, the DME/TACAN interrogator usually conducted at the highest permissible pulse repetition rate (40-150 pulse-pairs per second) in order to save time. Once locating the time slot in which the desired beacon replies are actually occurring, the track mode commences and it conducts at a much lower pulse-repetition rate, usually between 10 and 30 pulse-pairs per second. In the track mode, the gate is usually arranged to have some memory so that it does not immediately go into search upon loss of signal.

3.2.3 DME/TACAN Beacon

A DME/TACAN ground beacon serves all aircraft within a designated radius of coverage (typically between 100 and 300 nautical miles). It transmits a pulse pair reply to every received pulse pair from aircraft within range after a fixed delay of 50 μs (mode X) or 56 μs (mode Y).The frequency of transmission is 63 MHz above or below the interrogation frequency. The duty cycle of the ground transmitter is much larger than that of the interrogator, and the average power consumption is also greater. The peak power of DME beacon is in the range of 1 to 20 kw. Ground receiver AGC is continuously adjusted to maintain the pulse pair reply transmission rate constant, at approximately 700 to 2700 pulse pairs per second. DME/TACAN ground beacon must always transmit a minimum number of pulses otherwise aircraft interrogators would never send and interrogate even when in the beacon range. If there are enough aircrafts interrogating the beacon, then there is no issue since the beacon would transmit enough pulse pairs further detected by an airborne DME/TACAN interrogator entering the radius of coverage. In the case where no interrogations are received, the ground beacon is designed to transmit pulsed pairs called squitter to distinguish them from replies. Thus a ground beacon is specified to transmit at least 700 pulse pairs per second apportioned between distance replies as well as squitter. Military TACAN sites transmit an additional 900 pulse pairs per second as reference marks for their rotating antennas, and often employ high power (up to 10 kW for ground-based beacon transmitters). Usually TACANs are set at their maximum standardized 3600 ppps rate. In our study, the DME ground beacon is considered to transmit 2700 ppps, and 3600 ppps for TACAN, which correspond to a worst pulsed interference environment over the Europe.

Some reflected or echo interrogations may arrive to the DME/TACAN ground beacon a short time after the direct interrogation depending on the terrain configuration. The beacon must be prevented from triggering the transmitter after reception of such a signal to avoid the aircraft receiver tracking an echo. The way employed to guarantee this protection is to suppress the receiver function of the ground beacon for a dead-time period of up to 60 μs [1]. DME and TACAN systems are not passive systems, they have an inherent capacity limitation. The value generally quoted is 110 aircrafts per beacon. The number of aircraft that a beacon can handle is usually based on the assumption that 95% of the aircrafts will be in the track mode at not over 25 interrogations per second; 5% are in the search mode, at not over 150 interrogations per second. For 100 aircrafts, this means 3125 pulse-pairs per second [9].

3.2.4 DME/TACAN signals

The basic DME/TACAN pulse pair is assumed as having a Gaussian-shape with a half-amplitude duration of 3.5 μs, the two pulses in the pair are separated by either 12 μs (X mode) or 36 μs (Y mode). In our study, only DME/TACAN signal in X mode is of interest, which has the following expression.

$$S_{pulsepair}(t) = e^{\frac{-\alpha}{2}t^2} + e^{\frac{-\alpha}{2}(t-\Delta t)^2} \tag{3.1}$$

where,

- $\alpha = 4.5 \times 10^{11} s^{-2}$

- $\Delta t = 12\ \mu$s is the inter-pulse interval

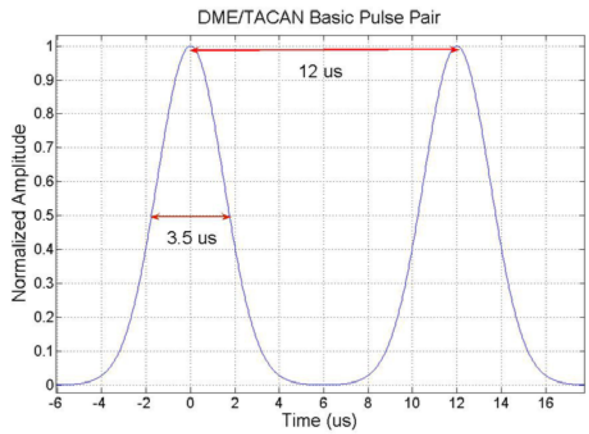

Figure 3.2: Normalized DME/TACAN pulse pair

The transmitted DME/TACAN signal is made of succession of such pulse pairs, the arrival times of pulse pairs are random. Smoothed pulse rise and fall shaping minimizes adjacent-channel interference. DME/TACAN frequencies are spaced in 1 MHz increments throughout the 962 to 1213 MHz band. 99 percents of the transmitter energy falls within ±400 kHz of the channel center frequency. Base-band DME/TACAN signal and power spectrum are shown in Fig. 3.3. Peak power can be as great as 2 kW but current air transport DME installations rarely exceed 650 W EIRP (transmitter power - line loss + antenna gain). Interrogation frequencies (on which aircraft transmit) are within the band 1025 to 1150 MHz, and reply frequencies from the beacon are on paired channels on frequencies either 63 MHz below or above the corresponding interrogation frequency [11].

Received signal at the aircraft GNSS antenna port from one single DME/TACAN beacon can be expressed as

$$\begin{aligned} S_{DME/TACAN}(t, EL) &= \sqrt{P_I \cdot G_{beacon}(EL) \cdot L_{free} \cdot G_{air}(-EL)} \\ &\cdot \sum_k \left(e^{\frac{-\alpha}{2}(t-t_k)^2} + e^{\frac{-\alpha}{2}(t-\Delta t-t_k)^2}\right) \cdot cos(2\pi f_I t + \theta_I) \end{aligned} \quad (3.2)$$

where,

- P_I is the DME/TACAN beacon transmitted peak power (W)
- t_k is the set of pulse pairs arrival times
- f_I is the frequency of the received DME/TACAN signal (Hz)

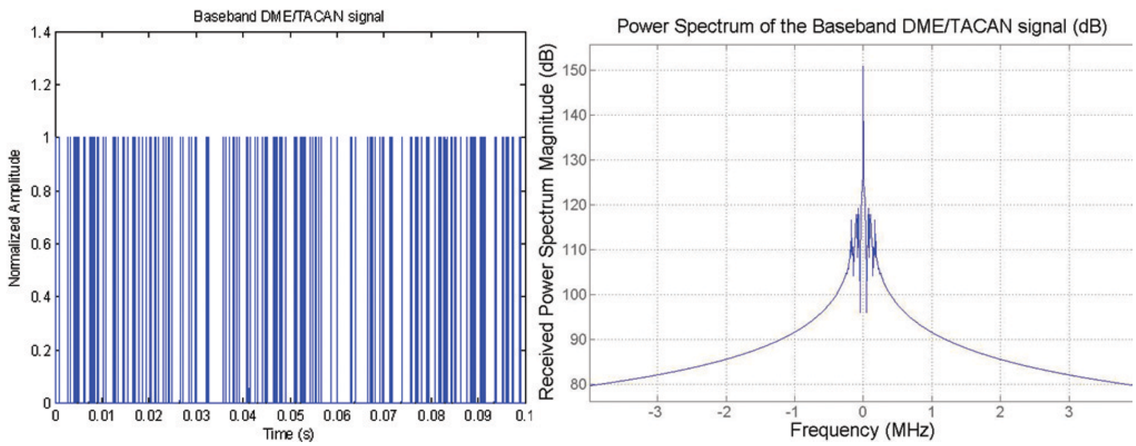

Figure 3.3: Typical DME/TACAN signal and its power spectrum

- θ_I is the DME/TACAN signal carrier phase at the GNSS receiver. antenna port. It was chosen as uniformly distributed over $[0,2\pi]$
- L_{free} is the classical free-space propagation losses from ground beacon to the aircraft
- $G_{beacon}(EL)$ is the normalized DME/TACAN beacon antenna gain at the elevation angle EL
- $G_{air}(-EL)$ is the normalized aircraft antenna gain at elevation angle -EL

The loss L_{free} is inversely proportional to the square of the radio-electric range between the ground beacon d and the frequency used.

$$L_{free} = (\frac{c}{4\pi df})^2 \tag{3.3}$$

where,

- c is the velocity of light,3×10^5 km/s
- f is the signal frequency (Hz)
- d is the propagation distance (km)

Typical DME/TACAN beacon transmitter antenna and GNSS receiver antenna gain patterns are presented in Fig. 3.4.

A database of European DME/TACAN beacons is obtained from [8], which contains beacon locations, transmitted powers(EIRP) and transmitting frequency. Single-beacon DME/TACAN signals are then independently added to form the composite received signal at the GNSS receiver antenna port.

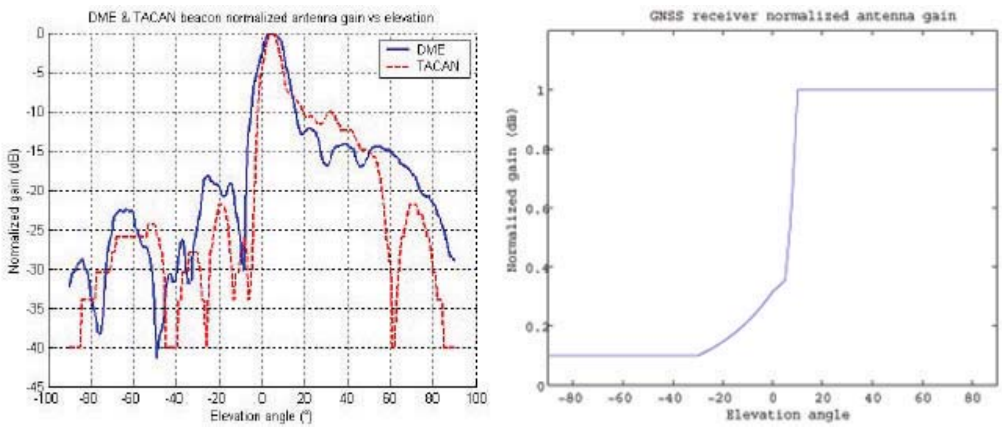

Figure 3.4: Typical DME/TACAN (left) and GNSS receiver (right) normalized antenna gain vs elevation angle

3.3 DME/TACAN Signal Contribution to Noise Floor

3.3.1 Effective Carrier-to-noise Density Calculation due to RFI

One algorithm for the effective carrier-to-noise density ratio calculation caused by RFI is presented in [11], which is described as follows. The algorithm estimates an effective noise + interference density ratio at the output of the signal correlator due to the pulse blanker [11]. (In [11], blanker duty cycle is denoted as "PDC_B", while, in this thesis, it is denoted as "Bdc")

$$C/N_{0,EFF} = \frac{C \cdot (1 - Bdc)^2}{(N_0 + I_{0,WB}) \cdot (1 - Bdc) + (\frac{1-Bdc}{BW}) \cdot \sum_{i=1}^{N} P_i \cdot dc_i} \tag{3.4}$$

Where,

- C is the post-collelator recovered satellite carrier power (W)
- Bdc (blanker duty cycle) is the total duty cycle of all DME pulses exceeding the blanking threshold
- N_0 is the GNSS receiver system thremal noise power spectral density, which is -200 dBW/Hz
- $I_{0,WB}$ is the power spectral density of constinnuous broadband RFI
- BW is the pre-correlator IF bandwidth
- P_i is the received peak power of i^{th} RFI (referred to antenna output) with peak level below the blanking threshold
- dc_i is the i^{th} below-blanker RFI duty cycle

Implemented only the antenna, equivalent RF/IF front-end filter Digital pulse blanker and correlator in GNSS receiver, the impact of DME/TACAN pulsed interfering signal can be evaluated from the degradation of post correlator effective carrier-to-noise density ratio. The blanker "zeros" the signal and noise into the correlator during the time duration of strong pulses, whose power levels are above the blanker threshold. So strong pulses determine the blanker duty cycle (Bdc).

The degradation of useful signal power $deg(signal)$ at correlator output, due to the presence of interference and blanker, is

$$deg(signal) = (1 - Bdc)^2 \tag{3.5}$$

The degradation of thermal noise power $deg(thermal\ noise)$ at correlator output, due to the presence of interference and the blanker, is [6]

$$deg(thermal\ noise) = (1 - Bdc) \tag{3.6}$$

The blanker effect on the below-blanker RFI, $deg(RFI)$, is

$$deg(RFI) = (1 - Bdc) \tag{3.7}$$

3.3.2 Effective Carrier-to-noise Density Calculation due to DME/TACAN signals

When $I_{0,WB} = 0$, we derive the degradation of post correlator effective carrier to noise density ratio ($C/N_{0,eff}$) caused by DME/TACAN signal only. Dividing out the common $(1 - Bdc)$ term, we simplifies (3.4) to be

$$C/N_{0,EFF} = \frac{C}{N_0} \cdot \frac{(1 - Bdc)}{1 + (\frac{1}{N_0 \cdot BW}) \cdot \sum_{i=1}^{N}(P_i \cdot dc_i)} \tag{3.8}$$

Define

$$R_I = (\frac{1}{N_0 \cdot BW}) \cdot \sum_{i=1}^{N}(P_i \cdot dc_i) \tag{3.9}$$

R_I represents the power density ratio of the below blanker DME/TACAN pulses to the receiver thermal noise. Then we further simplify (3.8), and the result is

$$C/N_{0,EFF} = \frac{C}{N_0} \cdot \frac{(1 - Bdc)}{1 + R_I} \tag{3.10}$$

The effective noise density ratio then is shown in (3.11)

$$N_{0,EFF} = N_0 \cdot \frac{(1 + R_I)}{(1 - Bdc)} \tag{3.11}$$

which, in logarithmic form is

$$N_{0,EFF}(dB) = N_0(dB) - 10\log(1 - Bdc) + 10\log(1 + R_I) \tag{3.12}$$

Then the noise floor consists of suppressed thermal noise by the blanker and weak DME/TACAN pulses that are not blanked.

The degradation of $C/N_{0,eff}$, $deg(C/N_{0,eff})$, due to the DME/TACAN interference pulses and blanker is

$$deg(C/N_{0,eff}) = \frac{(1 - Bdc)}{(1 + R_I)} \tag{3.13}$$

or in logarithmic form is

$$deg(C/N_0)(dB) = 10\log(1 - Bdc) - 10\log(1 + R_I) \tag{3.14}$$

Following situations should be considered in degradation calculation. First, strong DME/TACAN pulses whose peak powers are above the blanking threshold, not only determine the blanker duty cycle (Bdc), but also contribute to the noise power increase because of the residual part of Gaussian DME/TACAN pulse and the carrier amplitude variations. Weak DME/TACAN (below-blanker) pulses are assumed not to affect the Bdc computation, they only contribute to the noise floor increase. Second, overlapping of DME/TACAN pulses is common especially at high altitude, because more DME/TACAN signals are received by the victim GNSS receiver (overlapped pulses are shown in Fig. 3.5). Some previous studies didn't consider the case of strong pulses collision. For example, when deriving Bdc, they determined the number of the DME and TACAN signals whose power are received above the blanking threshold at a fixed location of the victim GNSS receiver and then multiply the number of DME and TACAN by their respective average PRF, and the resulting total average arrival rate then multiplied 3.5×2 μs to obtain Bdc. This would overestimate the DME/TACAN impact on $C/N_{0,eff}$.

3.3.2.1 RI Calculation

Strong DME/TACAN pulses also contribute to the noise floor. Calculation of below blanker pulse power density ratio to the receiver thermal noise R_I should include the power of both weak DME/TACAN pulses and the residual portion of strong DME/TACAN pulses. In [11] and [1], rectangular equivalent pulse width is used to model the equivalent DME/TACAN pulse width, when calculating the duty cycle. For weak DME/TACAN pulses whose received power is below the blanking threshold, DME/TACAN pulse pair equivalent width is 2×2.64 μs. Duty cycle for a weak DME signal then can be expressed as

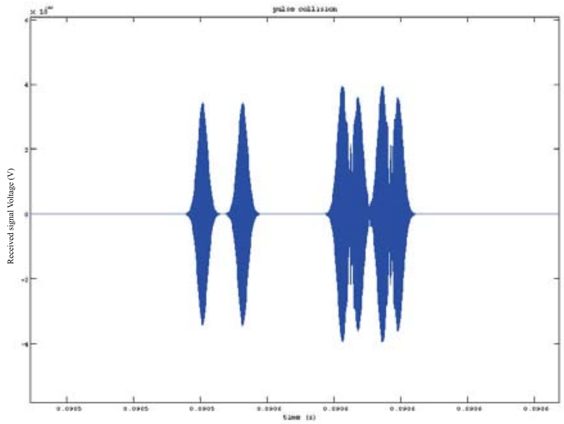

Figure 3.5: Example of composite DME/TACAN signals environment

$$\begin{aligned} dc_{weak,i} &= PW_{weak,i} \cdot PRF_{weak,i} \\ &= 2 \times 2.64 \cdot PRF_{weak,i} \end{aligned} \tag{3.15}$$

where,

- $dc_{weak,i}$ is the equivalent pulse width of the i^{th} weak DME/TACAN signal
- $PRF_{weak,i}$ is the pulse pair repetition frequency of the i^{th} weak DME/TACAN signal

For strong DME/TACAN pulses, the time period that the instantaneous received power exceeds the blanking threshold decides the blanker duty cycle (Bdc). The blanked width of the strong pulse pair is,

$$PW_{blanked} = 2 \times 2\sqrt{\frac{\ln\left(P_{strong}/th\right)}{\alpha}} \tag{3.16}$$

where,

- P_{strong} is the received peak power of DME/TACAN pulse pair;
- th is the blanking threshold power.
- $\alpha = 4.5 \times 10^{1}1\ s^{-2}$, one of the DME/TACAN basic pulse pair Gaussian shape parameter.

The residual portion of strong DME/TACAN pulse could be modeled as a rectangle with peak power of the original peak power of the strong DME/TACAN pulse. The post-blanking residual rectangular equivalent pulse pair width is,

$$PW_{residual} = 2\sqrt{\pi/\alpha} \cdot erfc(\sqrt{\ln{(P_{strong}/th)}}) \tag{3.17}$$

Then the duty cycle for the residual portion of a strong DME/TACAN signal caused by the pulse blanker is,

$$dc_{residual,i} = PW_{residual,i} \cdot PRF_{strong,i} \tag{3.18}$$

where,

- $PRF_{strong,i}$ is the pulse pair repetition frequency of the i^{th} strong DME/TACAN signal.

Considering the residual portion of Gaussian DME/TACAN pulse after the pulse blanking, R_I is all below-blanker DME/TACAN power density ratio to the receiver thermal noise. Both weak DME/TACAN pulses and the residual portion of the strong DME/TACAN pulses contribute to R_I. (3.9) for calculating the parameter R_I can be rewritten as,

$$R_I = (\frac{1}{N_0 \cdot BW}) \cdot (\sum_{i=1}^{M}(P_{weak,i} \cdot dc_{weak,i}) + \sum_{j=1}^{N}(P_{strong,j} \cdot dc_{residual,j})) \tag{3.19}$$

where,

- $P_{weak,i}$ is the received peak power of the i^{th} weak DME/TACAN signal whose received peak power is below the blanking threshold
- $P_{strong,j}$ is the received peak power of the j^{th} strong DME/TACAN signal whose received peak power is above the blanking threshold

3.3.2.2 Bdc Calculation

Following model is used when taking overlapping of the strong DME/TACAN pulses into account. DME/TACAN pulse pair arrival times may be assumed independent and of constant behavior over time for each DME/TACAN beacon. The general model for this is Poisson process. The signal transmitted by a single beacon is not a pure Poisson process, since there is a dead-time of 60 μs between pulse pairs. However, signals received at the victim GNSS receiver is made of multiple signals transmitted by different and independent DME ground beacons. Thus the composite signal pulse pair arrival times also follow a Poisson distribution, whose parameter λ is the sum of each individual parameter λ_i, where λ_i equates the beacon PRF. The Poisson probability density function (pdf) p, is defined as the probability that k arrivals will occur within some arbitrary time interval $[t_0, t_0 + t]$.

$$p = Prob\{k\ arrivals\ occur\ within\ [t_0, t_0 + t]\} = \frac{(\lambda t)^k e^{-\lambda t}}{k!} \tag{3.20}$$

The expected value of number of arrivals in the time interval is given as λt, and with a variance of $\sigma^2 = \lambda t$. The process is memoryless, the probability of finding no arrival in the interval is,

$$Prob\{no\ arrival\ occur\ within\ [0, t]\} = e^{-\lambda t} \tag{3.21}$$

Then the probability of finding at least one arrival in the interval is,

$$Prob\{one\ or\ more\ arrival\ occur\ within\ [0, t]\} = 1 - e^{-\lambda t} \tag{3.22}$$

Each pulse pair arrival in the interval has some finite duration, which is decided by the pulse peak power and the blanking threshold (3.16), taken as a random variable with some arbitrary distribution with an expected value of $\hat{w}$. Considering the pulse overlapping, then

$$Prob\{one\ or\ more\ arrival\ in\ interval\ \hat{w}\} = 1 - e^{-\lambda \hat{w}} \tag{3.23}$$

Bdc considering the strong pulses overlapping can be expressed as ,

$$Bdc = 1 - e^{-\lambda \hat{w}} = 1 - e^{-\lambda \cdot E[PW_{blanked}]} \tag{3.24}$$

Therefore, $deg(C/N_0)$ can be obtained from the DME/TACAN pulse RFI parameters by inserting (3.19) and (3.24) into (3.14).

3.3.2.3 Theoretical $C/N_{0,eff}$ Degradation Caused by DME/TACAN Pulses

The minimum received power of E5a/L5 and E5b signals at the victim GNSS receiver is -160 dBW. The filter bandwidth of E5a/L5 is 20 MHz, for E5b,the bandwidth is 14 MHz. The thermal noise power spectral density for GNSS receiver system is -200 dBW/Hz. When the victim aircraft is at a location of 50°N 9°E with flying height of 10 kft and 40 kft, there exist optimal blanking thresholds that minimize the degradations. Then the impact on $C/N_{0,eff}$ caused by DME/TACAN signals and blanker operating at the optimal threshold (optimal thresholds for different cases are obtained from the MATLAB simulation result) is shown in Table 3.1.

From Table 3.1, clearly we can see Bdc and R_I at high altitude are larger than at the low altitude for both E5a and E5b bands. In other words, the interference due to DME/TACAN beacon sources increases with the altitude. And the impact of the DME/TACAN pulses on E5a band is more severe than E5b.

Victim GNSS Receiver Hight	E5a/L5		E5b	
	FL100	FL400	FL100	FL400
$OptimalBlankerThreshold(dBW)$	-116.1	-115.5	-117.7	-117.1
$Bdc(\%)$	19.48	30.92	18.56	28.04
R_I	0.0414	0.2307	0.0283	0.2224
$deg(C/N_{0,eff})$ (dB)	-1.1171	-2.5421	-1.0128	-2.3014

Table 3.1: DME/TACAN pulse RFI parameters and the $C/N_{0,eff}$ degradation calculation at 50°N 9°E

Table 3.2 shows that when the DME/TACAN frequency components peak powers are uniformly distributed in same power level, larger duty cycle interference signal causes larger Bdc and RI, which leads to a larger $C/N_{0,eff}$ degradation. DME/TACAN signals with the same duty cycle, larger power level will result in a larger $C/N_{0,eff}$ degradation. While, the value of optimal blanking thresholds do not change much.

DME/TACAN Power Level (dBW)	dc=25% [-120 -100]	dc=15% [-120 -100]	dc=15% [-130 -110]
$OptimalBlankerThreshold(dBW)$	-115.1	-116.1	-116.8
$Bdc(\%)$	30.44	20.73	2.62
R_I	0.1539	0.0676	0.0514
$deg(C/N_{0,eff})$ (dB)	-2.1980	-1.2930	-0.3329

Table 3.2: Duty cycle and peak power level influence on the DME/TACAN pulse RFI parameters and the $C/N_{0,eff}$ degradation calculation

4 DME/TACAN Pulsed Interference Environments Simulation

The impact of the DME/TACAN interference on the effective post-correlation $C/N_{0,eff}$ in GNSS receivers has already been analyzed in Chap.3. In this chapter, the DME/TACAN pulsed interference environments of an airborne GNSS receiver at high altitude are simulated for both E5a/L5 and E5b. For each simulation, we generate a DME/TACAN interference IF signal at the output of GNSS receiver mixer with a length of 0.1 second each time.

Two kinds of simulation modes are simulated for different purposes. One of the DME/TACAN pulsed interference environments which would be of great interest is the interference at GNSS antenna port of an aircraft flying at high altitude over the European hot-spot. In this case, we develop a mode called ”Hot-spot” mode which simulates the real situation of European hot-spot based on the information of DME/TACAN beacons located in Europe. And the impact of this interference environment on GNSS receiver is presented for both Galileo E5a/GPS L5 and E5b with flight heights of 10 kft and 40 kft. In the other mode ”Duty cycle” mode, we generate DME/TACAN pulses at the given duty cycle, then test the impacts on $C/N_{0,eff}$ degradation caused by these pulses when changing input DME/TACAN duty cycle and power distribution. This mode can be used to find out the influence of DME/TACAN duty cycle on the $C/N_{0,eff}$ degradation, and can be used to test the GNSS receiver performance under large duty cycle DME/TACAN pulsed environments.

4.1 ”Hot-spot” Mode

”Hot-spot” mode is used to simulate the DME/TACAN pulsed interference environment at the victim aircraft flying over the European hot spot with a certain flight height. Signals from each DME/TACAN ground beacon are aggregated to form the pulsed interference environment. Received signal from single DME/TACAN ground beacon is generated from the expression (3.2), which is,

$$\begin{aligned} S_{DME/TACAN}(t, EL) &= \sqrt{P_I \cdot G_{beacon}(EL) \cdot L_{free} \cdot G_{air}(-EL)} \\ &\cdot \sum_k (e^{\frac{-\alpha}{2}(t-t_k)^2} + e^{\frac{-\alpha}{2}(t-\Delta t-t_k)^2}) \cdot cos(2\pi f_I t + \theta_I) \end{aligned} \quad (4.1)$$

t_k can be derived from PRF, elevation angle EL and L_{free} can be obtained from DME/TACAN beacon location (latitude/longitude/altitude), P_I, f_I, PRF, and DME/TACAN beacon location are given by the DME/TACAN database. Then DME/TACAN pulsed interference can be expressed as,

$$S = \sum_i S_{DME/TACAN,i} \tag{4.2}$$

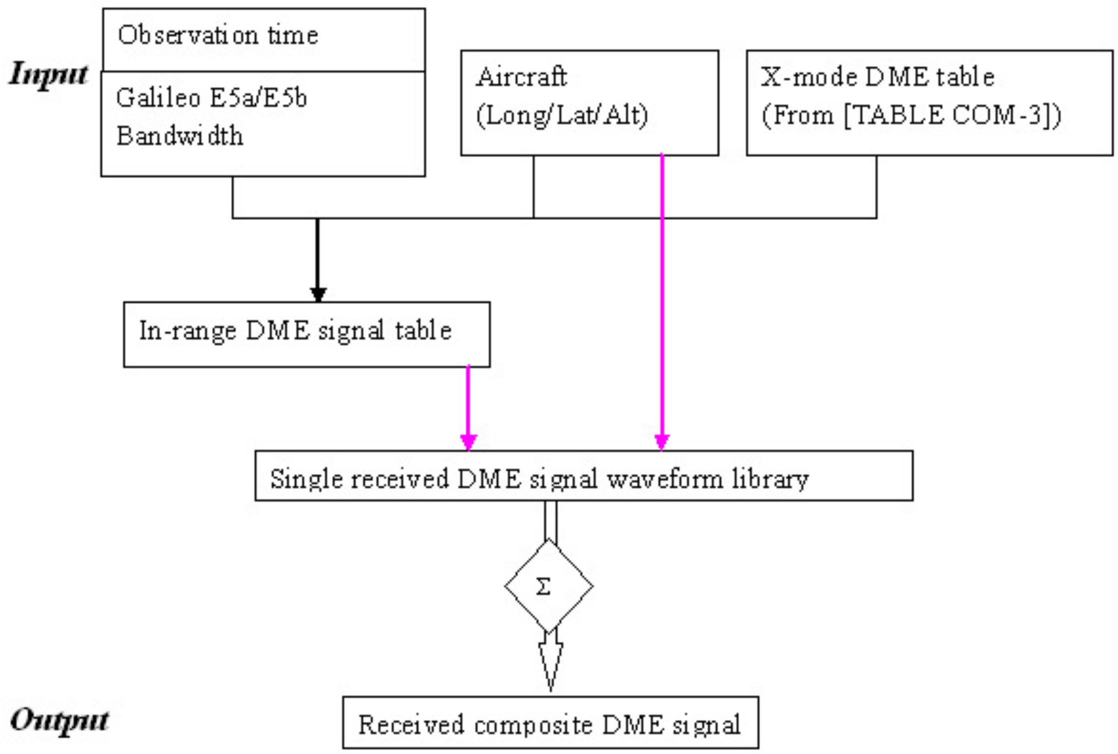

Figure 4.1: "Hot-spot" Simulation Mode System Structure

As shown in Fig. 4.1, testing band and aircraft position are as input parameters. The simulated pulsed interference environment is made from each received signal from DME/TACAN beacon. Peak power of the received DME/TACAN pulses from a single DME/TACAN beacon is determined by DME/TACAN beacon transmitting peak power, antenna gains, and free-space loss. Program details for the simulation can be found in Appendix A.

4.1.1 Simulation Assumptions for "Hot-spot" Mode

4.1.1.1 Aircraft Flight

The aircraft is assumed to fly at a high altitude of 40 kft, which is a typical maximum level of flight for an en-route operation. The degradation of effective carrier to noise ratio due to the DME/TACAN pulses is maximal at this altitude. 10 kft is also simulated to show the influence of altitude on the degradations caused by the DME/TACAN pulses.

4.1.1.2 Testing Band

Simulations are carried on Galileo E5a/GPS L5 and E5b bands. We assume for both E5a/L5 and E5b signals, the IF frequency is 20 MHz. DME/TACAN pulses are also generated at IF bands. For E5a/L5, the bandwidth used is 20 MHz (the passband is [10 30] MHz), and 14 MHz for E5b (the passband is [10 24] MHz), which corresponds to RF bands 1176.45 ± 10 MHz for E5a/L5 and [1997.14 1211.14] MHz for E5b.

4.1.1.3 DME/TACAN Beacon Selection

Given the aircraft position, DME/TACAN beacons located inside the aircraft insight region of the earth are chosen. European DME/TACAN beacon database containing beacon locations (longitude/latitude/height), transmitting frequencies and transmitting peak powers can be found in [8].

4.1.1.4 DME/TACAN Beacon Pulse Pair Repetition Frequency

We assume DME ground beacons transmitting pulse pairs at 2700 ppps, and 3600 ppps for TACAN. It corresponds to a worst pulsed interference environment.

4.1.1.5 Antenna Gain

Antenna gain patterns of GNSS receiver and DME/TACAN beacon are shown in Fig. 3.4. Since the elevation angles are almost within 20°, so we assume the normalized antenna gain patterns for DME and TACAN beacons are the same.

4.1.1.6 DME/TACAN Beacon Transmitting Frequency

The IF DME/TACAN signals are generated in the simulation instead of the RF signals. The simulated transmitting frequency of the single DME/TACAN signal can be expressed as,

$$f_{DME/TACAN} = f_{real\ transmitting} - f_{central} + f_{IF} \tag{4.3}$$

where,

- $f_{DME/TACAN}$ is simulated IF DME/TACAN transmitting frequency
- $f_{real\ transmitting}$ is real RF transmitting frequency of DME/TACAN beacon
- $f_{central}$ is testing band central frequency, for E5a/L5 is 1175.45 MHz and 1207.14 MHz for E5b
- f_{IF} is IF frequency, which is 20 MHz in our simulation

4.1.1.7 Front-end Filter

Two kinds of front-end filters are used in ”Hot-spot” mode simulation. One is the ideal filter with rectangular frequency response which blocks all frequencies outside the passband. Signals whose frequencies are inside the passband pass the filter without attenuation. The other kind of front-end filters for E5a/L5 and E5b bands are shown in Fig. 4.2.

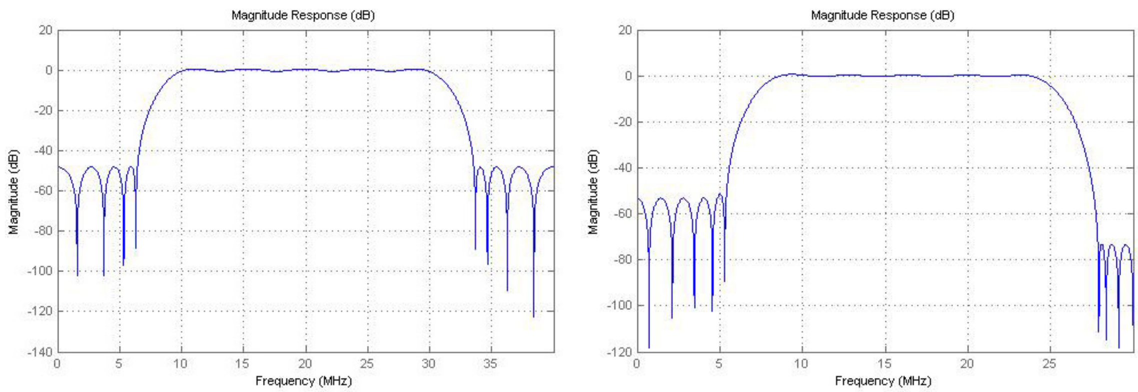

Figure 4.2: Simulated front-end filter of E5a/L5 (left) and E5b (right) receivers

4.1.1.8 Channel Characteristics

The channel between the single DME/TACAN beacon and aircraft only attenuates the amplitude of DME/TACAN signal (as shown in (3.2)).

4.1.2 Simulation Result of "Hot-spot" Mode

In [1], a worst location is in coordinates 50° North and 9° East. In order to compare our simulation results with the results presented in [1], we assume the same coordinates in our simulation. Following simulation results are obtained when the victim aircraft is at this worst location with a flight height of 10 kft and 40 kft.

4.1.2.1 Impact of DME/TACAN Pulsed Environment on Galileo E5a/GPS L5 Receiver

For Galileo E5a/GPS L5 signal, applied ideal front-end filter, the degradation and blanker duty cycle caused by DME/TACAN signal only are plotted on Fig. 4.3. Dashed lines represent $C/N_{0,eff}$ degradations vs blanking thresholds, dotted lines represent blanker duty cycles vs blanking thresholds.

Clearly on E5a/L5, the degradation is minimized for a blanking threshold of -116.1 dBW for 10 kft and -115.5 dBW for 40 kft. Degradation and duty cycle at the flight height of 40 kft (-1.4625 dB/19.08%) are larger than 10 kft (-0.8537 dB/14.56%). While, the optimal blanking threshold of 10 kft is 0.6 dB larger than of 40 kft. The maximum degradations and the associated blanker duty cycles as well as other simulation results for E5a band are summarized in Table 4.1.

Applied front-end filters shown in Fig. 4.2, more DME/TACAN beacon signals pass the filter with attenuation, and then contribute to the interference environment, and the degradations become larger, as shown in Fig. 4.4 (Dashed lines represent $C/N_{0,eff}$ degradations vs blanking thresholds, dotted lines represent blanker duty cycles vs blanking thresholds).

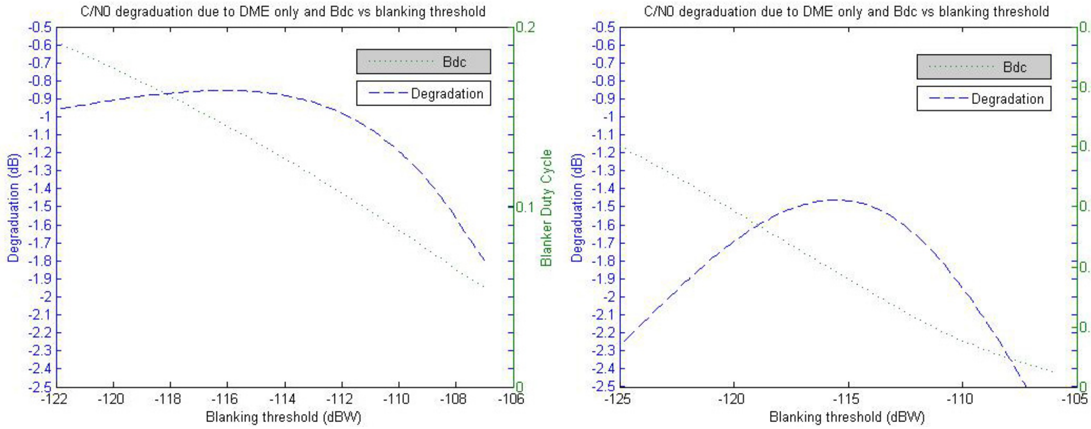

Figure 4.3: E5a/L5 C/N_0 degradation due to DME/TACAN beacons over the Europe Hot-spot at 10 kft (left) and 40 kft (right)

	$E5a$ 10 kft	$E5a$ 40 kft
DME/TACAN number	7	23
Received DME/TACAN signal Peak Power (dBW)	-86.9278	-95.7952
Average Power of Received DME/TACAN signal (dBW)	-109.1989	-115.6266
Optimal Blanking Threshold (dBW)	-116.1	-115.5
$Bdc(\%)$	14.56	19.08
R_I	0.0400	0.1333
$deg(C/N_{0,eff})$ (dB)	-0.8537	-1.4625

Table 4.1: E5a band simulation result due to DME/TACAN beacons over the Europe Hot-spot

	$E5a/L5$ 10 kft	$E5a/L5$ 40 kft
DME/TACAN number	26	87
Received DME/TACAN signal Peak Power (dBW)	-82.7790	-88.5739
Average Power of Received DME/TACAN signal (dBW)	-105.2021	-109.4320
Optimal Blanking Threshold (dBW)	-114.4	-113.4
$Bdc(\%)$	35.31	41.71
R_I	0.1636	0.3444
$deg(C/N_{0,eff})(dB)$	-2.5496	-3.6290

Table 4.2: E5a/L5 band simulation result due to DME/TACAN beacons over the Europe Hot-spot when applying the simulated front-end filter

With the simulated front-end filter, the simulation results of DME/TACAN interference

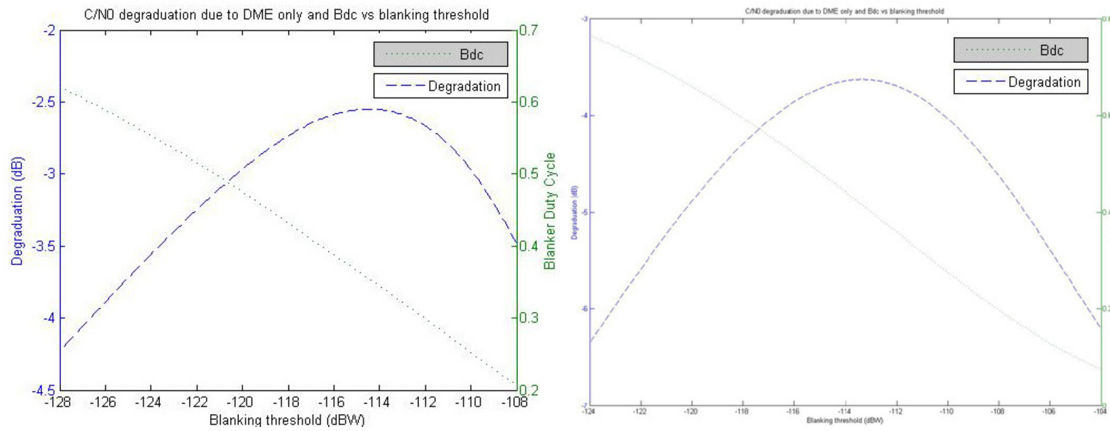

Figure 4.4: E5a/L5 $C/N_{0,eff}$ degradation due to DME/TACAN beacons over the Europe Hot-spot at 10 kft (left) and 40 kft (right) when applying the simulated front-end filter

impact on the E5a/L5 receiver are presented in Table 4.2.

4.1.2.2 Impact of DME/TACAN Pulsed Environment on Galileo E5b Receiver

For the simulation carried on the Galileo E5b band, we obtain a similar result as E5a/L5. Applying the ideal front-end filter, degradations and blanker duty cycles in presence of the DME/TACAN signal only for E5b band are plotted on Fig. 4.5 (Dashed lines represent $C/N_{0,eff}$ degradations vs blanking thresholds, dotted lines represent blanker duty cycles vs blanking thresholds).

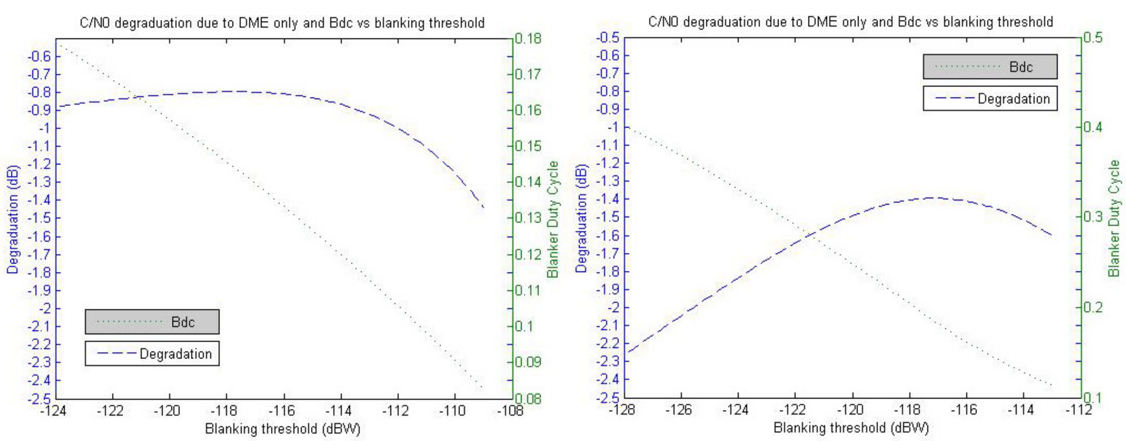

Figure 4.5: E5b $C/N_{0,eff}$ degradations due to DME/TACAN beacons over the Europe Hot-spot at 10 kft (left) and 40 kft (right)

Table 4.3 shows the maximum degradations and the associated blanker duty cycles as well as other simulation results for E5b band.

	$E5b$ 10 kft	$E5b$ 40 kft
DME/TACAN number	5	20
Received DME/TACAN signal Peak Power (dBW)	-88.2929	-92.5883
Average Power of Received DME/TACAN signal (dBW)	-111.5312	-115.0172
Optimal Blanking Threshold (dBW)	-117.7	-117.1
$Bdc(\%)$	14.39	18.41
R_I	0.0285	0.1246
$deg(C/N_{0,eff})$ (dB)	-0.7969	-1.3938

Table 4.3: E5b band simulation result due to DME/TACAN beacons over the Europe Hot-spot

From the Fig. 4.5, we can see that there is clearly an optimal blanking threshold that achieves the minimum degradations, and the threshold for 10 kft is 0.6 dB larger than for 40 kft, which is the same as the result for E5a/L5 band (Fig. 4.3). If the blanking threshold is too high, more interference is allowed to enter the receiver so the blanker duty cycle is low and the degradations are high. If the blanking threshold is too low, the useful Galileo signal is highly degraded so the overall degradation and the blanker duty cycle become large. So in between we could find an optimal threshold. The blanking threshold in E5b is smaller than in E5a/L5. The degradations caused by the DME/TACAN pulsed interference in presence of the pulse blanker are larger at a higher flight (40 kft) for both E5a/L5 and E5b bands.

When applying the simulated front-end filter, degradations and blanker duty cycles in presence of DME/TACAN signal only are plotted on Fig. 4.6 (Dashed lines represent $C/N_{0,eff}$ degradations vs blanking thresholds, dotted lines represent blanker duty cycles vs blanking thresholds). More DME/TACAN interference passes the simulated front-end filter than the ideal one.

With the simulated front-end filter, the simulation results of DME/TACAN interference impact on GNSS receiver on E5b band are presented in Table 4.4.

Clearly, the degradations are larger when applying the simulated filter, for more DME/TACAN interference power passes the front-end filter.

From the "Hot-spot" mode simulations above, we can see that degradations are larger at higher flight height. At the same flight height, degradations on the E5a/L5 band are larger than E5b. What is more, different types of front-end filter would affect $C/N_{0,eff}$ degradations because of the difference of the filtered DME/TACAN interference signals.

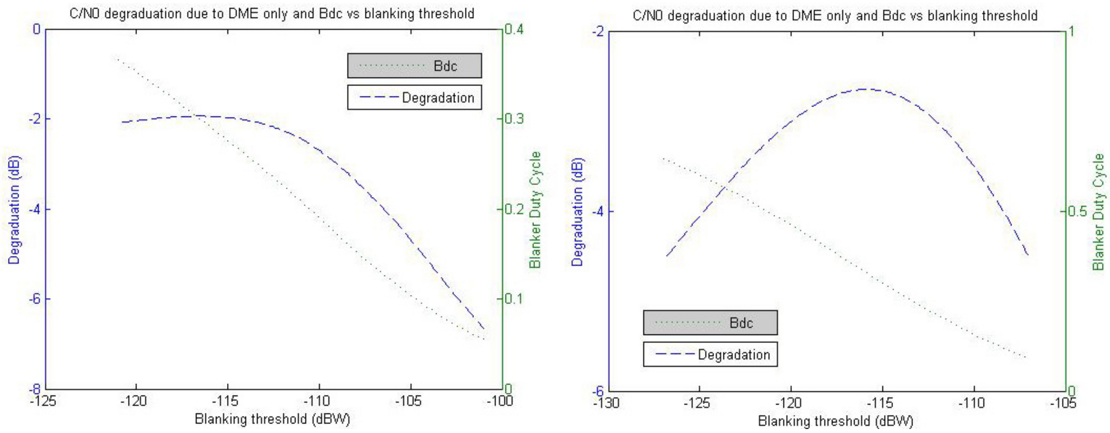

Figure 4.6: E5b $C/N_{0,eff}$ degradation due to DME/TACAN beacons over Europe Hot-spot at 10 kft (left) and 40 kft (right) when applying simulated front-end filter

	E5b 10 kft	*E5b* 40 kft
DME/TACAN number	26	87
Received DME/TACAN signal Peak Power (dBW)	-85.9103	-91.8198
Average Power of Received DME/TACAN signal (dBW)	-106.8343	-112.0749
Optimal Blanking Threshold (dBW)	-116.6	-115.9
$Bdc(\%)$	30.08	32.82
R_I	0.0931	0.2364
$deg(C/N_{0,eff})$ (dB)	-1.9402	-2.6493

Table 4.4: E5b band simulation result due to DME/TACAN beacons over the Europe Hot-spot when applying the simulated front-end filter

4.2 "Duty Cycle" Mode

"Duty Cycle" mode generates DME/TACAN interfering pulses according to the given duty cycle. At GNSS receiver, the only interested parameters are DME/TACAN signal's duty cycle and received peak power. DME/TACAN beacon's location and aircraft position are not under consideration in this mode. In this mode, we can observe the influence of DME/TACAN duty cycle and peak power level on GNSS receiver $C/N_{0,eff}$ degradations.

The number of the DME/TACAN signals, duty cycle and peak power distribution of these DME/TACAN interfering signal at the GNSS receiver antenna port as well as testing band are input parameters. Generated interference signal is the composite DME/TACAN pulses whose duty cycle equals to the input duty cycle. The generated pulsed interference signal can be used as the input signal to the GNSS software receiver (details can be found in Chap. 5) to test the GNSS receiver's performance (tracking threshold and acquisition threshold).

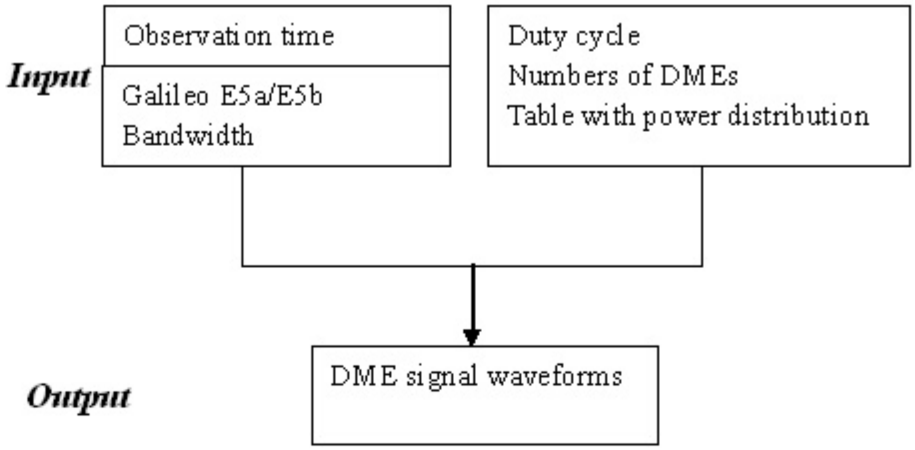

Figure 4.7: "Duty Cycle" Simulation Mode System Structure

4.2.1 Simulation Assumptions for "Duty Cycle" Mode

4.2.1.1 Testing Band

Like "Hot-spot" mode, Galileo E5a/GPS L5 and E5b IF bands are used in the simulation and bandwidth for E5a/L5 is 20 MHz , and 14 MHz for E5b. For software receiver (Chap. 5), the passband used is 4.092 ± 2 MHz. Frequencies of simulated DME/TACAN signals are within above bands.

4.2.1.2 Input Number of the DME/TACAN Signals

The number of DME/TACAN signals varies from 10 to over 50 relative to the input duty cycle. It is obvious that larger duty cycle comes from larger number of DME/TACAN signals based on reality.

4.2.1.3 DME/TACAN duty cycle

The input DME/TACAN duty cycle is simulated from 0% to 50%.

4.2.1.4 DME/TACAN Signal Power Distribution

At the GNSS receiver antenna port, the peak powers of DME/TACAN signals are assumed to be uniformly distributed between $[-120\ \ -100]$ dBW. This interval is chosen based on the power level of DME/TACAN signal received at aircraft antenna port at high altitude. Power level $[-130\ \ -110]$ dBW is also used in simulation to show the interference power influence on $C/N_{0,eff}$ degradations.

4.2.1.5 DME/TACAN Beacon Transmitting Frequency

The DME/TACAN signal frequencies at GNSS receiver are uniformly distributed in the testing band. Ideal front-end filter is used in the ”Duty cycle” mode.

4.2.1.6 DME/TACAN Beacon Pulse Pair Repetition Frequency

Each DME/TACAN pulse pairs' PRF is related to its individual duty cycle dc, as shown in (4.4).

$$PRF = dc/PW = \frac{dc}{2 \times 2.64} \tag{4.4}$$

where,

- PRF is the single DME/TACAN's pulse pair repetition frequency
- dc is the single DME/TACAN's duty cycle
- PW is the equivalent width of DME/TACAN pulse pair, which is 5.28 μs

Considering the overlapping of the DME/TACAN pulses, we can not simply divided the input duty cycle by the number of DME/TACAN signals to obtain each DME/TACAN signal's duty cycle. This is because the overlapped pulses' equivalent width is less than the sum of individual pulse equivalent width, and it results in the duty cycle less than the sum of individual DME/TACAN signals'. In order to generate DME/TACAN signal at the given duty cycle, we use an algorithm shown in Fig. 4.8 to assign duty cycle to each individual DME/TACAN signal.

The algorithm shown in Fig. 4.8 can be described as follows.

- Assume the first DME/TACAN pulses duty cycle is the total duty cycle divided by the number of DME/TACANs. Generate first DME/TACAN signal, calculate the duty cycle left, which is the difference between total duty cycle and generated DME/TACAN signal's duty cycle
- Next DME/TACAN pulses duty cycle is the left duty cycle divided by the number of unassigned duty cycle DME/TACANs. Generate this DME/TACAN signal, and calculate the duty cycle of the composite signal of all generated DME/TACAN signals, then left duty cycle equals to the given input duty cycle minus the generated composite signal duty cycle
- Redo the second step, until all DME/TACAN's duty cycles are known. If the final generated composite DME/TACAN signal's duty cycle is different from the given one because of the overlapping, define delta equals to given duty cycle minus the generated composite duty cycle
- Regenerate last DME/TACAN signal with duty cycle equal to the former duty cycle plus delta. Observe the new composite signal's duty cycle again, if the difference is still unaccepted, redo this step

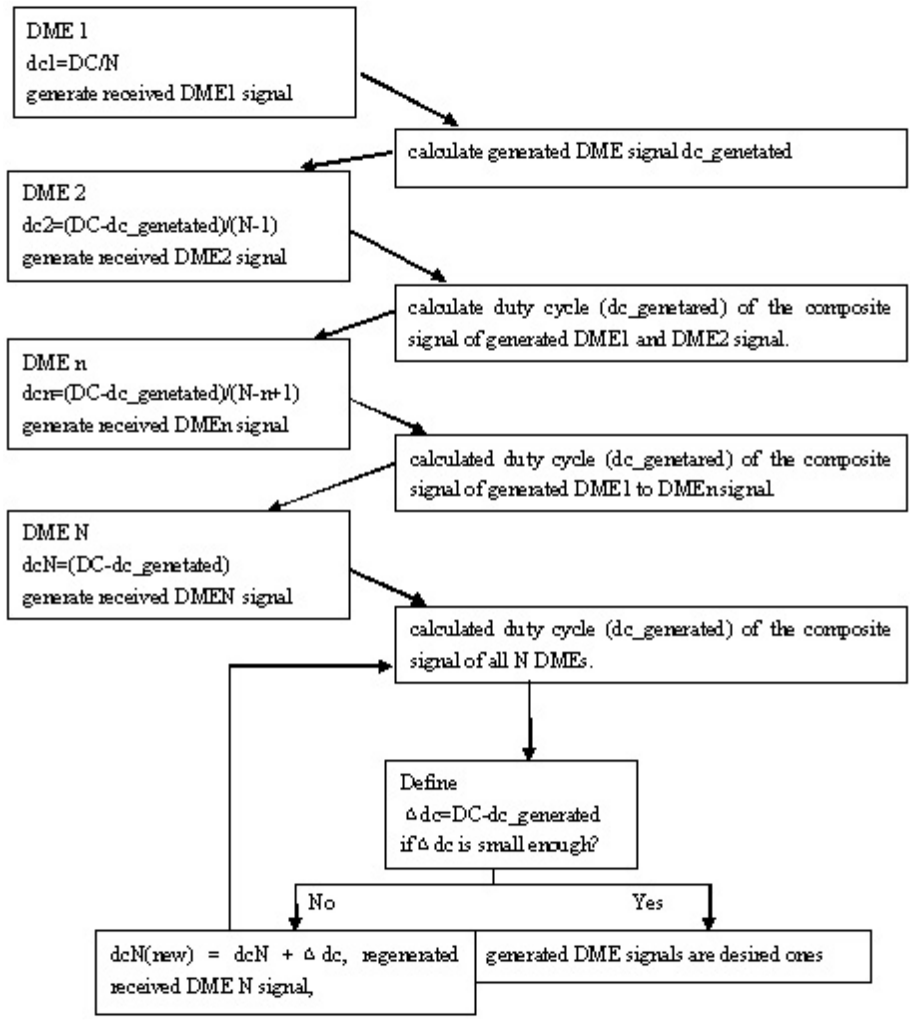

Figure 4.8: DME/TACAN signal individual duty cycle assignment algorithm

4.2.2 Simulation Result of "Duty Cycle" Simulation Mode

4.2.2.1 DME/TACAN duty cycle Influence on GNSS Receiver

Fig. 4.9 is plotted when the input power levels are $[-120\ -100]\ dBW$ (Dashed lines represent $C/N_{0,eff}$ degradations vs blanking thresholds, dotted lines represent blanker duty cycles vs blanking thresholds). Clearly larger input duty cycle leads to larger degradation. Table 4.5 shows the maximum degradations and the associated blanker duty cycle as well as other results simulated at the duty cycle of 15% and 25%.

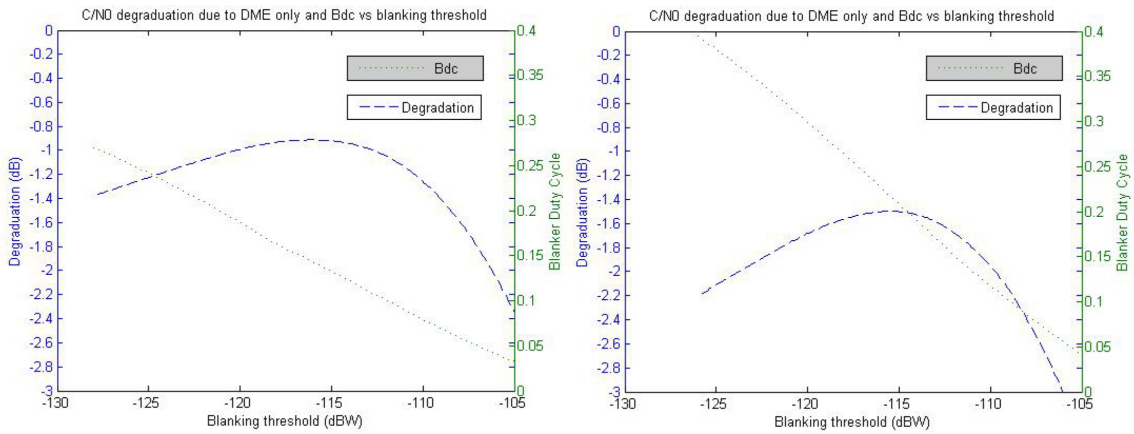

Figure 4.9: E5a C/N_0 degradation caused by DME/TACAN signal only when given DME/TACAN duty cycles are 15% (left) and 25% (right), when input power level is [-120 100] dBW.

	$E5a\ dc = 15\%$	$E5a\ dc = 25\%$
DME/TACAN number	14	23
DME/TACAN signal Peak Power (dBW)	-92.6702	-90.7675
Average Power of DME/TACAN signal (dBW)	-115.0523	-113.5544
Optimal Blanking Threshold (dBW)	-116.1	-115.5
$Bdc(\%)$	14.36	21.74
R_I	0.0564	0.1049
$deg(C/N_0)$ (dB)	-0.9117	-1.4980

Table 4.5: Degradation caused by DME/TACAN only when applying different input duty cycles

4.2.2.2 DME/TACAN Signal Power Level Influence on GNSS Receiver

Fig. 4.10 shows that $C/N_{0,eff}$ degradation decreases as the reduction of the input DME signal power level when input duty cycle is 15%.

Table 4.6 shows the maximum degradations and the associated blanker duty cycle as well as other results simulated at different input DME/TACAN signal power levels. DME/TACAN signal with larger power level results in a larger Bdc and RI, which leads to a larger $C/N_{0,eff}$ degradatoin.

Results obtained from "Duty cycle" mode simulations show that increasing duty cycle would cause larger $C/N_{0,eff}$ degradation. Decreasing the average power of DME/TACAN interfering signal would lead to a smaller $C/N_{0,eff}$ degradation.

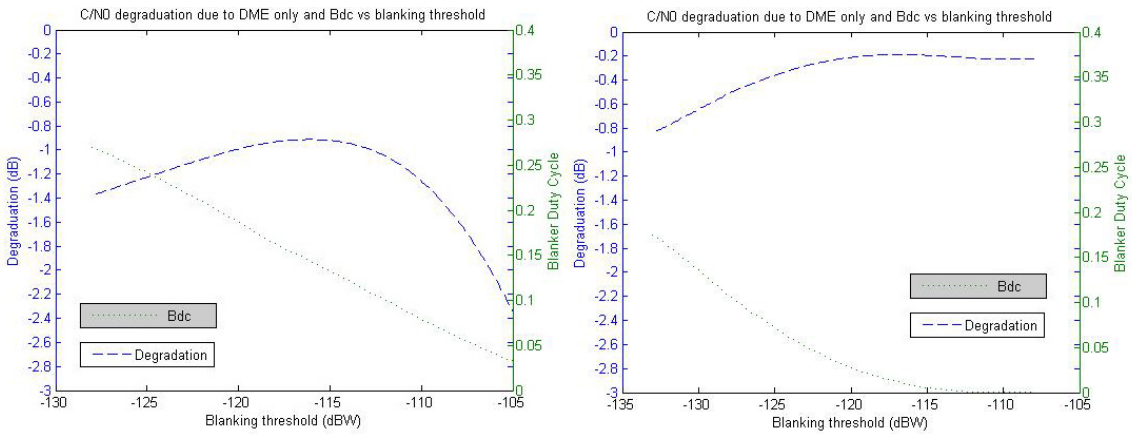

Figure 4.10: E5a/L5 C/N_0 degradation caused by DME signal only when DME/TACAN signals' power levels are $[-120 \;\; -100]dBW$ (left) and $[-130 \;\; -110]dBW$ (right), when dc is 15%

	$Power : [-120 \;\; -100] \; dBW$	$Power : [-130 \;\; -110] \; dBW$
DME/TACAN number	14	14
DME/TACAN Peak Power (dBW)	-92.6702	-107.4973
DME/TACAN Average Power (dBW)	-115.0523	-129.7734
Blanking Threshold (dBW)	-116.1	-116.8
$Bdc(\%)$	14.36	1.13
R_I	0.0564	0.0325
$deg(C/N_0)$ (dB)	-0.9117	-0.1885

Table 4.6: Degradation caused by DME/TACAN only on E5a/L5 band when applying different input power levels

5 GNSS Software Receiver Performance Testing Under DME/TACAN Pulsed Interference Environment

In this chapter, we combine the generated DME/TACAN signal with GPS signal in the GNSS software receiver available in Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), and then we test the acquisition and tracking thresholds by changing the duty cycle of the DME/TACAN pulsed interference environment, both with and without implementing the pulse blanker into the software receiver. By doing this, we find that pulse blanker would help the GNSS software receiver to cope with more severe DME/TACAN interference environment with larger duty cycle. Finally, in order to find out influence of the interference power on the acquisition and tracking thresholds of the software receiver, we test the receiver performance by changing the power level of the DME/TACAN signal.

In our testing, all simulation results obtained are from one trial. Note that the GPS signal generator we used is not perfect, as some spectrum aliasing occurs during the signal generation.

5.1 Pulse Blanker Influence on the GNSS Software Receiver Under DME/TACAN Interference Environment

Assuming that DME/TACAN signal components have a uniform peak power distribution in the given power level. In Chap. 4.2.2.1, we have shown that, with the pulse blanker, the $C/N_{0,eff}$ degradation of GNSS receiver is larger at higher duty cycle. In other words, $C/N_{0,eff}$ at the GNSS receiver correlator output decreases as the increasing of the duty cycle of the DME/TACAN pulses. This is verified by the following software receiver performance testing under strong pulsed DME/TACAN interference environment. The RF front-end filter of the software receiver is assumed as the ideal bandpass filter with Nyquist bandwidth. Since pulse blanking is a simple and near optimal technique to cope with strong pulsed interference, so we test the receiver performance by both inserting and not inserting a pulse blanker into the software receiver. Configuration of the software receiver is shown in Table 5.1. The pulse blanker works on the unquantized samples in our simulation.

When a pulse blanker is implemented in the software receiver, the blanking threshold to noise ratio is set to be around 76 to 77 $dBHz$. This blanking threshold is the optimal value obtained from the MATLAB simulation when analyzing $C/N_{0,eff}$ degradations caused by

DME/TACAN signal only. And the MATLAB simulation shows that DME/TACAN signal's duty cycle and power level don't affect the value of this optimal blanking threshold very much.

$Process\ Time\ (s)$	2
$ADC/AGC\ bits$	4
$RF\ Front-end\ Filter\ Bandwidth\ (MHz)$	8.1838
$IF\ (MHz)$	4.1304
$Sampling\ Frequency\ (MHz)$	16.3676
$Interference\ free\ C/N_0\ (dBHz)$	45
$Loss\ of\ Tracking\ Doppler\ std\ Threshold\ (Hz)$	10
$Loss\ of\ Tracking\ C/N_0\ Threshold\ (dBHz)$	40.5

Table 5.1: Software Receiver Configurations

Two cases would happen when the software receiver is under DME/TACAN interference environment. The first one is, the receiver suffers this pulsed interference all the time. In this case, larger duty cycle DME/TACAN signals would cause the receiver acquisition failure. Meantime, the software receiver sends a message of "acquisition unsuccessful". Combining GPS data with certain duty cycle DME/TACAN signal, *Acquisition threshold* is defined to be the receiver tracking mode $C/N_{0,eff}$, below this certain DME/TACAN duty cycle, the receiver can acquire data in presence of interference. When combined DME/TACAN signal's duty cycle is larger than this certain duty cycle, then the receiver doesn't acquire data any more, and will send the message of "acquisition unsuccessful". The second case is, the DME/TACAN signal appears when the receiver has already tracked a pure GPS signal. Then the *tracking threshold* is the receiver tracking mode $C/N_{0,eff}$ at certain DME/TACAN duty cycle, above which the receiver begins to lose tracking after the appearance of this DME/TACAN interference signal. The software receiver has a preset tracking threshold, $C/N_{0,eff} = 40.5\ dBHz$, which is the European minimum operational value for Galileo receiver [5]. The receiver will lose track when the instantaneous $C/N_{0,eff}$ is below 40.5 $dBHz$. So the tested tracking threshold should be above this value. In our testing, we generate DME/TACAN signals with different duty cycles, and combine them with GPS signal to find these two thresholds. The peak power to noise density ratio (p/N) of generated DME/TACAN signal's components are assumed to be uniformly distributed within [70 90] $dBHz$.

Fig. 5.1 shows the testing results of the software receiver acquisition threshold determination. When the pulse blanker is not implemented into the software receiver, the acquisition threshold is 42.6440 dB/9%. The software receiver can not acquire data when DME/TACAN's duty cycle is larger than 9%. When implementing the pulse blanker, the software receiver can keep on acquiring data at a lower $C/N_{0,eff}$ when the DME/TACAN's duty cycle is up to 15%. And the acquisition threshold is 40.6509 $dBHz$/15%.

Fig. 5.2 shows the tracking threshold determination with and without the pulse blanker.

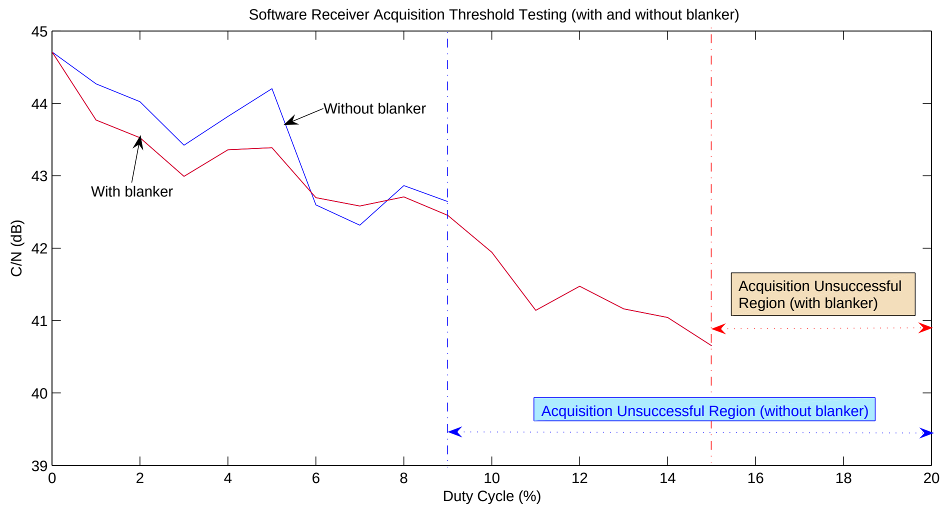

Figure 5.1: Acquisition threshold testing, when the receiver is with and without pulse blanker (DME/TACAN power level is [70 90] dBHz)

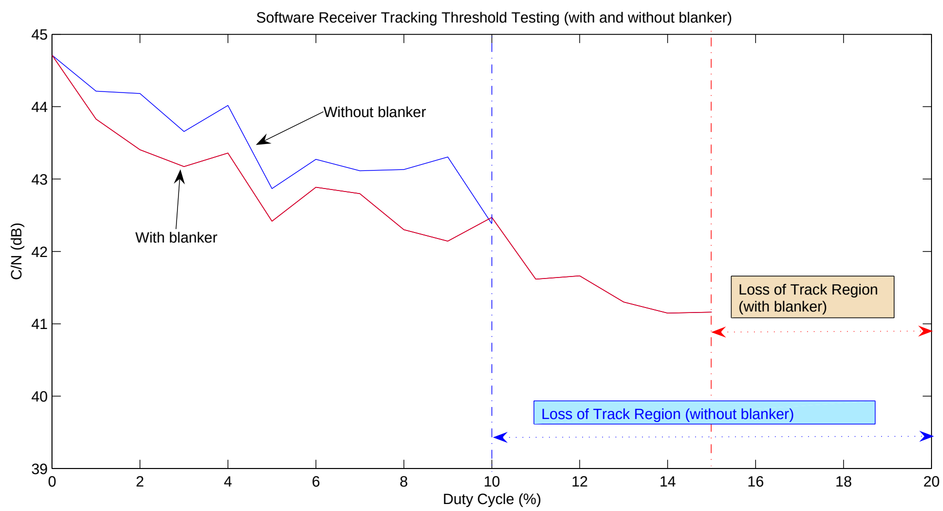

Figure 5.2: Tracking threshold testing, when the receiver is with and without pulse blanker (DME/TACAN power level is [70 90] dBHz)

The tracking threshold and $C/N_{0,eff}$ without the pulse blanker is 42.3812 $dBHz/10\%$, and 41.1617 $dBHz/15\%$ when applying the pulse blanker. Although there is a preset tracking threshold of 40.5 $dBHz$ in the software receiver, our testing results are different when with and without blanker, and both results are larger than 40.5 $dBHz$. The reason is, when the receiver enters tracking mode, the variation of $C/N_{0,eff}$ is around 0.4 dB (without blanker) and 0.1 dB (with blanker). So it is easier to get instantaneous $C/N_{0,eff}$ below

40.5 $dBHz$ without blanker, even though the mean $C/N_{0,eff}$ value is above 40.5 $dBHz$. It shows that the pulse blanker can decrease the variation of $C/N_{0,eff}$ to insure the software receiver working under lower $C/N_{0,eff}$.

The thresholds are summarized in Table 5.2. Clearly, when pulse blanker is implemented, both acquisition and tracking thresholds are smaller, and the DME/TACAN duty cycles are larger. The software receiver performance under DME/TACAN pulsed interference environment is improved when applying the pulsed blanker, and can cope with DME/TACAN pulsed environment with a duty cycle up to 15%. While, pulse blanker does not show much influence on the value of $C/N_{0,eff}$ in presence of strong DME/TACAN pulses.

	Acquisition threshold ($dBHz$) /DME/TACAN duty cycle (%)	Tracking threshold ($dBHz$) /DME/TACAN duty cycle (%)
Without blanker	42.6440/9%	42.3812/10%
With blanker	40.6509/15%	41.1617/15%

Table 5.2: Pulse blanker influence on acquisition and tracking thresholds (DME/TACAN power level is [70 90] dBHz)

5.2 DME/TACAN Signal Power Level Influence on GNSS Software Receiver Performance

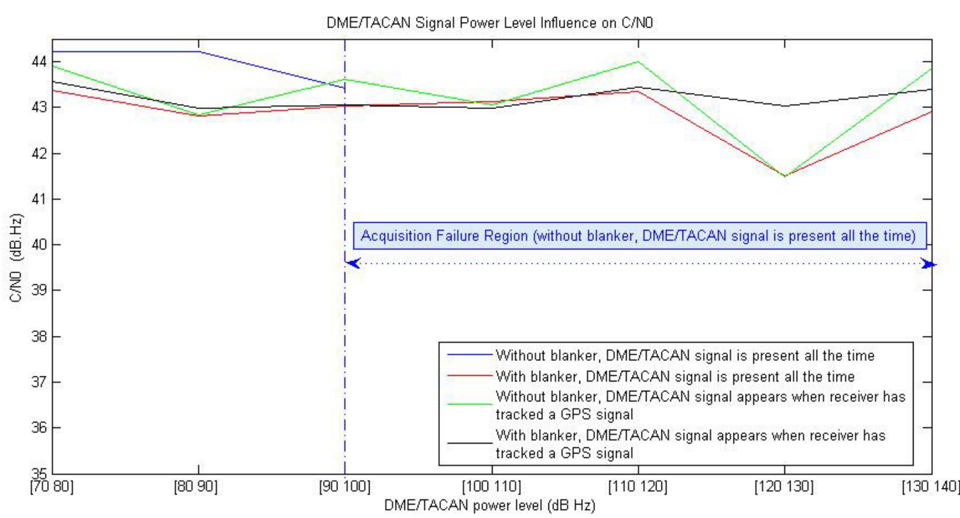

Figure 5.3: DME/TACAN power levels' influence on software receiver performance (dc=3%)

When the pulse blanker is not implemented into the software receiver, the software receiver will lose the ability to acquire data in presence of DME/TACAN pulses with larger peak power level, even though the duty cycle is small. As shown in Fig. 5.3 (blue curve), even at same duty cycle (3%), the software receiver can not acquire data when the power level of the DME/TACAN pulses is above 100 $dBHz$. In other words, DME/TACAN power level affects the acquisition threshold of software receiver when pulse blanker is not implemented. When we add the pulse blanker into the software receiver, power level will not affect software receiver's $C/N_{0,eff}$ that much (red curve in Fig. 5.3). In other words, DME/TACAN signal power level will not affect the software receiver's acquisition threshold in presence of the pulse blanker.

Power level does not show much influence on the receiver $C/N_{0,eff}$ in the case that DME/TACAN pulses appear when the receiver is in tracking mode, no matter the pulse blanker is implemented or not (as shown in Fig. 5.3, the case without blanker is shown in green curve, and blank curve represents the case with blanker). So DME/TACAN's power level will not affect tracking threshold of the software receiver.

6 Discussion of the Simulation Results

In this chapter, results obtained by the MATLAB simulation are compared with the values in [1] and the theoretical calculations. The MATLAB simulated degradations are smaller than both theoretical calculations and the values in [1]. Analysis of the results' difference is given in Chap. 6.1 and Chap. 6.2.

6.1 Comparison Between the MATLAB Simulation Results and the Theoretical Calculations

The MATLAB simulation results and the theoretical calculations of the DME/TACAN pulsed interference impact on E5a/L5 band for "Hot-spot" mode are listed in the following table (Table 6.1).

	E5a/L5 10 kft		E5a/L5 40 kft	
	Theory	Simulation	Theory	Simulation
$Bdc(\%)$	19.48	14.56	39.19	19.08
R_I	0.0414	0.0400	0.2307	0.1333
$deg(C/N_{0,eff})$ (dB)	-1.1171	-0.8537	-3.0619	-1.4625

Table 6.1: Comparison between the MATLAB simulation results and the theoretical calculations in E5a/L5 band

In the MATLAB simulation, following situations are considered when obtain R_I and Bdc:

- Strong DME/TACAN pulse (above blanker pulses) overlaps
- Residual portion of Gaussian DME/TACAN pulse after the pulse blanking
- Erasure of weak DME/TACAN pulses by strong pulse blanking
- Erasure of residual portion of strong pulses by strong pulse blanking
- Weak DME/TACAN pulse and Residual portion of strong DME/TACAN pulse overlaps
- Carrier variation

In theoretical approach, when calculating the effective carrier to noise $C/N_{0,eff}$ degradation at the output of the GNSS receiver correlator, only the first two cases are considered, and the probability of weak DME/TACAN pulses overlapping is assumed to be very small, so it is ignored, which is the same for the left cases. While, erasure of the weak DME/TACAN pulses as well as other strong DME/TACAN residual part would reduce the below blanker interference power density (R_I), especially at high altitude, for more signals are aggregated. This is verified by the simulation. The simulated R_I is smaller for both 10 kft (0.04 in simulation and 0.0414 in theory) and 40 kft (0.1333 in simulation and 0.2307 in theory), and the difference is larger at 40 kft, the theoretical R_I is almost two times of the simulation value.

The received DME/TACAN signal is usually modulated by a carrier, whose frequency depends on the receiver IF frequency and DME/TACAN transmitting frequency. Because of the carrier variation, the blanker duty cycle would be smaller than a baseband DME/TACAN signal.

It is true that the chance is very small for the instantaneous aggregate peak power of overlapped weak pulses above the blanking threshold. So Bdc obtained from the MATLAB simulation is smaller than the theoretical values, which results in a smaller $C/N_{0,eff}$ degradation in the simulation, as shown in Table 6.1. We can have the same conclusion for E5b band by comparing Table 3.1 and Table 4.3, as well as the comparison between Table 3.2 and Table 4.5 Table 4.6 for the DME/TACAN duty cycle and power level influence simulation.

6.2 Comparison Between the MATLAB Simulation Results and [1]

The $C/N_{0,eff}$ degradations in [1] are much larger than our simulation results. In [1], for both 10 kft and 40 kft, optimal blanking threshold for E5a/L5 is 117.1 dBW, and -120 dBW for E5b. Table 6.2 compares $C/N_{0,eff}$ degradations in E5a/L5 band between [1] and the MATLAB results.

	[1]		Simulation	
	E5a/L5 10 kft	E5a/L5 40 kft	E5a/L5 10 kft	E5a/L5 40 kft
$OptimalBth\ (dBW)$	-117.1	-117.1	-114.4	-113.4
$Bdc(\%)$	20	28	35.31	41.71
$deg(C/N_{0,eff})\ (dB)$	-5.1	-8.2	-2.5496	-3.6290

Table 6.2: Comparison between values of [1] and MATLAB simulation results, E5a/L5 band

[1] gets a smaller Bdc and larger degradation compared to our simulation results. One possible reason may be that front-end filters used are not totally the same in our simulation and [1], this would cause different DME/TACAN power level and duty cycle at the output of the front-end filter. Another possible reason would be the DME/TACAN beacon

database used. More than 120 DME/TACAN beacons are observed simultaneously when the victim aircraft flying at 40 kft, while in our simulation, only 87 beacons are in the aircraft's insight region.

7 Summary

Results obtained from the MATLAB simulation (Chap. 4.1.2.1 and Chap. 4.1.2.2) show that DME/TACAN pulsed interference has stronger impact on GNSS receiver when the aircraft flying at a higher altitude on both E5a/L5 and E5b bands, because more in-band DME/TACAN beacons transmit interference signals within the aircraft insight region. So that blanker duty cycle is larger and more below blanker power is left at the output of pulse blanker. Increasing both RFI parameters Bdc and RI at high altitude result in larger $C/N_{0,eff}$ degradations at 40 kft than 10 kft. What is more, front-end filter also affects simulation result. Transition band of the front-end filter allows more DME/TACAN signals enter into GNSS receiver, although these out-band DME/TACAN signals are attenuated.

In "Duty cycle" mode (Chap. 4.2), when simulating the DME/TACAN pulsed signals with the same peak power levels, higher $C/N_{0,eff}$ degradation is caused by the DME/TACAN signal with higher duty cycle. The DME/TACAN signals' peak power level also affect $C/N_{0,eff}$ degradations. Simulation results show that higher peak power level of DME/TACAN signal causes larger value of Bdc and R_I, which leads to higher $C/N_{0,eff}$ degradations.

The software receiver's acquisition and tracking thresholds are summarized in Table 5.2. Under strong pulsed DME/TACAN interference environment, the software receiver's performance is improved when applying a pulse blanker, and can cope with interference signals with duty cycle up to 15%. Acquisition and tracking can be proceeded at a smaller $C/N_{0,eff}$ and a larger DME/TACAN duty cycle. What is more, pulse blanker helps software receiver to cope with DME/TACAN environment with very high power level when acquiring data. DME/TACAN pulses' power level only influences the acquisition of the software receiver without pulse blanker. And there is little influence on the tracking of the software receiver, no matter pulse blanker is implemented or not.

Improvement suggestions

Front-end filters used in our simulation are assumed to be ideal or to fulfill the minimum requirement of GNSS receiver (simulated front-end filter). The DME/TACAN impact on GNSS receiver may be assessed with more practical front-end filters.

Normalized antenna patterns for DME and TACAN transmitter are assumed to be the same. This is because the differences between the two are quite small at low elevation angles. For simplicity, we use the same antenna pattern. To obtain more accurate simulation results, two separate antenna patterns could be used.

The database of DME/TACAN ground beacons in our simulation does not contain PRF of each beacon. So we assume it is 2700 ppps for DME and 3600 ppps for TACAN. More realistic database is needed to simulate the DME/TACAN pulsed interference environment at the European hot spot with high flight height.

Influence of other GNSS receiver components is not considered in this thesis, such as ADC/AGC. ADC with different bit resolutions affects the output DME/TACAN quantized samples. Adaptive ADC/AGCs with different response time are also not considered. What is more, mitigation and detection techniques also affect $C/N_{0,eff}$ at the correlator output, while, they are not under consideration in this thesis.

APPENDIX

A MATLAB Program

A.1 "Hot-spot" Mode Simulation Steps

- Define simulation parameters in *test.m*, run *test.m* to generate desired DME/TACAN signal.
- Call function *blanker* to obtain the effective C/N_0 degradation analysis
- Read the value of "*AV_Power*" returned in the MATLAB command window (dBm). It is the average power of the simulated DME/TACAN signal, which would be used as the value of the "Amplitude" on "Agilent E8267D" platform.
- Call function *IQ* to change the format of MATLAB generated DME/TACAN signal to IQ data, which would be used by "Agilent E8267D". Then call *hardware_connection* to load DME/TACAN IQ data into hardware signal generator "Agilent E8267D", and activate "Agilent E8267D" to generating DME/TACAN signals;

One more simulation is taken on E5a/L5 and E5b. Simulated front-end filters are used in our simulation. The generated DME/TACAN signal in step 1 is then convolved with the filter taps to obtain the filtered DME/TACAN signal received by the GNSS receiver.

A.2 "Duty cycle" Mode Simulation Steps

- Define simulation parameters in *test2.m*, run *test2.m* to generate desired DME/TACAN signal.
- Call function *blanker* to obtain the effective C/N_0 degradation analysis
- Read the value of "*AV_power*" returned in the MATLAB command window (dBm). It is the average power of the simulated DME/TACAN signal, which would be used as the value of the "Amplitude" on "Agilent E8267D" platform.
- Call function *IQ* to change the format of MATLAB generated DME/TACAN signal to IQ data, which would be used by "Agilent E8267D". Then call *hardware_connection* to load DME/TACAN IQ data into hardware signal generator "Agilent E8267D", and activate "Agilent E8267D" to generating DME/TACAN signals;

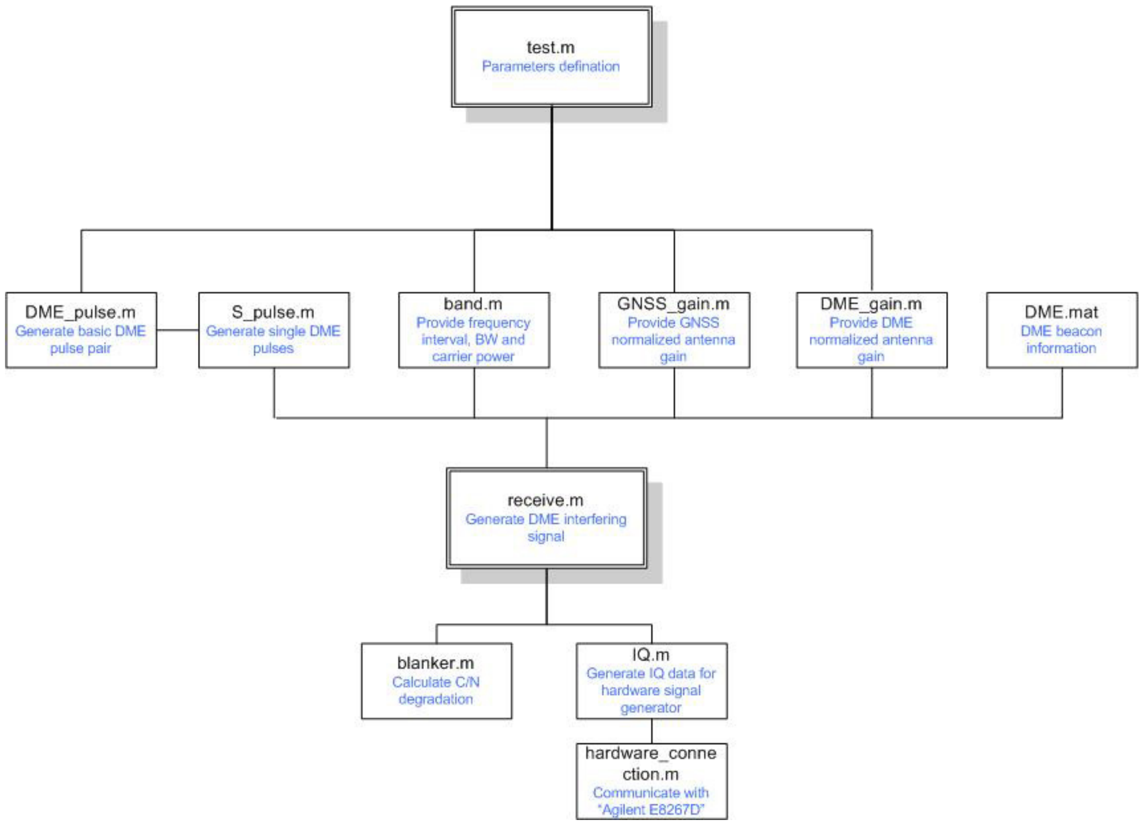

Figure A.1: "Hot-spot" mode program structure

A.3 Functions Instructions

test.m

Victim aircraft position (longitude, latitude, height), IF frequency, observed time interval and testing band is defined in *test.m*. Basic DME/TACAN pulse pair parameters are also defined in *test.m*. After running *test.m*, desired DME/TACAN signal is generated and saved in "*Hotspot.mat*" as well as optimal blanker duty cycle and DME/TACAN average power, and a series of simulation results are returned in MATLAB command window.

receive.m

Generating received DME/TACAN composite signal based on input DME beacon database and testing band name. It returns the bandwidth of testing band, GNSS signal carrier power, and received DME/TACAN signals as well as a matrix of received peak powers and PRF of DME/TACAN ground beacons. Received DME/TACAN signal is stored in output variable *S_receive*. Each role of *S_receive* represents received composite DME/TACAN signal at one aircraft position. The number of roles equals to the number of aircraft positions.

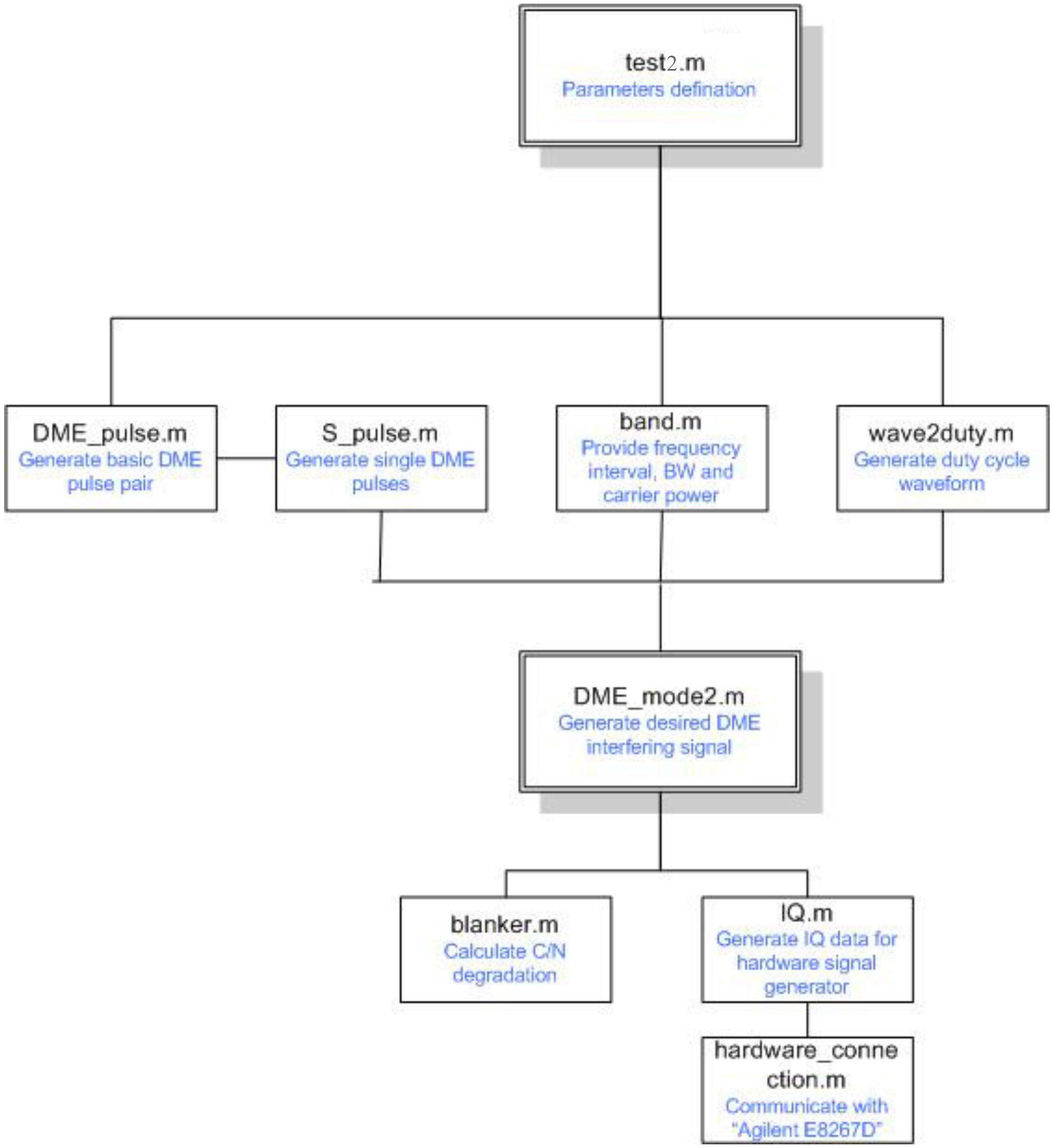

Figure A.2: "Duty cycle" mode program structure

DME.mat

Ground DME/TACAN beacon database is stored in *DME.mat*. It includes DME/TACAN beacons transmitting in X-mode. The beacon information format is

Longitude	*Latitude*	*Altitude (km)*	*TransmittingFrequency (Hz)*	*EIRP (W)*	*PRF (ppps)*

band.m
Bandwidth, frequency interval and carrier power are defined in *band.m*. It acts as a rectangular frequency response front-end. Signals in the passband (bandwidth) are passed without attenuation, signals outside the passband are blocked.

S_ pulse.m
Normalized single DME/TACAN baseband signal is generated in *S_pulse.m*. PRF and DME/TACAN transmitting frequency are input parameters of *S_pulse.m*. The output variable is one row vector with maximum value of "1".

DME_ pulse.m
Basic DME/TACAN pulse pair is generated in $DME\_pulse.m$.

GNSS_ gain.m
Victim aircraft GNSS receiver antenna gain pattern is defined in $GNSS\_gain.m$.

DME_ gain.m
DME/TACAN ground beacon normalized antenna gain pattern is defined in $DME\_gain.m$.

test2.m
Basic DME/TACAN pulse pair parameters, observed time interval, IF frequency, DME/TACAN power distribution, DME/TACAN beacon transmitting frequency distribution and duty cycle are defined in $test2.m$. After running $test2.m$, desired DME/TACAN signal is generated and saved in "*dutycycle.mat*" as well as optimal blanker duty cycle and DME/TACAN average power, and a series of simulation results are returned in MATLAB command window.

DME_ mode2.m
Received DME/TACAN signal in Mode 2 with given duty cycle is generated in $DME\_mode2.m$. Received DME/TACAN signals' peak power distribution, transmitting frequency and duty cycle are as input parameters. Received DME/TACAN signal, carrier power and bandwidth of testing band as well as a matrix of received peak powers and PRF of DME/TACAN ground beacons are as output variables.

wave2duty.m
This function is used to calculate single DME/TACAN signal's duty cycle. Input parameters are single DME/TACAN signal and threshold for deciding this DME/TACAN signal's duty cycle. Output waveform sets samples of input DME/TACAN signals with amplitude above threshold to be "1", else to be "0". Output waveform has the same length of DME/TACAN signal.

blanker.m
Effective carrier to noise ratio degradation is evaluated in *blanker.m*. And it returns the optimal threshold and DME/TACAN signal average power (dBm).

hardware_ connection.m
hardware_connection.m is used to connect PC with hardware signal generator "Agilent E8267D" and load input signal into signal generator.

IQ.m
IQ.m is used to change the input data's format adapt to the hardware signal generator "Agilent E8267D".

theory.m
Theoretical effective carrier to noise ratio degradation for both "Hot-spot" and "Duty cycle" modes. is calculated in *theory.m*.

B Agilent E8267D PSG Signal Generator

The steps for generating DME/TACAN interference signal by Agilent E8267D PSG signal generator are as follows.

- Generating DME/TACAN signal by using "Hotspot" mode or "Duty cycle" mode MATLAB files.
- Use *IQ.m* to change the DME/TACAN data to IQ data and quantized IQ data with 16 bits.
- Use *hardware_connection.m* to load the quantized IQ data to volatile memory of signal generator from user PC.
- Adjust the "Amplitude" and "Frequency" on the control panel of Agilent E8267D PSG signal generator. The value of "Amplitude" is the average power of generating DME/TACAN signal. The value of "Frequency" is the IF or RF frequency, for Galileo E5a is 1176.45 MHz, 1207.14 MHz for E5b, (or 20 MHz for IF analysis), 4.092 MHz for L1 band used for software receiver.

Connecting Agilent E8267D PSG signal generator to oscilloscope or spectrum analyzer, DME/TACAN signals generated by software (MATLAB) is then as the input of signal generator Agilent E8267D. When observed from oscilloscope, baseband DME/TACAN interference signal and the modulated DME/TACAN pulse pair shape generated by signal generator are shown in following figures.

Figure B.1: Baseband DME/TACAN pulses generated by signal generator Agilent E8267D

Figure B.2: Modulated DME/TACAN pulse pair generated by signal generator Agilent E8267D

System structure described in Fig. B.3 can be used to test the C/N_0 degradation caused by DME/TACAN only as well as the GNSS receiver performance. Agilent E8267D is used to generating DME/TACAN interference signals exactly same as the software (MATLAB) simulated signals. Then the generated pulsed DME/TACAN signal together with the GNSS signal will be put into the hardware simulator which gives the feed back of the GNSS receiver performance.

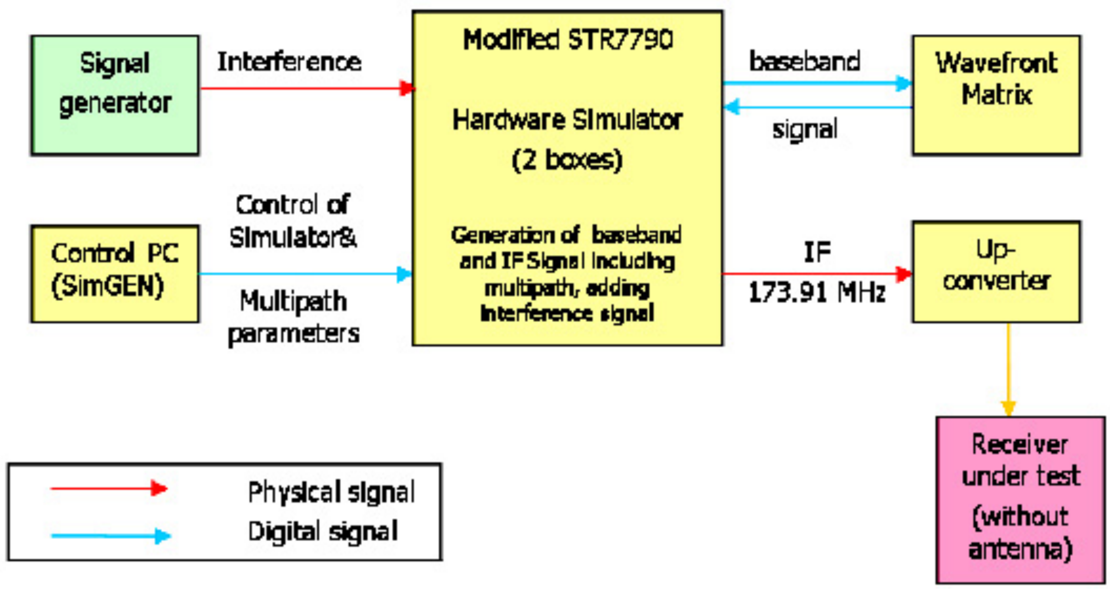

Figure B.3: Hardware simulation system structure

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Glossary

A/D	the analog-to-digital
ADC	analog-to-digital converter
AGC	automatic gain controller
ARNS	Aeronautical Radio Navigation Services
Bdc	blanker duty cycle
BOC	binary offset carrier
BPSK	binary phase shift keying
CDMA	code division multiple access
dB	decibel
dBW	decibel Watts
DME	Distance Measuring Equipment
EUROCAE	European Organization for Civil Aviation Equipment
FAA	Federal Aviation Administration
GHz	Gigahertz
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
Hz	Hertz
IF	Intermediate Frequency
kW	kilowatt
LO	local oscillator
LPF	low-pass filter
Mcps	mega chips per second
MHz	MegaHertz
ms	milliseconds
NH	Neuman-Hoffman
ppps	pulse pair per second
PRN	pseudo-random noise
PRF	pulse repetition frequency
QPSK	quadrature phase shift keying
RF	radio frequency
RFI	radio frequency interference
SoL	safety-of-life
SNR	signal-to-noise ratio
TACAN	Tactical Air Navigation
VOR	VHF Ominidirectional Range