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Agenda item 6: Preparation for the upcoming CPM and WRC 2000;
(presented by Torsten Jacob)

COMPATIBILITY OF DME AND ENSS-1 IN THE BAND 1210 –1215 MHz

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The purpose of this document is to analyze the impact of DME/TACAN transmission to RNSS (ENSS-1) receivers and to verify that ENSS-1 emissions do not cause significant interference to DME/TACAN interrogators

1 General

WRC-2000 agenda item 1.15.1. calls to consider new allocations to the radionavigation-satellite service in the range from 1 to 6 GHz. CEPT FM Working Group identified the band 1210 – 1215 MHz as a possible candidate for such an allocation. SE 28 were ask by FM Working Group to investigate the sharing possibilities between RNSS and ARNS in the band 1210 – 1215 MHz. In order to carry out such a study the channel E3 of the envisaged satellite navigation system ENSS-1 currently planed for the use of the frequency 1215.324 MHz was placed in the frequency band 1210 –1215 MHz. This band partly overlaps with the ARNS systems DME (Distance Measurement Equipment) and TACAN (Tactical Air Navigation). Therefore it is important to study the compatibility between the existing systems and the planned navigation system before such an allocation can be made.

2 Introduction

The Distance Measurement Equipment (DME) and the Tactical Air Navigation (TACAN) system are used in aviation for a two-way distance measurement with respect to a ground transponder. TACAN provides an additional direction finding. An interrogator on-board of an aircraft transmits pulses in the frequency range 1025 to 1150 MHz and the ground transponder re-transmits the pulses with a frequency shift of plus or minus 63 MHz in the frequency range 962 to 1213 MHz. The distance is determined by measuring the traveling time of the pulses. The application of pulse pairs allows an easier discrimination between DME/TACAN-signals and pulses from interfering signals (e.g. Radar systems).

The envisaged satellite navigation system ENSS-1 will use similar techniques like GPS but with improved performance. It makes use of three channels E1, E2 and E3 with different center frequencies. The ENSS-1 has been advanced published by ITU with a center frequency of 1215.324 MHz and a code clock frequency of 0.383625 MHz for the E3-signal

For the compatibility analysis it is supposed to place the E3 signal in the band 1210 to 1215 MHz and to use the same parameters e.g. a code clock frequency 3.069 MHz as for the E1 and E2-signals. This Paper will analyze the compatibility of this assumed E3-signal with DME and TACAN.

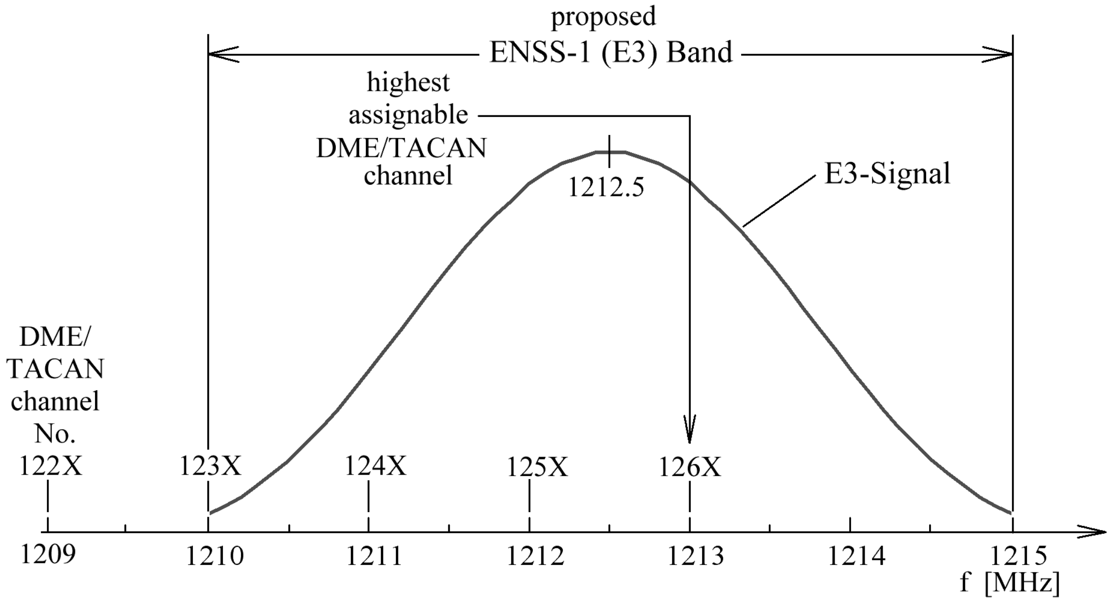

Fig. 1: Spectrum usage in the 1210 - 1215 MHz band

3 System Characteristics

3.1 Characteristics of DME and TACAN-transponder signals

Only the ground transponders of DME and TACAN with their transmit frequency range of 962 MHz to 1213 MHz transmit signals with frequencies close to the E3-frequency of ENSS. The operation parameters of DME or TACAN transponder are specified in [2]:

Tab. 1: DME and TACAN-transponder signals

	DME/N	TACAN
Frequency range:	962 to 1213 MHz	
Channel spacing	1 MHz	
Pulse peak Power:	1 kW = 30 dBW	4 kW = 36 dBW
Pulse duration:	3.5 ± 0.5 µs	
Pulse pair spacing:	12 µs (X-Mode) 30 µs (Y-Mode)	
Transmission rate	800 to 4800 pulse pairs per second (depends on number of interrogating aircraft)	2700 to 4800 pulse pairs per second (depends on number of interrogating aircraft)

Transmit Antenna Gain:	9 dBi, max. at 3° elevation	6 dBi, max. at 3° elevation
Typical Pulse Peak EIRP:	39 dBW	42 dBW

* e.g. Alcatel FSD-45 DME receiver, FTA-43 TACAN receiver

3.2 Characteristics of ENSS-1 E3-signal

As mentioned above, it has been proposed to modulate the E3-signal of ENSS-1 with a PN-code that has a code clock frequency of 3.069 MHz. Such a signal requires a frequency band with an bandwidth that is twice the code clock frequency that means 6.138 MHz. The proposed frequency band is only 5 MHz wide. If the bandwidth of the transmitted signal would be limited to 5 MHz by a filter it would still be of a certain use but with a reduced performance since the sharpness of the correlation peak would suffer. Provided that that signal would be transmitted with a bandwidth of 5 MHz it would be reasonable to place the center frequency at the middle of the band, i.e. at the frequency 1212.5 MHz. The following table presents some known and assumed characteristics of ENSS-1 signals:

Tab. 2: ENSS-1 Signals

Signal frequencies:	E1: 1589.742 MHz, E2: 1561.098 MHz (not relevant) (according to [3]) E3: 1212.5 MHz (assumption)
Nominal signal power:	-157.3 dBW (according to [3])
Code clock frequencies:	3.069 MHz (E1, E2, E3)
Noise power density at antenna port, N_0	-203.2 dBW/Hz (according to [3])
Preamplifier limiting level:	-70 dBW (assumption comparable with GPS, according to [4])
Receive Antenna gain:	3 dBi max. -4.5 dBi at 5° Elevation

4 Impact of DME/TACAN transmission to ENSS-1 receivers

The transmit channels of the DME/TACAN ground transponder in the frequency range 1210 to 1213 MHz operate in the X-mode and has a pulse pair spacing of 12 µs. For a worst case scenario, the signal parameters that causes the highest duty cycle have to be chosen. Therefore a pulse duration of 4 µs and the maximum transponder transmission rate of 4800 pulse pairs per second is assumed. The maximum transmission rate indicates the maximum number of pulse pairs that are transmitted if the maximum number of users interrogate the ground transponder. Because of the higher transmit power TACAN is chosen for the worst case scenario.

Tab. 3: Scenario TACAN vs. ENSS-1:

TACAN	
Frequency:	1210 to 1213 MHz

Pulse duration:	4 µs
Pulse pair spacing:	12 µs (X-Mode)
Maximum transmission rate	4800 pulse pairs per second
EIRP:	42 dBW
ENSS-1 (E3)	
Center frequency:	1212.5 MHz
Maximum antenna gain G_r:	3 dBi
A/D converter saturation level P_{Sat}:	-127.3 dBW (calculated from assumption that $P_{Sat} = 2.5^2 \cdot N$ according to [7])
Preamplifier limiting level P_{Limit}:	-70 dBW (comparable with GPS, according to [4])

4.1 Limiting of preamplifier and saturation of A/D-converter

Since the TACAN signal consists of pulse pairs with a high pulse peak power one has to consider limiting of the ENSS-1 receivers preamplifier and A/D-converter. The limiting and saturation levels are not specified yet. For the preamplifier a limiting level of –70 dBW is assumed as was used in [4] for GPS receivers.

According to [7] it is common to have a limiting voltage of the analogue-to-digital converter (A/D converter) that is by a factor 2 to 3 higher than the rms value of the noise. If we assume a factor of 2.5 the saturation power level is 2.5^2 times the noise power. The noise power in turn can be calculated from the given noise power density of -203.2 dBW/Hz (according to [3]) by assuming that the bandwidth is twice the code clock frequency. With a bandwidth of 2·3.069 MHz we yield a noise power of -135.3 dBW and an A/D-saturation level of -127.3 dBW.

With the knowledge of limiting and saturation levels one is able to calculate the required distances to prevent preamplifier limiting and/or A/D converter saturation. For the worst case scenario it is assumed that the aircraft is tilted in direction of the TACAN/DME transponder in such a way that the interfering signal is received with the maximum antenna gain of 3 dBi.

From the maximum allowable interference power (e.g. limiting or saturation level), the required separation distance can be calculated as follows:

$$d_{\min} = \frac{l}{4p} \cdot 10^{\frac{EIRP + G_r - J_{\max}}{20}} \qquad \text{Eq. 1}$$

With:

d_{min}: minimum required distance in m

J_{max}: maximum allowable interference power in dBW,
for preamplifier limiting $J_{max} = P_{Limit} = -70$ dBW
for A/D converter saturation $J_{max} = P_{Sat} = -127.3$ dBW

EIRP: equivalent isotropically radiated transmitted power of interference source in dBW

λ: wavelength of interference signal in m
G_r: receive antenna gain in dBi towards the interference source

4.1.1 Calculation of required distances to prevent preamplifier limiting

Front-end filters of preamplifiers satellite navigation receivers usually have a bandwidth in the order of 10 to 25 MHz. Therefore, is assumed that the selectivity of the font-end filter does not cause attenuation of the part of the spectrum that interferes with the ENSS-1 reception.

Eq. 1 yields a minimum required separation distance between the TACAN ground transponder and the ENSS-1 receiver on-board of an aircraft of 11.1 km. If short pulses drive the preamplifier into saturation they can cause severe signal distortions. Although the interference is caused by short pulses, due to the recovery time of the preamplifier and other circuits the impact of the interference is prolonged additionally.

4.1.2 Calculation of required distances to prevent A/D converter saturation

From the assumed interference EIRP values at the chosen center frequency of the E3-signal a minimum required distance of 8110.6 km was calculated by means of Eq. 1. In practice, the required distance is limited by the radio horizon of e.g. 425 km for an aircraft flying at an altitude of 10000 m

Tab. 4: Minimum required distances to prevent A/D-converter saturation

center frequency of ENSS-1 (E3):	1212.5 MHz
type of interference	in-band
EIRP of interference signal	42 dBW
A/D-converter saturation level P_{Sat}	-127.3 dBW
Minimum required distance to prevent A/D-converter saturation	8110.6 km (limited by the radio horizon of approx. 425 km)

4.2 Impact on the signal to noise ratio of the ENSS-1 signal

Since the DME and TACAN signal has a rather low duty cycle it is easier to determine their impact in the time domain, rather than in the frequency domain. Fig. 2 depicts two pulse pairs of a DME or TACAN signal.

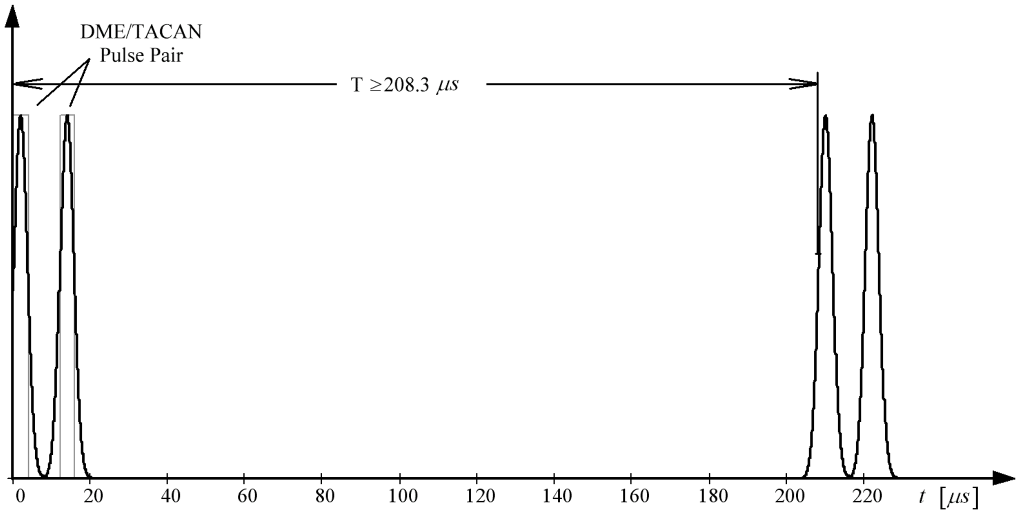

Fig. 2: DME/TACAN signal

As mentioned above, TACAN is chosen for the worst case scenario. At first, the impact of a single TACAN signal shall be assessed. For this it is necessary to calculate it's duty cycle. It is very difficult to define a duty cycle for a TACAN signal. The transponders are interrogated by the users in randomly spaced time intervals. Also, the time intervals between consecutive bearing pulse groups, auxiliary pulse groups, identification signals and equalizing pulse pairs are very different. In addition, the spacing between pulse pairs does depend on the type of the pulse group.

For the sake of simplicity it is assumed here that a periodical signal with the maximum possible transmission rate is transmitted. Due to the maximum transmission rate of 4800 pulse pairs per second of TACAN the period of the signal is T = 208.3 μs. For the width of the TACAN pulse we assume T_P = 4 μs (worst case of 3.5 ± 0.5 μs). With this assumptions we yield a duty cycle as follows:

$$a = \frac{2 \cdot T_P}{T} = \frac{8\ ms}{208.3\ ms} = 0.0384 = 3.84\ \% \qquad \text{Eq. 2}$$

With:

α: duty cycle

Tp: Pulse duration of the TACAN pulses

T: Period of the TACAN signals T = 1/(Transmission rate)

As it has been mentioned in [7] usually the automatic gain control (AGC) of a satellite navigation receiver tries to maintain the rms of the noise σ_N at the A/D converter at a level that is by a factor 2 to 3 below the saturation voltage A. If we assume a factor of 2.5 as it was done in [7] and with $N = s_N^2$ and $P_{Sat} = A^2$ we yield:

$$N = \frac{P_{Sat}}{2.5^2} \qquad \text{Eq. 3}$$

It is assumed that an interfering pulse is saturating the AD converter during the percentage α·100 of the time. During the remaining percentage (1-α)·100 of the time only noise can be observed at the AD converter. The AGC tries to maintain the arithmetic average of both at the same level as without interference:

$$P_{Sat} \cdot \alpha + N \cdot (1-\alpha) = \frac{P_{Sat}}{2.5^2} \qquad \text{Eq. 4}$$

To do this, the gain of the AGC has is reduced by a value that is represented here by the AGC-attenuation a_{AGC} with:

$$a_{agc} = \frac{(1-\alpha)}{(1-2.5^2\alpha)} \qquad \text{Eq. 5}$$

In addition, it is assumed that during the presence of the pulse the navigation signal cannot be correlated with the code replica in the receiver. Therefore the power of the navigation signal has to be multiplied in addition by a factor (1-α). The reduction of the carrier-to-noise-density ratio now can be assessed by:

$$\Delta C/N_0 = a_{agc} \cdot (1-\alpha) = \frac{(1-\alpha)^2}{(1-2.5^2\alpha)} \qquad \text{Eq. 6}$$

From Eq. 6 the degradation of the carrier-to-noise-density ratio $\Delta C/N_0$ as a function of the duty cycle α can be calculated (Fig. 3). For the duty cycle of 3.84 % of a TACAN signal we yield a $\Delta C/N_0$ of 0.85 dB which is almost negligible.

It is conceivable that the pulses from several TACAN transponders could be aligned in such a way that the duty cycle of the combined signal is the sum of the single duty cycles. To assess how much signals have to be received to cause intolerable interference following assumptions are made. It is assumed that the E3-signal has parameters that are comparable to those given in [3]. For example the C/N_0 at the edge of the coverage are is 45.9 dBHz. The required C/N_0 is 41.2 dBHz. This means that without applying a safety margin a degradation of $\Delta C/N_0$ = 4.4 dB can be tolerated.

This degradation can be caused by a pulsed signal with a total duty cycle of 11.4 % (Fig. 3). This duty cycle value can already be caused by 3 (in theory 2.6) aligned TACAN signals. That means in the case that there is a possibility that more that two TACAN or DME signals can saturated the AD converter of an ENSS-1 receiver an there is caused an intolerable C/N_0-degradation.

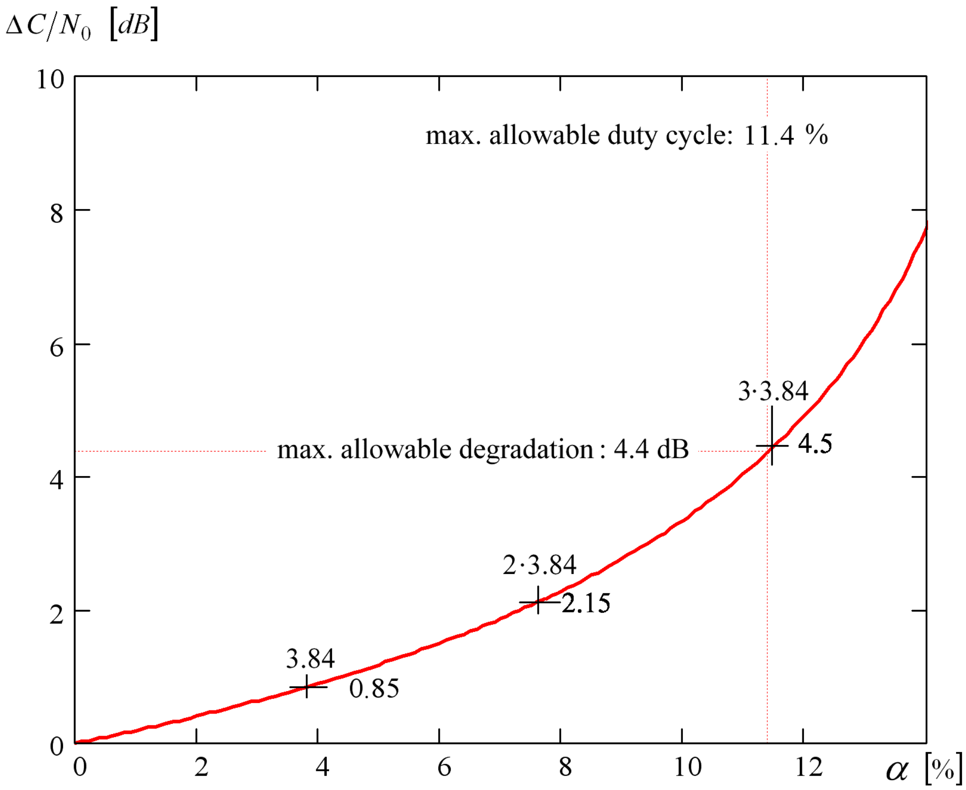

Fig. 3: Carrier-to-noise-density degradation vs. duty cycle

To assess the possibility that more than one TACAN signals can interfere with the ENSS-1 reception at the same time, it is necessary to know the number of TACAN-transponders that can be received at the same time. According to [6], the minimum separation distance between two DME and/or TACAN stations with a designated operational coverage of 25 nm / FL 1000 operating at the same frequency with the same pulse code is 88 nm (163 km).
Within the an area that is describe by the radio horizon of 425 km approximately 30 TACAN transponders with the same channel can be received theoretically. Since within the bandwidth of the ENSS-receiver (1210 to 1215 MHz) four TACAN channels with the frequencies 1210, 1211, 1212 and 1213 MHz are received nearly without attenuation by HF- or IF-filters and can interfere at the A/D-converter the possibility of receiving more than one TACAN signal that causes saturation is additionally increased.

In addition, it is likely that duty cycle of a single signal exceeds the value of 3.84 % that was calculated above. The minimum allowed spacing between two consecutive pulse pairs is 60 µs ([8]). As long as the maximum number 4800 pulses per second is not exceeded, it can occur that for a part of a second, due to the high number of users sequence of pulse pairs are transmitted with this lowest possible spacing. If a bit duration of 20 ms is assumed for the navigation data of ENSS-1 (comparable to 50 baud data rat of GPS), 333 pulse pairs are transmitted during the duration of one data bit. That yields a short-term duty cycle of:

$$a = \frac{333 \cdot 2 \cdot 4\ ms}{20\ ms} = 0.133 = 13.3\ \%$$

This means, that it is possible that due to the varying duty cycle a single TACAN signal can already exceed the maximum tolerable duty cycle of 11.4 % and in this way cause single bit errors.

5 Impact of ENSS-1 transmissions to DME/TACAN interrogators

The frequency of the E3-signals of ENSS-1 is suitable to be received from the antenna and front-end of the DME interrogator. Although an impact of the ENSS-1 signal on the DME-reception is unlikely this case has to be analyzed to rule out any harmful influence. For the worst case scenario it is assumed that the ENSS-1 signal is transmitted at the center frequency of the DME/TACAN channel at 1213 MHz. (There is not much difference whether the center frequency is 1212.5 or 1213 MHz because of the high bandwidth ($2 \cdot 3.072$ MHz) of the ENSS signal.)

Tab. 5: Worst Case Scenario for ENSS-1 vs. DME/TACAN

Frequency : ENSS-1	1213 MHz
Nominal signal power: ENSS-1	-157.3 dBW w.r.t. ENSS-1 antenna gain of 3 dBi
Sensitivity of DME/TACAN receiver	-85 dBm = -115 dBW (corresponds to a required power flux density of -89 dBW/m^2 according to Table C-7 in [5])
Assumed gain of DME/TACAN antenna towards ENSS-1 Satellite	3 dBi
Remaining safety margin (sensitivity - signal power):	42.3 dB

Here, it is assumed that the nominal signal power of the ENSS-1 signal is referred to the port of an ENSS-1 antenna with a gain of 3 dBi in the direction of the satellite. The receive antenna of the DME- or TACAN interrogator is designed to receive signal in the frequency range of 962 MHz to 1213 MHz at low elevation angles with a gain in the order of –4 dBi (Section 7.2 in [5]). It is quite reasonable to expect that in the worst case the ENSS-1 signal received from a DME or TACAN receiver with antenna gain that does not exceed +3 dBi.

Therefore, to assess the impact of the interfering ENSS-1 signal one has to compare the nominal signal power of the E3-signal (-157.3 dBW) with the sensitivity of DME or TACAN of –115 dBW. This calculation yields a remaining safety margin of 42.3 dB.

6 Summary and Conclusion

For the investigation the center frequency of the E3-signal was placed at 1212.5 MHz, the middle of the range 1210 to 1215 MHz. The minimum required distance to prevent limiting of the ENSS-1 receiver's preamplifier is 11 km. The possibility that saturation of the ENSS-1 receiver's A/D causes intolerable degradation of the E3 signal is very likely. A geographical separation of 8110.6 km (limited by the radio horizon of approx. 425 km) between RNSS and ARNS will be necessary to rule out the interferences.

In the investigation also the impact of the ENSS-1 (E3) signal to the DME- or TACAN was considered. The analysis showed that no intolerable interference can occur due to a remaining safety margin of more than 42 dB between the maximum received power of an ENSS-1 signal and the sensitivity of a DME or TACAN interrogator.

The analysis in this paper demonstrates that the required geographical separation necessary to protect future RNSS from signals produced by existing ARNS stations is only limited by radio horizon. It is therefore concluded that sharing of the band 1210 – 1215 MHz between RNSS and ARNS is not feasible.

Subsequently, an allocation to RNSS in the band 1210 – 1215 MHz should not be supported by CEPT members.

7 Reference documents

[1] ITU 8D/Temp15 (Rev.2)-E
[2] Chapter 3, DME/N of ICAO-Annex 10, Nov. 1996
[3] ITU 8D/172-E, October 1998
[4] ITU-R M.1088
[5] Guidance Material for DME/N, ICAO-Annex 10, Attachment C-7, Nov. 1996
[6] Foreword of Table COM 3 of the ICAO European Air Navigation Plan, Part X
[7] CEPT/SE28-121, „Sharing between radiolocation radars and RNSS radiobeacons", Oslo, 1998
[8] STANAG 5034, Edition 3, December 1989