Nationaal Lucht- en Ruimtevaartlaboratorium
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Interference of GPS signals: Influence of Licensed Transmitters on the GPS Signal Quality in the Netherlands' Airspace

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ABSTRACT

Interference to civil aviation GPS receivers in the Netherlands airspace was analysed. Two types of GPS receivers were considered: one for installation in commercial aircraft and one hand-held receiver commonly used in the general aviation practice.

The offending transmitters were selected for having their frequency or harmonics in or near the GPS L1 frequency band.

The results of the analysis show that potential interference near FM and TV broadcast transmitters may exist if the official limits for spurious emissions are used. The same situation applies to airports where some VHF radio navigation and communication systems can be identified as potential interfering sources.

However, in practice there is little evidence of interference in these situations. It was postulated therefore that in practice the level of the harmonics in the emitted fields is (much) lower than required according to ITU regulations, which could be caused by extra suppression of harmonics by the transmitter antennas. Measurements have shown that this postulation indeed is correct.

1 INTRODUCTION

The need to maintain GPS integrity is of considerable interest to the aviation community. One of its aspects is the requirement to operate when interference renders reception difficult. Interference contributes to the noise floor of the receiver and degrades its performance. In such a case no extra visible satellite or other redundancy will overcome the problem.

If wilful interference is excluded, two possibilities exist in which the GPS receiver operation can be disturbed:

- Unintended interference from transmitters with a carrier frequency very close to that of GPS;
- Unintended interference from other users of the spectrum on a frequency below that of GPS, having harmonic components which fall inside the GPS spectrum.

This paper assesses the vulnerability of airborne GPS receivers to interference in the Netherlands airspace. To perform the assessment the following steps were carried out:

- Determination of the required GPS accuracy with respect to the phase of flight;
- Determination of the corresponding GPS receiver errors;
- Conversion of these errors to in-band interference level bounds at the GPS receiver input;
- Determination of the GPS receiver out-of-band interference susceptibility;
- Selection of the potential sources of interference;
- Calculation of the interference level at the GPS receiver;
- Determination of the areas in the Netherlands airspace where and how much interference to GPS occurs;
- Measurement of the actual harmonics levels of potential interference sources.

These points will be discussed in the following chapters.

2 GPS RECEIVER CHARACTERISTICS

2.1 Required accuracy with respect to phase of flight

In the Minimum Operational Performance Standards [1], the following is stated for the horizontal radial position fixing error as function of the phase of flight:

- During the en-route and terminal phase: less than 100 m, 95th percentile, with HDOP equal to 1.5. This requirement shall be met under minimum signal conditions and interference conditions.
  The specified error can be split in a signal-in-space component of 33 m (1σ) which is due primarily to selective availability (SA) and an avionics component of no more than 5 m (1σ) due to receiver noise, multipath, etc.
- During a non-precision approach: the same as for the previous item.
- During a precision approach: no horizontal radial position fixing error has been specified yet. However, the pseudorange rms error caused by receiver-noise and interference (under minimum signal conditions) shall not exceed 0.70 m.

2.2 Pseudorange error versus GPS receiver input signal quality

The relation between the pseudorange rms error and the receiver input signals (satellite signals, noise and interference) is taken from reference 2.

For a standard airborne GPS receiver using carrier smoothing of the code pseudorange measurements, the previously specified rms error of 0.70 m for a precision approach is attained at a carrier-to-noise+interference ratio, C/(N_o+I_o), of 30 dBHz at the receiver input. The 5 m rms error allowed for during en-route, terminal and non-precision approach operations requires a C/(N_o+I_o) of 12 dBHz. However, this value is well below the 16 dBHz treshold of the (aided) code tracking loop which provides the unsmoothed pseudorange samples.

Therefore, in commercial aviation, a C/(N_o+I_o) of at least 16 dBHz is required except for precision approach operations where 30 dBHz or more is needed. In general aviation the use of unaided, hand-held GPS receivers is common practice. These receivers generally exhibit a code tracking threshold of 24 dBHz. Another requirement is the 34 dBHz C/(N_o+I_o) ratio for acquisition of the satellite signals.

2.3 Out-of-band signals

The C/(N_o+I_o) values given in the previous section can be used to calculate the permissible interference level at the GPS frequency. However, the majority of the interfering signals will have frequencies different from GPS. In general, the GPS receiver will show an increased resistance against off-frequency interference as is shown by the out-of-band signal rejection graph in [1], which covers the range from 1315 to 2000 MHz. The off-frequency interference resistance of the system is further increased by the antenna/preamplifier signal rejection characteristics as shown in the Arinc Characteristic 743A-2 [3], resulting in a total out-of-band rejection versus frequency graph as shown in figure 1.

An example of the out-of-band rejection characteristic of a simple hand-held GPS receiver, taken from [4], is included in figure 1 to illustrate the large difference with the characteristics given in [1] and [3].

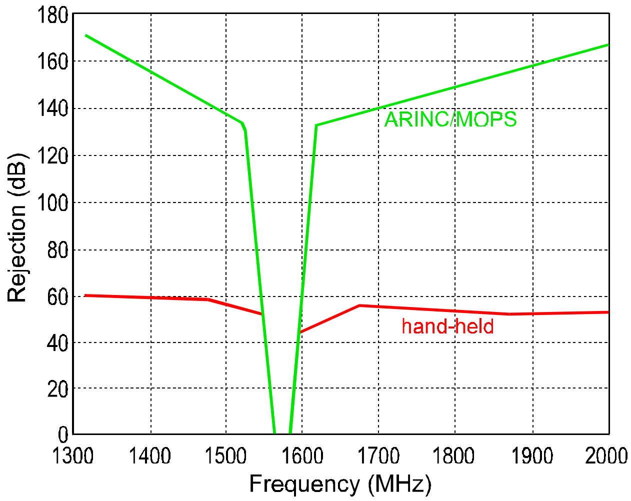

Fig. 1 Out-of-band rejection curves

3 POTENTIAL SOURCES OF INTERFERENCE

3.1 General

Interference in GPS receivers due to external sources can occur in two ways:

- The offending source transmits on the same frequency as that of GPS or close to it;
- It operates on a frequency well below that of GPS but generates harmonics which are on the same frequency as that of GPS or close to it.

The range of frequencies to be considered is therefore quite extensive. However, the lower boundary is about 50 MHz (Band I TV) since, according to reference 5, no problems caused by emissions at lower frequencies (HF radios for instance) are known. The upper boundary is 2000 MHz which is the limit of the GPS receiver response specification [1].

To identify potential interfering transmitters in the Netherlands the following sources were consulted:

- The International Frequency List (Edition 94-2) of the Radio Communication Bureau of the ITU;
- The List of VHF Sound Broadcasting Stations (VHFFM 40 0195) of the European Broadcasting Union;
- The List of VHF/UHF Television Stations (TV 39 0395) of the European Broadcasting Union;
- The HIRF database (version of September 1997) which is maintained at NLR on behalf of the Netherlands Department of Civil Aviation (RLD).

3.2 Selection criteria

The databases were explored for potential sources of interference using the following criteria:

- The transmitter is located on the Netherlands land territory, and
- the transmitter frequency lies in the range 50-2000 MHz, and
  - the fundamental frequency lies in the range 1315-2000 MHz, or
  - the harmonics fall in the band 1565-1585 MHz, or
  - the culprit is an FM or TV transmitter with an output power exceeding 50 kW, or
  - the culprit is located on or near Schiphol Airport, Lelystad Airport or Eelde Airport. These airports were specified by the Netherlands Department of Civil Aviation (RLD) as places of particular interest in view of GPS interference.

In this way a list containing 100 transmitters which have the potential to cause interference to GPS has been composed and used in the analysis. Radar transmitters are not included in this list because, according to [5], laboratory tests show that most current GPS receiver designs are immune to short pulses up to pulse widths greater than 125 µs. Such long pulse length radars are not deployed in the Netherlands.

3.3 Spurious emission limits

For the analysis, the spurious emissions of the offending transmitters are very important. No data however are given in the databases, only the transmitter output power and the antenna gain (or EIRP) at the proper operating frequency.

Limits for spurious emissions are specified in Appendix 8 of the Radio Regulations of the ITU [6,7]. These limits are defined as a minimum attenuation with respect to the level of the desired signal and are applicable at the interface between transmitter and antenna.

The relevant values of these limits for this study are:

- Transmitter operating frequency between 30 MHz and 235 MHz: 60 dB;
- Transmitter operating frequency between 235 MHz and 960 MHz: 60 dB;
- Transmitter operating frequency between 960 MHz and 17.7 GHz: 60 dB.

In view of the development of space services and the protection of radio astronomy and passive services, ITU-R Task Group 1/3 has completed a draft revision of Recommendation ITU-R SM329-6 [8] on spurious emissions. This contains more stringent limitations than Appendix 8, was discussed at the 1997 World Radiocommunication Conference (WRC-97) and is scheduled for implementation at the 2000 WRC.

In [8] the limits for spurious emissions are divided into four categories (A-D) of which A and B are relevant for this analysis. The category A limits are generally applicable. However, for those countries where there is a need for more stringent limits, those of category B can be applied. For all services not quoted under category B, the category A limits apply. The relevant specifications for minimum attenuation below the power provided at the antenna transmission line for category A are:

- All services : 70 dB, except
- Radiolocation/Radionavigation : 60 dB;
- Broadcast TV : 60 dB.

For category B the appropriate figures are:

- Radiolocation/Radionavigation : 80 dB;
- Broadcast FM : 85 dB.

Obviously, the requirements of Appendix 8 of [6] are worst case figures with respect to GPS interference. Therefore, these figures were used as a starting point in the analysis.

The fact that the spurious emission limits are defined at the interface between the transmitter and the antenna is an important problem. Since the transmit antenna characteristics on the frequencies of the spurious signals are not known, the field strength of the generated (spurious) signals cannot be determined in an unambiguous way. Although the problem has been recognised in [8], solutions have yet to be devised. [9] gives an impression of the total harmonic suppression which can be attained: using the results of field strength measurements made on a 525 MHz UHF TV transmitter, a total attenuation of 100 dB of the third harmonic with respect to the desired signal is calculated. Comparing this figure with the Broadcast TV limit of 60 dB shows an antenna suppression of 40 dB.

It is interesting to note that, with the advent of digital television systems, fear has increased that the stringent limitation of spurious emissions as maintained by the analogue TV community may be slackened. The reason for this is the fact that in analogue TV systems picture quality in the fringe areas is greatly enhanced by a very low level of close-in spurious emissions [10]. To accomplish this, a considerable filtering effort is required with the additional benefit of increased harmonic reduction. In contrast, in digital TV systems there is either a high-quality picture or no picture at all, depending on the signal-to-noise ratio and the applied error correction method. Picture quality is far less dependent on the close-in spurious emission levels than in analogue TV systems.

4 CALCULATION MODEL

The calculation model was made in such a way that the results are independent of the aircraft trajectories. Only the altitude and the geographic area to be considered have to be specified as input. As output, a map of the area overlaid with $C/(N_o+I_o)$ contour lines is generated. To that end the following calculations are carried out in the model:

- determination of the total interference power density in each observation point in the following way:

for each interfering source:

- Determination if the frequency or the harmonics of the interfering source are in the range between 1315 MHz and 2000 MHz as specified in [1]. If so, the following steps are carried out, otherwise the next interfering source is selected. This procedure does not quite correspond with the description given in section 3.2 where only the harmonics which fall in the smaller GPS frequency range of 1565 to 1585 MHz are considered. It is felt however, that the chosen calculation procedure is a better approximation of the real situation.
- Calculation of the diffraction loss caused by the presence of the earth near the propagation path between the interfering source and the observation point.
- Calculation of the path loss.
- Determination of the attenuation of the interfering signal by the selectivity of the GPS antenna, preamplifier and receiver (Fig. 1).
- Determination of the processing gain of the GPS receiver for the interfering signal.
- Addition of its contribution (modified by the effects mentioned in above steps) to the total interference power density.

next interfering source:

- determination of the $C/(N_o+I_o)$ ratio in this observation point where the minimum performance value for C as given in [1] has been used;
- next observation point.

The $C/(N_o+I_o)$ values are stored as function of the geographic coordinates of the observation points for off-line plotting purposes.

5 RESULTS

A number of variables have been used in the analysis of possible interference to GPS:

- receiver type (MOPS/ARINC; Hand-held).
- spurious emission limits (Appendix 8 of [6]; Category A of [8]; Category B of [8]; Category B of [8] plus extra antenna suppression).
- flight altitude (10000 ft; 3000 ft; 1000 ft; 300 ft).
- geographical area (the Netherlands territory; Schiphol airport and vicinity; Lelystad airport and vicinity; Eelde airport and vicinity).

The $C/(N_o+I_o)$ values are presented in the form of contour curves in the geographic area. Four contour values were selected for display, viz. 16, 24, 30, and 34 dBHz. These values have been discussed in section 2.2. The meaning of the colours in the figures 2-10 is as follows:

$C/(N_o+I_o)$	Colour
< 16 dBHz	red
< 24 dBHz	yellow
< 30 dBHz	blue
< 34 dBHz	green

In this paper, the presented results have been restricted to altitudes of 3000 ft (over the Netherlands territory) and 300 ft (in the vicinity of Schiphol and Eelde airport). Other data have been reported in reference [11].

To obtain an impression of the problem and to see if there are any differences in operation of the two receivers in an interference environment, the following calculations were carried out for the Netherlands:

RX-type	Limits	Alt. (ft)	Fig.
ARINC	RR App.8 (60 dB)	3000	2
Hand-held	RR App.8 (60 dB)	3000	3

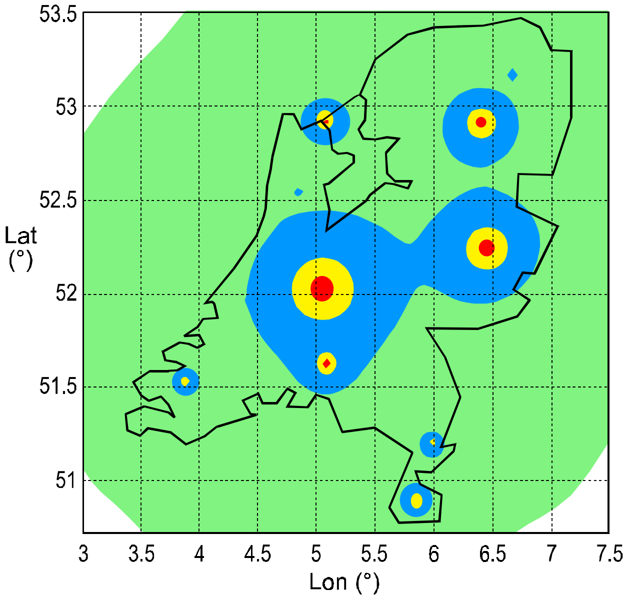

Fig. 2 $C/(N_o+I_o)$ contours over the Netherlands for ARINC receivers and ITU limits, at 3000 ft

It is seen from these figures that serious problems may exist, assuming this low suppression of harmonics (60 dB). Comparing figures 2 and 3 leads to the conclusion that there is no difference in performance between the two receivers when subjected to this particular interference environment. Therefore, the remaining analyses were carried out using the MOPS/ARINC receiver only. Furthermore, it was indicated that most of the interference was caused by the high-power FM and TV broadcast stations. Consequently, the Spurious emission limits for these stations were gradually lowered and the calculations repeated for the following conditions:

- Cat. A for FM (70 dB) and TV (60 dB); others RR Appendix 8 (60 dB); see Fig. 4;
- Cat. B for FM (85 dB) and TV (60 dB); others RR Appendix 8 (60 dB); see Fig. 5;
- Cat. B for FM (85 dB); TV Cat. B + an estimated 25 dB antenna suppression; others RR Appendix 8 (60 dB) ; see Fig. 6.

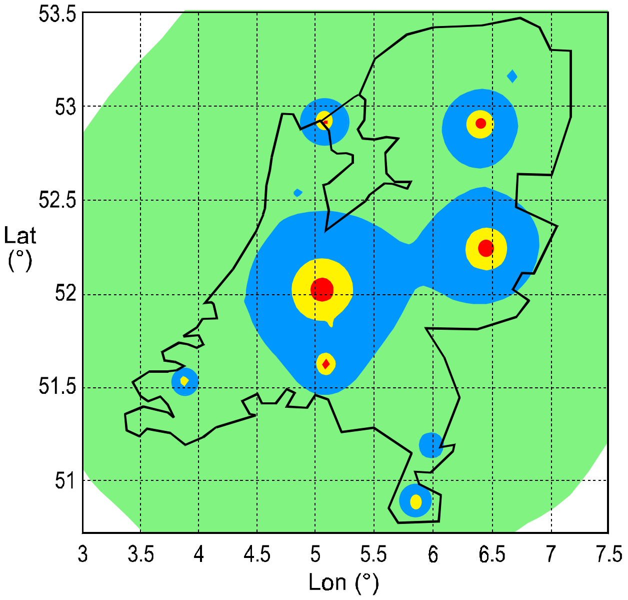

Fig. 3 $C/(N_o+I_o)$ contours over the Netherlands for hand-held receiver and ITU limits, at 3000 ft

Figure 6 shows that, as a result of lowering the spurious emission limits of FM and TV broadcast transmitters, there remains only local interference in the vicinity of the airports and some near the Lopik UHF TV transmitter (522 MHz). The latter could be improved if an antenna suppression of 40 dB is assumed [9] instead of the rather conservative value of 25 dB used here.

To investigate the local interference some close-ups of the airport areas were made for the following conditions:

- FM and TV both 85 dB; others RR Appendix 8 (60 dB); Schiphol Airport; Fig. 7.
- Idem, for Eelde Airport; Fig. 8.

The low C/(No+Io) values in the few areas at and near Schiphol airport are caused by a Localizer, by six VHF-COM transmitters and one UHF-COM transmitter; at Eelde airport by a VOR station and two VHF-COM transmitters.
It must be noted that the VHF-COM and UHF-COM related interference could originate not only from the ground-based transmitters but also from mobile (e.g. airborne) transmitters which use these frequencies (section 6.5).

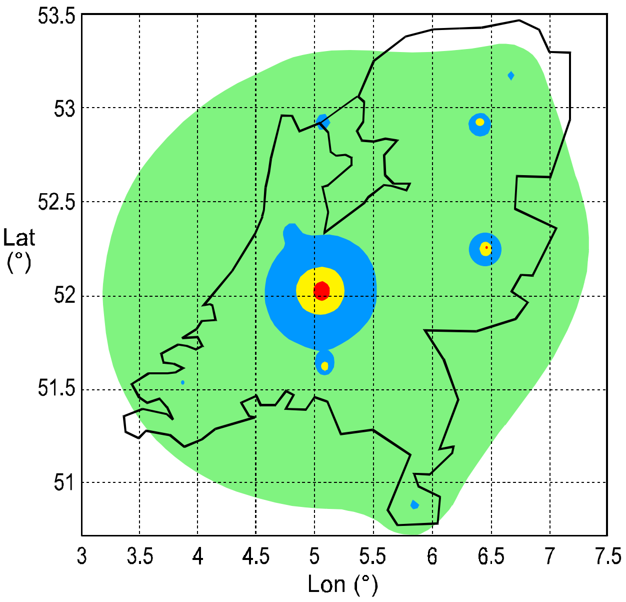

Fig. 4 C/(N_o+I_o) contours for Cat. A for FM (70 dB) and TV (60 dB); others RR Appendix 8 (60 dB), at 3000 ft

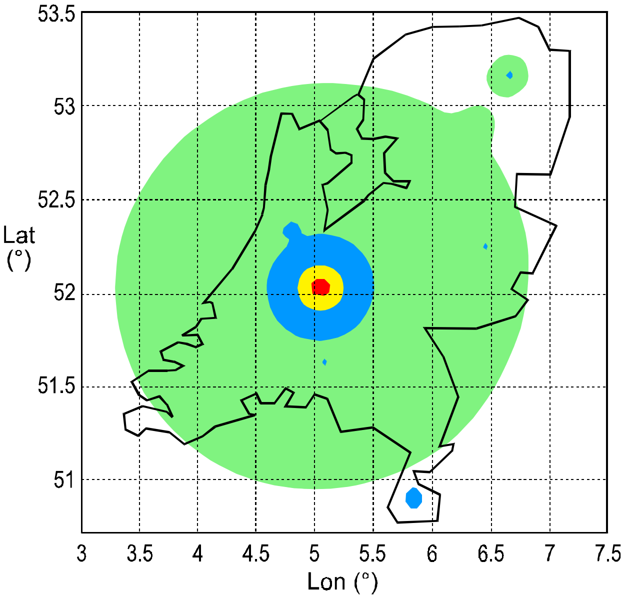

Fig. 5 C/(N_o+I_o) contours for Cat. B for FM (85 dB) and TV (60 dB); others RR Appendix 8 (60 dB), at 3000 ft

Lowering the spurious emission limits for these stations cured the problems as is shown in figures 9 and 10 which were obtained for the following conditions:

- FM and TV both 85 dB; VHF-COM Cat. A (70 dB); Radio-navigation Cat. B (80 dB); others RR Appendix 8 (60 dB); Schiphol Airport; Fig. 9.
- Idem, for Eelde Airport; Fig. 10.

6 DISCUSSION

6.1 General

When interpreting the results presented in the preceding chapter one has to consider the following points:

1. The GPS signal strength of –167 dBW as used in the calculations, is a rather conservative value. It is based on the assumption of a satellite signal of –160 dBW at the aircraft, a receiver antenna gain of -4.5 dB and an implementation loss of 2.5 dB. These figures stem from [1] which also specifies a receiving system noise temperature of 513 °K. Without interference, the maximum attainable C/N_o is then 34.5 dBHz. During a straight and level flight the receiver antenna gain in the direction of the satellites can be much greater than the -4.5 dB specified. In fact, a value of about +5 dB is more likely in this case, resulting in a C/N_o of about 43 dBHz. This figure is commonly observed in commercial aviation systems specified according to the MOPS/ARINC requirements operating in an interference-free environment. However, when the aircraft is manoeuvring, as in the Cat. I Precision approach phase, the antenna gain in the direction of the satellites may decrease while that in the direction to the interfering transmitter may increase, a situation corresponding to the scenario used in the analysis. No allowance was made for the effects of screening or scattering of GPS and interfering signals by aircraft parts, such as fuselage, wings, and tail plane.
2. In contrast to the above situation is the use of a hand-held GPS receiver in general aviation aircraft. Here the assumed GPS signal strength of –167 dBW is certainly a representative value. Although the receiver is often placed near one of the cockpit windows, screening and distortion of the antenna field-of-view by the metallic fuselage structure result in a considerable attenuation of the satellite signals. The use of an external antenna would be a better solution.
3. As the behaviour of the interference transmitting antennas at the spurious emissions frequencies are not known, hemispherical radiation patterns were assumed for these antennas.
4. Ground reflections were not included in the calculation model [11].

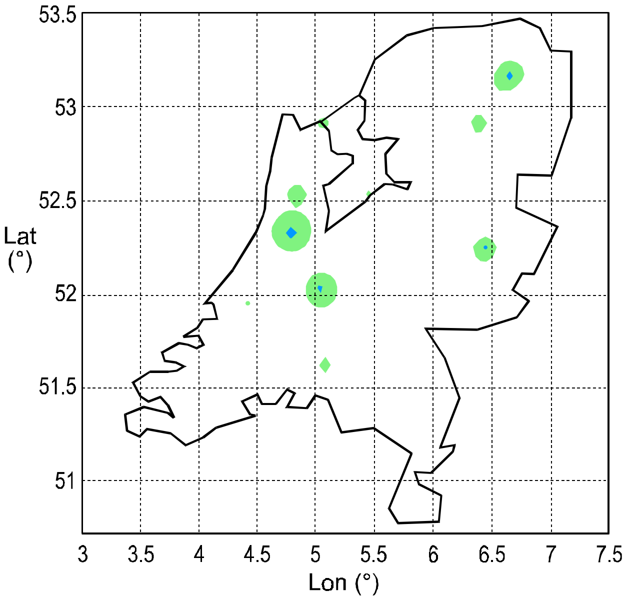

Fig. 6 C/(N_o+I_o) contours for Cat. B for FM (85 dB); TV Cat. B + an estimated 25 dB antenna suppression; others RR Appendix 8 (60 dB), at 3000 ft

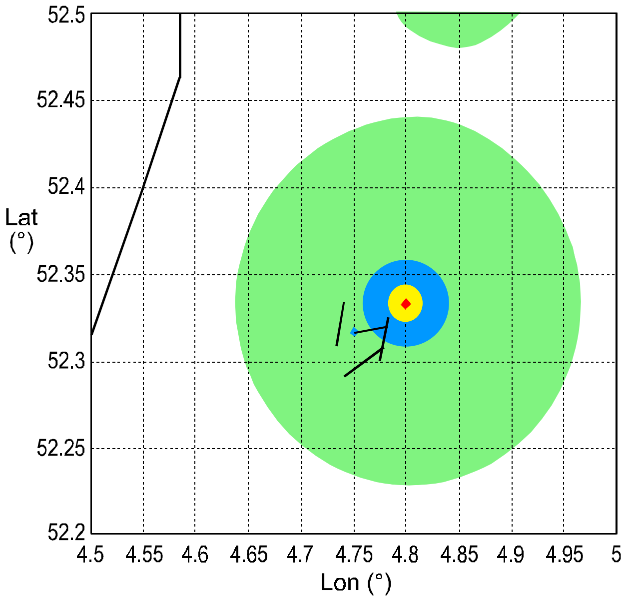

Fig. 7 $C/(N_o+I_o)$ contours for FM and TV both 85 dB; others RR Appendix 8 (60 dB) around Schiphol Airport, at 1000 ft

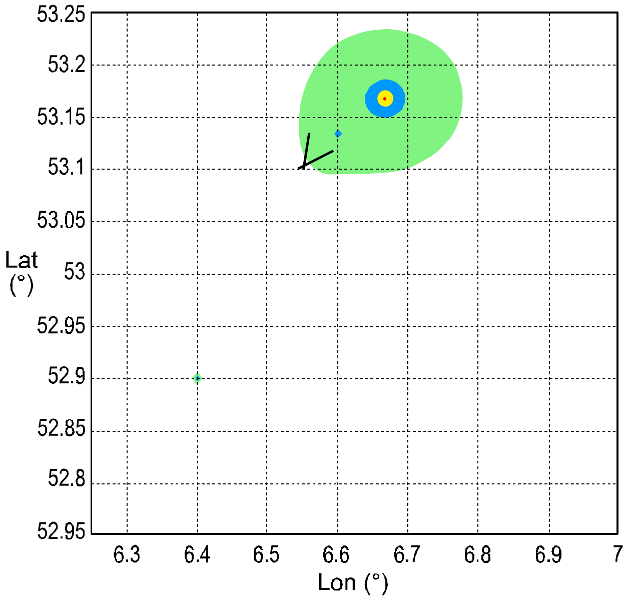

Fig. 8 $C/(N_o+I_o)$ contours for FM and TV both 85 dB; others RR Appendix 8 (60 dB) around Eelde Airport, at 1000 ft

6.2 MOPS/ARINC receiver versus hand-held receiver

By comparing figures 2 and 3, it was concluded that there is no difference in behaviour between MOPS/ARINC receivers and hand-held receivers. This means that an out-of-band signal rejection of 60 dB is sufficient in this interference environment. Interference sources with fundamental frequencies or harmonics between 1315 and 1550 MHz and between 1590 and 2000 MHz are not a threat for GPS operation over the Netherlands territory.

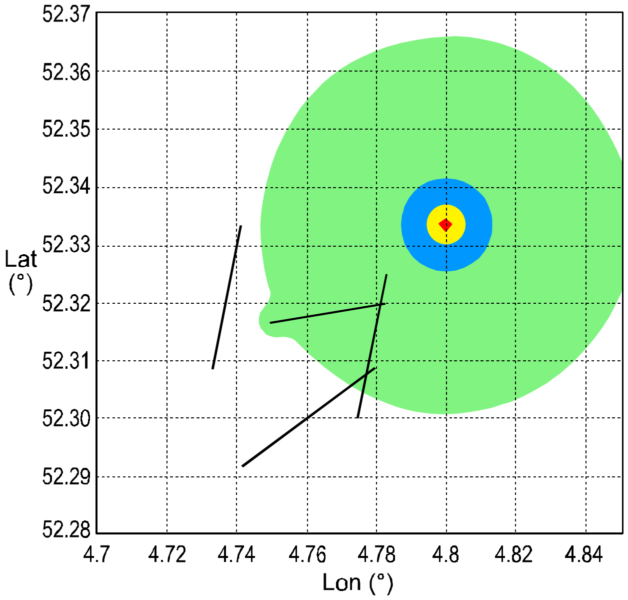

Fig. 9 Contours for FM and TV both 85 dB; VHF-COM Cat. A (70 dB); Radionavigation Cat. B (80 dB); others RR Appendix 8 (60 dB) at Schiphol Airport, at 300 ft

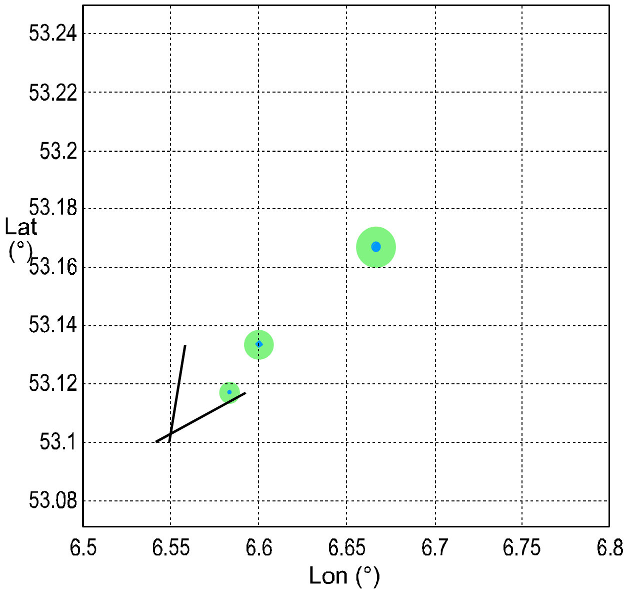

Fig. 10 $C/(N_o+I_o)$ contours for FM and TV both 85 dB VHF-COM Cat. A (70 dB); Radionavigation Cat. B (80 dB); others RR Appendix 8 (60 dB) at Eelde Airport, at 300 ft

The culprits are transmitters having fundamental or harmonic frequencies in the band between 1550 and 1590 MHz. Therefore, the GPS receiver skirt selectivity (i.e. the transition from passband to stopband) is of greater importance than a very high stopband attenuation.

6.3 Broadcast FM and TV transmitters

When the spurious emission limits of the Radio Regulations Appendix 8 are used in the definition of the spurious output of the various sources, it is clear from the results shown in the figures that most of the interference originates from the FM and TV broadcast transmitters.

In next table, the location and the culprit frequencies are summed up.

Location of TX	FM freq	TV freq
Wieringermeer	87.7, 92.2	
Goes	87.9	
Smilde	88.0	
Roermond	88.2	
Hulsberg	92.1, 98.7	786.0
Lopik	92.6, 98.9	522.0
Hilversum	93.1	
Loon op Zand	98.2	
Markelo	98.4, 104.6	

However, to assume only the RR Appendix 8 limits as a measure of spurious emissions is rather unrealistic as is proved by the measured antenna suppression of 40 dB quoted in [9]. Therefore, the spurious emission limits for broadcast transmitters were gradually lowered as indicated in chapter 5. Figures 4 and 5 show the result of increasing the spurious suppression of only the FM transmitters from 60 dB to 70, resp. 85 dB.

The remaining culprit is the Lopik TV transmitter (522 MHz) if its spurious emission limit is kept at 60 dB as specified in RR Appendix 8. Increasing the TV transmitter harmonic suppression to 85 dB results in the curves shown in figure 6. The disturbance caused by the Hulsberg TV transmitter has completely disappeared while that of the Lopik TV transmitter has been reduced to such extent that it only affects a very small area.

Hence, it may be concluded that GPS interference caused by FM and TV broadcast transmitters of which harmonics fall in or near the GPS frequency band, is no problem if a spurious emission limit of at least 85 dB is realised. Caution is required in the case where the antenna suppression forms a considerable part of the spurious emission suppression because of its unstable character (corrosion, weather conditions).

6.4 Interference in the vicinity of Schiphol and Eelde Airport

The situation at Schiphol Airport and at Eelde Airport is shown figures 7 and 8. The interfering sources were identified in chapter 5 as aeronautical systems, either radio-communication or radio-navigation. As in the previous section, the starting point for the spurious emission limits was RR Appendix 8 giving the results shown in figures 7 and 8 Increasing the harmonic suppression from 60 dB to 70 dB for the radio communication systems and to 80 dB for the radio navigation systems resulted in the curves shown in figures 9 and 10, indicating that GPS interference is predicted as non existing for practically most of the areas.

The increase in harmonic suppression of about 20 dB could be attributed to the antenna harmonic suppression; also in this case caution is required for the same reason mentioned in the previous section.

6.5 Mobile sources

It was assumed in the analysis that on-board GPS receivers are not disturbed by the aircraft's own avionics systems. The results show that harmonics from VHF-COM ground-based transceivers are potential sources of interference if the spurious emission limits of RR Appendix 8 are used. When a VHF-COM transceiver and a GPS receiver are co-located on an aircraft the interference problem might be much more severe because of the relatively small antenna separation involved. Use of low-pass filters in the feed-lines between transceivers and antennas may be required to reduce the amount of harmonic level.

However, operators not using GPS on board of their aircraft lack the stimulus of cleaning up VHF transmitted signals to a level beyond that of RR Appendix 8. Therefore, these aircraft may become interfering sources for other, GPS equipped aircraft. It can be shown that, based on the spurious emission limit of RR Appendix 8, a VHF transceiver with an output power of 25 W creates a $C/(N_o+I_o)$ ratio of 16 dB or less, up to a distance of about 150 m. This situation is particularly serious when it occurs in an airport holding area prior to take-off where a large number of aircraft wait in close proximity. As [9] states:

"Cockpit checks will have been completed, the INS programmed (maybe from GPS), and then the crew discover erratic indications on the GPS output. If this is due to interference from the VHF in one of the surrounding aircraft, then it may well affect all his GPS receivers at once and thus indicate a no-go situation. Should he return to the stand to investigate and so lose his take-off slot? That could be expensive."

Thus, it can be concluded that VHF transceivers used in aircraft without GPS may cause interference problems to GPS equipped aircraft in close proximity situations on the ground.

7 MEASUREMENT OF HARMONICS

From the table in section 6.3 one can conclude that the stations at Lopik and Hulsberg are the most suitable for the measurement of harmonic suppression because they include both FM transmitters (vertically polarised), and TV transmitters (horizontally polarised).

The location of the measurement site with respect to the transmitter antenna is subject to certain constraints. Obviously, the maximum distance is given by line-of-sight considerations, the minimum distance by the shape of the transmitter antenna vertical radiation pattern and the interference patterns due to ground reflections. Together with such requirements as an unobstructed view to the antenna and accessabilty, this led to the following measurement site selection criteria:

- distance from the transmitter about 5 km,
- an unobstructed view to the antenna,
- no built-up area,
- accessible by car.

Around each transmitting station three measurement sites were selected. The measurement set-up consisted of a biconical antenna (20-250 MHz) as receiving antenna for the FM signals, while a logarithmic-periodic antenna (300-2200 MHz) was used in the case of the TV signals and the harmonics. A spectrum analyser served as indicator. For the harmonic level measurements at about 1575 MHz, a 50 MHz wide bandpass filter (IL < 0.4 dB) followed by a low-noise amplifier (F < 1.2 dB) was connected between the antenna and the spectrum analyser to increase the dynamic range. For the measurements at Hulsberg, the gain of the low-noise amplifier was increased to 47 dB to cope with the much lower signal levels due to the smaller transmitter powers. Primary power (230 Vac) was supplied by a portable generator.

The results were such that only harmonics of the powerful Lopik TV transmitter (1 MW) were sufficiently above the noise level to be observed. The other transmitters produced no harmonics which were above the measurement system noise level. In case of the FM transmitters this can be attributed to the high harmonic number (16), which implies increased harmonic suppression and spreading of the residual signal over a large bandwidth. For the Hulsberg TV transmitter the low power (100 W) can be considered as the reason for the obscurance of the harmonics by the noise.

Details on the measurements can be found in [12]. Including the effects of the equipment accuracy, and the accuracy with which the propagation factors such as atmospheric attenuation and ground reflection could be determined, the results for the harmonic suppression values were:

- Lopik FM (98.9 MHz)	> 85 +/-3 dB (noise limited),
- Lopik TV (522 MHz)	> 88 +/- 3 dB,
- Hulsberg FM (98.7 MHz)	> 88 +/-3 dB (noise limited),
- Hulsberg TV (783 MHz)	> 82 +/-3 dB (noise limited).

8 CONCLUSIONS

The following conclusions can be drawn from the GPS interference analysis and harmonics measurement campaign:

1. Interference to airborne GPS receivers (either MOPS/ARINC or hand-held types) depends strongly on the emission levels of spurious signals.
2. No difference in performance is expected between well-engineered hand-held GPS receivers and MOPS/ARINC GPS receivers, provided attention is paid to the operational location of the hand-held.
3. If the spurious emission limits of the sources only just comply with the ITU Radio Regulations Appendix 8 specifications (60 dB) then the GPS carrier-to-noise+interference power density ratio is well below the value of 30 dBHz, required for Cat. I Precision Approach, in large areas of the Netherlands. Consequently, unaided receivers could experience loss-of-lock near the FM and TV broadcast transmitters of Wieringermeer, Smilde, Markelo, Lopik, Loon op Zand, Goes, Roermond and Hulsberg. INS aided receivers could experience loss-of-lock near the FM and TV broadcast transmitters of Smilde, Markelo, Lopik and Loon op Zand.
4. If the spurious emission suppression of the FM and TV broadcast transmitters is better (increased for example from 60 dB to 85 dB), GPS interference due to these sources virtually disappears. This 25 dB higher suppression may be attributed to the harmonic suppression capability of the antenna, since the spurious emission limits in the regulations are defined at the interface between transmitter and antenna instead of in terms of field strength.
5. Measurements of actual field strength levels of harmonics, generated by the Lopik and Hulsberg TV and FM transmitters, have shown that a suppression values of 85 dB may very well be attained. This explains that hardly any incident report about consistent GPS interference exists.
6. In the vicinity of airports, interference to GPS may be caused by harmonics of VHF radionavigation systems (VOR, ILS) and VHF communication systems if their spurious limits just comply with the ITU Radio Regulations Appendix 8 specifications. Also VHF-COM systems, used on aircraft not equipped with a GPS system, may give problems. An increase in the spurious emission suppression will relieve the GPS interference problem in this case. An amount of 20 dB for the radio navigation systems and 10 dB for the radio communication systems will suffice. The harmonic suppression capability of the antennas may provide the required increase, but is not known so-far.

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