GPS and GLONASS Radio Interference in Germany

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BIOGRAPHY

Mr. Felix Butsch studied electrical engineering at the University of Karlsruhe. Since 1991 he has been working as a research associate at the Institute of Navigation at the University of Stuttgart. Until 1994 he was involved in the development of hardware for the spectral calibration of remote sensing radars. Since then he has been working in the field of GPS signal interference.

ABSTRACT

The goal of the work described here was to search for interference sources that could pose a threat to the application of GPS for automatic airport approach and landing of aircraft. For this purpose field measurements were conducted in the vicinity of airports, radar facilities and other radio frequency transmitters throughout Germany, and interference resistance measurements of commercial GPS receivers were taken. An additional aim was to examine the interference problems of GLONASS signals.

The paper presents a short description of the theoretical background of interference problems. After this, it describes the test configurations which were used for laboratory and field measurements. Also it shows typical power spectra of interference sources measured in the field, which are compared with interference resistance versus frequency curves determined in the laboratory.

1. INTRODUCTION

In the past, researchers at institutes of several German universities who deal with GPS, repeatedly observed that their GPS receivers on roofs of their buildings and other locations did not operate or lost their signals repeatedly without any detectable reason. Therefore, it was concluded that this was due to electromagnetic interference. It was feared this could be a potential problem to the application of GPS for approach and landing of aircraft.

Therefore the subject of electromagnetic interference on satellite navigation was included as a research subject into the research program ISAN (Integrity for Satellite Navigation). Since the use of GLONASS for GNSS has been proposed and commercial GLONASS receivers have become more easily available, the current work concentrates on the interference problems of GLONASS.

2. THEORETICAL BACKGROUND

Both GPS and GLONASS satellites transmit a signal that is modulated with pseudo noise codes and it additionally conveys data that allow the determination of the satellite position. The quality of the received satellite signal can be described by the signal to noise ratio S/N. The noise power N in turn is proportional to the band-width. The bandwidths of the delay lock loop (DLL), the carrier tracking loop (PLL) and the data discriminator are different, and also can be adjusted by software to the predicted line of sight dynamic. Therefore it is common to normalize the S/N to a bandwidth of 1 Hz and to deal with the signal to noise density ratio S/N_0.

Within the GPS or GLONASS receiver, the satellite signal is multiplied with a self-generated replica of the pseudo noise code of the selected satellite. In this way the PN-modulation is cancelled out. During this process, the interference signal is multiplied with the same pseudo noise code. If the bandwidth of the interference signal was narrow before (<<1 MHz, which is almost always true), it then has a power density spectrum with an approximately $SINC^2$-shape which has nearly the same properties as the spectrum of the normal GPS-signal.

Within the bandwidth of the tracking loops and the data discriminator (1 Hz to 100 Hz), this spectrum is nearly independent of the frequency and has a value of J/f_C (f_C=code clock frequency), which corresponds to the maximum of the $SINC^2$-shaped spectrum.

Since the spectrum of thermal noise is also nearly constant over all frequencies, the interference signal that was multiplied with the PN-code can be observed as artificially generated noise with noise power density of J/f_c. The voltages of thermal and artificial noise are uncorrelated, therefore their power densities have to be summed to give the total noise power density. The effect of the additional noise on the quality of the signal can be described by the so-called effective signal to noise density ratio [1]:

$$\left(\frac{S}{N_0}\right)_{eff} = \frac{S}{N_0 + I_0} \qquad (1)$$

where:

- S: power of the received signal [W], depending on elevation of received satellite
- N_0: thermal noise power density [W/Hz]
- S/N_0: signal to noise power density ratio without interference
- I_0: artificially generated noise power density

The artificially generated noise power density in Eq. 1 can be calculated as follows:

$$I_0 = \frac{a(f_J) \cdot J}{f_c} \qquad (2)$$

where:

- $a(f_J)$: normalized overall frequency response
- f_J: frequency of the interfering signal
- J: power of the received interference or jamming signal [W]
- f_C: code clock frequency ,
  1.023 MHz for GPS C/A- code,
  10.23 MHz for GPS P-code, and
  0.511 MHz for GLONASS C/A-code,
  5.11 MHz for GLONASS P-code

In the case of $I_0 << N_0$ the thermal noise dominates over the artificially generated noise, in Eq. 1 (flat areas in Figs. 1, 3). The value for the undisturbed $S/N_{0,eff}$ is in the order of 45 dBHz to 50 dBHz.

For $I_0 >> N_0$ the artificial noise dominates. In this case the $S/N_{0,eff}$ decreases by 1 dB if the jamming power J increases by 1 dB until the satellite signal can not be tracked any more (steep areas in Figs. 1, 3). Usually the loss of lock threshold is between 28 dBHz and 30 dBHz.

If the frequency f_J of the received interference signal is outside of the channel of a GPS or GLONASS signal, it is attenuated with respect to the GPS-signal by a factor of $a(f_J)$. The GPS-channels occupy the two frequency ranges with a bandwidth of 2x1.023 MHz (C/A-Code) or 10.23 MHz (P(Y)-Code) centered at 1575.42 MHz and 1227.42 MHz.

GLONASS has an individual channel for each satellite with a bandwidth of 2x0.511 MHz for the C/A-code or 2x5.11 MHz for the P-Code at the frequencies
1602 MHz + k·0.5625 MHz for L1 and
1246 MHz + k·0.4375 MHz for L2, with k=0 to 24.

The factor $a(f_J)$ is the frequency response of the gain of the signal path between antenna and the DLL with respect to it's maximum value at signal frequency f_S. It consists of the normalized frequency responses of antenna, low noise amplifier (LNA), antenna cable and the receiver itself:

$$\begin{aligned} a(f_J) &= g_{Ant}(f_J) + g_{LNA}(f_J) \\ &\quad + l_{Cable}(f_J) + g_{Rc}(f_J) \\ &\approx g_{Rc}(f_J) \end{aligned} \qquad (3)$$

with:

- $a(f_J)$: norm. overall frequency response [dB]
- g_{Ant}: norm. antenna gain [dB]
- g_{LNA}: norm. gain of low noise amplifier [dB]
- l_{Cable}: norm. loss of antenna cable [dB]
- g_{Rc}: norm. receiver gain [dB]

Here g_{Rc} is the normalized frequency response of the signal path between antenna input connector (interface 2 in Fig. 2) of the receiver and DLL.

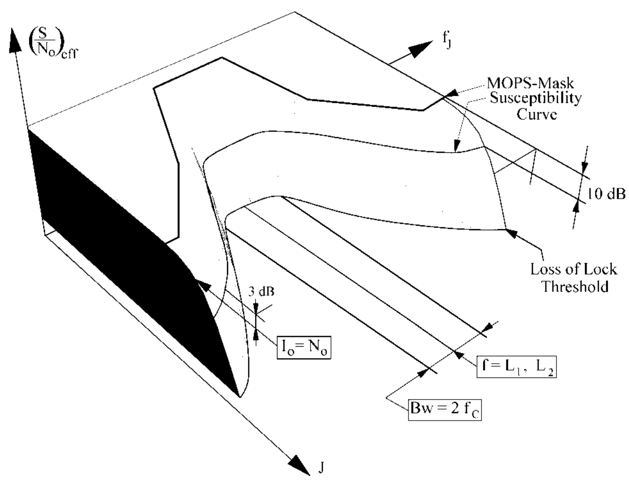

Fig. 1 $S/N_{0,eff}$ vs. jamming power and frequency f_J

In Figure 1, a simulation of the $S/N_{0,eff}$-ratio versus interference power J and frequency f_J for the case of GPS is depicted. In this simulation for $a(f_J)$, a butterworth bandpass filter was used as it is common in real receivers. This figure shows that near the center frequency of the L1- or L2-channel with a bandwidth of $Bw=2 \cdot f_c$, only a little power, and outside the channel much more jamming power is needed to cause a loss of lock of a delay lock loop. It is useful to work with different sections through this three-dimensional surface.

A section at a given frequency (as in Fig. 3) indicates how much S/N-degradation can be expected for a certain interference power. A section at a given S/N-degradation, here called susceptibility curve, (like in Fig. 4) indicates how much interference power is needed for a given frequency to cause a certain S/N-degradation.

In some aviation standards like MOPS [3] a curve is defined that indicates for a given frequency the interference power that must not cause a degradation of the receiver's performance.

The S/N_{eff}-ratio is crucial for the accuracy of pseudorange and carrier measurements as well as the Bit error rate of the navigation message. To get the S/N_{eff} from the $S/N_{0,eff}$, it has to be divided by the bandwidth of the individual tracking loop (B_{DLL} or B_{PLL}) or data discriminator (B_{bit}). The standard deviation of the pseudo range measurement is as follows (standard early late correlator) [2]:

$$\sigma_{PSR} = L \cdot \sqrt{\frac{B_{DLL}\ 2d^2}{\left(\frac{S}{N_0}\right)_{eff}} \left(2(1-d) + \frac{B_{ID}\ 4d}{\left(\frac{S}{N_0}\right)_{eff}} \right)} \quad (4)$$

$$\approx L \cdot \sqrt{\frac{B_{DLL}\ 4d^2(1-d)}{\left(\frac{S}{N_0}\right)_{eff}}} \quad [m]$$

$$\rightarrow L \cdot \sqrt{\frac{B_{DLL}}{2\left(\frac{S}{N_0}\right)_{eff}}} \quad for\ d = \tfrac{1}{2}$$

with:

L:	chip length (C/A-Code L= 293.26m, P-Code L= 29.326 m)
B_{DLL}:	DLL noise bandwidth [Hz]
d:	distance between early- and prompt-correlator or late- and prompt-correlator, (1/16 to 1/2 Chip, d=1/2 for 1 chip E-L correlator)
$(S/N_0)_{eff}$:	effective signal- to noise density ratio [W/Hz]
B_{ID}:	noise bandwidth of the predetection filter [Hz] (Integrate&Dump filter)

The accuracy of the carrier phase measurement is given by [2]:

$$\sigma_{\varphi} = \frac{180°}{\pi} \sqrt{\frac{B_{PLL}}{\left(\frac{S}{N_0}\right)_{eff}} \left(1 + \frac{B_{ID}}{2\left(\frac{S}{N_0}\right)_{eff}} \right)} \quad (5)$$

$$\approx \frac{180°}{\pi} \sqrt{\frac{B_{PLL}}{\left(\frac{S}{N_0}\right)_{eff}}} \quad [°]$$

where:

B_{PLL}:	bandwidth of the PLL [Hz]
B_{ID}:	noise bandwidth of Integrate&Dump filter

Also the Bit error probability P_e of the BPSK-modulated navigation message depends on the $(S/No)_{eff}$:

$$P_e = \tfrac{1}{2}\, erfc\left(\sqrt{\frac{B_{Bit}}{\left(\frac{S}{N_0}\right)_{eff}}} \right) \quad (6)$$

with:

erfc:	complementary error function
B_{Bit}:	data bandwidth

Since σ_{PSR}, σ_{φ}, and P_e are functions of the $(S/N)_{0,eff}$, by determing the impact of a interference signal to the $(S/N)_{0,eff}$, it is possible to assess it's impact on the measurement accuracies and Bit-Error Rate. In order to set a boundary to these values, one has to set a boundary for the maximum allowable degradation of the $(S/N)_{0,eff}$.

3. SUSCEPTIBILITY MEASUREMENTS

For the assessment of the impact of interference signals it is useful to determine the interference resistance of GPS and GLONASS receivers, i.e. one has to perform measurements that help to predict the degradation of the $(S/N_0)_{eff}$ for interference signals with given parameters like signal power, frequency etc.

One of the most important receiver properties is its frequency selectivity, which corresponds to the normalized frequency response which is described by Eq. 3. To determine this, the contributions of the antenna, g_{Ant}, low noise amplifier, g_{LNA}, cable, l_{cable}, and receiver, g_{Rc}, have to be measured. Despite the fact that g_{Rc} dominates in Eq. 3, the determination of g_{Ant} and g_{LNA} is also useful to assess whether interference effects can occur somewhere before the last filter of the receiver.

3.1 Preamplifier Measurements

Since the bandwidth of the preamplifier is always very narrow, compared with the bandwidth of the antenna (see in [4]), it is often not necessary to determine the gain of the antenna. In most cases it is sufficient to use (g_{Ant} + g_{LNA}) ≈ $g_{LNA.}$ The gain of the preamplifiers (low noise amplifier, LNA) and the attenuation of antenna cables were measured by means of a network analyzer.

Another important property for the characterization of the behavior of LNAs is their 1 dB-compression point. It characterizes the threshold between linear and nonlinear operation of an amplifier. LNAs usually consist of a combination of a narrow input filter, an amplifier with relatively broad bandwidth and a narrow output filter.

Mainly because of the input filter the 1 dB-compression point is a function of the frequency. Since the gain of the LNA includes also the output filter, the 1 dB-compression point versus frequency curve has to be measured separately. This curve is interesting to examine the impact of very strong interference sources that are very close to the GPS or GLONASS antenna e.g. transmitters on the same roof or aircraft.

3.2 Receiver Measurements

A typical user of commercial navigation receivers does not have the information needed to determine the effect of the interference signals on filters and subcircuits. The only option is to inject a generated jamming signal into the receiver and to look at how the S/N-ratio, which is estimated by the receiver, and the GPS-rawmeasurements behave. Usually the S/N-ratio of the received signal is estimated by the receiver from the correlation sum in the I-path of the prompt channel, ΣIP_S, as follows:

$$\hat{S}/\hat{N} = \frac{\left(\sum IP_S\right)^2 + \left(\sum QP_S\right)^2}{\left(\sum IP_N\right)^2 + \left(\sum QP_N\right)^2} \approx const \cdot \left(\sum IP_S\right)^2 \tag{7}$$

where:

$\hat{S}$:	estimated signal power
$\hat{N}$:	estimated noise power
ΣIP_S, ΣQP_S:	correlation sum in I- and Q-paths of the prompt channel, with a signal present
ΣIP_N, ΣQP_N:	correlation sum in I- and Q-paths of the prompt channel, with noise alone, (usually only determined once)

Since after the acquisition of the signal, the correlation sum in quadrature-phase channel ΣQP_S is very small, it is negligible for the determination of the S/N-ratio.

If the receiver noise increases due to an interfering signal, the error probability for the received code chips rises more and more. Thus the correlation sum decreases and the same is true for the actual and the estimated S/N-ratios. It was found that in most cases the displayed or output S/N-ratio gave a rather realistic picture of the influence of the interference signal.

Figure 2 shows a block diagram of experimental setup for the measurement susceptibility of GPS or GLONASS receivers. A signal generator generates a sinusoidal interference signal which is combined with the received satellite signal from the antenna. A computer controls the power J and frequency f_J of the interference signal. At the same time it registers the estimated S/N-ratio from the receiver. Several types of measurements can be performed.

The first is the measurement of the interference power that is required to prevent the acquisition of a satellite Signal. The second type is the determination of the S/N-ratio versus jamming power for a given frequency (Fig. 3). This type of measurement allows the determination of the power level at which the artificially generated noise begins to dominate, and at what power level the loss of lock of the DLL occurs.

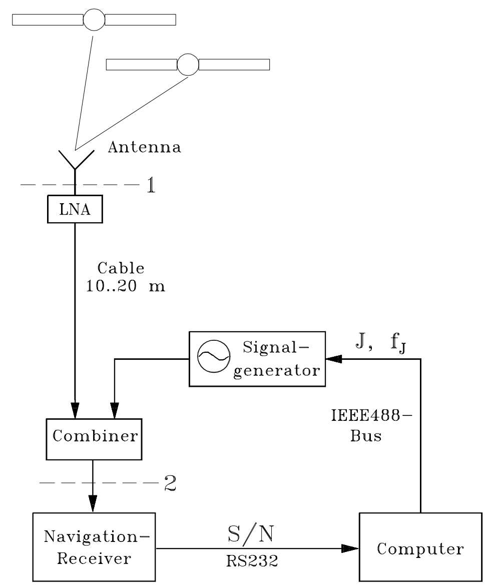

Fig. 2 Automatic susceptibility measurement

For receivers that are able to receive both GPS frequencies, it is interesting to examine additionally how the degradation of the S/N at the L1-frequency behaves if there is a interference signal near the L2-frequency (Fig. 4). For combined GPS/GLONASS receivers it is important to determine the isolation between the GPS and the GLONASS section of the receiver.

Another type of measurement is to determine the interference power needed to cause a given amount of degradation of the S/N (e.g. 10 dB), or loss of lock of the DLL, as a function of frequency. The resulting curve describes the frequency response of the receiver susceptibility, and can be compared with spectra from interference signals obtained during field measurements (Fig. 4). From this susceptibility curve one can also calculate the normalized receiver gain g_{Rc}.

With the configuration in Fig. 2 only the properties of the signal path within the main housing of the receiver can be determined. If we measure the spectrum of the interference signal at the same interface (interface number 2, dashed line in Fig. 2) we are able to compare both results to get an assessment of how severe the degradation of the GPS-measurements will be.

If we want to compare the results with other receivers, with different low noise amplifiers and different antenna cable length, it is more suitable to refer susceptibility curves and interference spectra to the interface between antenna and low noise amplifier (interface number 1, dashed line in Fig. 2).

Since most GPS and GLONASS antennas have an almost isotropic antenna diagram, most antennas have a comparable gain which leads to comparable conditions at the interface between antenna and LNA-input (interface 1). To transform the results from interface 2 to interface 1 (Figs. 2 and 7) the gain of the LNA and the antenna cable can be determined by a network analyzer, and taken into account for the indication of the susceptibility.

3.4 Susceptibility of GPS-receivers

For a quick comparison of different GPS receiver types one can determine the power levels to prevent acquisition and the power levels to cause loss of lock. In Table 1 these values are given for five commercial GPS-receivers.

GPS Receiver	no Acquisition for J(L1)>	Loss of Lock for J(L1)>
A-old	-107 dBm	-90 dBm
A-new	-104 dBm	-76 dBm
B	-108 dBm	-92 dBm
C	-109 dBm	-70 dBm
E	-120 dBm	-96 dBm

Table 1 Comparison of acquisition and loss of lock thresholds at L1

While there have been some improvements for the loss of lock performance of different receiver generations, the acquisition threshold of most receivers is in the same order. From Table 1, one can recognize that during acquisition, receivers are much more susceptible to interference. The reason is that during acquisition the bandwidths of the tracking loops have to be higher since the Doppler shift is not precisely known. Also there is a hysteresis for the S/N-thresholds at which the receiver detects accomplished acquisition or loss of lock.

In Fig. 3 a typical S/N-Degradation versus interference power curve is depicted. It corresponds to a cut through the graph in Fig. 1 at the frequency $f_J=f_{L1}$. The curve was obtained by the measurement setup in Fig. 2 and transformed from interface 2 to interface 1 by subtraction of the LNA gain and cable loss (in dB) that were determined by a network analyzer previously.

Figure 4 shows curves that represent the power to degrade the S/N-ratio by 10 dB on L1-frequency vs. frequency (here called susceptibility curve) for two different receiver generations of the same manufacturer (referred to interface 1 in Fig 2). The results were obtained with the measurement configuration in Fig. 2 that allows an automatic variation of frequency and signal power while registering the resulting S/N. The value of 10 dB for the threshold was chosen because at 10 dB S/N-degradation, the effect to the GPS observables is clear, and the automatic measurement is not interrupted by loss of lock of tracking loops.

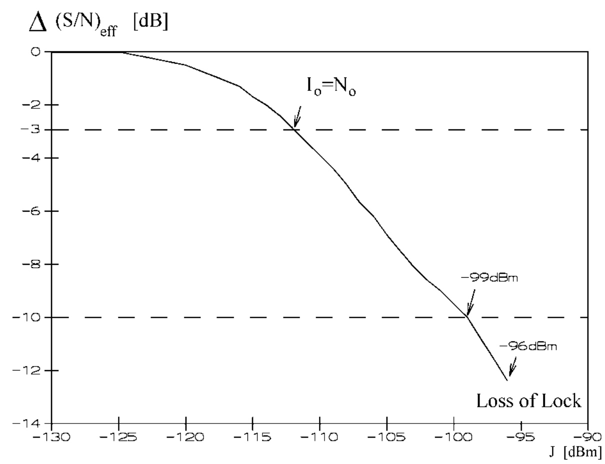

Fig. 3 S/N-Degradation vs. interference power

The plot in Fig. 4 illustrates that near the GPS L1-channel very little interference power is needed to degrade the S/N, while outside very much more is required. It is remarkable that near the L2-frequency there is another susceptible frequency range that should not be there since only the S/N on L1-frequency was observed. Presumably, this is due to bad interchannel isolation within the receiver.

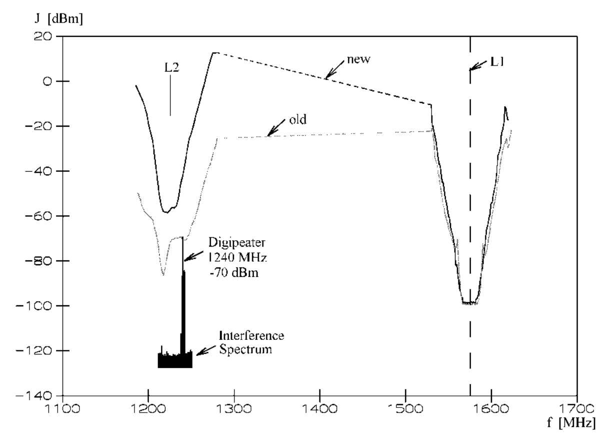

Fig. 4 Power to degrade L1-S/N by 10 dB and interference spectrum

Fortunately there has been an improvement between the two receiver generations which turned out to be very useful at the field measurements. For comparison a third curve is depicted that represents the spectrum of an interference signal near L2 frequency that also caused a degradation of L1-reception.

From the measured susceptibility curve as in Fig. 4 also the normalized receiver frequency response, g_{Rc} (in Eq. 3) can be computed:

$$g_{Rc}(f_J) = J(f_S) - J(f_J) \qquad (8)$$

where:

- f_J: interference frequency [Hz]
- f_S: center frequency of GPS or GLONASS channel (L1 or L2)
- $J(f_S)$: interference power at GPS-frequency to degrade the $S/N_{0,eff}$ by a certain amount (>>3 dB e.g. 10 dB) [dB]
- $J(f_J)$: susceptibility curve, i.e. interference power to degrade the $S/N_{0,eff}$ by a certain amount as a function of frequency [dB]

Figure 5 shows a comparison of the normalized overall frequency responses $a(f_J)$ of three different receiver types, a P/Y-code receiver, a C/A-code receiver with a narrow correlator and a standard C/A-code receiver. It helps to assess which frequency range has to be kept free from potential interference sources to prevent problems.

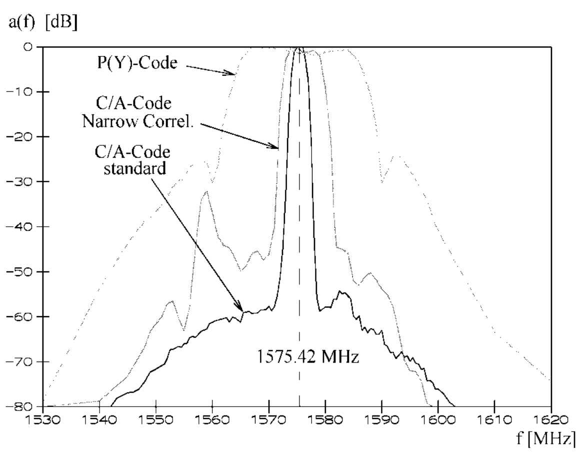

Fig. 5 Comparison of several GPS receiver types

3.5 Susceptibility of GPS/GLONASS receivers

The big advantage of GLONASS is that every satellite has its own frequency and therefore weak, narrowband signals can only interfere with the signals of one or two GLONASS satellites. But it turned out that it is also possible to jam the reception of all GLONASS satellites with a strong interference signal.

Figure 6 shows the interference power needed to cause a S/N-degradation of 10 dB (susceptibility curves) for two satellites with the frequency factors k=9 and k=12. For a 10 dB degradation at the center frequency, a power of -98 dBm is needed. But at the center frequency of the second satellite an additional power of 15 dB can cause the same degradation of the S/N of the first satellite signal.

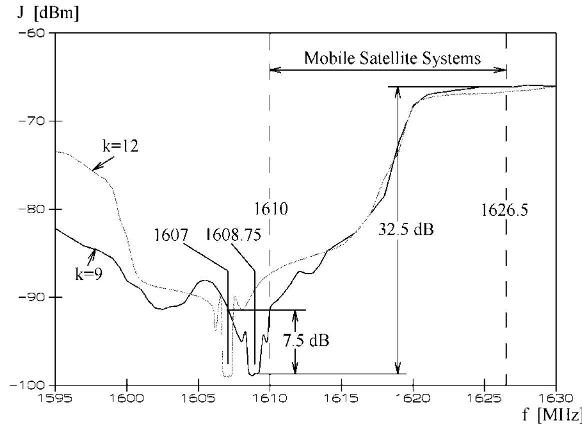

Fig. 6 Susceptibility curves of two GLONASS channels.

The special problem of the examined combined GPS/GLONASS receiver seems to be the crosstalk from the GPS section to the GLONASS section. In figure 7 the susceptibility curve for the GPS reception and for the reception of the GLONASS satellite with the frequency index k=12 are depicted.

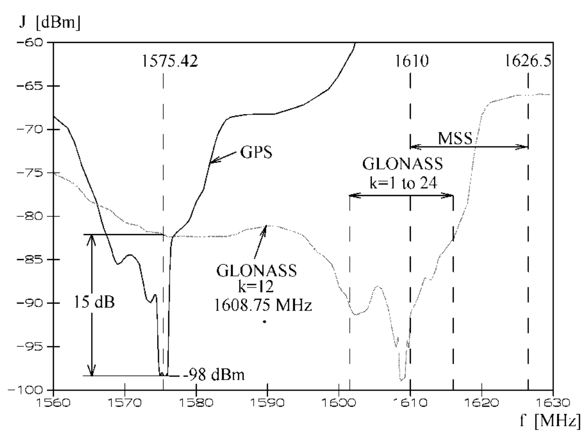

Fig. 7 Susceptibility curves for a combined GPS/GLONASS receiver

While for a signal in the frequency range of GLONASS it is almost impossible to degrade the GPS-reception, a signal near the L1 frequency of GPS can cause a degradation of the GLONASS reception. There is only an isolation of about 15 dB between the GPS and the GLONASS section of this combined receiver. That means that combined GPS/GLONASS receivers can have a higher interference risk than two separate receivers would have.

Another problem for the GLONASS reception may be the use of the frequency range between 1610 MHz and 1626.5 MHz by Mobile Satellite Systems (MSS). Until 1998 the frequency ranges of GLONASS (1601.5 MHz to 1616 MHz) and MSS are overlapping. Between 1998 and 2005 the satellite with the frequency index k=12 (1608.75 MHz) will be the satellite closest to the MSS-frequency range.

Remarkable is that the receiver, we examined had only a minimum isolation of 7.5 dB between the channel of the satellite with the frequency index k=12 and the lowest MSS-frequency 1610 MHz (Fig. 7).

4. FIELD MEASUREMENTS

Until now, mainly GPS-measurements and spectral measurements in the frequency ranges near the GPS and the GLONASS channels have been conducted in the field. For the spectral measurements, the signal at the output of low noise amplifiers of the navigation receivers was analyzed and transformed to the interface between antenna and LNA by subtraction of LNA gain versus frequency. The spectra obtained from the poten-tial interference signals could then be compared with the susceptibility curves which were discussed earlier.

Figure 8 allows a comparison of an interference spectrum from a Italian military transmitter with the MOPS susceptibility mask and the loss of lock threshold versus frequency of a C/A-code receiver. Although several lines exceed the MOPS mask they are not able to cause a loss of lock of the DLLs since the receiver has a better interference suppression performance than required.

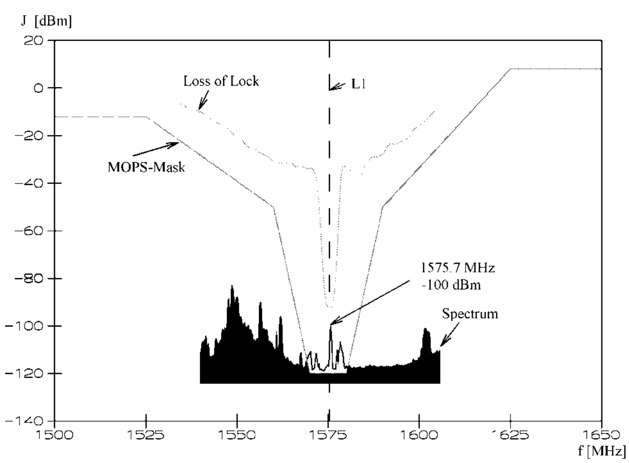

Fig. 8 Interference spectrum in the L1-band

During field measurements all over Germany, no interference sources in or near the L1-band were found that caused severe degradations. But there were a lot of locations where GPS reception on L1-frequency was impossible or at least degraded. But this was only true for L1/L2-receivers. In these cases the L2-reception was also impossible or more severely degraded. It turned out that the interference sources in these cases were Amateur Radio relay transponders, called Digipeaters.

4.1 Interference by Amateur Radio

The Digipeaters that cause interference to GPS are part of a Europe wide network (Fig. 9), run by Amateur Radio organizations for transmission of digital data in a manner similar to the Internet (also called Packet Radio). There are more than 250 such Digipeaters in Germany. They transmit in the frequency range from 1240 MHz to 1243.25 MHz. They are a major problem because they operate permanently.

In addition, there are some amateur FM-relay stations for speech transmission in the frequency range from 1242 MHz to 1242.7 MHz, and some amateur television (ATV) transmitters between 1243.25 MHz and 1260 MHz, which also could be a potential problem. All these transmitters are allowed to transmit with a maximum power of 25 W EIRP (equivalent isotropic radiated power = electrical power x antenna gain).

It very likely that in other European countries, the frequency range above 1240 MHz is also used by amateur radio for permanently transmitting links. There has been a report about interference to GPS due to Digipeaters at several locations in the Netherlands and we also found one case in Switzerland with interference at 1240.7 MHz.

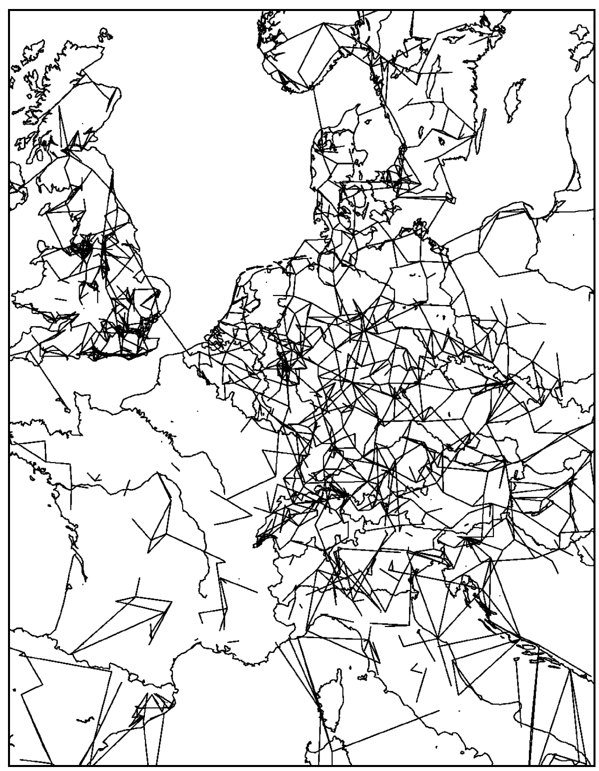

Fig.9 Amateur Radio Digipeater Links in Europe

The Digipeater links in Germany span distances between 5 km and 150 km and operate with EIRPs between 10 mW and 25 W, and their antennas have half power beamwidth between 5° and 20°, depending on the length of the link to bridge.

One of the worst cases observed was at a location 11 km from a Digipeater. No reception of GPS at L1 and L2 was possible there.

This problem on L1 was caused by crosstalk from L2-channel as observed in the laboratory measurements (Fig. 4). Figure 10 shows a comparison of the spectrum of the Digipeater signal with the susceptibility curve of a P(Y)-code receiver. The peak at 1240 MHz exceeds the line that marks the 10 dB degradation at L2. It can also be seen that a signal at 1240 MHz is only attenuated about 16 dB with respect to a signal with a frequency of 1227.6 MHz, i.e. a (1240 MHz) = -16 dB.

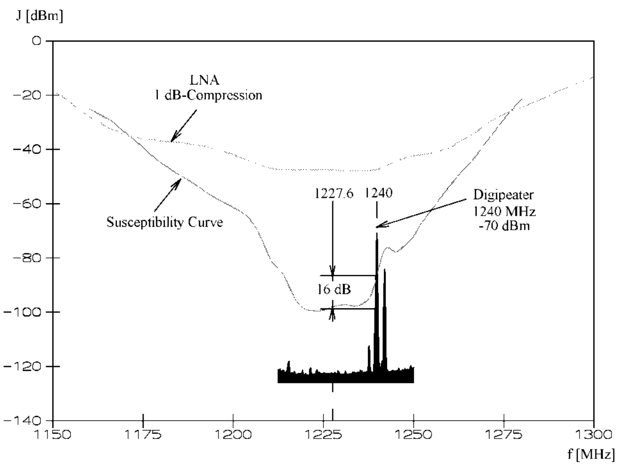

Fig. 10 Spectrum from a Digipeater near L2-band

To get an impression of how easy it is to jam GPS, a simulation was done to calculate the received power for the case that a transmitter with an EIRP of 1W transmits a signal on either L1- or L2-frequency and the GPS antenna has an antenna gain of 0 dB in direction of the transmitter (Fig. 11). Because of the small difference between 1240 MHz and L2-frequency, the curve for L2 is also valid for Digipeater signals.

To cause a S/N-degradation of 10 dB for the receiver mentioned above, an interference power of -99 dBm is required. This occurs at a distance of about 43 km for the L1-frequency, and at 55 km for the L2-frequency. For the same degradation at the frequency of the Digipeaters (1240 MHz), due to the filter attenuation, a received interference power of -83 dBm (Fig. 11) is required. This is reached at a distance of 8.7 km from a transmitter with 1 W EIRP.

Another severe case occurred in a distance of 24 km from a Digipeater. At that location L1-reception was not influenced while L2-reception was interrupted with almost every Digipeater data package. Figure 12 shows the P-code pseudorange measured on L2 (antispoofing turned of) versus time.

More common than these spectacular cases are interference problems in a distance of up to 3 km from Digipeaters which have short links and therefore low transmit power values and antennas with low directivities.

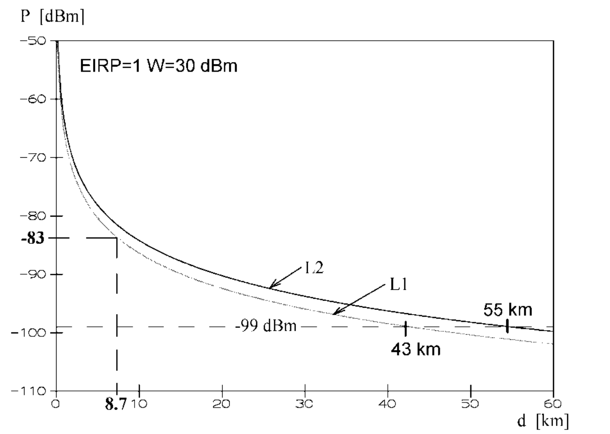

Fig. 11 Received interference power of a transmitter with 1 W EIRP versus distance

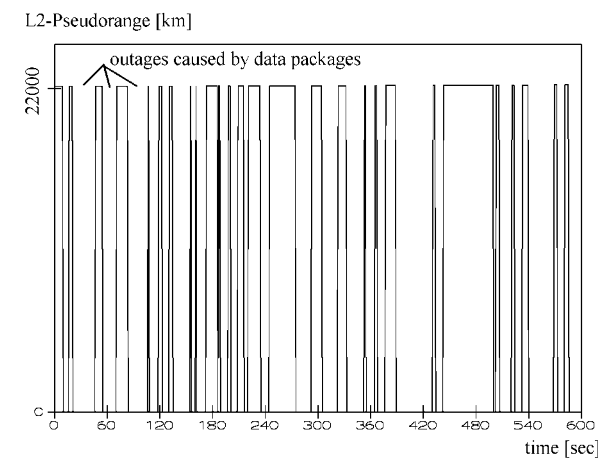

Fig. 12 P-Code pseudorange at L2 versus time

In Figure 13 a typical plot of the triple differences of the L2-phase measurement that was disturbed by data packages from a by Digipeater is depicted

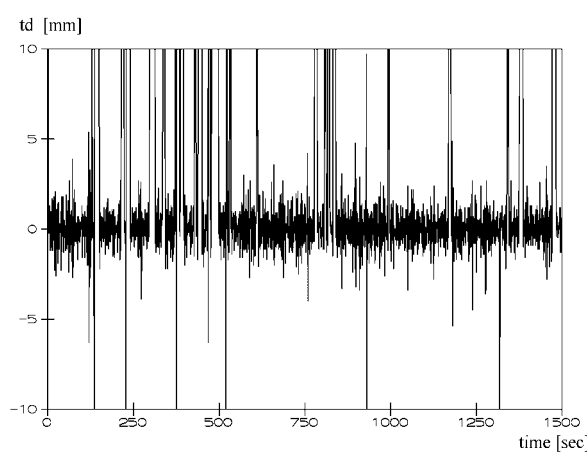

Fig. 13 Triple differences of L2-phase versus time

Digipeaters are also interfering with the L2-reception of GLONASS. Figure 14 shows an interference spectrum near the L2-frequency ranges of GPS and GLONASS. In this case the interference signals were strong enough to prevent the acquisition of all GLONASS satellites in sight.

Unfortunately no L2-receiver was available for susceptibility measurements. Presumably the reason was the poor isolation between the single GLONASS channels as found at the susceptibility measurements of the L1-receiver.

Between the L2-frequency ranges of both navigation systems is only a narrow gap where the Digipeaters are located. Therefore their signals are not damped by the filters of preamplifiers of combined GPS/GLONASS receivers.

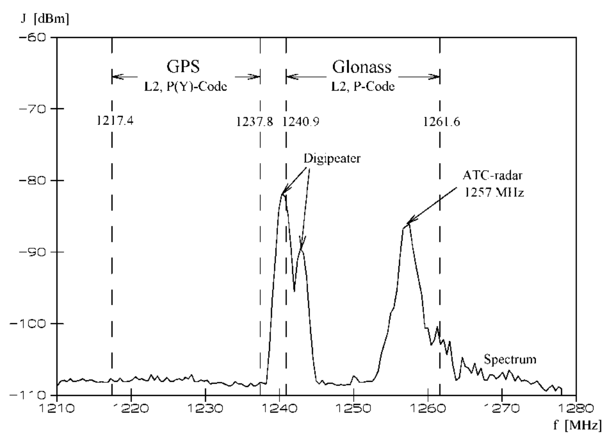

Fig. 14 Interference spectrum near the L2-frequency ranges of GPS and GLONASS

Problems due to signals interfering with the L1-reception of GLONASS did not occur yet. But field measurements are still going on. A potential interference source for near the L1-frequency range (1602 MHz to 1616 MHz until 1998) are the mobile satellite system (MSS), between 1610 MHz and 1626.5 MHz, like Inmarsat, Iridium and others.

4.2 Interference potential of ATC-radar

In Germany there are about 12 medium range air traffic control radar facilities (carrier frequency 1250 MHz to 1259 MHz, pulse repetition rate 0.25 kHz to 0.45 kHz, pulse length 0.8 μs to 2 μs, pulse peak power up to 2.5 MW). Their carrier frequencies are adjacent to the L2 frequency of GPS and within the L2 frequency range of the GLONASS L2 frequency (e.g. radar in Fig. 14, more in [4]).

The pulse length of the radar signal is comparable with the length of 1 or 2 C/A-code chips and 10 or 20 P-code chips respectively. The pulse period is in the order of 2 to 4 C/A-code periods. It is common to have integration times in the order of 1 data-Bit which corresponds to 20 C/A-code cycles. Therefore, in the worst case only about 20 of 20x1023 C/A-code chips or 200 of 20x10230 P-code chips could be flipped by such a radar signal (Fig. 15). Thus the effect on the S/N-ratio is absolutely negligible.

On L2-frequency there is only the P-Code, but nevertheless to consider the impact on C/A-Code is interesting since, as mentioned above, due to crosstalk the L1-frequency can be interfered by a interference signal near L2. Since the code clock frequency of the P-Code is ten times higher than that of the C/A-code, the power density of the artificial noise power is only 1/10. Therefore the probability that a code-chip is altered due to interference is much lower than in the case of the C/A-code.

In the vicinity of German Airports there are about another 10 short range ATC-control radars (carrier frequency 2816 MHz to 2889 MHz, pulse length 0.6 μs, pulse repetition rate 1 kHz, pulse peak power up to 1.2 MW). Their signals can only flip about 1 out of 1023 C/A or 10 of 10230 P-code chips. That means that the impact on the S/N-ratio is also negligible (<0.01 dB). Since their frequency is far from the GPS-band and their power is lower this is only possible in the vicinity of the radar-facility.

At a short distance from the radar facility (<300 m), it is conceivable that the pulse peaks could cause compression of amplifier stages, and therefore cause nonlinear distortions that force tracking loops to lose lock and therefore need time for reacquisition. During the field measurements in the vicinity of four different medium range ATC-radars, and near the short range ATC-radars located at five German Airports, no impact of radar on GPS reception could be found.

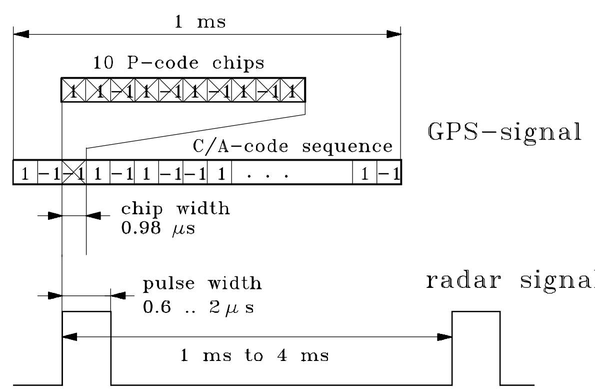

Fig. 15 Comparison of PN-codes and radar-signal

4.3 Impact of results to the proposed L5-frequencies

In reference [5] candidates for the L5-frequency were proposed and discussed: 1207.14 MHz, 1214.3 MHz, 1217.37 MHz, 1237.83 MHz, 1248.06 MHz, 1258.29 MHz (dashed lines in Fig. 16).

The frequency range of VORTAC, TACAN and DME is between 960 MHz and 1215 MHz. In Germany, like in many other countries, the frequency range 1240 MHz to 1300 MHz is used by Amateur Radio.

Especially the frequency range between 1240 MHz to 1243.25 MHz is used by permanently operating Digipeater links and FM relays. The frequency range 1250 MHz to 1259 MHz is used by medium range air traffic control (ATC) radars.

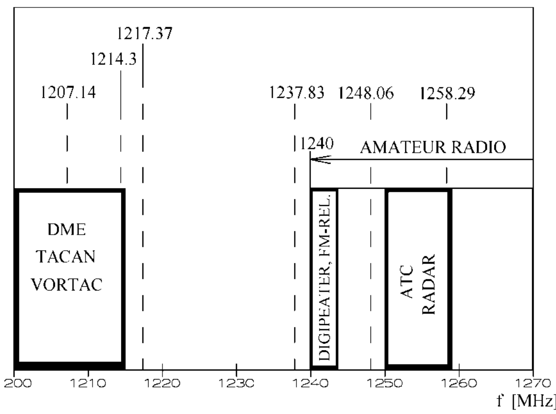

Fig. 16 Proposed candidates for L5-frequency

We expect possible problems for the proposed the frequencies at 1207.14 MHz, 1214.3 MHz and 1217.37 MHz because they are in, or adjacent to the frequency range of VORTAC, TACAN and DME. For the frequency candidates 1237.83 MHz and 1248.06 MHz we expect severe problems due to amateur radio. The frequency candidate 1258.29 MHz is within the band of the medium range ATC-radar. For this frequency there may arise interference problems only in the vicinity of the radar facilities.

CONCLUSION

Field measurements were conducted at several airports, in the vicinity of ATC radar facilities and at about 30 other locations with GPS interference problems all over Germany. During these measurements, it was found that nearly all problems were caused by Amateur Radio Digipeaters and FM relays operating in the frequency range from 1240 MHz to 1243.25 MHz. In some cases they not only disrupted the GPS reception on L2, but due to bad interchannel isolation in the receivers, also on L1. That means that one can expect that there will only seldom be interference problems for the use of pure L1-receivers, as is planned for precision approach and landing of aircraft. But this is different in the field of Geodesy where dual frequency receivers are used. Fortunately some manufacturers have already recognized the problem and are developing or selling meanwhile more robust GPS-receivers.

Interference due to Amateur Radio also proved to be also a problem for the reception of the L2-signals of GLONASS. Although GLONASS is a Frequency Division Multiple Access (FDMA) system, we found that strong signals were able to prevent acquisition of signals from all satellites in view. Susceptibility measurements showed that combined GPS/GLONASS receivers can be more vulnerable than two single receivers, since signals near the GPS frequency band can also degrade the GLONASS reception by crosstalk.

The concept of comparing measured spectra of interference signals with susceptibility curves has proofed to be useful. It can also be applied for automatic monitoring of GPS or GLONASS channels at airports or on aircraft.

It is desirable that the manufacturers of navigation receivers provide such susceptibility curves, since the use of the signal to noise ratio (S/N), that is estimated by the navigation receivers to gain susceptibility curves is sometimes not reliable. At least it would help if a standard for the determination of the S/N could be introduced, not only for this, but also for many other applications e.g. positioning algorithms and integrity monitoring. Although, there are several standards for susceptibility masks for C/A-code receivers for airborne applications, apparently there is no such standard for geodetic, P(Y)-code, dual frequency receivers yet.

Almost all frequency candidates proposed in [5] are in or adjacent to the frequency ranges of VORTAC, TACAN, DME, Amateur Radio and ATC-radar. Therefore, it would be advisable to look for a more suitable frequency.

ACKNOWLEDGEMENTS

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