INVESTIGATION OF POTENTIALLY CRITICAL INTERFERENCE ENVIRONMENTS FOR GPS/GALILEO MASS MARKET RECEIVERS

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ABSTRACT

This paper presents new findings about radio interference threat in L1/E1 frequency band of GPS and coming Galileo. The results of a dedicated interference measurement campaign are presented. One type of the interference encountered during the campaign on several locations inside Germany has been modelled and the impact of this interference on mass-market GPS/Galileo L1 receivers has been assessed by performing hardware and software simulations. The results of the simulations show that under certain conditions this strong wideband interference may lead to the loss-of-lock in the receiver tracking units or non-ability to acquire the signal.

1. INTRODUCTION

It is currently a common belief that the L1/E1 band is relatively quiet in terms of radio frequency interference. However, evidence or counterevidence of this belief is still an open issue. The opportunity to prove this belief has occurred during an interference measurement campaign carried out by the German Aerospace Centre (DLR) within the framework of the GJU project GIRASOLE [1].

1.1. The Common View on GPS and Galileo

As Galileo enters the satellite navigation field already pioneered by GPS, it is of course compared to the existing system. Comparison is done evaluating accuracy, precision, robustness and several other properties depending on the application having in mind. In the area of robustness, Galileo is considered facing a challenge because of the utilisation of new frequency bands with multiple potentially strong radio interference threats. But what has to be considered is that the biggest benefit for future mass market receivers comes from the doubled number of satellites. This enables navigation in urban areas with higher availability and precision, and this by just receiving signals from both systems, GPS and Galileo. Therefore, even mass market receivers will need to increase the bandwidth of their front ends for the reception of Galileo signals. Thinking further in this direction leads us to the conclusion that the radio interference situation changes for GPS as well and this circumstance has to be considered in robustness evaluations of future combined L1 receivers.

[1] http://www.galileoju.com/page.cfm?voce=s3&idvoce=58

1.2. Girasole Measurement Campaign

Within the GIRASOLE (Galileo Integrity Receiver for Advanced Safety Of Life Equipment) project, a measurement campaign was carried out to assess the real existing environment in terms of radio frequency interference (RFI). This is the basis for developing underlying signal models for advanced interference detection and mitigation algorithms and for assessing the receiver performance under corresponding interference conditions. Especially the safety-of-life receivers that are in focus of GIRASOLE activities shall be more robust than traditional receivers.

For assessing the radio interference environments in railway applications of GPS and Galileo, DLR carried out measurements across Germany at different sites at typical modes of railway operation. The task during the campaign was not to identify the origin of radio interference, but rather to characterise the encountered interference signals and the interference scenarios (i.e. combinations of different individual interference signals) to be expected in practice in railway environments.

During the measurement campaign, a measurement vehicle based on a Mercedes Vito van that was kindly provided by the European Space Agency ESA was used. Joanneum Research in Graz, Austria did the modification and adaptation of the measurement vehicle with regard to the desired measurement profiles. Additionally, an Agilent vector spectrum analyser of DLR was used. The equipment set-up is shown in Figure 1.

The equipment allowed measurements in all Galileo and GPS frequency bands:

- E5/L5 +L2: 1146-1238 MHz

Fig. 1. Left: Measurement equipment in 19” from top to bottom: 1) Laptop with control software for Agilent PSA, 2) R&S FSH6, 3) Amplification and control unit by Joanneum Research, 4) Control and storage PC for the Joanneum Research unit, 5) Agilent PSA E4443A Right: Conical hemispherical antenna for interference measurements and two GPS-antennas

- E6: 1260-1300 MHz
- E1-L1-E2: 1555-1596 MHz

The Joanneum system was used to maintain a broadband overview over the whole spectrum and the Agilent PSA as digitiser, storing the records of baseband I/Q samples containing interesting interference signals and enabling a closer look on the signal evolution in temporal and frequency domains in post processing. With this approach, DLR was able to acquire a broad family of signals ranging from continuous wave (CW) and broadband signals to temporarily occurring pulsed interference.

One important part of this measurement campaign where most of the information was acquired was a train transit over roughly 600km distance from Munich in the southern part to Hamburg in the northern part of Germany. During this train transit, a variety of interference signals were recorded, which range from Distance Measuring Equipment (DME) [1] in E5/L5 over L-Band radar to unidentified communication systems and noise-like signals. In the following we describe our findings and assess the impact of the interference signals on GNSS receivers.

2. WIDEBAND INTERFERENCE

During the measurement campaign described in section 1.2, one kind of interference was measured repeatedly at different locations and in varying configurations. Figure 2 gives an overview of this type of interference. Figures 3 and 4 give a more detailed view. In Figure 2, multiple versions of this type of interference is present all over the L1 frequency band. In the following, we assume these to be multiple instances of one kind of interference and only one representation in the middle of L1 is evaluated by having a closer look.

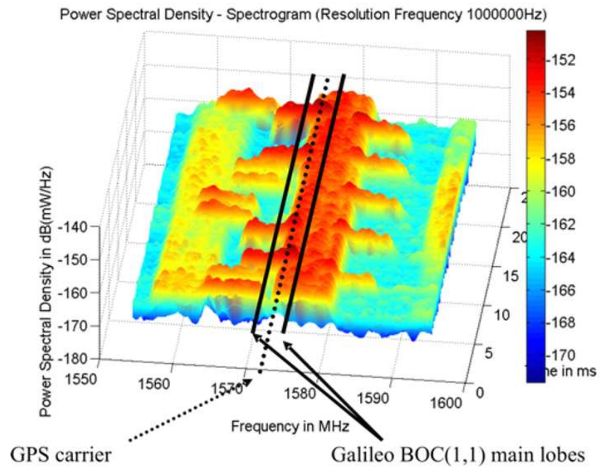

Fig. 2. The spectrogram shows the power density (bottom to top in dB(mW/Hz)) depending on frequency (left to right in MHz) versus time (front to back in ms) plot. Visible is one high power interference source approximately in the middle of the spectrum and two low power ones at the left and the right band edges. Additionally, one frequency hopping transmission is present simultaneously. For comparison, GPS and BOC main lobe frequencies are given as dotted and solid lines, respectively.

2.1. A Closer Look

Evaluation of Figure 3 reveals the interference source to have a bandwidth of 7 MHz and integration over this bandwidth results in an overall power of -84.4 dBm that is received by this interference source. Assuming a GNSS power of -130 dBm, this calculates to an interference to signal ratio (ISR) of 42.6 dB. Furthermore, Figure 3 reveals a time slot structure with a slot duration of roughly $552\,\mu s$. Figure 4 brings in a slightly different view, as here the frequency occupied by interference is subdivided into three subcarriers with a fixed frequency separation between them and each one using a 2 MHz bandwidth.

2.2. Modelling

For further analysis on the impact of these interference occurrences, a detailed model was needed to generate the interferer with different parameters as power level, slot duration, frequency distribution and so on. We chose to model the variant with the three subcarriers. The alternative with flat power spectral density would be not much different to filtered white

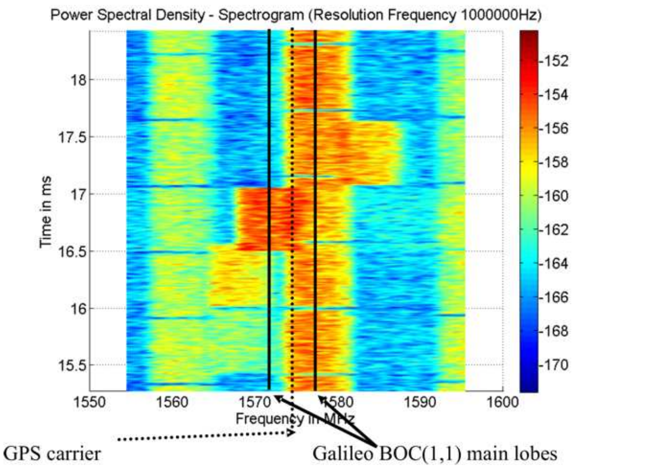

Fig. 3. Using a closer view a time slotted structure is revealed.

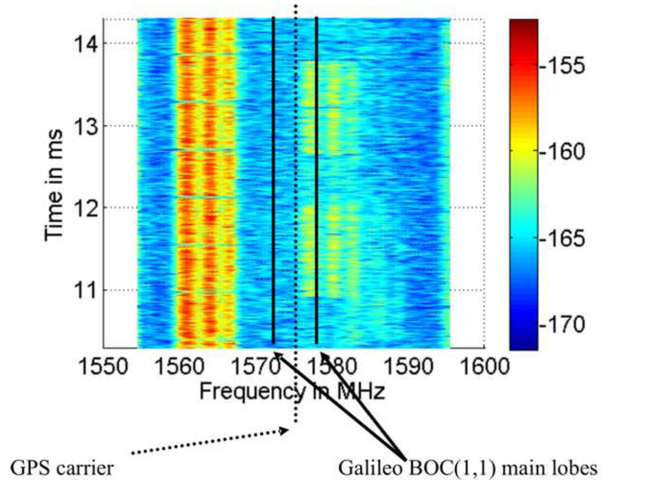

Fig. 4. In some measurements, the frequency occupied by the interference is subdivided into three subcarriers using 2 MHz bandwidth each.

noise where the impact is well documented in standard literature [2][3][4].

We assumed the interference source to be a communication system with 7 MHz bandwidth, three subcarriers with 2 MHz bandwidth each and a time slot duration T_{data} of $552\,\mu s$. Creating first only one subcarrier, using a symbol duration of $T_s = 1/2\,\mu s$ and $g(t)$ to be the the signal of a rectangular pulse shape this leads us to a signal

$$s_{sub}(t) = \sum_{n=1}^{N_{data}} C_n g(t - nT_s) \quad (1)$$

where N_{data} is the number of data symbols in one time slot and C_n the nth complex value from a 8PSK modulation output [5]. Furthermore, one data burst consisting of three subcarriers with an frequency offset $f_{off} = 3\,MHz$ each can be expressed as

$$s_{data}(t) = s_{sub}(t) + s_{sub}(t)e^{j2\pi(-f_{off})t} + s_{sub}(t)e^{j2\pi(+f_{off})t},\ 0 \le t \le T_{data} \quad (2)$$

The baseband signal therefore calculates to

$$s(t) = \sum_{n=-\infty}^{\infty} s_{data}(t - nT_{slot}) \quad (3)$$

with $T_{slot} = 552\,\mu s + 32\,\mu s$.

The alignment of the created data using equations 1 to 3 with the recorded interference is illustrated in figure 5 in time domain and in figure 6 in frequency domain.

3. IMPACT ON SATELLITE NAVIGATION RECEIVERS

In order to assess the impact of the recorded type of interference, we followed a dual approach, using a software GNSS receiver created at DLR and using Novatel and Nordnav hardware receivers connected to the DLR adapted Spirent GNSS signal generator. In both cases, simulations were carried out with worst case assumptions what means that the carrier of the created interference fell right on the GPS centre frequency. In this work, the terms 'acquisition threshold' and 'tracking threshold' are defined as the ratio of C/N0, enabling acquisition in the one and tracking in the other case, of the GNSS signal with the maximum possible RFI, respectively.

3.1. Software Approach

Within this approach, simulations of the GPS or GIOVE-A signal acquisition and tracking have been performed making use of DLR's MATLAB™-based software receiver and GNSS signal generator. The signal records processed in the simulations consisted of the mixture of the GNSS signal (GPS or GIOVE-A), band-limited white Gaussian noise and radio frequency interference signal. The signal records were generated by a GNSS signal generator assuming 4 MHz@3dB IF bandwidth of the receiver RF-Front-End, 4 bit analog-to-digital conversion with a uniform quantifier characteristic, sampling rate of 16 MHz and the intermediate frequency of 4 MHz. The signal records were stored on the PC hard disk in binary format files and were used as input to the software receiver simulations (see Figure 7). Multiple signal records were produced corresponding to different radio interference conditions defined by the interference-to-signal power ratios (ISR) which were in the range of 0 . . . 70 dB. Please note that the GNSS signal power in all records was chosen according to the interference-free carrier-to-noise density ratio (C/N0) of 45 dB-Hz. In every simulated interference scenario, the

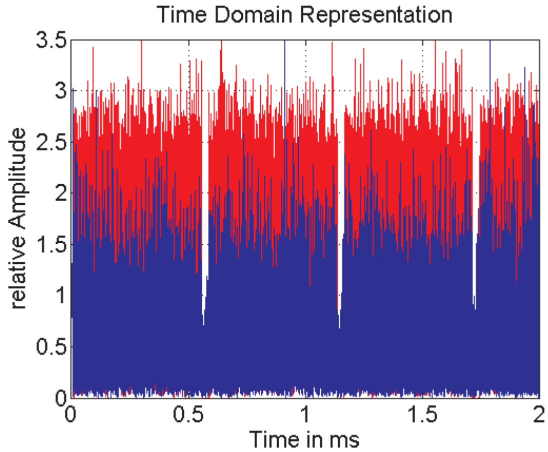

Fig. 5. Modelled interference time representation (red) compared with measured one (blue). Amplitude levels differ for visualisation purpose only.

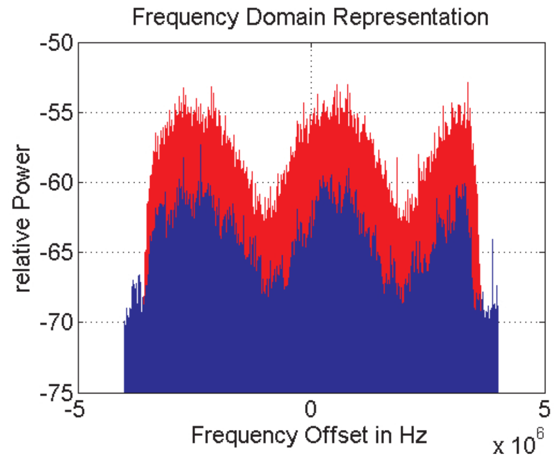

Fig. 6. Modelled interference spectrum (red) compared with measured spectrum (blue). Power levels differ for visualisation purpose only.

radio interference signal appeared first after 2 seconds of the simulation. This allowed us to put the interference into effect in different receiver signal processing operation modes (acquisition, pull-in, tracking) by choosing the offset between the record beginning and the first signal sample actually used by the receiver

The acquisition of the GNSS signals in the simulation was performed utilising an acquisition process consisting of two stages: global maximum search in code and Doppler dimensions at the first stage, and fine Doppler resolution at the second stage. The adopted target detection and false alarm probabilities of the acquisition process were of 99.9% and 0.1% correspondingly.

The signal tracking was realised making use of common DLL and PLL architectures. In order to reach signal tracking with a representative accuracy, two intermediate tracking stages were used in order to enable transition to target integration times and loop filter bandwidth. At the third last tracking stage, PLL and DLL had the following settings:

- PLL: atan phase discriminator, integration time of 10 ms, loop filter bandwidth of 5 Hz;

- DLL: coherent dot product discriminator, spacing between early and late correlators of 1 PRN chip with a GPS C/A signal and 1/3 of PRN chip with the GIOVE-A signal, integration time of 20 ms, loop filter bandwidth of 1 Hz.

In case of the GIOVE-A signal, the data channel signal was used for acquisition because of the code length, 4 ms, that is the same as planned for the use with Galileo L1 Open Service signals, but the pilot channel signal was used for tracking.

3.2. Hardware Approach

A satellite signal simulator system, the Multi-output Advanced Signal Test Environment for Receivers (MASTER), developed by Spirent and DLR [6][7], generates up to 48 digital I/Q-baseband signals corresponding to 48 individual GPS or Galileo satellites, signal multipath and interference. These baseband signals are digitally weighted and combined by an external digital processing device in order to map the individual signals to the elements of an array antenna by considering the phase shifts due to the spatial distribution of the antenna elements (i.e., wavefront generation). After weighting and summing, the digital signals are fed back to the simulator for digital to analog conversion, mixing to a common intermediate frequency, and then final up-conversion to the carrier. This simulator enables research on beam forming algorithms [8] and many other topics related to GNSS receiver algorithms and architectures. But apart from testing beam forming algorithms, DLR's MASTER is also a good choice for interference impact verification especially when combined with an Agilent E8267D arbitrary waveform signal generator.

In this experiment, we used a setup illustrated in figure 7. The interference signal modelled in section 2.2 was generated in software and then fed into the hardware arbitrary waveform generator. The resulting RF signal was then combined with the RF output from DLR MASTER and provided to one Novatel and one Nordnav receiver. Since the two hardware receivers have different needs in terms of active antenna requirements, the power P_M from DLR MASTER was adjusted to have the same carrier to noise density ratio $(C/N_0)_{nom}$ of $45\, dBHz$ on each receiver. The output power P_I of the interference generator was then divided by P_M to get a receiver independent interference to noise ratio (ISR). After setting a

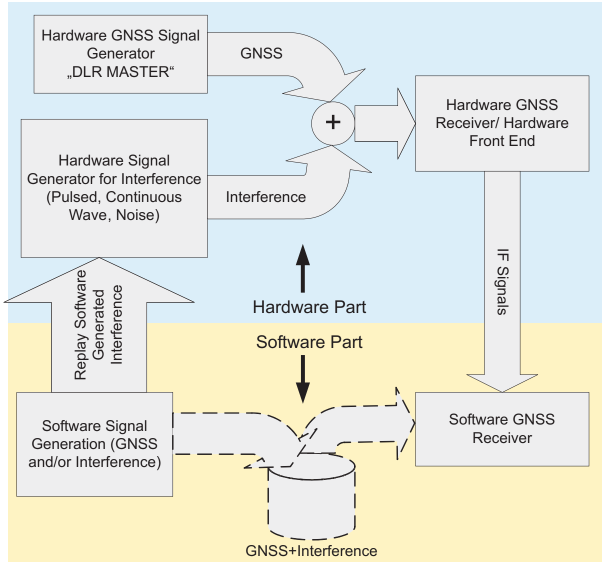

Fig. 7. Hardware/Software setup for interference measurements. Pure software verifications (software generated GNSS signals combined with software generated RFI and fed into a software receiver) as well as pure hardware evaluations and even a mix of both are possible.

specific ISR value, the resulting C/N_0 ratio at the NordNav R30 and the Novatel EuroPak-15a receiver was logged. Then the ISR was increased by 5 dB. If loss of lock occurred, no values were logged. The results of this experiment are discussed in section 4.2.

4. RESULTS

This section follows the structure of section 3, dividing the results in a software and hardware approach. Section 4.1 lists the results of the software evaluation then leading to the hardware part in section 4.2.

4.1. Software Receiver Results

With growing ISR level, the C/N_0 starting with $45\,dBHz$ decreases non-linearly until loss of lock. The software has multiple lock detectors and one of them is a C/N_0 threshold. During these measurements, this was set to $30\,dBHz$. Therefore, all curves with software results end at $30\,dBHz$ where the receiver detected loss of lock. Speaking in ISR values, this corresponds to $35\,dB$ in the GPS and the Galileo case as well. Additional test series were carried out for acquisition threshold determination. From the outcome, we can say that for ISRs beyond $25\,dB$ for GPS and $30\,dB$ for Galileo, acquisition was not possible using the DLR software receiver using the parameter settings listed in section 3.1. The detailed

GNSS signal generator:	Extended Spirent 7790 GNSS Signal Generator (DLR MASTER)
Interference generator:	Agilent PSG E8267D
Hardware receivers:	Novatel EuroPak-15a NordNav R30

Table 1. This hardware was used for assessing the impact on hardware receivers.

graphs are shown in figure 8 and 9 for GPS and Galileo, respectively.

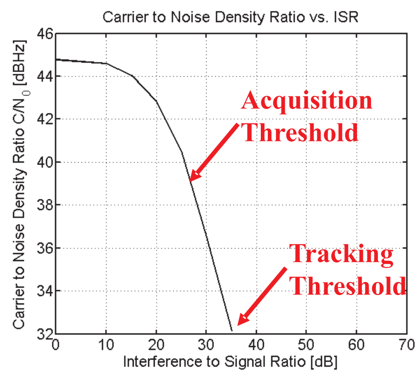

Fig. 8. The C/N_0 ratio decreases with growing interference to signal ratio (ISR) starting at a value of $45\,dBHz$ for no interference. In the GPS case loss of lock is experienced at $35\,dB$ ISR and acquisition is not possible at ISR values beyond $25\,dB$.

Figure 10 and 11 show the code tracking error in metres resulting from a given ISR for GPS and Galileo, respectively. With increasing ISR, the code error increases vastly for values greater than $20\,dB$ in both cases. The maximum code error right before loss of lock is with $2.2\,m$ in the Galileo case much less than $4.5\,m$ in the GPS case.

4.2. Hardware Receiver Results

Using our setup described in section 3.2, figure 12 shows the C/N_0 resulting for a given ISR ratio. For both hardware receivers under test, loss of lock occurred at $40\,dB$ ISR. As indicated within figure 12, extra test series for acquisition lead to different acquisition thresholds, namely $26\,dBHz$ for the Novatel and $33\,dBHz$ for the NordNav receiver.

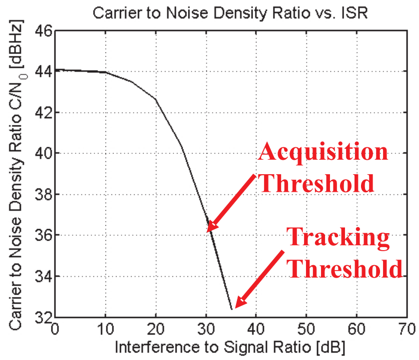

Fig. 9. In the case of Galileo, loss of lock is experienced also at 35 dB ISR, but the acquisition threshold lies at 30 dB. ISR is increased in steps of 5 dB.

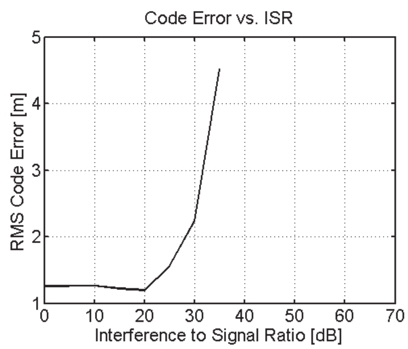

Fig. 10. For the GPS case: The root mean square (RMS) of the code error in metres resulting from the chip error in seconds multiplied with the speed of light. A maximum error of 4.5 metres is reached before loss of lock.

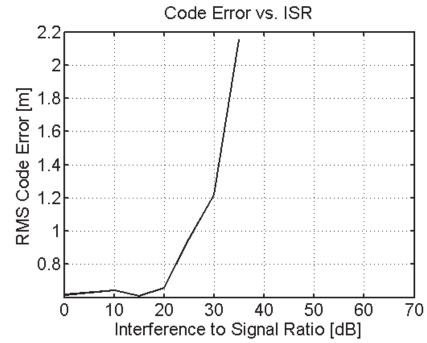

Fig. 11. For the Galileo case: The RMS of the code error reaches a maximum of 2.2 metres before loss of lock.

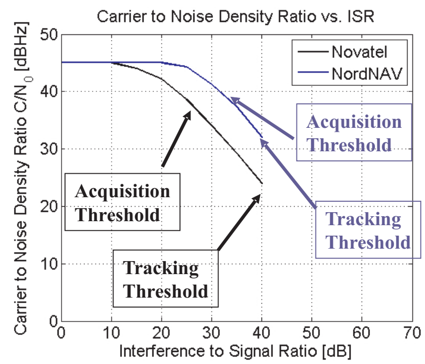

Fig. 12. Results of hardware evaluation for the GPS case using a NordNav (blue) and a Novatel (black) receiver. The figure shows the C/N_0 versus the ISR and the resulting acquisition and tracking thresholds.

5. CONCLUSION

During a measurement campaign carried out within the framework of the Girasole project and funded by GJU, an interference source was identified that may introduce critical interference on future GNSS receivers. In this work, we presented the evaluation results of effects created by this interference source. The evaluation was done with the use of the DLR software receiver and additionally with DLR's hardware simulation environment MASTER.

Figure 13 and table 5 show a comparison of all results with respect to C/N_0 degradation. What can be seen is that the Novatel receiver seems to be most sensitive to this kind of interference. This might be due to a larger front end bandwidth that allows more interference power passing through the filters.

Due to the fact that we do neither know the local origin of the interferer nor the distance to it, a final conclusion of the possible impact can not be given. But the measured RFI level during the measurement campaign was at 42.6 dB ISR and we can assume that the possibility exists to encounter this kind of interference even at less distances than we did at the campaign. The presented simulation results indicate that under such interference conditions a GPS/Galileo L1 mass market receiver can definitely experience problems with acquisition/re-acqusition of the satellite signals and continuous signal tracking.

6. ACKNOWLEDGEMENT

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7. REFERENCES

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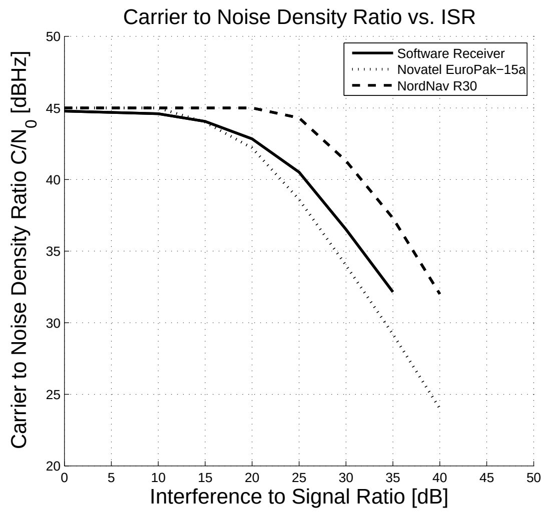

Fig. 13. Comparison of software and hardware results. The software receiver loss of lock parameter (one of multiple loss of lock parameters) was set to 30dB.

	Acquisition Threshold ISR	Tracking Threshold ISR
Software Rx GPS:	25 dB	35 dB
Software Rx Galileo:	30 dB	35 dB
Hardware Rx Novatel:	26 dB	40 dB
Hardware Rx NordNav:	33 dB	40 dB

Measured ISR during campaign: 42.6dB !

Table 2. Comparison of acquisition and tracking thresholds following software and hardware approaches.

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