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R-Mode Noise Investigation Study

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Executive Summary

Position, Navigation, and Timing (PNT) is part of the critical infrastructure necessary for the safety and efficiency of vessel movements, especially in congested areas such as the North Sea. Global Navigation Satellite Systems (GNSS), especially the U.S. Global Positioning System (GPS), have become the primary PNT sources for maritime operations. The GNSS position is used both for vessel navigation and as the position and timing source for other bridge systems, such as Automatic Identification System (AIS). Unfortunately, GNSS is vulnerable to jamming and interference, whether intentional or not, which can lead to the loss of positioning information or, even worse, to incorrect positioning information. The user requirement is for dependable PNT information at all times, even under GNSS jamming conditions. A variety of technological solutions to an alternative PNT system are possible; in the radio frequency (RF) domain we have the so-called "Signals of OPportunity" (SoOP) approach (e.g. [1]). This term refers to the opportunistic use of RF signals, typically communications signals, which exist in the geographical area of the receiver. While these signals are not primarily intended for positioning, a SoOP navigation receiver attempts to exploit them as such. Specifically, if each SoOP can provide a (pseudo) range to the receiver from a known location, a trilateration position solution is possible. Usually, there is no alteration of the SoOP signal. In some instances, minor improvements are initiated to improve the signal's characteristics; for example, synchronizing the signal to a known (and GNSS independent) source of UTC.

The term R-Mode, or Ranging Mode, refers to the use of navigation system communications signals being used as SoOPs or dedicated signals for Alternative Position, Navigation, and Timing (APNT). The Accessibility for Shipping, Efficiency Advantages and Sustainability (ACCSEAS) project included a feasibility study of R-Mode based upon the DGNSS and Automatic Identification System (AIS) broadcasts [2] (also disseminated in [3] and [4]). One result of this study was the suggestion that the potential of R-Mode ranging off of the DGPS/DGNSS signal could be greatly improved by adding one or two continuous wave (CW) signals to the transmission, so that a navigation receiver could track both the message bit edges and the CW signal's phase. Developing a dedicated R-Mode system solves the SoOP transmitter synchronization problem in that the transmitters can all be synchronized to a common clock reference (such as UTC). Another common SoOP problem of having enough transmitters for positioning can be resolved through system planning, to ensure that sufficient signals are available with suitable geometry throughout the desired coverage area.

A formal R-Mode specification has not been developed to date. However, certain things have been set nominally during development efforts. These are:

- The system is designed to work within the 500 Hz channels used in Europe (this is the tighter bound as North America uses 1,000 Hz channel spacing).
- Second, the system is designed to work with 200 bps Minimum Shift Keying (MSK). If the system works at 200 bps which is the widest bandwidth (BW) MSK signal then it will work at 100 bps.
- Nominally, the CW amplitudes are ½ the MSK amplitude at the transmitter.
- Nominally, the CWs are set at ±225 Hz from the channel center.

In the original R-Mode feasibility study [13] we considered the number of stations that it would be possible to receive in the North Sea area to ensure that there were sufficient stations for the positioning application. However, we did not look at the related question; how would introducing a large number of R-Mode broadcasts impact a legacy DGNSS user? The goals of this report are to (1) understand how a legacy MF DGNSS receiver would respond to MF R-Mode transmissions from a single transmitter (experimentation to date shows no evidence of an impact) and (2) to estimate how many such R-Mode signals can be tolerated without significant impact on legacy DGNSS communications performance.

We start with a review of the relevant MF DGNSS standards and specifications that have been disseminated over the past 25 years. In Europe the DGNSS channels are nominally at 500 Hz spacing (283.5 to 325 kHz at integer multiples of 500 Hz spacing); the MSK transmissions being at 100 or 200 bits per second. Furthermore, channel reuse occurs to accommodate the large number of transmitters. Hence, a receiver might receive its desired in-band MSK signal plus an interfering in-band MSK signal, and multiple out-of-band MSK signals. Adding the R-Mode transmissions potentially adds in-band and out-of-band CW signals to the mix. And on top of this is included atmospheric and man-made noise. The Standards do not provide much in the way of noise/interference regulation other than the table of Protection Ratios defining a receiver's minimum response to interfering signals both at the desired channel (0 kHz frequency separation) and for adjacent channels.

A detailed analysis is presented that examines the impact of interference from the added CW R-Mode signals, both in-band and in adjacent bands. This is compared to the interference from MSK signals both in-band and in adjacent bands. In all scenarios, the worst-case is examined (most interference) in order to provide a bound on performance.

All of the analysis has been conducted using the power ratio from the published protection limit tables. These tables specify total allowable interference energy; for our purposes, this means that as long as the total MSK power does not exceed the protection limits, it does not matter if it is one interferer or N interferers, the analysis is the same as if it is a single interferer of the maximum power. And since the ratio of CW power to MSK power remains the same as the number of interferers grows, the only relevant case to examine is that of a single interferer in each band.

It is theoretically possible for an MSK receiver to experience interference from multiple adjacent bands concurrently. The standards reviewed in Section 2 are silent on this; except for the IEC test procedures [5] that seem to explicitly exclude this possibility by only requiring tests with a single interferer. However, setting this aside, we examined the impact of multiple interferers.

For interfering MSK signals, we have found that the in-band interference is at most 18% of the desired signal response, leaving plenty of headroom for noise and other interference. Using the protection ratio signal levels, the adjacent band MSK interferers would generate interference at levels larger than the desired signal response thus inducing bit errors. Since the IEC performance standards require a receiver to operate in the presence of this interference with 0% Word Error Rate (WER), legacy MSK receivers must use digital filtering to reduce the adjacent band interference. A simple digital filter was designed for analysis purposes. When this filter is applied, the only adjacent band signals that have any appreciable interference energy are the first adjacent band (±500 Hz). These bands then contribute interference of about 35% of the desired level, giving a total interference from MSK of 53% of the desired signal.

For the interfering CW signals, the interference energy in all cases is less than that produced by the interfering MSK. We consider the three cases:

- R-Mode being transmitted along with MSK: The worst-case interference to the two CWs at ± 225 Hz is only 6.6% of the error margin.
- Interfering R-Mode in the same channel: The significant protection ratio for this co-channel interference (15 dB) makes the worst-case interference to the two CWs at ± 225 Hz very small 1.2% of the error margin.
- Interfering R-Mode in any of the four adjacent channels, up or down in frequency: The filtering required for a MSK receiver to work with MSK interferers also reduces the CW interference, to 11.4% for each of the two adjacent bands (±500 Hz).

The total interference contribution from the CW signals is thus 24% from interfering signals and another 6.6% from the "desired" CW signal for a total of about 31%, as compared to 53% from the MSK. The total interference from all sources (84%) is still less than the desired signal response and thus should not induce bit errors.

In summary, an examination of a matched-filter version of a standard MSK receiver verifies that adding a CW R-Mode signal does not negatively impact performance of a legacy receiver (as has been observed in field testing). In fact, the CW signals have less impact on the desired MSK signal than an in-band interfering MSK signal at allowable levels. In-band interfering R-Mode signals (from another station on the same frequency) have even less impact.

If however, additional protection for legacy receivers is desired, some options are (there is, of course, other consequences of doing any of these, which need to be considered):

1. Reduce the amplitude of the CW signals.
2. Reduce the spacing of the CW frequencies.
3. Dropping one of the CW signals.
4. Reduce the MSK bit rate.

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1 INTRODUCTION

High precision positioning and timing is now the norm since the introduction of the various Global Navigation Satellite System (GNSS) constellations. Unfortunately, it is known that as a low power, satellite-based system, GNSS are vulnerable to interference (both naturally occurring and manmade); hence, the development of an Alternative Position, Navigation, and Timing (APNT) backup system is recommended.

1.1 Signals of Opportunity

A variety of technological solutions to this backup requirement are possible; in the radio frequency (RF) domain we have the so-called Signals of OPportunity (SoOP) approach. This term refers to the opportunistic use of RF signals, typically communications signals, which already exist in the geographical area of the receiver. While these signals are not primarily intended for positioning or timing, a SoOP receiver attempts to exploit them for such. For positioning users, if each SoOP can provide a pseudorange to the receiver from a known location, a trilateration position solution is possible.

A number of challenges face a SoOP APNT system:

1) Typically, the transmissions are not synchronized either amongst themselves or to a known timing standard:
   - While RF broadcasts are designed to meet/exceed the requirements of some regulatory authority, these performance standards are usually much too imprecise for accurate positioning and timing by today's standards.
   - Synchronization to a known time standard such, as Coordinated Universal Time (UTC), is not usually a requirement for the typical SoOP signal.
   - If by some happenstance the SoOPs are synchronized, this is often achieved by using time derived from the Global Positioning System (GPS); hence, in a GPS denied environment, these signals would appear to be unsynchronized.
2) SoOP transmitters are often not widely spread geographically:
   - Commonly considered SoOP signals (e.g. commercial radio) are often concentrated about regions of high population density, so may not provide wide coverage.
   - Individual SoOP transmitters in a region are often (nearly) co-located (e.g. on a hilltop), limiting coverage.
3) Propagation characteristics of the signal may limit performance:
   - Depending upon the frequency range of the SoOP, this might be line-of-sight limited, or suffer from the effects of multipath including reflections off of the ionosphere (skywave).

In its most general sense, a SoOP system would exploit signals from as wide a frequency band and as many directions as possible as in cognitive radio. For implementation simplicity, research and development efforts on SoOPs have typically focused on one RF band and/or one type of signal. The past 15 years have seen a number of examinations of SoOPs focused on the positioning application. Examples include Amplitude Modulation (AM) radio, cellular telephone signals, digital audio, and television broadcasts (see, for example, [6-13]).

The authors of this report have done previous work on employing differential GPS/GNSS (DGPS/DGNSS) broadcasts as a standalone SoOP positioning system and also in concert with eLoran [14-17]. These investigations argued that the DGPS/DGNSS signal is a good candidate with respect to the three SoOP challenges above:

- While the transmissions are not currently synchronized, being under government control implies that implementing such synchronization for APNT is feasible.
- Intended to provide navigation data to users over a large area, the transmitters are widely spread geographically.
- While these medium frequency signals do suffer from skywave, quite a bit of research has been done on the characteristics of this phenomenon.

These prior efforts also showed that ranging off of the DGPS broadcast is possible, but that the network of DGPS transmitters in the U.S. is too sparse to alone support SoOP navigation at GPS levels of performance. We note, however, that Europe has a higher density of DGNSS transmitters.

1.2 R-Mode

The term R-Mode, or Ranging Mode, refers to the use of navigation system communications signals being used as SoOPs or dedicated signals for APNT. The Accessibility for Shipping, Efficiency Advantages and Sustainability (ACCSEAS) project included a feasibility study of R-Mode based upon the DGNSS and Automatic Identification System (AIS) broadcasts [2] (also disseminated in [3] and [4]). One result of this study was the suggestion that the potential of R-Mode ranging off of the DGPS/DGNSS signal could be greatly improved by adding one or two continuous wave (CW) signals to the transmission, so that a navigation receiver could track both the message bit edges and the CW signal's phase. Developing a dedicated R-Mode system solves item 1 from above, in that the transmitters can all be synchronized to a common clock reference (such as UTC). Item 2 from above can also be resolved through system planning, to ensure that sufficient signals are available with suitable geometry throughout the desired coverage area.

Adding additional signals to an existing service such as DGNSS; however, introduces an additional challenge to the list above regarding a SoOP APNT system:

4) Any change(s) to the SoOP broadcast signal to aid navigation must be done carefully so as to minimize its impact on the legacy users of the signal.

1.3 R-Mode Specification

A formal R-Mode specification has not been developed to date. However, certain things have been set nominally during development efforts. These are:

- The system is designed to work within the 500 Hz channels used in Europe (this is the tighter bound as North America uses 1,000 Hz channel spacing).
- Second, the system is designed to work with 200 bps Minimum Shift Keying (MSK). If the system works at 200 bps which is the widest bandwidth (BW) MSK signal then it will work at 100 bps.
- Nominally, the CW amplitudes are ½ the MSK amplitude at the transmitter.
- Nominally, the CWs are set at ±225 Hz from the channel center.

1.4 Development

Since the original effort, further work has been done on the R-Mode concept.

a) Development of a prototype modulator (see Figure 1) to create/combine the standard DGNSS signal (which uses MSK) with two CW signals as the proposed MF (medium frequency) R-Mode signal:

$$s_{MF\ R-Mode}(t) = s_{MSK}(t) + A_1 \cos 2\pi f_1 t + A_2 \cos 2\pi f_2 t$$

All three of these signals are synchronized to UTC at the modulator through the use of a precise clock (specifically, both the carrier phase and the time of bit transmission for the MSK component; and the phase for each CW signal). To provide flexibility for testing, the prototype modulator was designed so that the amplitudes (A_1, A_2) and frequencies (f_1, f_2) of the two CW signals are fully adjustable.

Current on-air testing has set the amplitudes so that the CW amplitudes are each ½ of the MSK amplitude. This means that the power in each CW signal is ¼ of the MSK power:

$$\text{amplitudes} \left\{ \begin{matrix} \text{MSK} & A \\ \text{CW 1} & \frac{A}{2} \\ \text{CW 2} & \frac{A}{2} \end{matrix} \right\} \qquad \text{powers} \left\{ \begin{matrix} \text{MSK} & \frac{A^2}{2} \\ \text{CW 1} & \frac{A^2}{8} \\ \text{CW 2} & \frac{A^2}{8} \end{matrix} \right\}$$

(for some constant *A*). The CW frequencies are currently set to 225 Hz above and below the carrier frequency of the MSK so as to fall within the RF spectrum requirements for DGNSS in Europe (limited to a 500 Hz channel width).

b) Development of a prototype receiver to simultaneously demodulate the MSK and track the CW phases. This receiver is described more fully in [18], but its details are not relevant to this report.

c) On-air testing of these prototypes along the coastlines of the Netherlands and Germany using the existing transmitters at Ijmuiden, Netherlands and Heligoland, Germany.

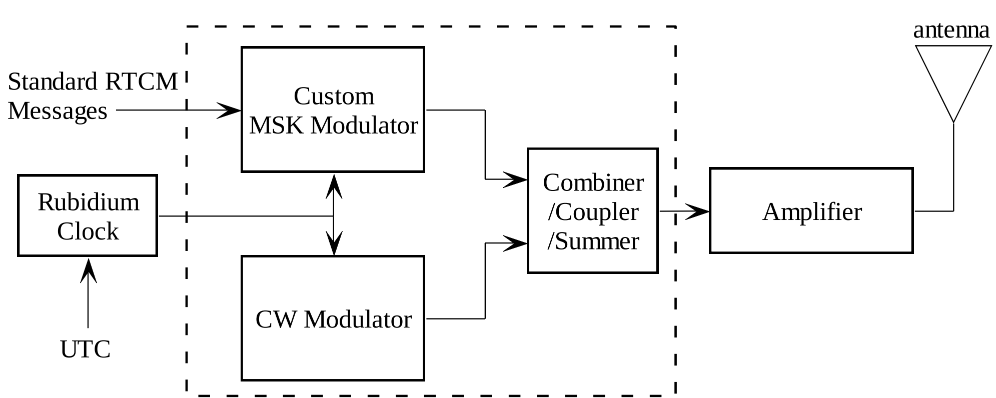

Figure 1: The prototype MF R-Mode transmitter.

1.5 R-Mode Interference

In the original R-Mode feasibility study [13] these authors considered the number of stations that it would be possible to receive in the North Sea area to ensure that there were sufficient stations for the positioning application. However, we did not look at the related question; how would introducing a large number of R-Mode broadcasts impact a legacy DGNSS user?

This report explores this question. The next section contains a review of the relevant MF DGNSS standards and specifications that have been disseminated over the past 25 years; we observe that while sometimes quite detailed, these references do not really address any other use of the band beyond the expected MSK and direction finding signals. To address R-Mode's CW component, we examine in Section 3 how a typical legacy MSK receiver might respond to a CW signal. This evaluation provides some insight into how the original DGPS receiver specifications were written with respect to direction finding beacons. More importantly, in Section 4, it allows us to predict how multiple R-Mode CWs, both from one transmitter and from groups of transmitters, might impact legacy MSK performance.

2 STANDARDS REVIEW

Table 1 lists the national and international standards that we have identified as relevant or potentially relevant to MF R-Mode. Some notes for each standard are presented in the following sections.

Table 1: Relevant International Standards

Number	Standard Number	Title
1	ITU-R M.1178	Use of the Maritime Radionavigation Band (283.5-315 kHz in Region 1 And 285-325 kHz in Regions 2 And 3)
2	ITU-R M.631	Use of Hyperbolic Maritime Radionavigation Systems in the Band 283.5-315 kHz
3	ITU-R M.823	Technical Characteristics of Differential Transmissions for Global Navigation Satellite Systems from Maritime Radio Beacons in the Frequency Band 283.5 - 315 kHz in Region 1 and 285 - 325 kHz in Regions 2 and 3
4	RTCM 10401.2	Differential NAVSTAR GPS Reference Stations and Integrity Monitors (RSIM)
5	IALA Rec. R-121	On the Performance and Monitoring of DGNSS Services in the Frequency Band 283.5 – 325 kHz
6	IALA Rec. R-135	On the Future of DGNSS
7	RTCM 10402.3	Differential GNSS (Global Navigation Satellite Systems) Service - Version 2.3
8	RTCM 10403.1	Differential GNSS (Global Navigation Satellite Systems) Services - Version 3.1
9	COMDTINST M16577.1	Broadcast Standard for the USCG DGPS Navigation Service
10	IEC 61108-4	Maritime Navigation and Radiocommunication Equipment and Systems - Global Navigation Satellite Systems (GNSS) - Part 4: Shipborne DGPS and DGLONASS Maritime Radio Beacon Receiver Equipment - Performance Requirements, Methods of testing and Required Test Results

2.1 Recommendation ITU-R M.1178

Recommendation ITU-R M.1178 [19] (International Telecommunication Union) says very little other than to recommend that the protection ratios specified in ITU-R M.823 [20] are followed "to facilitate coexistence with radiobeacons." It also recommends that protection ratios specified in ITU-R M.631 [21] are followed; however this standard has been withdrawn and suppressed on 4/28/2011. Finally, it recommends "to permit more efficient use of the band, regulatory arrangements should be made to allow for the transmission of maritime navigational information using narrow-band techniques from stations other than radiobeacons."

This recommendation does provide some support for the use of R-Mode in the band, but no direct information relating to noise/interference.

2.2 Recommendation ITU-R M.631

Recommendation ITU-R M.631 [21], which has since been withdrawn as a standard and suppressed as of 4/28/11, sketched out a Hyperbolic navigation system that would operate in the beacon band. The proposed system would use up to 20 unmodulated carriers (CW signals) in the band. So this recommendation provides some precedence for the use of a CW-based R-Mode system in the beacon band, but contained limited information relating to noise/interference.

2.3 Recommendation ITU-R M.823

Recommendation ITU-R M.823 [20] provides a wealth of information about the DGNSS system; however it is primarily concerned with the message formats and the data link. There is very little practical information relevant to noise/interference. About the only RF specification is that carriers are at 500 Hz intervals with a frequency tolerance of ±2 Hz.

2.4 RTCM 10401.2

RTCM Standard 10401.2 [22] (Radio Technical Commission for Maritime Services) provides quite a bit more information on RF specifications than ITU-R M.823. In addition to the 500 Hz carrier spacing it gives requirements for frequency stability better than 4 ppm with less than 1 ppm aging per year. It also sets some requirements for phase discontinuities being less than 0.3 degrees and phase noise for each tone less than -80dB/Hz at an offset of 10 Hz. Also of relevance to R-Mode, it specifies that the bits are synchronized to GPS seconds to within 100 µsec (although this may not be implemented in general as it is unimportant from the communications perspective).

This standard has some useful information relative to R-Mode, but not a lot relative to noise/interference.

2.5 IALA R-121

IALA Recommendation R-121 [23] (International Association of Marine Aids to Navigation and Lighthouse Authorities) has very little relevant information; there is nothing about spectrum or protection levels. It refers to IEC 61108 for technical details.

2.6 IALA R-135

IALA Recommendation R-135 [24] is short with very little technical content but does mention ranging in the beacon band stating that "The feasibility of providing ranging signals giving redundant position-fixing, independent from GNSS, should be investigated." It also mentions that any spectrum changes need to be approved by ITU.

2.7 RTCM 10402.3

RTCM Standard 10402.3 [25] is primarily focused on the message specification and data link and does not really contain anything relevant to noise/interference.

2.8 RTCM 10403.1

RTCM Standard 10403.1 [26] is version 3.1 of the DGNSS message specification and, like the version 2.3 standard [25], is primarily focused on the message specification and data link and does not really contain anything relevant to noise/interference.

2.9 COMDTINST M16577.1

COMDTINST M16577.1 [27], published by the United States Coast Guard (USCG), which is the original DGPS broadcast specification from 1993 contains a lot of information, some of which is repeated in other standards. Some key points from the standard are:

- A "binary 0" is represented by a linear 90 degree phase retard relative to the carrier phase in one bit duration and a "binary 1" is represented by a linear 90 degree phase advance relative to the phase of the carrier in one bit duration.
- The frequency separation between the antipodal binary tones is equal to one-half of the transmission rate.
- The modulation rates chosen assure phase continuity at bit transitions.
- The carrier shall maintain frequency accuracy within plus or minus 6 parts per million (ppm)[1] (e.g., 2 Hz for a 325 kHz broadcast).
- The Single Side Band (SSB) Phase Noise of each tone shall be less than -80 dB/Hz at an offset of 10 Hz.
- All spurious outputs shall be less than -60 dBc.
- The 99 percent power containment bandwidth of the MSK modulated signal is equal to 1.17 times the transmission rate, and the half power bandwidth is given by 0.59 times the transmission rate.
- All broadcast scenarios contain a subcarrier id tone at 1020 Hz above the main carrier. This tone is broadcast solely for the use of Direction Finder (DF) Receivers, which mix it with the main carrier to create a signal that is AM Modulated at a level of 70%. The subcarrier id tone is broadcast at a level, which is 3 dB below the main carrier[2].
- The protection ratios that are relevant to the reception of DGPS are given in Table 2.
- The IFRB (International Frequency Registration Board) has recommended that DGPS transmissions be treated as independent as opposed to composite transmissions when applying protection ratios. Presently, all radiobeacon protection ratios are computed for the main carrier with the effect of the subcarrier inherent in its determination (i.e., the composite method). Since up to three carriers in two different formats will now be

[1] Note that the more recent RTCM Standard [22] "Differential NAVSTAR GPS Reference Stations and Integrity Monitors (RSIM)," Radio Technical Commission for Maritime Services, Arlington, VA, RTCM Standard RTCM 10401.2, 18 December 2006. sets this stability requirement at 4ppm vice 6ppm.

[2] Although this is listed in the 1993 specification, this is not done anymore to the best of our knowledge.

broadcast, the previous method would be overly cumbersome and not explicative in nature. No change is being implemented at this time for computing the protection of Radio Direction Finder (RDF) carriers (which is done in a composite form), even those with DGPS information directly on them (i.e., not dual carriers).[3]

- The protection ratios presented in Table 2 were derived on the basis of a maximum transmission rate of 200 bits per second (bps).
- All 200 bps transmissions are centered at 283 kHz + n(2 kHz) where n is an integer having values of 1 through 21.[4]
- No band limiting/filtering of the transmitted signal is utilized since in the medium frequency range the realization of ideal filters would be difficult to approach and thus intersymbol interference becomes a concern.
- The main emphasis in the determination of the protection ratios was to minimize the cost of the user equipment and to allow effective impulse processing within the framework of the existing marine radiobeacon network.
- To accommodate receiver designs with wide bandwidth burst detection and IF (intermediate frequency) circuitry, as they possess a superior impulse processing capability, a 4 kHz (i.e. plus or minus 2 kHz) bandwidth was considered in the determination of the values of Table 2.
- A DGPS broadcast is protected by the protection ratios of Table 2 at the minimum "wanted signal" field strength of 75 µV/m for its full advertised coverage range.

2.10 IEC 61108-4

IEC Standard 61108-4 [5] (International Electrotechnical Commission) is the standard for testing DGNSS receivers and contains a number of functional requirements repeated here. The DGPS and differential Global Navigation Satellite System (DGLONASS) maritime radio beacon receiver equipment shall:

- Operate in the band of 283.5 to 315 kHz in Region 1 and 285 to 325 kHz in Regions 2 and 3 in accordance with ITU-R M.823 (114/3.1).
- The receiver shall perform to the requirements of this standard while subjected to typical radio frequency interference and noise sources, as follows:
    - atmospheric noise (e.g. local thunderstorms);
    - man-made noise (e.g. own ship, shipyard industrial, etc.);
    - Gaussian noise;
    - interference from Low Frequency (LF) and MF radio stations outside the band.
- Signal quality is deemed acceptable at less than 10% Word Error Rate (WER) and unacceptable with WER>10%, measured over 5 minutes.
- The carrier frequency of the differential correction signal of a radio-beacon station is an integer multiple of 500 Hz (M.823/1.1).
- Frequency tolerance of the carrier is ±2 Hz (M.823/1.2).

[3] It is not totally clear what was meant by this statement in the 1993 standard; no other explanation or guidance could be found on this topic.
[4] This 2 kHz spacing for 200 bps stations is not followed in Europe.

- The receiver shall have a dynamic range of 10 µV/m to 150 mV/m (M.823/1.11). 10 µV/m is the requirement to be met while tracking, 20 µV/m is the requirement for acquisition.
- The receiver shall operate at a maximum bit error ratio (BER) of 1 x10^{-3} in the presence of Gaussian noise at a signal to noise ratio (SNR) of 7 dB in the occupied bandwidth (M.823/1.12).
- The receiver shall have adequate selectivity and frequency stability to operate with transmissions 500 Hz apart having frequency tolerances of ±2 Hz and protection ratios given in Table 2 (M.823/1.14).
- Receivers should be able to decode 200 bps signals in the 20 µV/m-150 mV/m range with no noise with 0% WER over 30 seconds (after 30 seconds settling).
- Receivers should be able to acquire with a SNR of 7dB (in the 99% BW), at a signal level of 75 µV/m.
- Protection against another differential transmission. Given: two signals in band, one wanted and one interfering (300 µV/m MSK modulated at 200 bps), in the absence of noise. With the wanted signal varied in power and frequency in accordance with Table 2, columns 1 and 3, a WER of 0% should be achieved.
- Protection against a radio beacon transmission. Given: two signals in band, one wanted and one interfering (a 300 µV/m continuously keyed carrier), in the absence of noise. With the wanted signal varied in power and frequency in accordance with Table 2, columns 1 and 2, a WER of 0% should be achieved.

Table 2: Published Protection Ratios.

Frequency separation between wanted and interfering signal (kHz)	Protection ratio (dB)	
Wanted:	Differential (G1D)	Differential (G1D)
Interfering:	Radio beacon (A1A)	Differential (G1D)
0	15	15
0.5	–25	–22
1.0	–45	–36
1.5	–50	–42
2.0	–55	–47

2.11 Summary

International standards for DGPS/DGNSS identify the potential signals that can be generated and/or observed in the maritime band [17,18]. In Europe the DGNSS channels are nominally at 500 Hz spacing (283.5 to 325 kHz at integer multiples of 500 Hz spacing); the MSK transmissions being at 100 or 200 bits per second. Furthermore, channel reuse occurs to accommodate the large number of transmitters. Hence, a receiver might receive its desired in-band MSK signal plus an interfering in-band MSK signal, and multiple out-of-band MSK signals. Adding the R-Mode transmissions potentially adds in-band and out-of-band CW signals to the mix. And on top of this is included atmospheric and man-made noise.

The Standards do not provide much in the way of noise/interference regulation other than the table of Protection Ratios (reproduced above as Table 2) defining a receiver's minimum response to interfering signals both at the desired channel (0 kHz frequency separation) and for adjacent channels. (We note that the standards only look to channels offsets up to ±2 kHz based on a receiver front-end bandwidth of 4 kHz.) This table could be applied to the proposed R-Mode method of adding CW signals into the band for ranging by treating them as interfering radiobeacon signals (A1A). The difficulty is that the table of protection ratios is only defined at five points; it is ambiguous on what the protection level is between those points. There are numerous interpretations that could thus be made. Note: the radio beacon signal designation is A1A (single sided amplitude modulated, one channel, aural telegraphy), the DGPS signal designation is G1D (phase modulated, one channel, data transmission).

Based on the information from the standards above, 99% of the MSK power is contained within 1.17*R Hz, where R is the MSK bit rate (see Figure 2 for an illustration of this power spectrum, with R=200 bps). In this figure it is clear that most of the area under the MSK curve is contained within the yellow 99% bounds (it is less obvious visually when plotted on a dB scale which magnifies the small values).

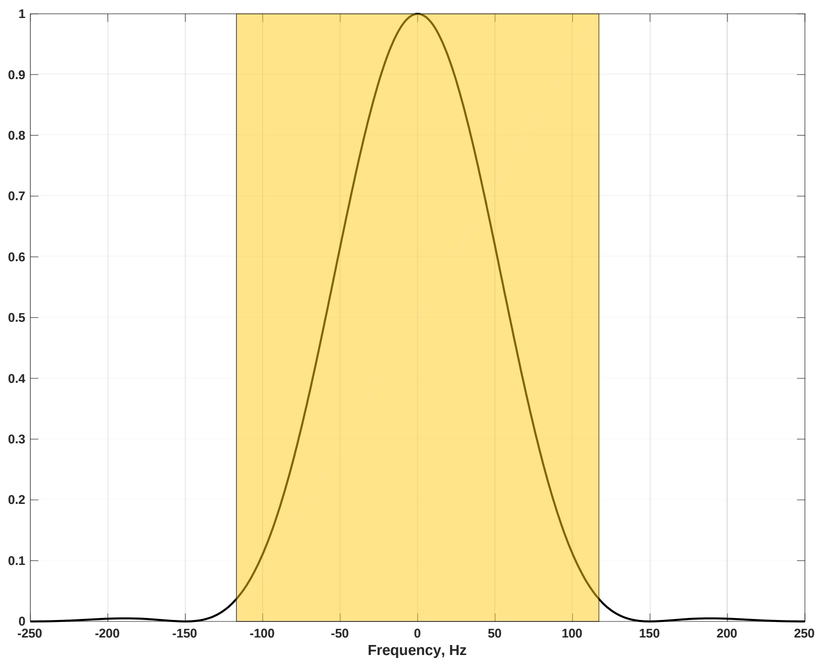

Figure 2: 200 bps MSK signal power envelope with 99% containment BW in yellow.

Figure 3 shows the same 200 bps MSK signal plotted on a dB scale along with the protection limits from Table 2. If we assume that the desired signal is normalized to 0 dB power, then the yellow box shows the power level of 0 dB as well as the 99% bandwidth. The black line shows the power spectral density (PSD) of the desired MSK signal (for 0 dB power, the peak of the PSD is at -18 dB at the center frequency. The protection limits are based on the signal power (which are based on the 99% bandwidth even though the table pins them at just the center frequency), so they are shown as horizontal lines which cover the 500 Hz bandwidth of the channel. Both sets of protection limits are shown; those for G1D in dotted lines, and those for A1A in dashed lines. The PSDs of the interfering signals that correspond to power levels at the protection limits are shown in red for the in-band and blue for the out-of-band (in decreasing line thickness the farther from the band). In each band, the MSK PSDs are shown with dotted lines and the companion R-mode CWs with dashed lines (corresponding to the line type of the green protection limit lines).

For the R-Mode CW signals, the power is equal to $0.5B^2$, where B is the CW amplitude. Since the CW amplitudes are set at half the amplitude of the MSK signal, the power in each CW signal is at -6 dB relative to the MSK power. The CW power levels are indicated in Figure 3 by the vertical lines at the CW frequencies, the height of the line indicating the CW power.

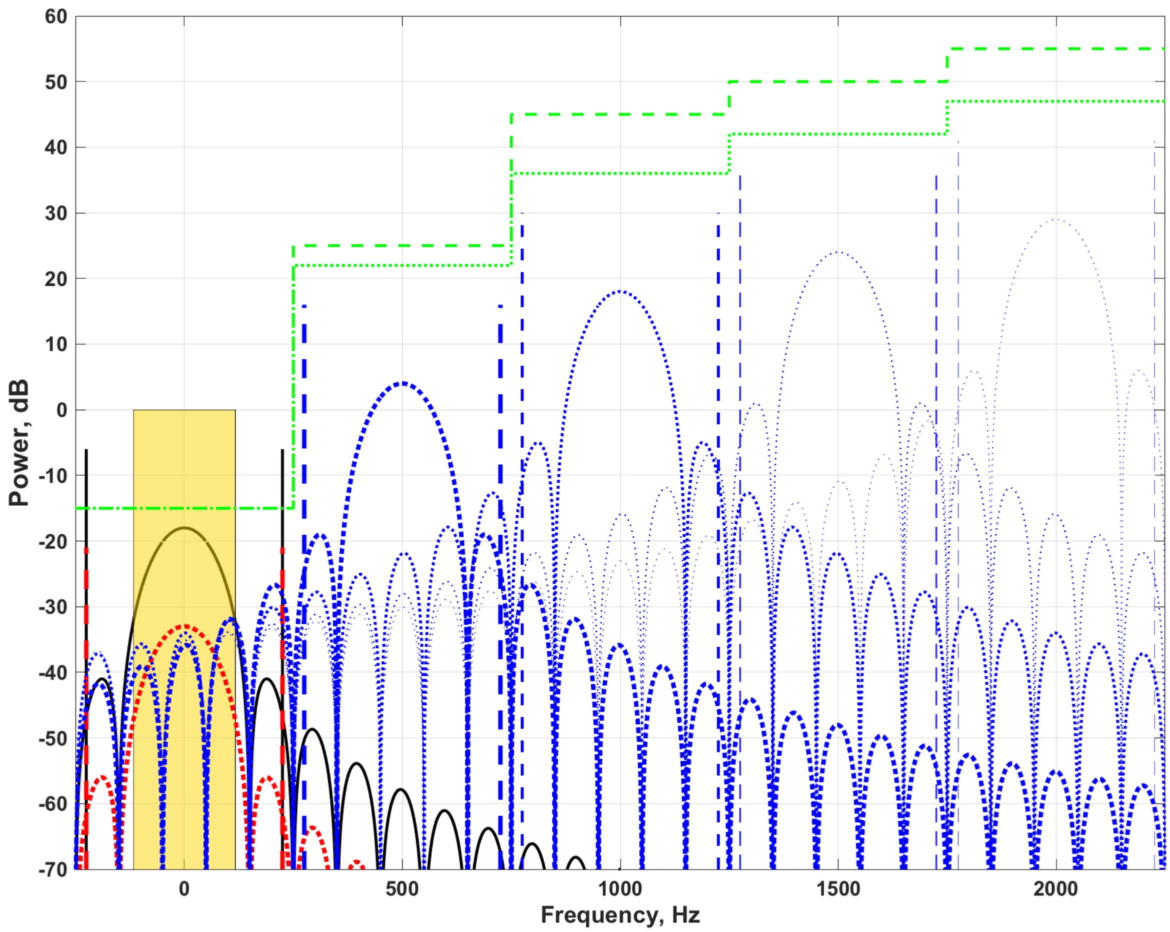

Figure 3: MSK PSDs and CW power plotted in dBs: black = desired, red = in-band interferer, blue = out-of-band interferers. MSK in dotted lines, CW signals in dashed lines. Green horizontal lines indicate protection levels (G1D in dotted lines and A1A in dashed lines). All signals plotted at power of the protection level, relative to a 0 dB desired signal. MSK power measured within the 99% BW as indicated by the yellow box.

3 THEORETICAL IMPACT OF A CW SIGNAL ON LEGACY RECEIVERS

The goals of this report are to (1) understand how a legacy MF DGNSS receiver would respond to MF R-Mode transmissions from a single transmitter (experimentation to date shows no evidence of an impact) and (2) to estimate how many such R-Mode signals can be tolerated without significant impact on legacy DGNSS communications performance. To consider the first question from a theoretical perspective, this analysis begins (in Section 3.1) with a review of a simple MSK receiver algorithm for the actual MSK signal; this analysis also provides insight to the specified protection ratios when it is used to estimate the impact of an interfering co-channel MSK signal (in Section 3.2). Section 3.3 develops the response of this same receiver to a single CW signal; these results are then used to evaluate the worst-case interference due to a single R-Mode transmission (Section 3.4).

3.1 MSK through an MSK receiver

Pasupathy [28] provides a clear introduction to MSK communications. First, he shows that the MSK signal can be written as a form of offset quadrature modulation

$$s_{MSK}(t) = a_I(t)\cos\frac{\pi t}{2T}\cos 2\pi f_c t + a_Q(t)\sin\frac{\pi t}{2T}\sin 2\pi f_c t$$

in which T is the bit interval, f_c is the carrier frequency, and $a_I(t)$ and $a_Q(t)$ are the in-phase (even) and quadrature (odd) bits to be transmitted. Letting b_k represent the binary data stream, values of ± 1, then these are

$$a_I(t) = b_{2k} \qquad (2k-1)T < t < (2k+1)T$$
$$a_Q(t) = b_{2k+1} \qquad 2kT < t < (2k+2)T$$

Note that since the bits are either $+1$ or -1 then the waveform is

$$s_{MSK}(t) = \pm\cos\frac{\pi t}{2T}\cos 2\pi f_c t \pm \sin\frac{\pi t}{2T}\sin 2\pi f_c t$$

or, by a trigonometric identity,

$$s_{MSK}(t) = \pm\cos\left(2\pi f_c t \pm \frac{\pi t}{2T}\right)$$

i.e. a unit magnitude sinusoid (as expected). Further, with this second form it is obvious that the data either advances or retards the sinusoid at frequency $\mathrm{f_c}$ by $\frac{\pi}{2}$ radians (90 degrees) every T seconds. For transmission this signal is scaled to amplitude A (matching the notation in Section 1.4)

$$s_{MSK}(t) = A\cos\left(2\pi f_c t \pm \frac{\pi t}{2T}\right) = Aa_I(t)\cos\frac{\pi t}{2T}\cos 2\pi f_c t + Aa_Q(t)\sin\frac{\pi t}{2T}\sin 2\pi f_c t$$

The channel then attenuates the signal resulting in a smaller amplitude for the received MSK; for simplicity we assume that this is accommodated within the value A.

Pasupathy also shows that an MSK receiver could be implemented by two parallel, but offset coherent demodulation channels, each with a sinusoidal matched filter response of duration 2T seconds (see Figure 4). In this figure the multiplications are by the functions

$$x(t) = \cos\frac{\pi t}{2T}\cos 2\pi f_c t \qquad \text{and} \qquad y(t) = \sin\frac{\pi t}{2T}\sin 2\pi f_c t$$

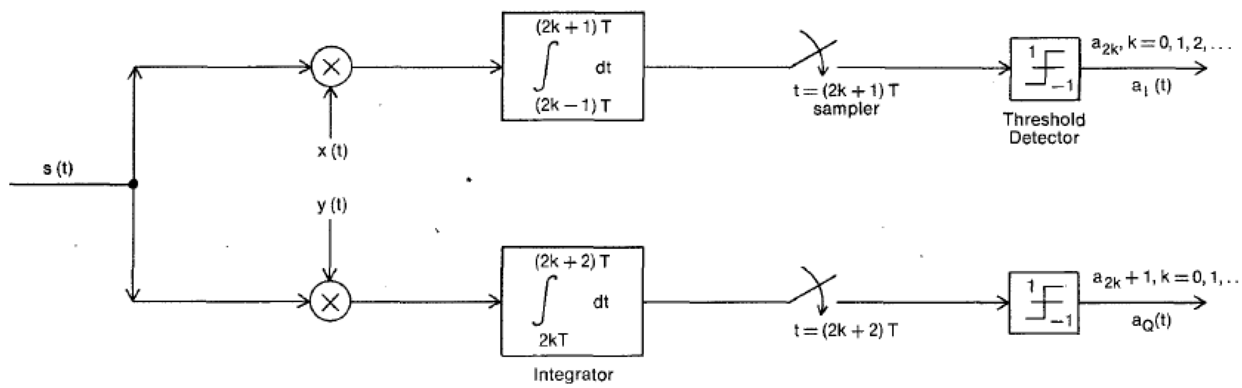

Figure 4: A simple MSK receiver structure (Figure 8 from Pasupathy [28]).

Assuming no noise at the receiver, the output of the top multiplier during the interval $(2k-1)T < t < 2kT$ is

$$z(t) = s_{MSK}(t)\, x(t) = A\, b_{2k} \cos^2 \frac{\pi t}{2T} \cos^2 2\pi f_c t + A\, b_{2k-1} \sin \frac{\pi t}{2T} \cos \frac{\pi t}{2T} \sin 2\pi f_c t\ \cos 2\pi f_c t$$

while during $2kT < t < (2k+1)T$ it is

$$z(t) = s_{MSK}(t)\, x(t) = A\, b_{2k} \cos^2 \frac{\pi t}{2T} \cos^2 2\pi f_c t + A\, b_{2k+1} \sin \frac{\pi t}{2T} \cos \frac{\pi t}{2T} \sin 2\pi f_c t\ \cos 2\pi f_c t$$

Employing trigonometric identities these are

$$z(t) = \frac{A}{2}\ b_{2k} \cos^2 \frac{\pi t}{2T} + \frac{A}{2}\ b_{2k} \cos^2 \frac{\pi t}{2T} \cos 4\pi f_c t + \frac{A}{2}\ b_{2k-1} \sin \frac{\pi t}{T} \cos \frac{\pi t}{2T} \sin 4\pi f_c t$$

for $(2k-1)T < t < 2kT$ and

$$z(t) = \frac{A}{2}\ b_{2k} \cos^2 \frac{\pi t}{2T} + \frac{A}{2}\ b_{2k} \cos^2 \frac{\pi t}{2T} \cos 4\pi f_c t + \frac{A}{2}\ b_{2k+1} \sin \frac{\pi t}{T} \cos \frac{\pi t}{2T} \sin 4\pi f_c t$$

during $2kT < t < (2k+1)T$. The second and third terms in both of these expressions are at frequencies near $2f_c$; hence, are filtered out by the integrator (which operates, essentially, as a low pass filter) and the low pass portions for the combined period, $(2k-1)T < t < (2k+1)T$, are

$$z(t)_{LP} = A\, b_{2k} \cos^2 \frac{\pi t}{2T} = A\, b_{2k} \left(1 + \cos \frac{\pi t}{T}\right)$$

Integrating and sampling, the top sampler's output

$$Z_{2k} \equiv \int_{(2k-1)T}^{(2k+1)T} z(t)\, dt \approx \frac{A}{2}\, b_{2k} \int_{(2k-1)T}^{(2k+1)T} \left(1 + \cos \frac{\pi t}{T}\right) dt = b_{2k} \frac{1}{2} AT = \pm \frac{1}{2} AT$$

is proportional to the transmitted even bit b_{2k}. Following a similar argument, the bottom channel's outputs are proportional to the odd bits

$$Z_{2k+1} = b_{2k+1} \tfrac{1}{2} AT = \pm \tfrac{1}{2} AT$$

and the simple threshold operators at the right of the receiver figure yield the bit stream. If noise and other interference are present we can model the top sampler's output as

$$Z_{2k} = b_{2k}\frac{1}{2}AT + n_{2k} + i_{2k}$$

in which n_{2k} and i_{2k} represent the receiver's response to the noise and interference, respectively (recall that the receiver is linear, so these components are additive). The bits are still perfectly decodable as long as $|n_{2k} + i_{2k}| < \frac{1}{2}AT$; a combined noise and interference component larger than $\frac{1}{2}AT$ in the wrong direction would cause a bit error. As we will refer to this again below, for 200 bps DGNSS this limit is $\frac{1}{2}AT = 0.0025A = 2.5A \times 10^{-3}$.

3.2 Interfering In-Band MSK

The analysis in Section 3.1 can be used directly to describe the response of the MSK receiver to an undesired, interfering MSK signal in the same channel. Imagine that this signal has amplitude A_i, so

$$s_{int-MSK}(t) = A_i \cos\left(2\pi f_c(t-\tau) \pm \frac{\pi(t-\tau)}{2T}\right)$$

in which we include a time shift, τ, recognizing that the interfering signal need not be synchronized with the MSK signal of interest (and, hence, the receiver's matched filter). We wish to compute the response of the top receiver path (multiplier, integrator, and sampler) to it

$$Z_{2k,int-MSK} \equiv \int_{(2k-1)T}^{(2k+1)T} s_{int-MSK}(t)\, x(t)\, dt$$

to see how much effect the interfering signal has on the bit decision. Recall that the definition of a matched filter is that it is the linear system that maximizes the signal to noise ratio at the output of the sampler for the signal of interest. (Equivalently, it is the linear system that maximizes the output of the sample while keeping the noise variance fixed.) Conversely, the maximum output at the sampler for this given filter occurs for a signal proportional to the signal of interest; hence,

$$\max_{\tau} Z_{2k,int-MSK} = Z_{2k,int-MSK}\big|_{\tau=0} = \frac{1}{2}A_i T$$

Further, the response is maximized when the interfering MSK is at the same rate (bps) as the desired one. Table 2 specifies that an in-band interferer must be 15 dB below the desired MSK; i.e. $A_i = A \times 10^{-15/20} = 0.1778\, A$ so that the maximum response at the detector is $\frac{1}{2}A_i T = 4.45A\ \times 10^{-4}$, well below the response to the desired MSK ($2.5A \times 10^{-3}$), a factor of 5.6 larger in fact, leaving some headroom for noise and other interference.

3.3 CW through an MSK receiver

Consider the response of this same MSK receiver to a single CW signal. Specifically, imagine the interfering input to be

$$s_{CW}(t) = B\cos(2\pi f t + \phi)$$

for arbitrary amplitude B, frequency f, and phase offset ϕ. The output of the top multiplier in Figure 4 during time interval $(2k-1)T < t < (2k+1)T$ is

$$
\begin{aligned}
z_{CW,top}(t) &= s_{CW}(t)\,x(t) = B\cos(2\pi f t+\phi)\cos\frac{\pi t}{2T}\cos 2\pi f_c t \\
&= \frac{B}{2}\cos\frac{\pi t}{2T}\cos(2\pi(f-f_c)t+\phi)+\frac{B}{2}\cos\frac{\pi t}{2T}\cos(2\pi(f+f_c)t+\phi)
\end{aligned}
$$

For interfering CW with frequency near f_c (recall that we are really only interested in offending CW within the passband of the DGNSS receiver) then the second term is near frequency $2f_c$ and is removed by the integrator; the low pass portion is

$$z_{CW,top}(t)_{LP} = \frac{B}{2}\cos\frac{\pi t}{2T}\cos(2\pi f_o t+\phi)$$

in which we define the offset frequency $f_o = f - f_c$. Integrating, the sampler output is

$$
\begin{aligned}
Z_{CW,top} &\equiv \int_{(2k-1)T}^{(2k+1)T} z_{CW}(t)\,dt \\
&\approx \frac{B}{2}\frac{\cos(4k\pi f_o T + k\pi + \phi)\sin\left(2\pi\left(f_o+\frac{1}{4T}\right)T+\phi\right)}{2\pi\left(f_o+\frac{1}{4T}\right)} \\
&+\frac{B}{2}\frac{\cos(4k\pi f_o T - k\pi + \phi)\sin\left(2\pi\left(f_o-\frac{1}{4T}\right)T+\phi\right)}{2\pi\left(f_o-\frac{1}{4T}\right)}
\end{aligned}
$$

Since adding an integer multiple of 2π to its argument does not change the value of the cosine function, the two cosine terms in the numerators are identical and

$$Z_{CW,top} \approx \frac{B}{2}\cos(4k\pi f_o T + k\pi + \phi)\left(\frac{\sin\left(2\pi\left(f_o+\frac{1}{4T}\right)T+\phi\right)}{2\pi\left(f_o+\frac{1}{4T}\right)}+\frac{\sin\left(2\pi\left(f_o-\frac{1}{4T}\right)T+\phi\right)}{2\pi\left(f_o-\frac{1}{4T}\right)}\right)$$

While a useful expression, being a function of the frequency offset of the CW, f_o, and the bit interval, T, this expression also contains the nuisance variables k and ϕ. From the perspective of evaluating the impact of CW interference on the legacy output, and recognizing that the receiver processing is linear (meaning that the response due to a sum of inputs is equal to the sum of responses), we are really interested in the maximum absolute value of this response to be sure that it does not cause the MSK receiver to make a bit error (i.e. change the sign of the decision variable). Since the leading cosine term is bounded between -1 and $+1$ for all values of f_o and T, we have

$$\max_k\left|Z_{CW,top}(f_o,T,k,\phi)\right| \le \frac{B}{2}\left|\frac{\sin\left(2\pi\left(f_o+\frac{1}{4T}\right)T+\phi\right)}{2\pi\left(f_o+\frac{1}{4T}\right)}+\frac{\sin\left(2\pi\left(f_o-\frac{1}{4T}\right)T+\phi\right)}{2\pi\left(f_o-\frac{1}{4T}\right)}\right|$$

which removes the dependence on the interval k. To deal with ϕ we evaluate this result for multiple values of ϕ on the range 0 to 2π. Note that an analysis of the bottom path of the receiver yields the same upper bound on the magnitude of its response to the interfering CW.

Assuming that $B = 1$ and $T = 1/200$ (200 bps MSK), Figure 5 shows the magnitude of the receiver's upper path's (the lower path is equivalent) response to a unit amplitude sinusoid on a logarithmic scale versus f_o for multiple values of ϕ. Since the CW phase is unknown, we use the worst case for choice for each offset frequency; the upper envelope of the dark region. The peaks at ± 50 Hz are expected in that these are the frequency offsets that the MSK receiver is looking for when $T = 1/200$ (200 bps MSK). Except for narrow bands about ± 50 Hz, the MSK receiver is quite insensitive to CW interference.

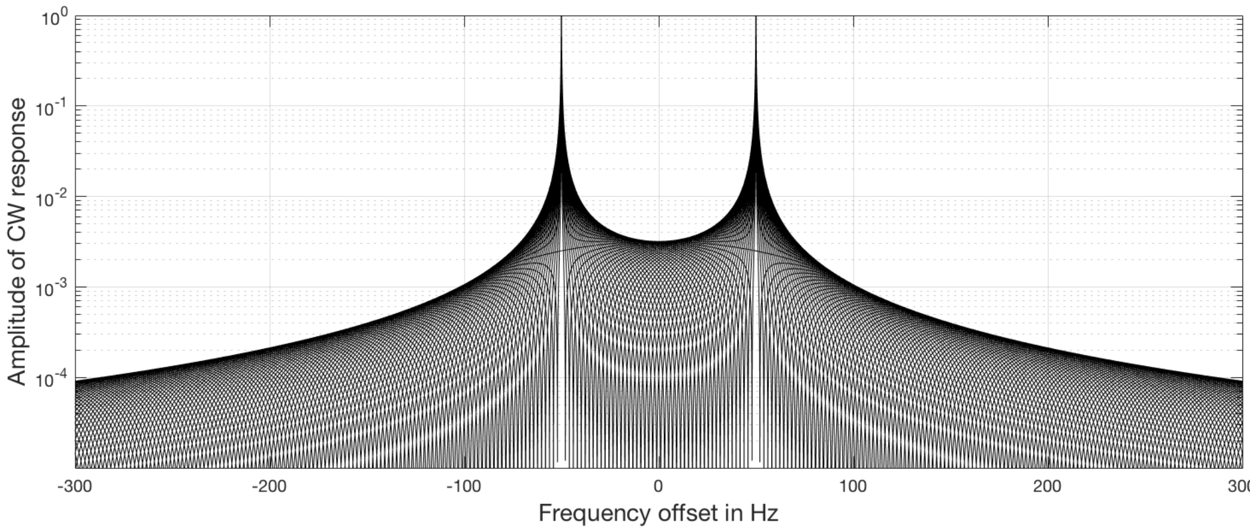

Figure 5: Magnitude response of the receiver to a unit amplitude CW signal.

As an example for interpreting this result, consider the R-Mode CW signal at $f_o = 225$ Hz with an amplitude $B = 0.5A$. Using the computation results in Figure 5, the output due to this single CW is $8.27\,A \times 10^{-5}$ (the maximum filter response from Figure 4 of 1.65×10^{-4} times the CW amplitude $0.5A$). Even with two such CWs, the worst-case impact at the bit detector is $1.65A \times 10^{-4}$, well below the value due to the desired bit ($2.5A \times 10^{-3}$). The computation for other CW frequencies is done in a like manner.

3.4 Impact of a Single R-Mode Transmission

The purpose of the Section has been to consider the response of a legacy MF DGNSS receiver to MF R-Mode transmissions from a single transmitter (we commented at the beginning of this Section that experimentation to date shows no evidence of an impact). To aid in the analysis, recall that since the receiver channels are linear systems, we can add the effects of any interference.

We consider several cases of potential interference to the desired MSK signal: an R-Mode (CW) signal that is being transmitted with the MSK (same transmitter), and an R-Mode (CW) signal that is being transmitted by a different station that is either in the same band or one of four adjacent bands (on either side). In each case, let A represent the received amplitude of the desired

MSK signal. Further, assuming 200 bps MSK, our performance benchmark is how the R-Mode response (at the bit decision point) compares to the amplitude of the receiver's response to the desired signal ($2.5A \times 10^{-3}$). The results are presented in Table 3 with some highlights here:

- R-Mode being transmitted along with MSK: The worst-case interference to the two CWs at ± 225 Hz is $1.65A \times 10^{-4}$, only 6.6% of the error margin of $2.5A \times 10^{-3}$, small when compared to the interference level of a co-channel MSK transmission (18% of the error margin).
- Interfering R-Mode in the same channel: The significant protection ratio for this co-channel interference (15 dB) makes the worst-case interference to the two CWs at ± 225 Hz very small, $2.94\,A \times 10^{-5}$, or 1.2% of the error margin.
- Interfering R-Mode in any of the four adjacent channels, up or down in frequency: In each of these cases the contribution of the two CWs is manageable, at most $7.81\,A \times 10^{-4}$ (found in the first adjacent band) or 31% of the error margin. And these calculations assume no other narrowband filtering (see the discussion in Section 3.5).

In conclusion, as observed anecdotally, a single R-Mode transmission has negligible impact on legacy MSK performance.

Table 3: R-Mode impacts at the linear receiver – in-band signals.

Case	Signal	Value
Desired signal is R-Mode	Amplitude of each R-Mode CW signal, $B = A/2$	$0.5\,A$
	Maximum receiver output due to the two R-Mode CW signals on the desired station ($f_o = \pm 225$ Hz)	$1.65A \times 10^{-4}$
R-Mode interference in the same channel	Amplitude of the interfering, in-band MSK signal (15 dB protection ratio) $A_i = A \times 10^{-PR/20}$	$0.178\,A$
	Maximum receiver output due to the in-band MSK interferer, $R = A_i T/2$	$4.45\,A \times 10^{-4}$
	Maximum receiver output due to the two R-Mode CW signals on the interfering in-band MSK (± 225 Hz), at amplitude $B_i = A_i/2$	$2.94\,A \times 10^{-5}$
R-Mode interference in a channel offset by ±500 Hz	Maximum receiver output due to the two R-Mode CW signals in the first adjacent band ($\pm 275, \pm 725$ Hz), -22 dB protection ratio	$7.81\,A \times 10^{-4}$
R-Mode interference in a channel offset by ±1000 Hz	Maximum receiver output due to the two R-Mode CW signals in the second adjacent band ($\pm 775, \pm 1225$ Hz), -36 dB protection ratio	$5.87\,A \times 10^{-4}$
R-Mode interference in a channel offset by ±1500 Hz	Maximum receiver output due to the two R-Mode CW signals in the third adjacent band ($\pm 1275, \pm 1725$ Hz), -42 dB protection ratio	$4.77\,A \times 10^{-4}$
R-Mode interference in a channel offset by ±2000 Hz	Maximum receiver output due to the two R-Mode CW in the fourth adjacent band ($\pm 1775, \pm 2225$ Hz), -47 dB protection ratio	$4.63\,A \times 10^{-4}$

3.5 Out-Of-Band MSK

In Europe, the DGNSS MSK channels are offset by integer multiples, m, of 500 Hz. Recognizing that the signal delays will vary for different transmitter locations, any out-of-band MSK signal will, in general, not be aligned in time with the signal of interest. Letting τ represent the additional delay, the received signal can be modeled as follows:

- For $(2k-1)T < t < (2k-1)T + \tau$

$$s_{OOB-MSK}(t) = A_i\,\tilde{b}_{2k-2}\cos\frac{\pi(t-\tau)}{2T}\cos 2\pi(f_c + 500m)(t-\tau) + A_i\,\tilde{b}_{2k-1}\sin\frac{\pi(t-\tau)}{2T}\sin 2\pi(f_c + 500m)(t-\tau)$$

- For $(2k-1)T + \tau < t < 2kT + \tau$

$$s_{OOB-MSK}(t) = A_i\,\tilde{b}_{2k}\cos\frac{\pi(t-\tau)}{2T}\cos 2\pi(f_c + 500m)(t-\tau) + A_i\,\tilde{b}_{2k-1}\sin\frac{\pi(t-\tau)}{2T}\sin 2\pi(f_c + 500m)(t-\tau)$$

- For $2kT + \tau < t < (2k+1)T$

$$s_{OOB-MSK}(t) = A_i\,\tilde{b}_{2k}\cos\frac{\pi(t-\tau)}{2T}\cos 2\pi(f_c + 500m)(t-\tau) + A_i\,\tilde{b}_{2k+1}\sin\frac{\pi(t-\tau)}{2T}\sin 2\pi(f_c + 500m)(t-\tau)$$

Note that we have added tildes to indicate the data bits of this undesired signal are not the same as the desired data.

Paralleling the analysis for in-band MSK, consider the output of the top multiplier in the basic MSK receiver. Employing the low pass filter approximation of the integrator's response and myriad trigonometric manipulations, the sampled component due to the interference is

$$
\begin{aligned}
Z_{OOB,2k} \approx & \int_{(2k-1)T}^{(2k+1)T} s_{OOB-MSK}(t)\, x(t)\, dt \\
= & \frac{A_i}{8} \frac{\tilde{b}_{2k-2} + \tilde{b}_{2k-1}}{2\pi 500m} \sin 2\pi(500mt - (500m + 50 + f_c)\tau)\Big|_{(2k-1)T}^{(2k-1)T+\tau} \\
& + \frac{A_i}{8} \frac{\tilde{b}_{2k} + \tilde{b}_{2k-1}}{2\pi 500m} \sin 2\pi(500mt - (500m + 50 + f_c)\tau)\Big|_{(2k-1)T+\tau}^{2kT+\tau} \\
& + \frac{A_i}{8} \frac{\tilde{b}_{2k} + \tilde{b}_{2k+1}}{2\pi 500m} \sin 2\pi(500mt - (500m + 50 + f_c)\tau)\Big|_{2kT+\tau}^{(2k+1)T} \\
& + \frac{A_i}{8} \frac{\tilde{b}_{2k-2} - \tilde{b}_{2k-1}}{2\pi 500m} \sin 2\pi(500mt - (500m - 50 + f_c)\tau)\Big|_{(2k-1)T}^{(2k-1)T+\tau} \\
& + \frac{A_i}{8} \frac{\tilde{b}_{2k} - \tilde{b}_{2k-1}}{2\pi 500m} \sin 2\pi(500mt - (500m - 50 + f_c)\tau)\Big|_{(2k-1)T+\tau}^{2kT+\tau} \\
& + \frac{A_i}{8} \frac{\tilde{b}_{2k} - \tilde{b}_{2k+1}}{2\pi 500m} \sin 2\pi(500mt - (500m - 50 + f_c)\tau)\Big|_{2kT+\tau}^{(2k+1)T} \\
& + \frac{A_i}{8} \frac{\tilde{b}_{2k-2} - \tilde{b}_{2k-1}}{2\pi 100(5m+1)} \sin 2\pi(100(5m+1)t - (500m + 50 + f_c)\tau)\Big|_{(2k-1)T}^{(2k-1)T+\tau} \\
& + \frac{A_i}{8} \frac{\tilde{b}_{2k} - \tilde{b}_{2k-1}}{2\pi 100(5m+1)} \sin 2\pi(100(5m+1)t - (500m + 50 + f_c)\tau)\Big|_{(2k-1)T+\tau}^{2kT+\tau} \\
& + \frac{A_i}{8} \frac{\tilde{b}_{2k} - \tilde{b}_{2k+1}}{2\pi 100(5m+1)} \sin 2\pi(100(5m+1)t - (500m + 50 + f_c)\tau)\Big|_{2kT+\tau}^{(2k+1)T} \\
& + \frac{A_i}{8} \frac{\tilde{b}_{2k-2} + \tilde{b}_{2k-1}}{2\pi 100(5m+1)} \sin 2\pi(100(5m-1)t - (500m - 50 + f_c)\tau)\Big|_{(2k-1)T}^{(2k-1)T+\tau} \\
& + \frac{A_i}{8} \frac{\tilde{b}_{2k} + \tilde{b}_{2k-1}}{2\pi 100(5m+1)} \sin 2\pi(100(5m-1)t - (500m - 50 + f_c)\tau)\Big|_{(2k-1)T+\tau}^{2kT+\tau} \\
& + \frac{A_i}{8} \frac{\tilde{b}_{2k} + \tilde{b}_{2k+1}}{2\pi 100(5m+1)} \sin 2\pi(100(5m-1)t - (500m - 50 + f_c)\tau)\Big|_{2kT+\tau}^{(2k+1)T}
\end{aligned}
$$

a long expression with lots of parameters:

- The amplitude of the interferer, A_i; we can bound this from the protection ratios. In the figures and table below, A is set to 1.
- The carrier frequency of the desired MSK signal, f_c; nominally 300 kHz.
- The time offset, τ; again, we look for the worst case absolute value on the range of the offset, $0 < \tau < T$.
- The data bits on the interferer $\{\tilde{b}_{2k-2}, \tilde{b}_{2k-1}, \tilde{b}_{2k}, \tilde{b}_{2k+1}\}$; without loss of generality, we can set one and allow the others to range over all 8 combinations, looking for the worst case output. (Specifically, we note that the data bits appear only in the coefficients of the output, not in the arguments of the sinusoids, and recall that we are looking for the worst case output *magnitude*; hence, setting one of the bits, say $\tilde{b}_{2k-2} = +1$, if the worst case occurs for a particular choice of $\{\tilde{b}_{2k-1}, \tilde{b}_{2k}, \tilde{b}_{2k+1}\}$ then for $\tilde{b}_{2k-2} = -1$ the same worst case value occurs for a the opposite choice $\{-\tilde{b}_{2k-1}, -\tilde{b}_{2k}, -\tilde{b}_{2k+1}\}$.)
- The offset parameter to the channel of interest, m, specifically, values of 1, 2, 3, and 4.

Running through all possibilities of these parameters yields Figure 6 through Figure 9, where each figure contains the results for one adjacent channel (m = 1,2,3, or 4). Each figure consists of eight subfigures, each of which contains the results for a different bit combination. Each subfigure plots the interference calculation for the time offset across the range of 0 to T.

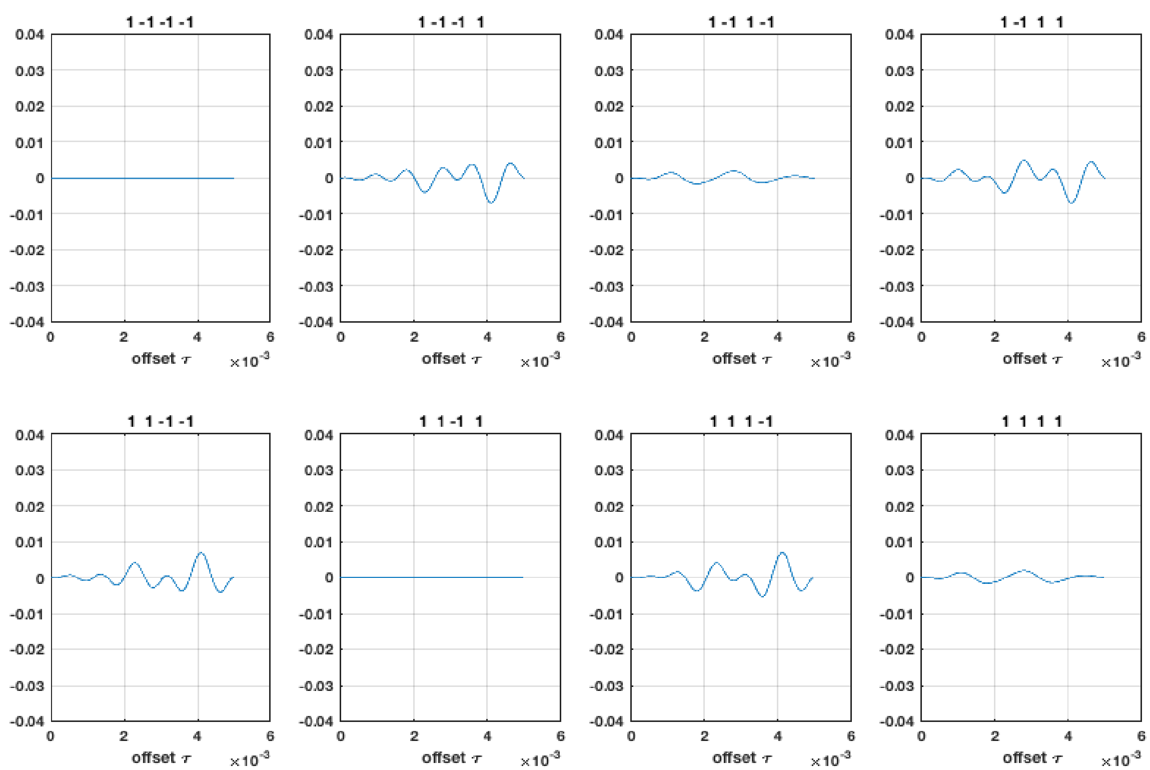

Figure 6: First adjacent band (+500 Hz).

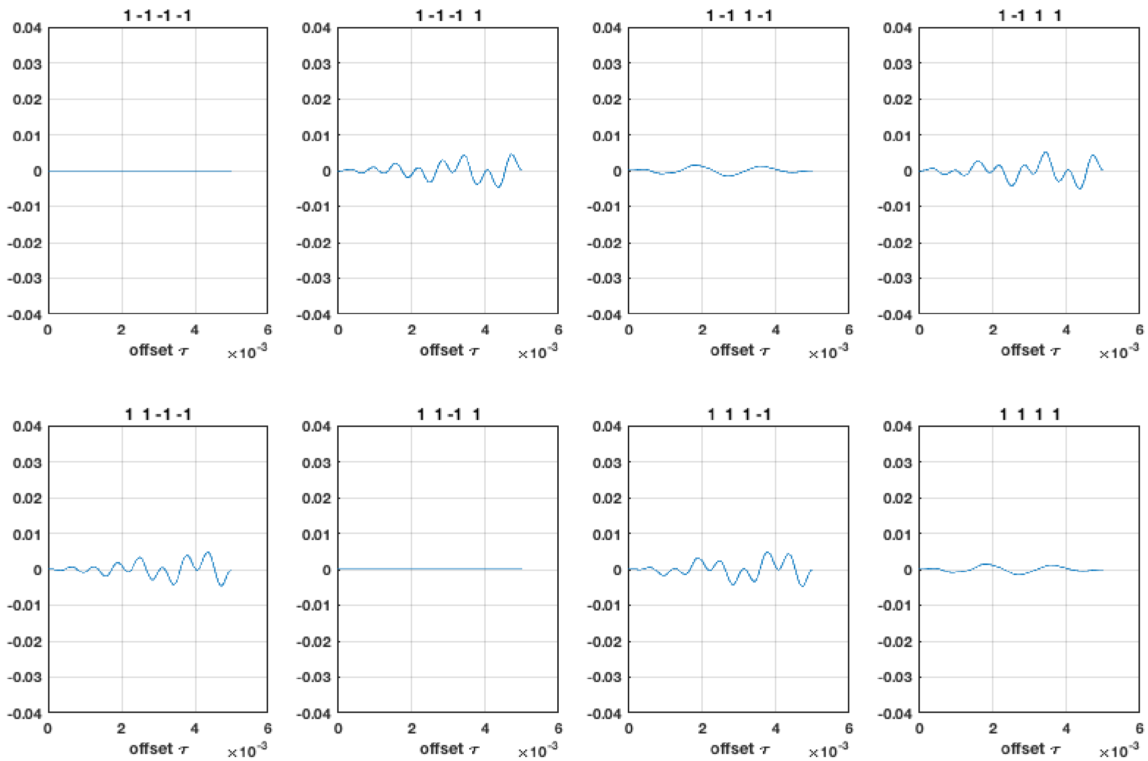

Figure 7: Second adjacent band (+1000 Hz).

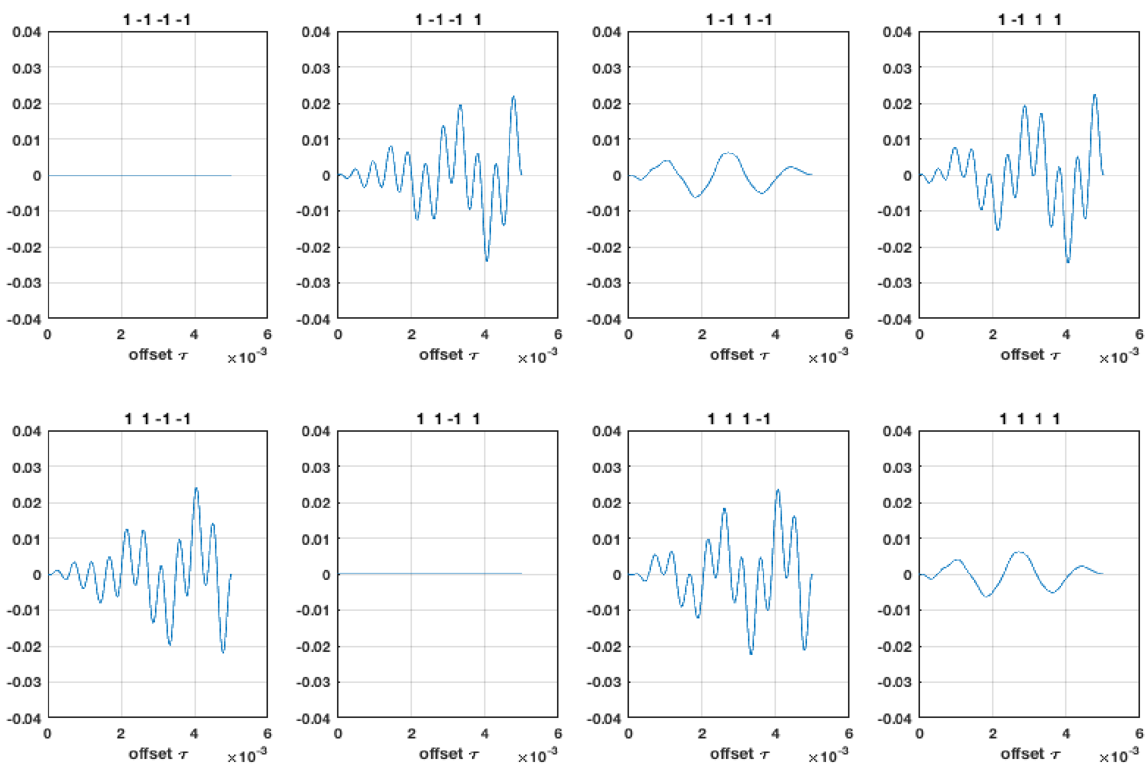

Figure 8: Third adjacent band (+1500 Hz).

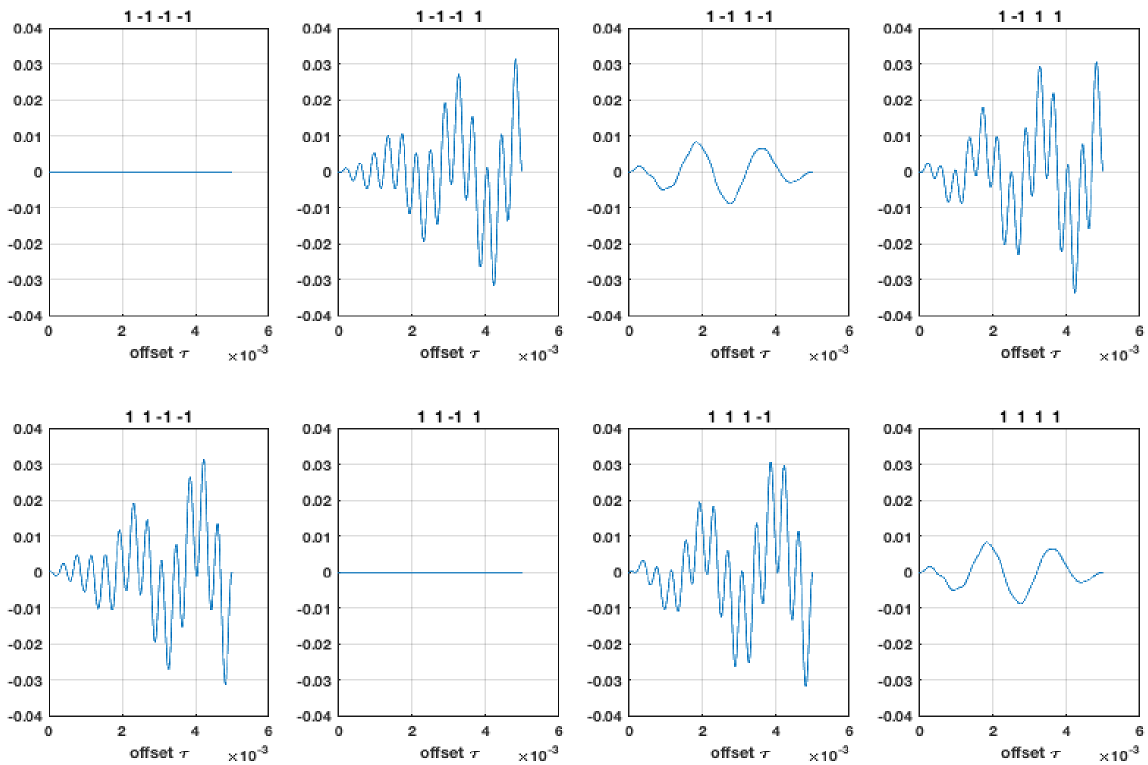

Figure 9: Fourth adjacent band (+2000 Hz).

The maximum impact across the time delay for each of the 8 possible bit patterns for each of the 4 adjacent channels is captured in in Table 4. The maximum of the 8 possible bit patterns for each adjacent channel is highlighted. Interestingly, the worst-case amplitude of the matched filter receiver is **larger** than the response to the desired MSK ($2.5A \times 10^{-3}$).

Our interpretation of this result is that a typical MSK receiver must include *additional* narrowband filtering to remove adjacent channel interference:

- Recall that the matched filter receiver is optimum under the assumption that the signal is received in white noise; there is no accommodation for structured interference. We chose the matched filter receiver in this report in that it would allow for an analysis of the impacts of CW R-Mode.
- A modification to the matched filter receiver would be another linear filter with greater attenuation outside of the ± 250 Hz channel of the desired signal. Recalling that the matched filter's magnitude transfer function is identical to that of the signal, and that almost all of the MSK signal's energy is within the channel, a steeper roll-off outside of the channel would cause negligible change in the output of the sampler due to the mismatch of the signal and receiver. However, this steeper roll-off could greatly reduce the impact of the out-of-band MSK signals.
- Usefully, this steeper roll-off would also help in reducing the component due to R-Mode CW from out-of-channel transmissions.

Table 4: Maximum Interference Across all Time Delays for Each Bit Pattern and Channel offset (*A* was set to 1 in all cases so is not shown).

	Adjacent Channel Offset			
Bit pattern	**+500 Hz**	**+1000 Hz**	**+1500 Hz**	**+2000 Hz**
1 -1 -1 -1	0	0	0	0
1 -1 -1 1	4.06E-03	4.56E-03	2.19E-02	3.11E-02
1 -1 1 -1	1.88E-03	1.45E-03	6.14E-03	8.30E-03
1 -1 1 1	4.75E-03	**5.17E-03**	2.25E-02	3.05E-02
1 1 -1 -1	6.91E-03	4.71E-03	**2.40E-02**	**3.15E-02**
1 1 -1 1	0	0	0	0
1 1 1 -1	**6.92E-03**	4.81E-03	2.35E-02	3.06E-02
1 1 1 1	1.88E-03	1.45E-03	6.14E-03	8.30E-03

If we assume that the interference needs to be limited to no more than that caused by the in-band MSK, $(4.45\,A\ \times 10^{-4})$, then each of the adjacent channels needs to be reduced by filtering by the scale factor listed in Table 5. These scale factors are also listed in dB to aid in the filter design. A digital filter was designed to provide these levels of attenuation; the driving factor is the attenuation in the first adjacent channel. The passband of the filter was set at 250 Hz and the cutoff for the filter was set at 12 dB at 500 Hz. The minimum order Butterworth filter to meet the design criteria is a 3rd order; the magnitude and phase response of this representative filter are shown in Figure 10 and Figure 11 respectively. The response at each of the adjacent channels is listed in the table; in each case the filter provides well beyond the required attenuation. The filtered MSK values are now all below the in-band MSK interference value.

This same filter will reduce the out-of-band R-Mode interference as well. For each CW at ±225 Hz from the center, the attenuation values of the digital filter are listed both in dB and as a scale factor. The scale factors are applied to the R-Mode interference values derived previously (also listed in the table) and the new R-Mode interference values arrived at. These values are all well below the in-band interference values for the MSK signals.

Table 5: Representative filter reductions to adjacent channel MSK and CW signals (*A* was set to 1 in all cases so is not shown).

	Adjacent Channel Offset			
	+500 Hz	**+1000 Hz**	**+1500 Hz**	**+2000 Hz**
Maximum interference	6.92E-03	5.17E-03	2.40E-02	3.15E-02
Scale factor (4.45E-4/max)	0.0643	0.0860	0.0185	0.0141
Scale factor in dB (10log10(SF))	-11.9	-10.7	-17.3	-18.5
3rd order Butterworth Filter	-12 dB	-30.5 dB	-42 dB	-51.5
MSK Interference after Filter	4.37E-4	4.612E-6	1.52E-6	2.23E-7
Percent of allowable (in-band MSK=18%)	17.5%	0.2%	0.06%	0.009%

	Adjacent Channel Offset			
	+500 Hz	**+1000 Hz**	**+1500 Hz**	**+2000 Hz**
CW R-Mode interference	7.81E-4	5.87E-4	4.77E-4	4.63E-4
Filter response at +225/-225 Hz from Adjacent Channel Offset	-1.4 / -21.7	-23.5/ -36.2	-37.4 / -46.5	-47.4 / -55.6
CW R-Mode Scale Factors	7.24E-1 / 6.76E-3	4.47E-3 / 2.49E-04	1.82E-4 / 2.24E-5	1.82E-5 / 2.75E-6
CW R-Mode Interference after Filter	2.86E-4	1.38E-6	4.87E-8	4.85E-9
Percent of allowable (in-band MSK=18%)	11.88%	0.008%	0.00009%	0.000004%

This was just a representative filter for analysis purposes; it is not known what exactly has been implemented by receiver manufacturers. The point is, that in order to meet the Protection Limits for adjacent band MSK interference, digital filtering is required. This same digital filtering reduces the R-Mode (CW) interference as well, to values that are much less than the in-band contribution.

In summary, while it is possible to analyze the matched filter's response to out-of-band MSK, we do not think that the values so obtained are significant to the characterization of R-Mode impact in that a real receiver would yield small responses. The in-band MSK interference analysis, is, however, of value in that it mimics how a commercial receiver would respond, so sets the performance floor for R-Mode interference.

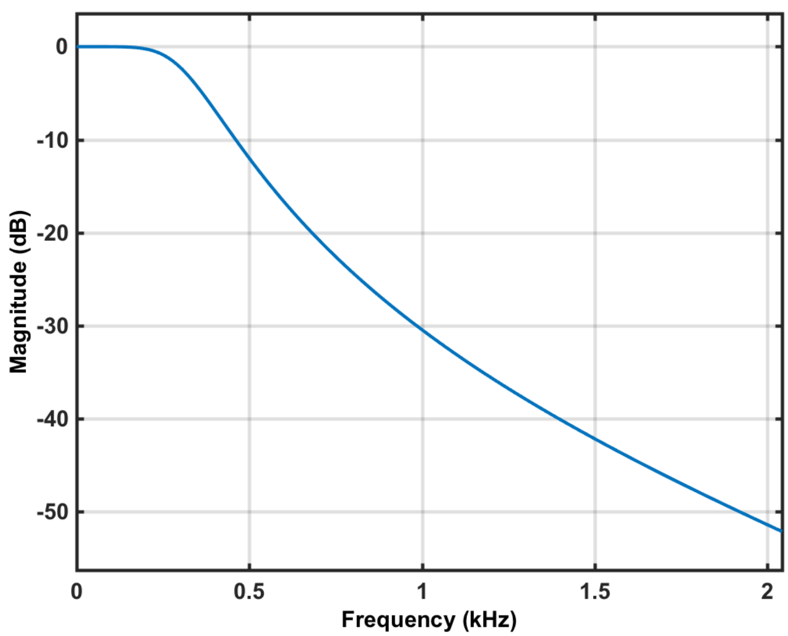

Figure 10: Magnitude response of designed filter.

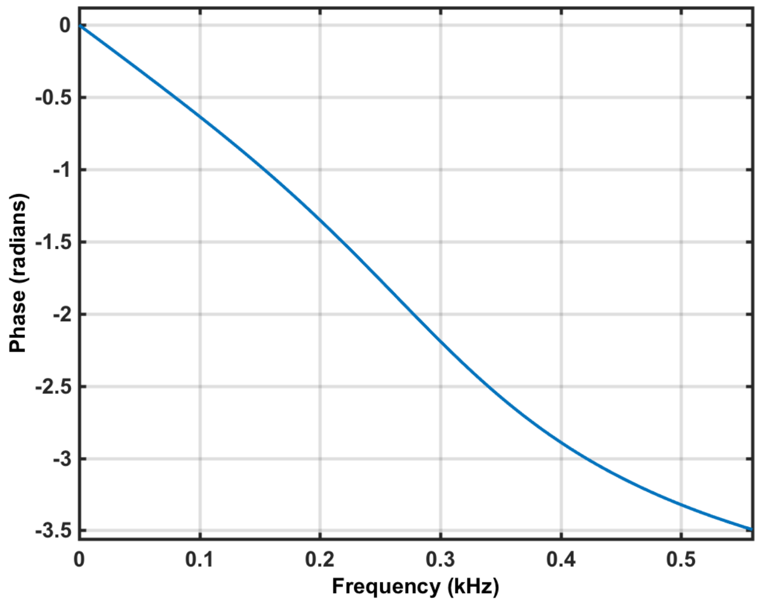

Figure 11: Phase response of designed filter.

4 MULTIPLE R-MODE SIGNALS INTO LEGACY RECEIVERS

The second concern in this work is to estimate how many such R-Mode signals can be tolerated without significant impact on legacy DGNSS communications performance. Since the examined MSK receiver operates in a linear fashion (there could, of course, be non-linear versions of MSK receivers), the results of Section 3 can be extended directly to multiple R-Mode signals.

4.1 Multiple Interferers in a Single Channel

Consider the case of a single interfering signal (whether it is in-band or out-of band is irrelevant at this time). Assume that the signal consists of an MSK signal with amplitude A and two CW signals, each with amplitude $A/2$ which can be written simply as

$$S = Amsk + \frac{A}{2}cw1 + \frac{A}{2}cw2$$

The power in the MSK signal is $\frac{A^2}{2}$ and the power in the CW signals is each $\frac{A^2}{8}$ or a total CW power of $\frac{A^2}{4}$. The ratio of MSK power to CW power is 2.

If there are two interfering signals of the same frequency (due to skywave reception and frequency reuse) then the interfering signal is now

$$S = A_1msk + \frac{A_1}{2}cw1 + \frac{A_1}{2}cw2 + A_2msk + \frac{A_2}{2}cw1 + \frac{A_2}{2}cw2$$

Let us assume for now the worst case of coherent combination and assume that both signals are equally strong (A1 = A2 = A), resulting in

$$S = 2Amsk + Acw1 + Acw2$$

The power in the MSK signal is now $\frac{4A^2}{2} = 2\,A^2$, and the power in the CW signals is each $\frac{A^2}{2}$ for a total CW power of A^2. The ratio of MSK power to CW power is still 2.

This analysis can be extended to any number of interfering signals of the same frequency; the ratio of MSK power to CW power is still a factor of 2. For our purposes, this means that as long as the total MSK power does not exceed the protection limits, it does not matter if it is one interferer or N interferers; the analysis is the same as if it is a single interferer of the maximum power. And since the ratio of CW power to MSK power remains the same as the number of interferers grows, the only relevant case to examine is that of a single interferer, which was examined in Section 3.

4.2 Multiple Channels of Interference

It is theoretically possible for an MSK receiver to experience interference from multiple adjacent bands concurrently. The standards reviewed in Section 2 are silent on this; except for the IEC test procedures [5] that seem to explicitly exclude this possibility by only requiring tests with a single interferer. However, setting this aside, we can examine the impact of multiple interferers.

From the analysis conducted in Section 3 it is clear that MSK receivers must have additional digital filtering around the channel of interest otherwise the adjacent channel MSK signals would generate too much interference to the desired signal. Using the representative digital filter as a guide, only the first adjacent channel has sufficient interference energy to be considered. This suggests limiting attention to a total of three simultaneous interferers (at -500, 0, and +500 Hz). Table 6 collects the interference data from the previous analyses for the cases of MSK and CWs for the three cases. This is then totaled (assuming that the three interferers add coherently; the worst-case scenario). The total is then compared to the desired signal, shown as a percentage. The three MSK interferers would total up to 53% of the desired signal, so should not result in bit errors. The 3 pairs of CW signals would total up to 24% of the desired signal, so have much less impact than the interfering MSK signals. If both are added together, the total is 77% of the desired signal, so still should not introduce bit errors.

This analysis was done just for a representative digital filter; an actual receiver may preform differently. And, the standards do not test for this case of multiple interferers so MSK receivers may actually suffer performance loss in this case.

Table 6: Multiple Interferers.

	MSK	**2 CW Signals**
-500 Hz	4.37E-04	2.86E-04
0 Hz	4.45E-04	2.94E-05
+500 Hz	4.37E-04	2.86E-04
Total	**1.32E-03**	**6.01E-04**
Percent of Desired Signal (2.5E-3)	**53%**	**24%**

To reduce the impact of the R-Mode CW, consider the variables/situation:

- R-Mode CW amplitude (currently set to 0.5 of the MSK amplitude): As developed above, the worst case impact on MSK performance is linear in the amplitude of the CW component; hence, reducing B to something smaller than $A/2$ will improve error protection. However, such a reduction will have a deleterious effect on R-Mode ranging performance.
- R-Mode CW frequency offset (currently ± 225 Hz): The largest terms in the combined CW interference response is from the signals at ± 275 Hz (R-Mode on the adjacent channels; they dominate because the protection ratio is low); making the frequency offset smaller will improve this somewhat as it moves these dominant signals further away from zero in Figure 5. This however could increase the in-band interference and decrease the R-Mode ambiguity resolution performance.
- MSK baud rate: 200 bps has been assumed in the analysis and the protection levels in Table 2 were based on this rate. Decreasing the baud rate to either 100 or 50 bps improves performance in two ways: (1) the desired MSK output increases (it is linear in T) and (2) the response of the receiver to CW drops faster with frequency (the peak responses move to ± 25 or ± 12.5 Hz while the in-band MSK interference response is the same. The analysis was conducted at 200 bps as the worst-case, but in actuality, many European beacons are at 100 bps.
- Number of CW signals per channel (currently 2): Having only one CW would still allow for phase estimation (i.e. ranging) and would reduce interference by a factor of two. During the conceptual state of DGNSS R-Mode, it was envisioned that this second CW signal might facilitate ambiguity resolution. This has not been successful yet in practice, so its removal is a reasonable option. More recently, it has been suggested that the second CW signal could help with skywave detection; of course, the second signal could have reduced amplitude to effectively eliminate much of its impact on legacy MSK.
- Channel frequency: this has no impact on the analysis.
- Channel separation (assumed to be 500 Hz): The channel separation is addressed in the protection table, which again covers the worst-case of 500 Hz separation (as used in Europe). Interference could be reduced by only using R-Mode on channels spaced 1000 Hz apart.
- Day vs night reception: It would seem that we should be concerned with day/night propagation issues; most notably, skywave reflection of distant signals which would increase the number of potential interferers. However, the DGNSS receiver specification directly addresses the protection level of an in-band or out-of-band interferer, not where it is coming from or whether it is the result of one or multiple interferers so this is not a concern.

5 CONCLUSIONS

An examination of a matched-filter version of a standard MSK receiver verifies that adding a CW R-Mode signal does not significantly impact performance of a legacy receiver (as has been observed in field testing) in a noise free environment. In fact, the CW signals have less impact on the desired MSK signal than an in-band interfering MSK signal at allowable levels. In-band interfering R-Mode signals (from another station on the same frequency) have even less impact.

In order to meet performance targets in the presence of adjacent channel MSK interferers at the allowed levels, an MSK receiver requires additional digital filtering. This filtering also reduces the interference from adjacent channel CW R-Mode signals. In fact, the CW interference is significantly less than that of the MSK interference.

The worst-case sum of adjacent bands (-500, 0, and 500 Hz) is 53% from MSK, 24% from CW, and 6.6% from the “desired” CW, for a total of 84% of the desired signal level. Since this is less than the decision threshold, this interference should not cause any bit errors. All of this analysis has ignored other noise sources (atmospheric, man-made, etc.) as the IEC testing standards for interference are structured for no noise (refer back to Section 2.10). We have shown that a legacy receiver should be able to operate error-free with the worst-case interference in this noise-free environment.

If additional protection for legacy receivers is desired, some options are (there is, of course, other consequences of doing any of these, which need to be considered):

1. Reduce the amplitude of the CW signals.
2. Reduce the spacing of the CW frequencies.
3. Dropping one of the CW signals.
4. Reduce the MSK bit rate.

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Acronyms

ACCSEAS	Accessibility for Shipping, Efficiency Advantages and Sustainability
AM	Amplitude Modulation
APNT	Alternative Position, Navigation, and Timing
BER	Bit Error Ratio
BPS	Bits per Second
BW	Bandwidth
COMDTINST	Commandant Instruction
CW	Continuous Wave
dB	Decibel
dBc	Power ratio of signal to carrier in dB
DF	Direction Finder
DGLONASS	Differential GLONASS
DGNSS	Differential GNSS
DGPS	Differential GPS
GLONASS	Globalnaya Navigatsionnaya Sputnikovaya Sistema (Global Navigation Satellite System)
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HZ	Hertz
IALA	International Association of Marine Aids to Navigation and Lighthouse Authorities
IEC	International Electrotechnical Commission
IF	Intermediate Frequency
IFRB	International Frequency Registration Board
ITU	International Telecommunication Union
ITU-R	ITU Radiocommunication Sector
kHz	kiloHertz
LF	Low Frequency
MF	Medium Frequency
MSK	Minimum Shift Keying
ppm	Parts per Million
ppb	Parts Per Billion
PSD	Power Spectral Density
RDF	Radio Direction Finder
RF	Radio Frequency
R-Mode	Ranging Mode
RTCM	Radio Technical Commission for Maritime Services
SNR	Signal to Noise Ratio
SoOP	Signals of Opportunity
SSB	Single Side Band
USCG	United States Coast Guard
UTC	Coordinated Universal Time
WER	Word Error Rate