Cross-Rate Interference and Implications for Core eLoran Service Provision

Jan Šafář[1], Paul Williams[2], Sally Basker[2] and František Vejražka[1]

[1]Czech Technical University, Prague

[2]The General Lighthouse Authorities of the UK and Ireland

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On the Road to eLoran

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- Recent advances in new technology transmitters have brought a significant increase in transmitter efficiency [1], [2] allowing for broadcast of LF signals from smaller towers
  - Reusing of existing assets (DGPS beacons, GWEN) [3]
  - Low power transmitters acting as “gap-fillers”
  - Tactical eLoran [4]
- Demanding system performance requirements
  - Sub-20 m accuracy (2DRMS) for Harbour Entrance and Approach required by USCG
  - Transmitter geometry is crucial

⇩

More stations needed
Cost-effective solutions are available

[1] Hardy, T., “Next Generation LF Transmitter Technology for (e)LORAN Systems,” in *Proceedings of the RIN NAV08/ILA 37th Annual Meeting*, 2008.
[2] Johnson, G. W. et al., “Test and Evaluation of a New eLoran Transmitter,” ditto.
[3] Peterson, B. et al., “Improving Loran Coverage with Low Power Transmitters,” ditto.
[4] Schue, Ch. A., “The Next Generation LF Transmitter and its Impact on Loran, eLoran, and Tactical (e)Loran Systems”, ditto.

What is the problem, then?

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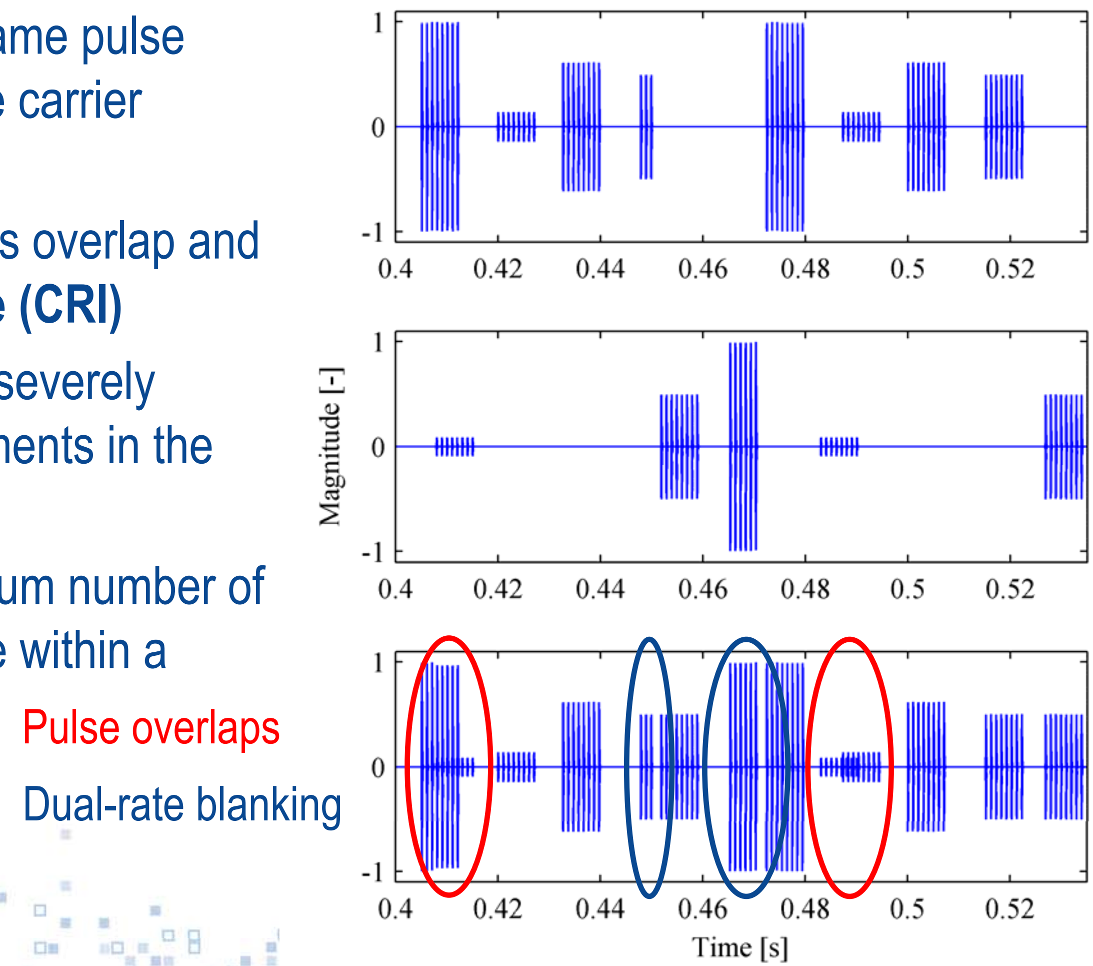
- All Loran transmitters use the same pulse shape broadcasted on the same carrier frequency
- Transmissions of different chains overlap and cause **Cross-Rate Interference (CRI)**
- If left uncompensated, CRI can severely distort Time of Arrival measurements in the receiver
- CRI places a limit on the maximum number of eLoran stations that can operate within a specific geographical area



6731 Lessay vs. 7499 Sylt (Harwich, UK)

What is the Bigger Picture?

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A. How should the new system be configured to make the best of modern eLoran technology?
   - GRI selection procedure (NAV08/ILA37 paper [5])
   - Optimal pan-European eLoran station configurations

B. What is the capacity of the system, in terms of the maximum number of eLoran stations operating within a specific geographical area, given increases in cross-rate interference and a modern receiver's ability to mitigate such interference?
   - Quantifying the impact of CRI on receiver's positioning performance
   - Evaluating Loran Data Channel performance under CRI conditions

[5] Šafář, J. et al., "Group Repetition Interval Selection for eLoran", in *Proceedings of the RIN NAV08/ILA 37th Annual Meeting*, 2008.

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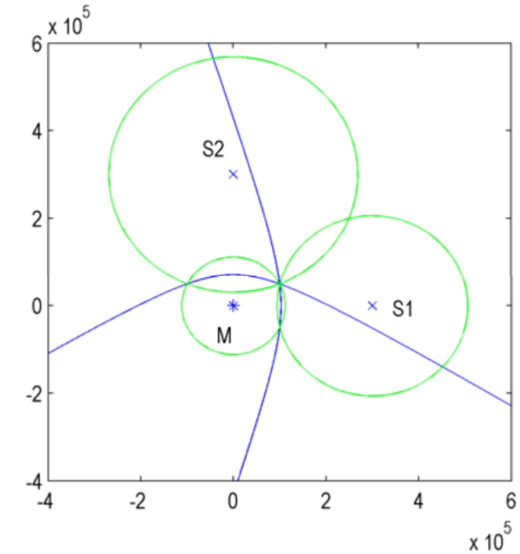
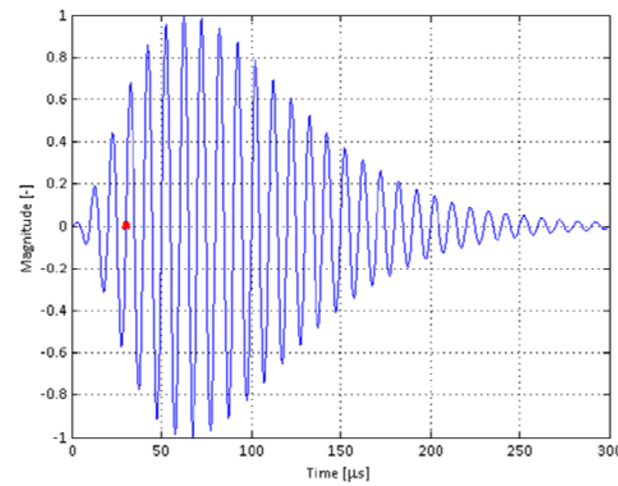
DEVELOPING THE TOOLS

Loran Signal Processing Basics

- Position solution is obtained from Time of Arrival (ToA) measurements of signals coming from at least 3 Loran stations, usually using the Weighted Least Squares (WLS) method
- Signals are acquired using correlation processing
- Coarse ToA measurements are made based on the shape of the pulse envelope
- Precise ToA measurements are based on the estimates of the **carrier phase** of individual Loran ground wave signals at the user position
- All Loran timing measurements should be related to a standard reference point in the Loran pulse – the Standard Zero Crossing (SZC)





Key Determinants of CRI

- CRI is largely deterministic ...
  - System design parameters
    - Group Repetition Intervals, Phase codes, Pulse shape, Number of stations
  - Position-dependent parameters
    - Time alignment between the interfering pulse trains,
      Ground wave signal strengths of (e)Loran stations
  - Signal processing algorithms
    - Averaging, Blanking, Cancelling, Beam-forming, ...
- ... but not entirely ...
  - Sky wave signal strengths
  - Sky wave delay
  - Transmitter related noise
  - ASFs
- Only deterministic factors will be considered in this analysis

Modelling the CRI Induced Errors

1. Unmitigated CRI
   - Phase distortions caused by overlapping pulses
2. Mitigating CRI through Blanking
   - Blanking loss

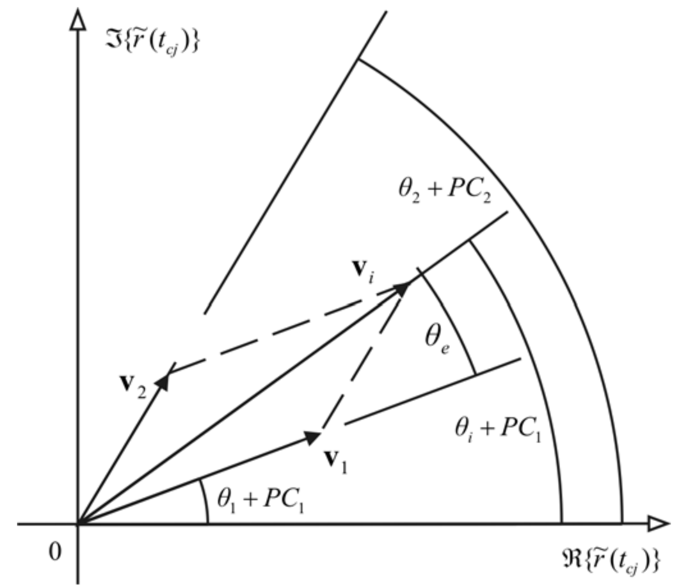
1. Unmitigated CRI

Calculating the Phase Error per One Pulse

- Representing individual pulses by vectors in the I-Q plane
  - show the magnitude of the pulse envelope at a specified sampling time and the carrier phase of the pulse
- The phase error caused by the interfering signal per one desired pulse can be calculated as:

$$\theta_e = \arctan\left\{\frac{m\sin(\theta_2 - \theta_1 + PC_2 - PC_1)}{1 + m\cos(\theta_2 - \theta_1 + PC_2 - PC_1)}\right\}$$

m is a function of signal amplitudes, pulse shape, and time offset between the overlapping pulses

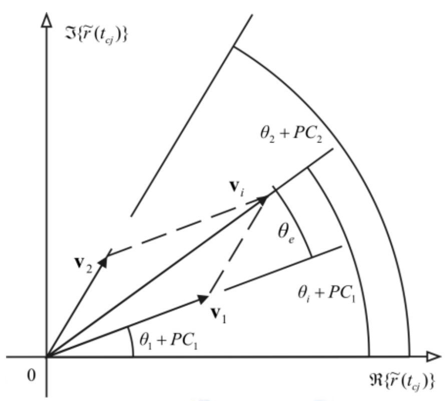


$\mathbf{v}_1$ wanted signal
$\mathbf{v}_2$ interfering signal
$\mathbf{v}_i$ resulting signal, as seen by the receiver

1. Unmitigated CRI

Tracking Error vs. Time

- The phase error, θ_e, is evaluated on a pulse by pulse basis within a sufficiently long time interval
- The average phase error due to CRI after correlating with the corresponding phase code sequence, θ_g, can be calculated in a similar manner based on 16 successive values of θ_e
- The error signal is then filtered by a low-pass filter
  - Smoothes measurement errors, but permits sufficient bandwidth to follow the navigation signal
- The filtered phase error, θ_{g0}, translates directly to an error in the measured ToA / pseudorange



$\xrightarrow{\{\theta_{e,1},\, \theta_{e,2},\, \ldots\}}$ $\theta_g = \arctan\left\{\dfrac{\sum_{n=1}^{16} \rho_n \sin(\theta_{e,n})}{\sum_{n=1}^{16} \rho_n \cos(\theta_{e,n})}\right\}$ $\xrightarrow{\{\theta_{g,1},\, \theta_{g,2},\, \ldots\}}$ LP filter $\xrightarrow{\{\theta_{g0,1},\, \theta_{g0,2},\, \ldots\}}$ ...

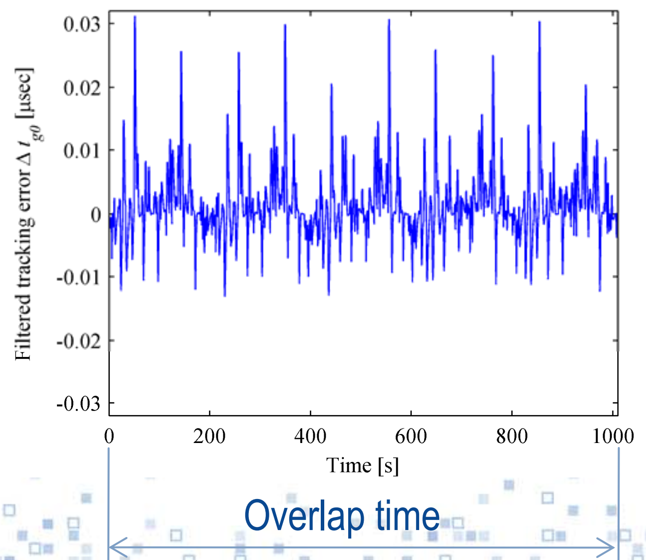
1. Unmitigated CRI

Estimating the Error Statistics

- The presented method allows plotting of the tracking error versus time
- The error signal is periodic in time with period T_o, (the Overlap time): $T_o = \mathrm{lcm}\left(2 \cdot GRI_1, 2 \cdot GRI_2\right) \cdot 10^{-5}\,[\mathrm{s}]$
- The error statistics can accurately be estimated on a time interval of length T_o
  - Verified by comparing with experimental data measured on commercial Loran receivers in [6]
- Using the error statistics for each station used in the position solution, 2DRMS position error due to CRI can be calculated

$\{\theta_{g0,1}, \theta_{g0,2}, \ldots\}$

...



Estimate error statistics

var[Δ**PR**]

E[Δ**PR**]

Position error calc.

2DRMS Error

Repeat the procedure for each station used

...

Transmitter geometry

[6] Zeltser, M. & El-Arini, M., "The Impact of Cross-Rate Interference on LORAN-C Receivers", *#IEEE_J_AES#*, 1985, *AES-21*, 36-46

2. Mitigating CRI by Blanking

- Unmitigated CRI is a serious source of interference to Loran
  - In typical conditions the theory gives ~10 m 2DRMS error due to CRI
- In order to meet the eLoran accuracy requirements for maritime HEA (20 m DRMS), the use of receiver CRI mitigation algorithms seems necessary
- With Blanking, the receiver **detects** the pulses likely corrupted by CRI and **discards** them
  - Blanking achieves the best reduction of CRI-induced noise, but ...
  - The percentage of discarded pulses may be rather high ➔ signal-to-atmospheric noise ratio may drop significantly
- How high is the attendant blanking loss in practical situations?

2. Mitigating CRI by Blanking

Evaluating the Blanking Loss

- Counting the number of overlaps per overlap time of two rectangular pulse trains
  a. "Brute Force" Approach

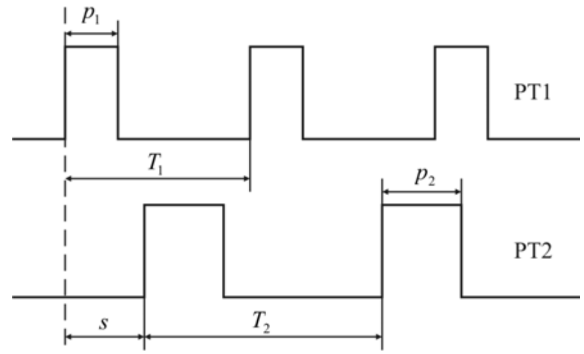
     $$t_{cj} = c \cdot GRI_1 \cdot 10^{-5} + j \cdot 10^{-3} + d_0$$

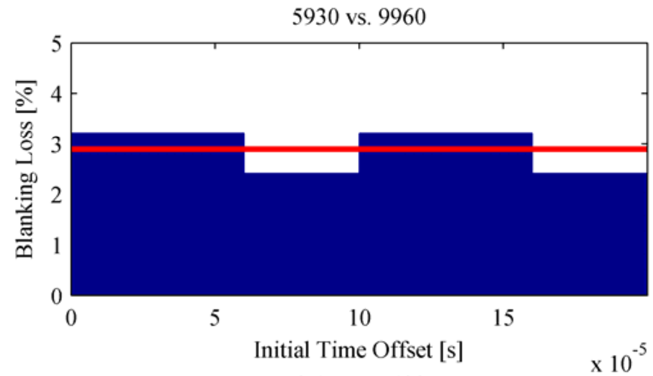
     - Rather computationally demanding

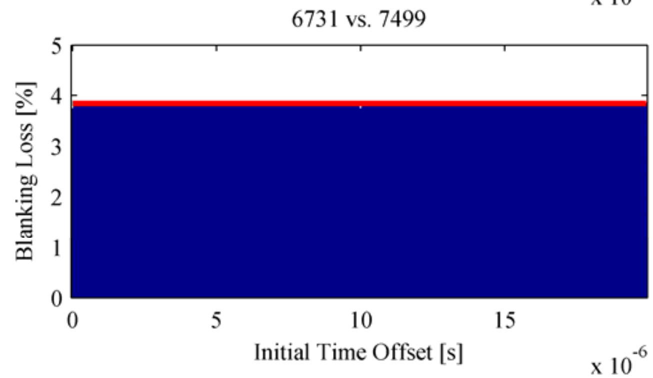
  b. Statistical Approach
     - Elegant, easy-to-use formulas
     - Only average values over all possible time offsets between the signals

  c. Number-Theoretic Approach
     - Theory of linear congruences
     - Exact results for any given time offset
     - Computationally efficient

- Transmitter dual-rate blanking
  - Pulse widths and number of pulses per period need to be adjusted accordingly







2. Mitigating CRI by Blanking

Effect of Blanking on Receiver's Performance

- Traditional approach to coverage prediction is amended to account for the blanking loss
- Blanking loss, L_{bl}, is the portion of pulses from a specific station hit by CRI, calculated using one of the methods described earlier
- SNR debit due to blanking:

$$D_{bl,dB} \approx 10\log_{10}\frac{1}{1-L_{bl}}$$

$$SNR_{proc,dB} = SNR_{pulse,dB} + G_{aver,dB} - D_{bl,dB}$$

- Pseudorange variance due to atmospheric noise [7]:

$$\sigma_i^2 = c_1 + \frac{337.5^2}{SNR_{proc,i}}\,[\mathrm{m}^2]$$

- Measurement covariance matrix, Geometry matrix ➔ 2DRMS error

[7] Lo, S.; Peterson, B.; Boyce, C. & Enge, P., "Loran Coverage Availability Simulation Tool," *in Proceedings of the RIN NAV08 / ILA 37th Annual Meeting,* 2008

CASE STUDY

1. Unmitigated CRI

Position Error Due to Unmitigated CRI in Europe

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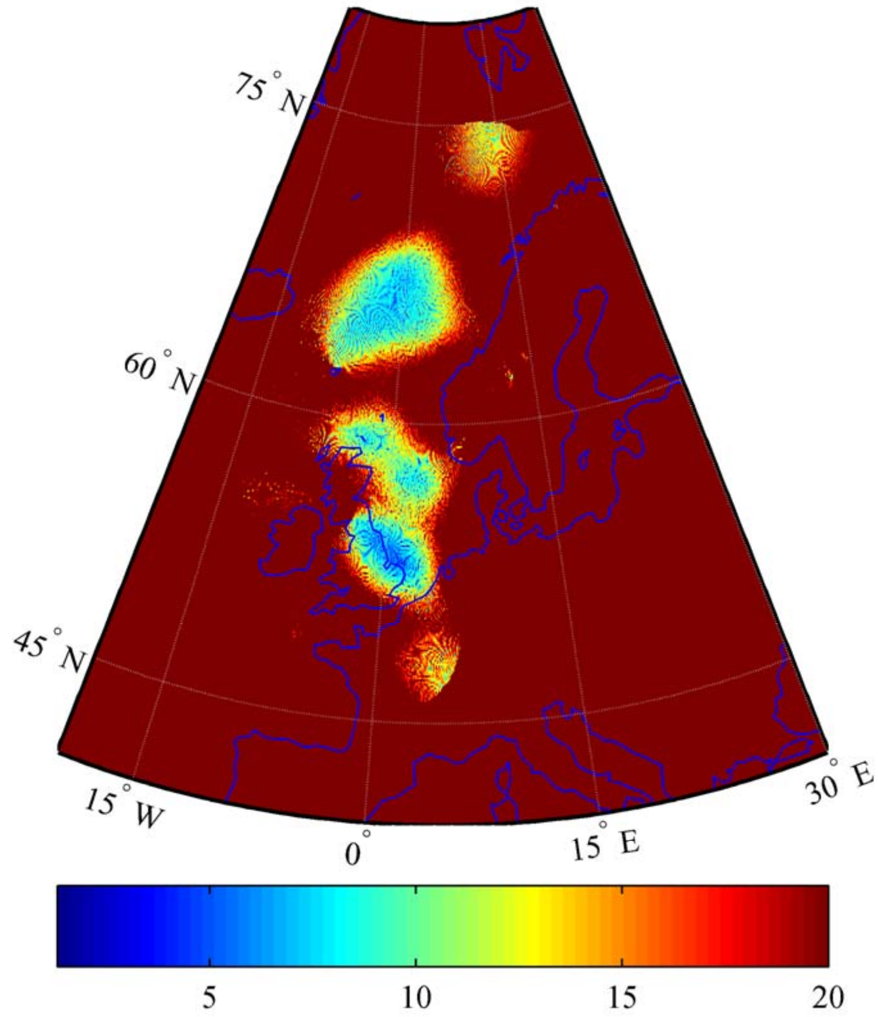
- 9 transmitters (14 stations) configured into 4 chains
- Area of sub-20 m accuracy was estimated using the traditional model first
- Error statistics for individual stations were estimated according to the model of unmitigated CRI described earlier
- Position error due to CRI was calculated

➔ Meeting the stringent eLoran accuracy performance standards require implementing CRI mitigation algorithms in eLoran receivers



2. Mitigating CRI by Blanking

Evaluating the Blanking Loss in Europe

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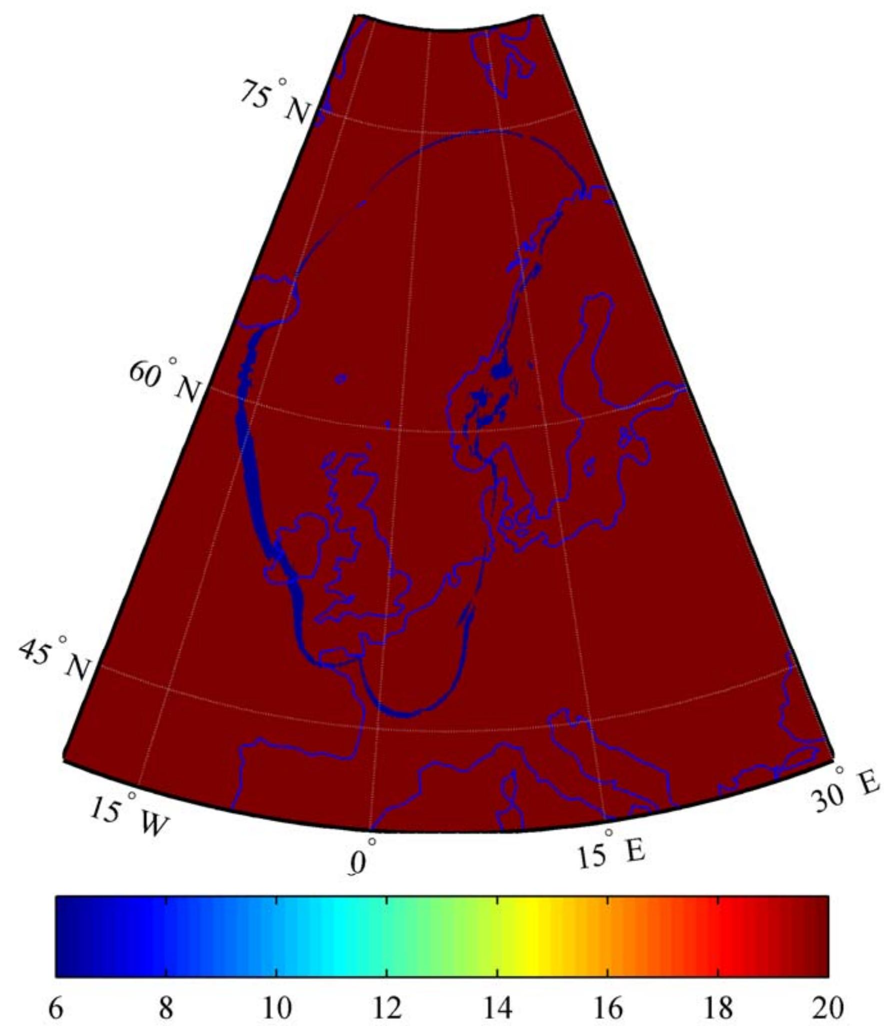
GRI ID and Station Name	$L_{b,DR,num}$ [%]	$L_{b,num}$ [%]	$L_{b,stat}$ [%]	$D_{b,approx}$ [dB]
6731 Lessay	0.00	32.81	32.81	1.7
6731 Soustons	0.00	36.65	36.65	2.0
6731 Anthorn	0.00	36.65	36.65	2.0
6731 Sylt	13.06	45.87	45.88	2.7
7001 Bø	10.87	49.10	49.11	2.9
7001 Jan Mayen	10.87	49.10	49.11	2.9
7001 Berlevag	0.00	41.43	41.43	2.3
7499 Sylt	0.00	37.97	37.98	2.1
7499 Lessay	14.54	52.51	52.53	3.2
7499 Værlandet	0.00	39.05	39.05	2.2
9007 Ejde	0.00	40.98	40.98	2.3
9007 Jan Mayen	0.00	36.86	36.86	2.0
9007 Bø	0.00	36.86	36.86	2.0
9007 Værlandet	13.06	50.19	50.21	3.0

➔ Approx. 6% reduction in the region of sub-20 m accuracy compared to the traditional model



FUTURE WORK

Future work

- Sky wave borne CRI might be a significant factor, which has not yet been accounted for in the current models
- Benefits delivered by current eLoran technology should be further explored
  - Advanced signal processing methods for CRI mitigation (cancelling, ...) and their limitations
- Possible alterations to the signal structure might be considered
  - GRI reassignment in Europe?
  - New phase codes??
- Pursue the long term goals
  - Evaluating the core eLoran service capacity
  - Identifying the optimal pan-European eLoran station configuration

Summary

- Models have been developed to describe the effects of CRI on (e)Loran positioning performance
- It has been shown that unmitigated CRI is a serious source of interference to Loran
  - CRI induced errors change rapidly in time and are highly uncorrelated in the position domain
  - The accuracy target for maritime HEA seems not achievable without employing receiver CRI mitigation algorithms
- The possibility of mitigating CRI within the European Loran network through blanking the interfering pulses at the receiver end has been analysed
  - For some stations **over 50% of pulses have to be discarded** (not accounting for the effects of sky wave borne CRI)
  - North-west Europe: approx. 6% reduction in the region of sub-20 m accuracy compared to the traditional model (geometry seems to be an important factor)
- Introducing measures to mitigate CRI should be the top priority in the design of the new eLoran system
- Tools are being developed, which allow us to reveal the limitations imposed by CRI and demonstrate the benefits to be gained from possible changes to the system configuration

Thank you!

Jan Šafář

Czech Technical University, Prague

+420 728 460 848

safarja1@fel.cvut.cz

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