Very low frequency (VLF) time and frequency transfer signal analysis using KiwiSDR recordings

http://kiwisdr.com/

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https://en.wikipedia.org/wiki/Anthorn_Radio_Station

https://github.com/jmfriedt/kiwisdr_timetransfer

February 1, 2026

Outline

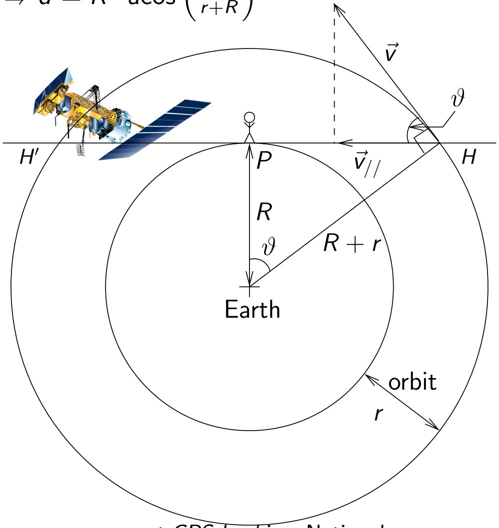
1. Why VLF communications, and which transmitters in Europe for time transfer?
2. Performance of VLF time-transfer transmitters
3. The case of (e)LORAN transmitters... in Europe and all over the world (thanks to KiwiSDR)
4. eLORAN analysis: CRC, FEC, payload structure
5. Results

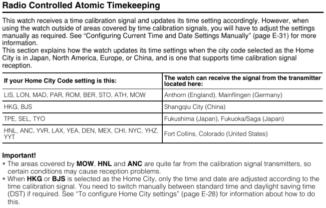
VLF time and frequency transfer

Earth radius R so emitter at altitude r communication range: $\Rightarrow d = R \cdot \mathrm{acos}\left(\frac{R}{r+R}\right)$

Long-range time and frequency transfer techniques:

- Global Navigation Satellite systems: $r = 20000$ km
  $\Rightarrow d \simeq 8500$ km
- geostationary satellite relay: $r = 36000$ km
  $\Rightarrow d \simeq 9080$ km
- Low Frequency (LF $30 - 300$ kHz) signals using ionosphere reflection/refraction travel many thousands of kilometers[1]



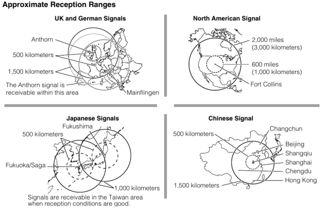


Radio Controlled Atomic Timekeeping

This watch receives a time calibration signal and updates its time setting accordingly. However, when using the watch outside of areas covered by time calibration signals, you will have to adjust the settings manually as required. See "Configuring Current Time and Date Settings Manually" (page E-31) for more information.
This section explains how the watch updates its time settings when the city code selected as the Home City is in Japan, North America, Europe, or China, and is one that supports time calibration signal reception.

If your Home City Code setting is this:	The watch can receive the signal from the transmitter located here:
LIS, LON, MAD, PAR, ROM, BER, STO, ATH, MOW	Anthorn (England), Mainflingen (Germany)
HKG, BJS	Shangqiu City (China)
TPE, SEL, TYO	Fukushima (Japan), Fukuoka/Saga (Japan)
HNL, ANC, YVR, LAX, YEA, DEN, MEX, CHI, NYC, YHZ, YYT	Fort Collins, Colorado (United States)

Important!
- The areas covered by **MOW**, **HNL** and **ANC** are quite far from the calibration signal transmitters, so certain conditions may cause reception problems.
- When **HKG** or **BJS** is selected as the Home City, only the time and date are adjusted according to the time calibration signal. You need to switch manually between standard time and daylight saving time (DST) if required. See "To configure Home City settings" (page E-28) for information about how to do this.



[1] *Introducing the advanced terrestrial navigation system (eLoran) that can even prevent GPS hacking*, National Maritime Positioning Information Institute (2021), at `https://www.youtube.com/watch?v=RaKvl3jj0QE` [in Korean]

[2] `www.casio.com/content/dam/casio/global/support/manuals/watches/pdf/32/3258/qw3258_EN.pdf`

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"With Auto Receive, the watch performs the receive operation each day automatically up to six times (up to five times for the Chinese calibration signal) between the **hours of midnight and 5 a.m.** (according to the Timekeeping Mode time). When any receive operation is successful, none of the other receive operations for that day are performed."[2]

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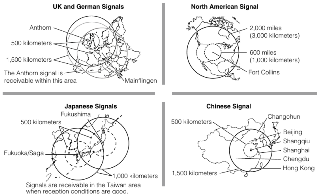
Approximate Reception Ranges



[1] *Introducing the advanced terrestrial navigation system (eLoran) that can even prevent GPS hacking*, National Maritime Positioning Information Institute (2021), at `https://www.youtube.com/watch?v=RaKvl3jj0QE` [in Korean]

[2] `www.casio.com/content/dam/casio/global/support/manuals/watches/pdf/32/3258/qw3258_EN.pdf`

VLF time and frequency transfer

List of European LF emitters for time & frequency transfer[3]:

- MSF (60 kHz), Rugby–Anthorn UK (1950–2007–)
- **DCF77** (77.5 kHz), Mainflingen Germany (1959–)
- **LORAN** (100 kHz), Anthorn UK (1942–1958–)
- **ALS162** (162 kHz), Allouis France (1977–1980–)
- e-CzasPL (225 kHz), Solec Kujawski Poland (2023–)[4][5]
- EFR[6] : Mainflingen (DE) 129.1 kHz, Burg (DE) 139.0 kHz, Lakihegy (HU) 135.6 kHz.
- R-Mode Baltic[7][8]: 300 kHz

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[3] "Time signal" at `https://en.wikipedia.org/wiki/List_of_VLF_transmitters`

[4] `https://e-czas.gum.gov.pl/wp-content/uploads/2024/06/e-CzasPL-Opis-ramki-czasu-e-Czas-Radio.pdf`

[5] M. Gruszczyński, *e-Czas Radio: Long-Wave radio distribution of legal time signals in Poland* (2025) at `https://www.youtube.com/watch?v=gNpU-UX_jYE`

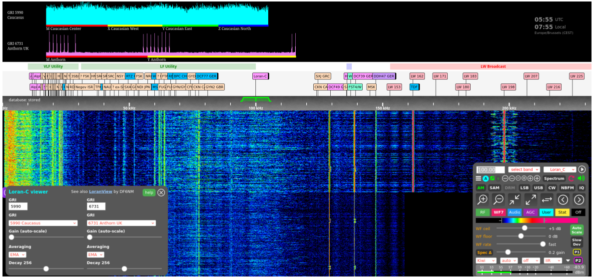
[6] F. Bräunlein & L. Melette, *BlinkenCity: Radio-Controlling Street Lamps and Power Plants*, 38C3 (2024) `https://media.ccc.de/v/38c3-blinkencity-radio-controlling-street-lamps-and-power-plants`

[7] `https://interreg-baltic.eu/project/r-mode-baltic/`: Germany, Poland, Sweden, Denmark, "The project R-Mode Baltic intended to tackle the challenges related to disturbances and develop a new independent of GNSS system that would allow a safe and more accurate positioning"

[8] Lars *& al.*, *Who cares about the Baltic Jammer? – Terrestrial Navigation in the Baltic Sea Region*, 39C3 (Dec. 2025) at `https://media.ccc.de/v/39c3-who-cares-about-the-baltic-jammer-terrestrial-navigation-in-the-baltic-sea-region`

VLF signal reception: relying on online SDR networks

- $f = 100$ kHz $\Rightarrow \lambda = 3$ km
- Can be received with ferrite core wound coil but antenna $Q \simeq \frac{1}{(k \cdot a)^3}$ factor[a] with $k = \frac{2\pi}{\lambda}$ and a the radius of the sphere including the antenna $\Rightarrow$ intrinsically **narrowband** antennas
- WebSDR (`http://websdr.org/`[b]): used to monitor e-CZAS but neither opensource[c] nor API for retrieving raw IQ[9] nor timestamped
- KiwiSDR (`http://map.kiwisdr.com/`) uses GNSS time-stamping of streams recorded using an open API[d]



[a] H.A. Wheeler, *Fundamental limitations of small antennas*, Proc. IRE **35**(12), 1479–1484 (1947)

[b] `http://websdr.ewi.utwente.nl:8901/`

[c] `https://www.websdr.org/faq.html`

[d] `https://github.com/jks-prv/kiwiclient`

[9] `http://websdr.ewi.utwente.nl:8901/websdr-sound.js`: "Other use, including distribution in part or entirety or as part of other software, or reverse engineering, is not allowed without my explicit prior permission."

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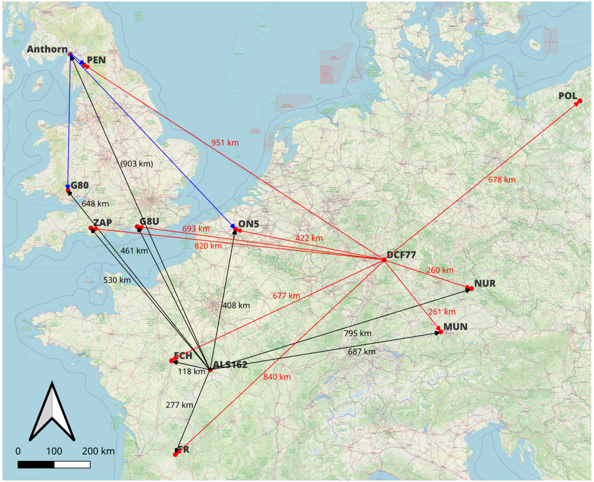

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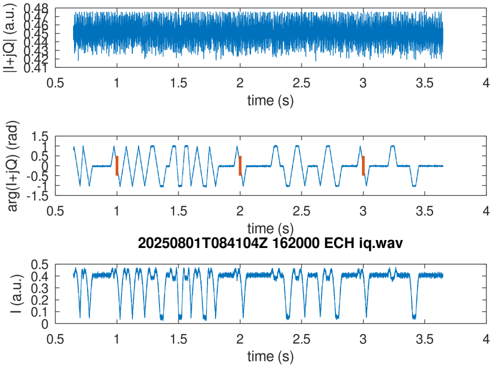
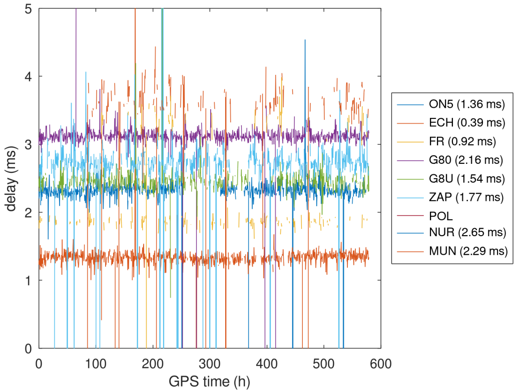
VLF signal reception: ALS162 [10] [11]

- Rather "high" frequency (162 kHz) covering mainland France only
- Narrowband signal (used to be sideband next to AM France Inter broadcast)
- Phase zero-crossing defines the time





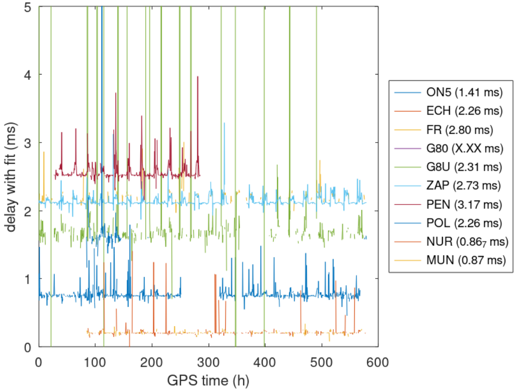
[10] https://github.com/henningM1r/gr_ALS162_Receiver
[11] https://pubs.gnuradio.org/index.php/grcon/article/view/134

VLF signal reception: DCF77[12]

- Historical DCF77 uses AM modulation to broadcast time and digital encoding of time and date
- 1988: Hetzel added phase modulation for spectrum spreading [a] with the PRN sequence generator[b]

[a] P. Hetzel, *Time dissemination via the LF transmitter DCF77 using a pseudo-random phase-shift keying of the carrier*, 2nd EFTF (1988) at `https://www.ptb.de/cms/fileadmin/internet/fachabteilungen/abteilung_4/4.4_zeit_und_frequenz/pdf/5_1988_Hetzel_-_Proc_EFTF_88.pdf`

[b] `https://en.wikipedia.org/wiki/DCF77`

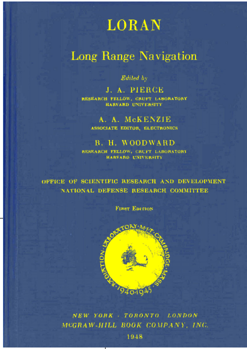


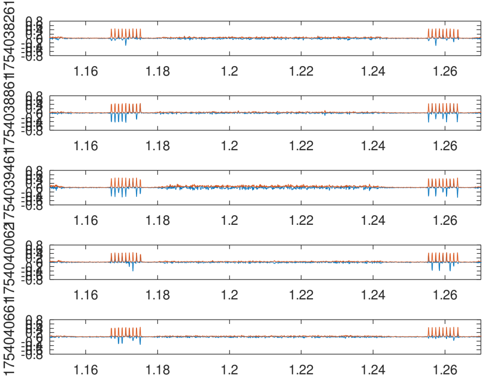
[12] J.-M Friedt, C. Eustache, É. Carry, E. Rubiola, *Software defined radio decoding of DCF77: time and frequency dissemination with a sound card*, Radio Science **53**(1) 48–61 (2018)

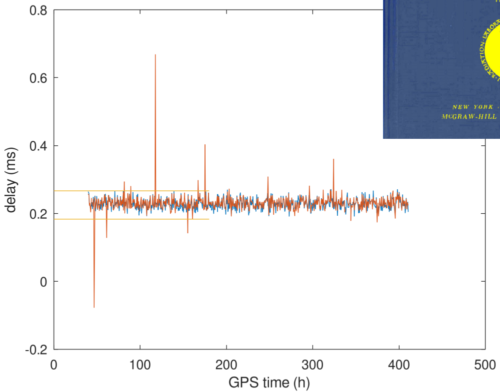
VLF signal reception: LORAN-C

- Designed and implemented during the second world war as a positioning system ...
- with "broadband" pulses (20 kHz, $\gg$ 700 Hz for DCF77 phase modulation and $\simeq 20$ *Hz* ALS162)
- "Positioning" using trilateration $\Rightarrow$ multiple emitters on the same carrier frequency of 100 kHz
- $\Rightarrow$ different GRI (*Group Repetition Interval*) indexed as delays in multiples of 10 μs
- Anthorn (UK) is GRI 6731 $\Rightarrow$ pulse sequence repeats every 67.310 ms

MIT Rad Lab Vol.4 (1948)







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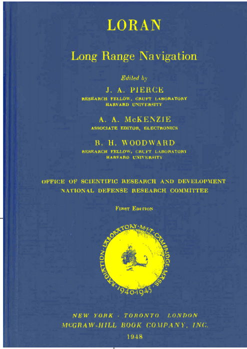

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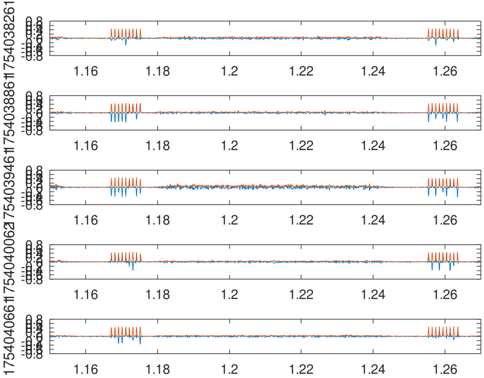
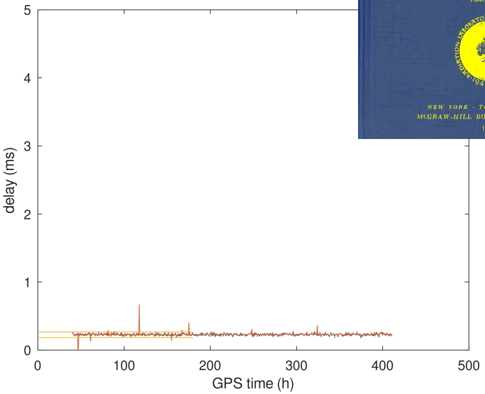




VLF signal reception: LORAN-C

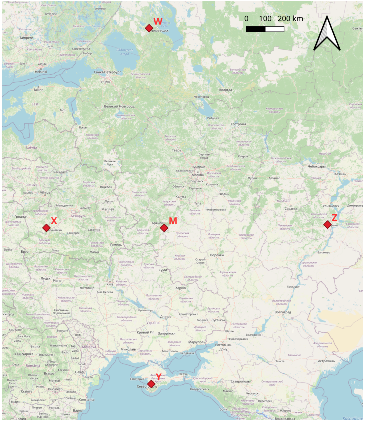
Russian equivalent to LORAN-C: Chayka, with 3 stations surrounding Ukraine (including Crimea)

Russia expected to ditch GLONASS for Loran in Ukraine invasion https://stage.gpsworld.com/russia-expected-to-ditch-glonass-for-loran-in-ukraine-invasion/

By Tracy Cozzens Published February 17, 2022

Russian military doctrine assumes GLONASS and other GNSS will not be available once a battle begins, so will instead turn to Loran-C for navigation

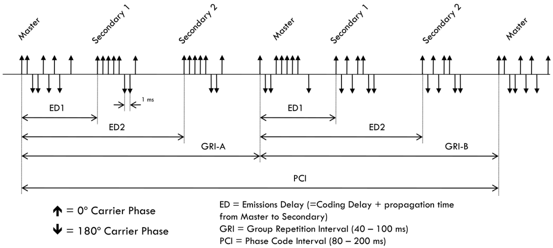
Russian forces are expert at jamming and spoofing GNSS. As a result, military analysts say, Russian military doctrine assumes that signals from space, including it's own GLONASS and other GNSS, will not be available once a battle begins.

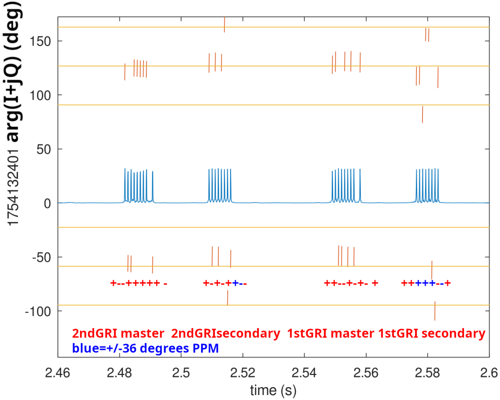


https://en.wikipedia.org/wiki/CHAYKA GRI8000

eLORAN master/secondary pulses[14]

- LORAN-C: differentiate Master and Secondaries with pulse sign[a] $\longrightarrow$
- Difference between LORAN-C and eLORAN: add a pulse position modulation on 6 of the 8 bits
- Protocol known as Eurofix[b]
- KiwiSDR records baseband signal so at 10 μs period, a ± 1 μs PPM delay is detected as $\pm 36°$ phase shift (GPSDO seems optional[13])





[a] A.Helwig *& al.*, *eLoran System Definition and Signal Specification Tutorial* (2011) at `https://www.ursanav.com/wp-content/uploads/UrsaNav-ILA-40-eLoran-Signal-Specification-Tutorial.pdf`

[b] "EUROFIX was developed by Delft University of Technology. LORAN-C or Chayka stations are upgraded to broadcast low-speed data reliable over ranges up to 1000 km." at `https://www.euspa.europa.eu/sites/default/files/virtual_library/2003-10-07_-_GALILEI_Project_-_Generic_Local_Element_Performance_Validation.pdf`

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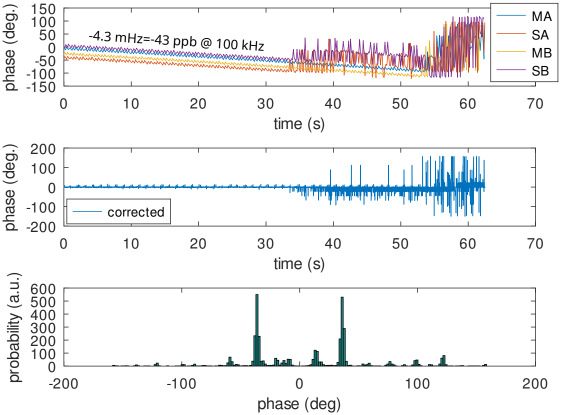

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[13] `http://kiwisdr.com/docs/KiwiSDR/KiwiSDR.design.review.pdf`

[14] `https://www.irishlights.ie/safety-navigation/notices-to-mariners/2012-13-eloran.aspx`: "The signals from Anthorn are transmitted with a Group Repetition Interval (GRI) of 67,310 microseconds and an Emission Delay (ED) of 27300 microseconds, **broadcasting as station 'Y' of chain 6731**. The signals are modulated with Eurofix data messages, with the facility to broadcast differential Loran, improved Additional Secondary Factor (ASF) data, differential GPS, integrity information and UTC (Co-ordinated Universal Time) parameters. Eurofix data messages can be received when **using an appropriate eLoran receiver**."

eLORAN: symbol to bits

- Documented in[a] ITU Recommendation ITU-R M.589-3 "Technical characteristics of methods of data transmission and interference protection for radionavigation services in the frequency bands between 70 and 130 kHz" (2001) [b]
- 6-pulse position of -1, 0 or $+1$ translated to 128 possible bit combinations: remove the $\pm 90°$ indicating Master/Secondary and threshold detect remaining phase at $\pm 18°$ [c]
- check the validity of the conversion: sum of phases must be 0 (to accomodate LORAN-C receivers)

[a] https://febo.com/pipermail/time-nuts_lists.febo.com/2025-August/109988.html

[b] https://www.itu.int/dms_pubrec/itu-r/rec/m/R-REC-M.589-3-200108-I!!PDF-E.pdf with no additional information in SAE9990/1 *Transmitted Enhanced Loran (eLoran) Signal Standard for Tri-State Pulse Position Modulation* (2018)

[c] L. Shifeng & al., *Research of Loran-C data demodulation and decoding technology*, Chinese Journal of Scientific Instrument **33**(6) (2012)

Pattern/data translation

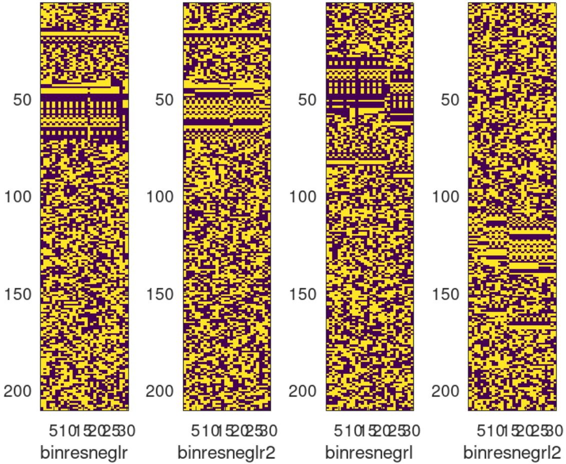
Decimal	Hexa-decimal	Pattern
0	0	--00++
1	1	--0+0+
2	2	--0++0
3	3	--+00+
4	4	--+0+0
5	5	--++00
6	6	-0-0++
7	7	-0-+0+
8	8	-0-++0
9	9	-00-++
10	A	-00+-+
11	B	-00++-
12	C	-0+-0+
13	D	-0+-+0
14	E	-0+0-+
15	F	-0+0+-
16	10	-0++-0
17	11	-0++0-
18	12	-+-00+
19	13	-+-0+0
20	14	-+-+00
21	15	-+0-0+
22	16	-+0-+0
23	17	-+00-+
24	18	-+00+-
25	19	-+0+-0
26	1A	-+0+0-
27	1B	-++-00
28	1C	-++0-0
29	1D	-++00-
30	1E	0--0++
31	1F	0--+0+
32	20	0--++0
33	21	0-0-++
34	22	0-0+-+
35	23	0-0++-
36	24	0-+-0+
37	25	0-+-+0
38	26	0-+0-+
39	27	0-+0+-
40	28	0-++-0
41	29	0-++0-
42	2A	00--++

Decimal	Hexa-decimal	Pattern
43	2B	00-+-+
44	2C	00-++-
45	2D	00+--+
46	2E	00+-+-
47	2F	00++--
48	30	0+--0+
49	31	0+--+0
50	32	0+-0-+
51	33	0+-0+-
52	34	0+-+-0
53	35	0+-+0-
54	36	0+0--+
55	37	0+0-+-
56	38	0+0+--
57	39	0++--0
58	3A	0++-0-
59	3B	0++0--
60	3C	+--00+
61	3D	+--0+0
62	3E	+--+00
63	3F	+-0-0+
64	40	+-0-+0
65	41	+-00-+
66	42	+-00+-
67	43	+-0+-0
68	44	+-0+0-
69	45	+-+-00
70	46	+-+0-0
71	47	+-+00-
72	48	+0--0+
73	49	+0--+0
74	4A	+0-0-+
75	4B	+0-0+-
76	4C	+0-+-0
77	4D	+0-+0-
78	4E	+00--+
79	4F	+00-+-
80	50	+00+--
81	51	+0+--0
82	52	+0+-0-
83	53	+0+0--
84	54	++--00
85	55	++-0-0

Decimal	Hexa-decimal	Pattern
86	56	++-00-
87	57	++0--0
88	58	++0-0-
89	59	++00--
90	5A	-0000+
91	5B	-000+0
92	5C	-00+00
93	5D	-0+000
94	5E	-+0000
95	5F	0-000+
96	60	0-00+0
97	61	0-0+00
98	62	0-+000
99	63	00-00+
100	64	00-0+0
101	65	00-+00
102	66	000-0+
103	67	000-+0
104	68	0000-+
105	69	0000+-
106	6A	000+-0
107	6B	000+0-
108	6C	00+-00
109	6D	00+0-0
110	6E	00+00-
111	6F	0+-000
112	70	0+0-00
113	71	0+00-0
114	72	0+000-
115	73	+-0000
116	74	+0-000
117	75	+00-00
118	76	+000-0
119	77	+-+-+-
120	78	-+-+-+
121	79	+-+--+
122	7A	-+-++-
123	7B	+--+-+
124	7C	-++-+-
125	7D	+--++-
126	7E	-++--+
127	7F	+0000-

eLORAN: payload interpretation

- A 15-min long record was collected from the KiwiSDR station G0GHK at 53.56° N, 0.88° W
- pulses are alternating Master and Secondary.
- We observe that all Master pulses exhibit 0 or 180° phases, i.e. no ± 1 μs shift indicating digital payload content.
- only secondary pulses include $\pm 36°$ phase shift.
- attributing $\pm 36°$ phase shift ± 1 bit state leads to two possible schemes, and accumulating the bits left to right or right to left to another 2, hence 4 resulting files



Each message is 210 bit long, each GRI (67.31 ms for Anthorn) broadcasts 7 bits so the duration between each sentence is $67.31 \times (210/7) = 2.02$ s

eLORAN: bitstream synchronization

Using the CRC as proposed in the RDS documentation[15]:
"The beginning and end of the data blocks may be recognized in the decoder by using the fact that the error-checking decoder will, with a high level of confidence, detect block synchronization slip. The blocks within each group are identified by different offset words added to the respective 10-bit checkwords."

Using the FEC has also been proposed[16]:
"it is necessary to synchronize on the message epoch. While it is possible to provide these features in different ways (e.g. forward error correction for the channel interference, CRC codes for integrity, and separate synchronization sequences or symbols), the LORAN 2003 Data Channel system employs a single Reed-Solomon code to accomplish all three."

However, once the generator polynomial has been defined, many degrees of freedom to tune:

- flip input bits (left to right or right to left)
- flip polynomial coefficients
- flip resulting CRC
- flip phase +36/0/-36 to +1/0/-1
- (flip symbol to data)

---

[15] Recommendation ITU-R BS.643-3, *Radio data system for automatic tuning and other applications in FM radio receivers for use with pilot-tone system* (2011) at
`https://www.itu.int/dms_pubrec/itu-r/rec/bs/R-REC-BS.643-3-201105-S!!PDF-E.pdf`

[16] K.M. Carroll *& al.*, *Differential Loran-C*, Proc. GNSS 2004 – The European Navigation Conference (2004) at
`https://web.stanford.edu/group/scpnt/gpslab/pubs/papers/CarrollPeterson_ENCGNSS_2004.pdf`

eLORAN: CRC calculation

- https://www.sunshine2k.de/articles/coding/crc/understanding_crc.html section 5 for a C-implemenation of 16-bit CRC … and truncate to 14-bits.
- reference to check 16-bit CRC implementation: https://crccalc.com/
- after testing all possible combinations, a single bit order/phase assignment generates multiple matches
- Either wrap the C-implementation in Octave using `mkoct`, or translate to interpreted Octave script

Resulting sentences:[17]

```
index                data (56 bits)                              CRC (14 bits)                  Reed Solomon FEC (140 bits)
0014 00110100111110101011001011011001110000111011010110100110 01101110110000 01011110010101001001000111100110100000100000110110001110100000001101100011110110101100111001101
0015 01101001111101010110010110110011100001110110101101001100 11011101100000 10111100101010010010001111001101000001000001101100011101000000011011000111101101011001110011010
0225 01100100010001111101011001110011100000000000001101100000 00010001001111 00110001101001000000010011011001110111100011110011111001000101000101110110101010111011010100011
0226 11001000100011111010110011100111000000000000011011000000 00100010011110 01100011010010000000100110110011101111000111100111110010001010001011101101010101110110101000110
0435 01101001001010001000110011110011100001110110101101001100 00101001001111 10000001000000011111011101101011010011110001110011110010010111111010110101001000010101101010010011
0642 01001100100111000100110111111111001110000000000001101100 00001100000010 01000100001101101011100010101011010010111111101110101110101111111000110000111001011110100110010
0643 10011001001110001001101111111110011100000000000011011000 00011000000100 10001000011011010111000101010110100101111111011101011101011111110001100001110010111101001100101
0644 00110010011100010011011111111100111000000000000110110000 00110000001001 00010000110110101110001010101101001011111110111010111010111111100011000011100101111010011001010
0645 01100100111000100110111111111001110000000000001101100000 01100000010010 00100001101101011100010101011010010111111101110101110101111111000110000111001011110100110010101
0646 11001001110001001101111111110011100000000000011011000000 11000000100100 01000011011010111000101010110100101111111011101011101011111110001100001110010111101001100101010
0853 00011010011001111011011101000010111000011101101011010011 00010110101111 00100100011001001100101000010101000011100000100101100100000110101001011110001110110010111101101
0854 00110100110011110110111010000101110000111011010110100110 00101101011110 01001000110010011001010000101010000111000001001011001000001101010010111100011101100101111011011
0855 01101001100111101101110100001011100001110110101101001100 01011010111100 10010001100100110010100001010100001110000010010110010000011010100101111000111011001011110110111
1065 01100100001101010000000110001011100000000000001101100000 01011010000001 00000010101001101011101010111110110101101100000111100100111000000101100011011101010011010000110
1066 11001000011010100000001100010111000000000000011011000000 10110100000010 00000101010011010111010101111101101011011000001111001001110000000101100011011101010011010000110
1275 01101001011110111010001001001011100001110110101101001100 00100101000011 00110010110111101010001100100100010000101000000011100000001100101110101101010010111100001001111
1276 11010010111101110100010010010111000011101101011010011000 01001010000110 01100101101111010100011001001000100001010000000111000000011001011101011010100101111000010011110
1485 01100100100010001101000011001011100000000000001101100000 01111010101111 11001100111101111100001110101101110010111101101101110000111111001101100000101110001010000001101
1694 10110100111000010000010111100101110000111011010110100110 01110100011110 11101011101000000111010111100100100100011111001010011010010110010001110101010101100111101001001
1695 01101001110000100000101111001011100001110110101101001100 11101000111101 11010111010000000111010111100100100100011111001010011010010110010001110101010101100111101001001
...
```

- Only keep sentences separated by indices 210 bits apart … sometimes (manually) resynchronize (when some bits lost)

[17] A.Helwig *& al.*, *eLoran System Definition and Signal Specification Tutorial* (2011) at https://www.ursanav.com/wp-content/uploads/UrsaNav-ILA-40-eLoran-Signal-Specification-Tutorial.pdf

eLORAN: payload interpretation [20] [21]

Reelektronika manuals:

- sentence starting with 0110 is LORAN UTC message
- payload content is documented[18] so that bitstreams

0110010011100010011011111111001110000000000001101100000
0110100110011110110111010000101110000111011010110100110 0
0110010000110101000000011000101110000000000001101100000 0
0110100101111011101000100100101110000111011010110100110 0

are analyzed as (message subtype 2):

- 0110: LORAN UTC (must be 0110)
- 01: message subtype (must be 01 or 10, **flipped bits** so 01 is type 2)
- 00111000100110111111110011100: time at master/secondary in hours (in 10 μs unit): `bin2dec(fliplr("00001101010000000110001011100"))*1e-5` indicates 1216.2486 and then 1220.2872, consistent with 2.02 s/message
- 0000000000: precise time is 10 ns (=0)
- 11011000: leap seconds between LORAN-C and UTC (=27, correct[19])
- 00: leap second change

TABLE 1. EUROFIX UTC MESSAGE FORMAT TYPE 6, SUBTYPE 1

Item	Bits	# bits	Unit	Range
Message type (0110)	1-4	4	1	16
Message sub-type (01)	5-6	2	1	4
Time at Master/Secondary in hour *	7-35	29	10 µs	5,368 sec (> 1 hour)
Hour of year	36-49	14	1 hour	16,384 hours (> 1 year)
Year	50-55	6	1	64 years (2000-2063)
Spare	56	1		
Cyclic Redundancy Check	57-70	14		
Total:		70		

* Indicates the UTC time of the standard zero-crossing of the first pulse of the next Eurofix message

TABLE 2. EUROFIX UTC MESSAGE FORMAT TYPE 6, SUBTYPE 2

Item	Bits	# bits	Unit	Range
Message type (0110)	1-4	4	1	16
Message sub-type (10)	5-6	2	1	4
Time at Master/Secondary *	7-35	29	10 µs	5,368 sec (> 1 hour)
Precise Time	36-45	10	10 ns	10.24 µs (> 10 µs)
Leap seconds ** (TAI-UTC)	46-54	9	1 s	-256 – 255 s
Leap second change ***	55-56	2	1 s	-1 – 1 s
Cyclic Redundancy Check	57-70	14		
Total:		70		

[18] https://www.loran.org/proceedings/Meeting2005/Session%204%20-%20Timing,%20Differential%20Loran/Helwig-In
[19] http://leapsecond.com/java/gpsclock.htm
[20] https://www.reelektronika.nl/manuals/reelektronika_Differential_eLoran_Manual_v1.0.pdf
[21] https://www.reelektronika.nl/manuals/reelektronika_LORADD_UTC_Manual_v1.21.pdf

eLORAN: payload interpretation (continued)

For message subtype 1 (filename including recording time and date is `20251014T122009Z_100000_G0GHK_iq.wav`):

- 0110: LORAN UTC
- 10: message subtype (flipped bits so 1 is 10)
- 011001111011011110100001011100: time at master/secondary in hours (in 10 μs unit): `bin2dec(fliplr("011001111011011110100001011100"))*1e-5=1218.2679` consistent with the previous value and 20 min within the hour
- 00111011010110: hour of year `bin2dec(fliplr("00111011010110"))=6876` h matching Oct. 14 at 12h UTC[22]
- 100110: year (`bin2dec(fliplr("10011"))=25`)
- 0: spare

Message 13 is[23] ASF Differential Timing Corrections (ADTC) and found in

101100010100110010100000000000000000000000000000000000000
101100000100110101000000000000000000000000000000000000000
101100000000001000111100000000000000000000000000000000000
101100010100110010100000000000000000000000000000000000000
101100000100110101000000000000000000000000000000000000000
101100010100110010100000000000000000000000000000000000000

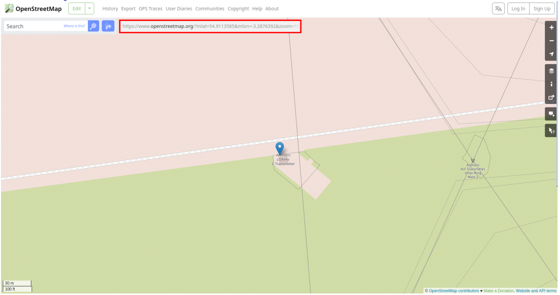
[24] hints at 4-bit message ID, 10 bit station ID & an ASF value in 2 ns (long string of 0s = small value after flipping bits)

[22]https://www.calculator.net/hours-calculator.html?today=01%2F01%2F2025&starttime2=0&startunit2=a&ageat=1(
[23]https://www.telecom-sync.com/files/pdfs/itsf/2014/Day1/1430-charles_curry2.pdf
[24]https://www.reelektronika.nl/manuals/reelektronika_Differential_eLoran_Manual_v1.0.pdf

eLORAN: payload interpretation (continued)

Message 4 is[25] station ID/Health message

0010101001000111110001010001100100011010010100000111111
0010101001000111110001101000111011100110101110100000100
0010101001000111110001010001100100011010010100000111111
0010101001000111110001101000111011100110101110100000100
0010101001000111110001010001100100011010010100000111111



Thanks to Eurofix revision 2.15 document, we analyze as

- 4 bit message ID (0010 for 4)
- 10 bits of station ID, matching the value `bin2dec(fliplr("1010010001"))=549` [26]
- 3 bits of station health: 111 meaning that the reference station is not working
- 2 bits of system indicator (10 flipped meaning eLORAN v.s Chayka)
- 3 bits of master/secondary with 001 flipped (100) meaning Yankee secondary, matching earlier description
- 2 bits whether latitude or longitude is broadcast
- 32 bits of latitude or longitude in degrees in 2's complement since 00011001000110100101000001111111 translates to -32876392 and 10001110111001101011101000000100 to 549113585 which nicely fit the WGS84 position[27] of Anthorn once multipied by 10^{-7} $^\circ$

[25] p.46 of `https://www.reelektronika.nl/manuals/reelektronika_Differential_eLoran_Manual_v1.0.pdf`
[26] `https://febo.com/pipermail/time-nuts_lists.febo.com/2025-August/109995.html`
[27] `https://www.openstreetmap.org/?mlat=54.9113585&mlon=-3.2876392&zoom=18`

eLORAN: Reed Solomon FEC (thanks to Daniel Estévez)

01101001111101010110010110110011100001110110101101001100 11011101100000 10111100101010010010001111001101000001000001101100011101000000011011000111101101011001110011010111101
01100100010001111101011001110011100000000000011011000000 00010001001111 0011000110100100000001001101100111011110001111001111100100010100010111011010101011101101010001100101

- GF(128): group bits by 7-bit packets (=symbol) after *flipping* bit order

  03 3B 19 35 5C 1C 6D 1A 5F 16 3D 77 1E 46 37 7E 75 4E 35 5E 1B 00 5C 36 04 0B 1E 12 2A 3D
  79 08 01 58 00 1C 73 2F 44 26 27 6F 7E 72 65 3E 4C 2B 3A 56 74 28 4F 4F 0F 39 59 00 4B 0C

- RS(30,10): 10 symbols generate 20 RS parity bits (matching 56+14=70 bits in 10 symbols)
- "LORAN-C data encoding uses shortened RS(30,10) error correction coding, which involves setting several bits before the valid information bits to zero before RS encoding."[28] ⇒ RS(30,10) is actually RS(127,107) with zero-padding the 107 symbols

97 x 0s	input 10 data+CRC	output 20 Reed Solomon

127 x 7-bit symbols

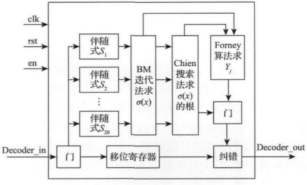


Figure 5 RS Decoding Block Diagram

- "The relationship between GF(128) elements and binary data should be to consider the value of the power of α as a 7-bit binary value converted to decimal."[29]

  $b_6 \cdot \alpha^6 + b_5 \cdot \alpha^5 + \ldots b_0 \cdot \alpha^0 \rightarrow \alpha^{b_6 b_5 \cdots b_0}$ thanks to `ALPHA_TO`→`encode_rs_char()`→`INDEX_OF`
- least significant symbol number is multiplied by lowest power of polynom
- "The first transmitted pattern of an FEC-encoded message should correspond to the least significant symbol of that message."

Inconsistent with A. Helwig *& al.*, https://www.ursanav.com/wp-content/uploads/UrsaNav-ILA-40-eLoran-Signal-Specification-Tutorial.pdf showing (p.23) the FEC *after* the data+CRC

```
         index        data              CRC                            RS FEC codeword
eLORAN: 0015 03 3B 19 35 5C 1C 6D 1A 5F 16 RS 3D 77 1E 46 37 7E 75 4E 35 5E 1B 00 5C 36 04 0B 1E 12 2A 3D
libfec:      79 08 01 58 00 1C 73 2F 44 26    3D 77 1E 46 37 7E 75 4E 35 5E 1B 00 5C 36 04 0B 1E 12 2A 3D
eLORAN: 0225 79 08 01 58 00 1C 73 2F 44 26 RS 27 6F 7E 72 65 3E 4C 2B 3A 56 74 28 4F 4F 0F 39 59 00 4B 0C
libfec:      79 14 19 35 5C 1C 79 44 29 16    27 6F 7E 72 65 3E 4C 2B 3A 56 74 28 4F 4F 0F 39 59 00 4B 0C
eLORAN: 0435 79 14 19 35 5C 1C 79 44 29 16 RS 29 35 43 34 07 67 69 15 54 12 6B 7A 27 4E 1E 2D 37 3E 01 01
libfec:      24 06 01 58 00 1C 7F 59 0E 26    29 35 43 34 07 67 69 15 54 12 6B 7A 27 4E 1E 2D 37 3E 01 01
eLORAN: 0645 24 06 01 58 00 1C 7F 59 0E 26 RS 1F 79 5B 49 70 42 6A 4C 5E 4E 0C 3F 57 2E 7F 25 55 0E 5B 04
```

[28] L. Shifeng *& al.*, *Research of Loran-C data demodulation and decoding technology*, Chinese J. Sci. Instr. **33**(6) (2012)
[29] https://www.itu.int/dms_pubrec/itu-r/rec/m/R-REC-M.589-3-200108-I!!PDF-E.pdf

Reed Solomon error correction: see `libfec/rstest.c`[30] for usage

- RS(30,10) can correct $(30-10)/2 = 10$ transmission errors
- corrupt one symbol and assess recovery capability

```c
  const int codeword_size=(1<<S)-1;        // 2^7-1 for 7-bit (S=7)
  unsigned char codeword[codeword_size];   // 127 symbols input
  bzero(codeword,codeword_size);           // 0 padding 1st 97 symbols
  const int nroots = N - K;                // N=30, K=10 => 20 FEC symbols
  rs=init_rs_char(7,0x89,1,1,nroots,0);    // symsize,genpoly,fcs,prim,nroots,padding
  struct rs *r; r=(struct rs*)rs;          // cast void* to rs* to access alpha_to
  for (i=0;i<sizeof(data);i++) codeword[codeword_size-N+i]=r->alpha_to[data[i]];
  encode_rs_char(rs,codeword,&codeword[codeword_size-nroots]);
////////// corrupt symbol number i on purpose
i=5;
printf("data[%d] was %02hhx\n",i,data[5]);
data[i]=0x42;
codeword[codeword_size-N+i]=r->alpha_to[data[i]];
////////// decode corrupted codeword: recover corrupted symbol
int erasures=0,derrors;
int derrlocs[codeword_size];
derrors = decode_rs_char(rs,codeword,derrlocs,erasures);
printf("%d errors @ %d: %02hhx\n",derrors,derrlocs[0],r->index_of[codeword[derrlocs[0]]]);
// display full message: return with index_of
  for (i=codeword_size-N;i<sizeof(codeword);i++) codeword[i]=r->index_of[codeword[i]];
```

	power of α	polynomial in α	vectors $k_2\,k_1\,k_0$
z_0	$\alpha^{-\infty}=0$	0	000
z_1	$\alpha^0=1$	1	001
z_2	α^1	α	010
z_3	α^2	α^2	100
z_4	α^3	$\alpha+1$	011
z_5	α^4	$\alpha^2+\alpha$	110
z_6	α^5	$\alpha^2+\alpha+1$	111
z_7	α^6	$\alpha^2\quad+1$	101

returns (position $102 = 97\times$ 0-padding $+5$):

```
data[5] was 1c
1 errors @ 102: 1c
```

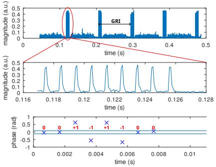
https://en.lntwww.de/Aufgaben:Exercise_2.07:_Reed-Solomon_Code_(7,_3,_5)_to_Base_8

[30] `https://github.com/quiet/libfec` "Clone of Phil Karn's `github.com/ka9q/libfec` with capability to build on x86-64"

Extending to Saudi Arabia[30], Korea and Russia

Saudi Arabia: KiwiSDR receiver in Doha (Qatar) at 25.2854N, 51.5310E

- Can only receiver Secondary signals, with phase consistent with SecondaryA/Secondary B
- Secondary with 9-pulses (?!) but pulses 3 to 8 include ± 1 μs PPM modulation
- Discard pulse 9: Anthorn decoding software compatible once GRI has been adapted:



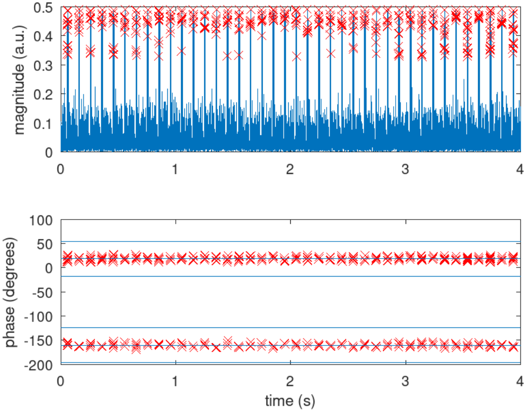

```
0057 data 10000010101111010000001111001111010111110000000010001001
0267 data 00100001111100000100100101101011001001100010010001111000
0477 data 01101000110100101110001001001101010011001000110101001100
...
```

- New sentence: 1 is documented in ITU-R M.589-3 (DGPS correction)
  - bin2dec(fliplr("001010111010"))=3028: modified Z count [a]
  - 0: scale (PRC in 0.02 m and RRC in 0.002 m/s)
  - 00: User Differential Range Error (UDRE)
  - bin2dec(fliplr("00111"))=28: satellite PRN
  - bin2dec(fliplr("100111101011111"))=32121: Pseudo-Range Correction (PRC): 2's complement on 15 bits $= -646$
  - bin2dec(fliplr("00000000"))=0: Range Rate Correction (RRC)
  - bin2dec(fliplr("10001001"))=145: Issue of data (IOD)
- Sentence 4 was known as Eurofix Station ID/Health message
- Sentence 6 was known and leads to date+time Aug. 25, 2025 @ 06:30:09.5 UTC consistent with recording file name `20250825T063002Z_100000_QTR_iq.wav`

[a] 3028×0.6 s=1816.8 s=30'16.8"

Korea: KiwiSDR receiver located at 35.888778N, 128.574964E

- Can only receive Master signals, but pulse phases consistent with alternating MasterA/MasterB
- no eLORAN digital payload on Master signals

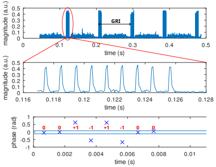


[30] `web.archive.org/web/20110210111415/http://www.ports.gov.sa/section/full_story.cfm?aid=307`

Extending to Saudi Arabia[30], Korea and Russia

Saudi Arabia: KiwiSDR receiver in Doha (Qatar) at 25.2854N, 51.5310E

- Can only receiver Secondary signals, with phase consistent with SecondaryA/Secondary B
- Secondary with 9-pulses (?!) but pulses 3 to 8 include ± 1 μs PPM modulation
- Discard pulse 9: Anthorn decoding software compatible once GRI has been adapted:




```
0057 data 1000001010111101000000111100111101011111000000001000100 1
0267 data 0010000111110000010010010110101100100110001001000111100 0
0477 data 0110100011010010111000100100110101001100100011010100110 0
...
```

- New sentence: 1 is documented in ITU-R M.589-3 (DGPS correction)
  - bin2dec(fliplr("001010111101 0"))=3028: modified Z count [a]
  - 0: scale (PRC in 0.02 m and RRC in 0.002 m/s)
  - 00: User Differential Range Error (UDRE)
  - bin2dec(fliplr("00111"))=28: satellite PRN
  - bin2dec(fliplr("100111101011111"))=32121: Pseudo-Range Correction (PRC): 2's complement on 15 bits $= -646$
  - bin2dec(fliplr("00000000"))=0: Range Rate Correction (RRC)
  - bin2dec(fliplr("10001001"))=145: Issue of data (IOD)
- Sentence 4 was known as Eurofix Station ID/Health message
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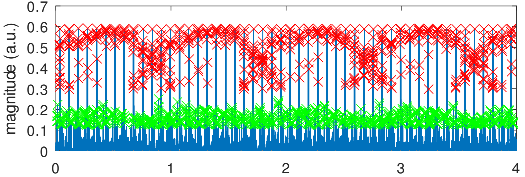
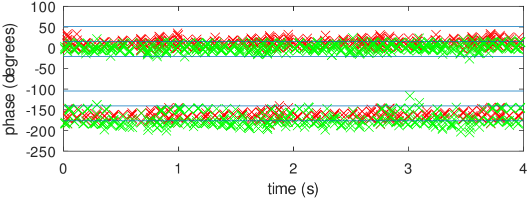
[a] 3028×0.6 s=1816.8 s=30'16.8"

Russia: KiwiSDR receiver located in Finland at 62.5N, 30.18E

- Pulse phases consistent with alternating MasterA/MasterB and SecondaryA/B
- no eLORAN digital payload on signals





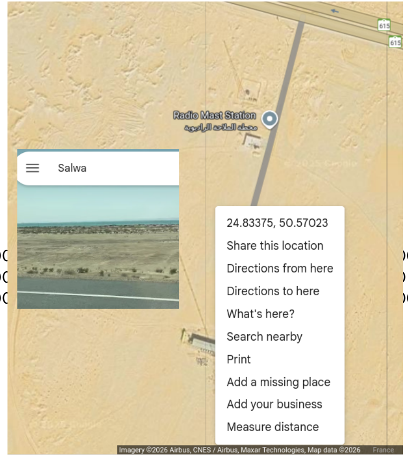
[30] `web.archive.org/web/20110210111415/http://www.ports.gov.sa/section/full_story.cfm?aid=307`

Extending to Saudi Arabia[30]

Saudi Arabia: KiwiSDR receiver in Doha (Qatar) at 25.2854N, 51.5310E

- Can only receiver Secondary signals, with phase consistent with SecondaryA/Secondary B
- Secondary with 9-pulses (?!) but pulses 3 to 8 include ± 1 μs PPM modulation
- Discard pulse 9: Anthorn decoding software compatible once GRI has been adapted:

```
0057 data 1000001010111101000000111100111101011110000000010001001 CRC 100 ... 0010100000
0267 data 0010000111110000010010010110101100100110001001000111000 CRC 100 ... 1000000001
0477 data 0110100011010010111000100100110101001100100011010100110 CRC 100 ... 0000111111
...
```



- New sentence: 1 is documented in ITU-R M.589-3 (DGPS correction)
  - bin2dec(fliplr("0010101111010"))=3028: modified Z count [a]
  - 0: scale (PRC in 0.02 m and RRC in 0.002 m/s)
  - 00: User Differential Range Error (UDRE)
  - bin2dec(fliplr("00111"))=28: satellite PRN
  - bin2dec(fliplr("100111101011111"))=32121: Pseudo-Range Correction (PRC), 2's complement on 15 bits $= -646$
  - bin2dec(fliplr("00000000"))=0: Range Rate Correction (RRC)
  - bin2dec(fliplr("10001001"))=145: Issue of data (IOD)
- Sentence 4 was known as Eurofix Station ID/Health message
- Sentence 6 was known and leads to date+time Aug. 25, 2025 @ 06:30:09.5 UTC consistent with recording file name `20250825T063002Z_100000_QTR_iq.wav`

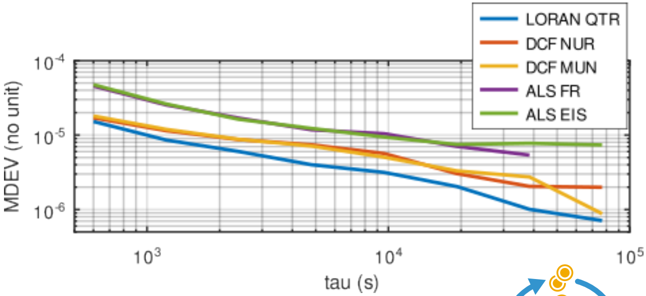
Eurofix/ Station ID/Health analysis

- bin2dec(fliplr("0001111100"))=248: station ID
- 000: health (000 is UDRE Scale Factor=1)
- 10: eLORAN
- 010: Whiskey Secondary
- 01: Longitude
- bin2dec(fliplr("0110101100100110001001000111000"))$\times 10^{-7}$ 50.5701590 deg. E matching the Salwa transmitter longitude

[a] 3028×0.6 s=1816.8 s=30'16.8"

Conclusion: https://github.com/jmfriedt/kiwisdr_timetransfer

- Comparison of the time transfer capability of various VLF emitters in Western Europe…
- … without local SDR receiver but relying on web services.
- Become familiar with the eLORAN digital payload encoding, including CRC & FEC,
- decoded all publicly documented sentences, results consistent with date/position.



Perspectives:

- Check compatibility with Korean (9930) and Chinese[31] (6780 & 8390) GRIs (visible from Hanoi) & Chayka
- get message 10 "positioning correction information" according to Korean National Maritime Positioning Information Institute[32], described in Reeltronika manual as *Differential eLORAN Phase Correction* (tentative format)

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[31] L. Shifeng *& al.*, *Research of Loran-C data demodulation and decoding technology*, Chinese J. of Scientific Instrument **33**(6) (2012): "The BPL long wave time service system and the "Changhe 2" system have adopted the "Eurofix" technology to achieve the communication navigation integration" at https://image.eworldship.com/2013/0108/20130108033044714.pdf

[32] https://www.nmpnt.go.kr/en/sub.do?menukey=5208