Unintended interference from the perspective of a Network RTK provider

GNSS Satelliet positionering jamming en spoofing

HSB / NIN / GIN

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Company Information 06-GPS

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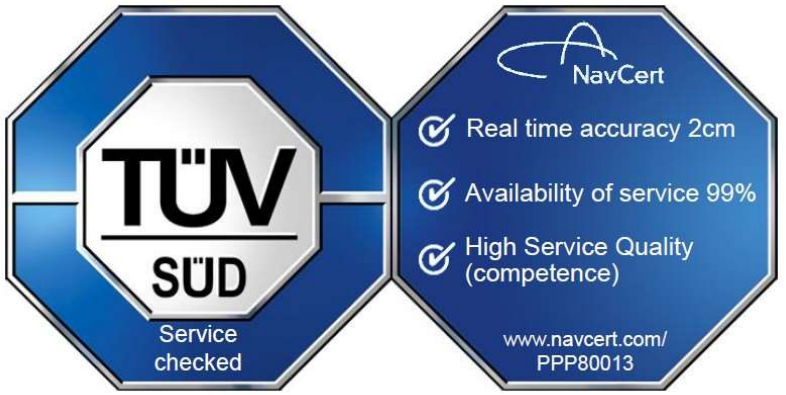
Company Information 06-GPS

- Independent, commercial provider of GNSS-data
- > 20 years of expertise in Network GNSS
- 5 employees full time, 6 employees part time
- Part of group of companies in surveying and engineering with 150 employees in total
- Thousands of registered users, from surveyours to farmers
- Benelux coverage
- Full support of GPS, GLONASS, Galileo, Beidou
- Delivery RTK (VRS) over NTRIP (internet) using RTCM 3 format
- Over 10 years of cooperation with (among others):
  - LTO Nederland
  - Bouwend Nederland

Quality 06-GPS

- Certifications:
  - ISO9001:2015
  - TüV SüD
    - Static Accuracy 2cm (95%)
    - Availability (99%)
    - Competence and service
  - TüV SüD
    - Dynamic Acc. 2cm (95%)
    - Suited for Precise Farming
    - Suited for Guidance Systems



3 Different cases:

1. Mobile network provider
2. Radio amateurs
3. Ionospheric activity

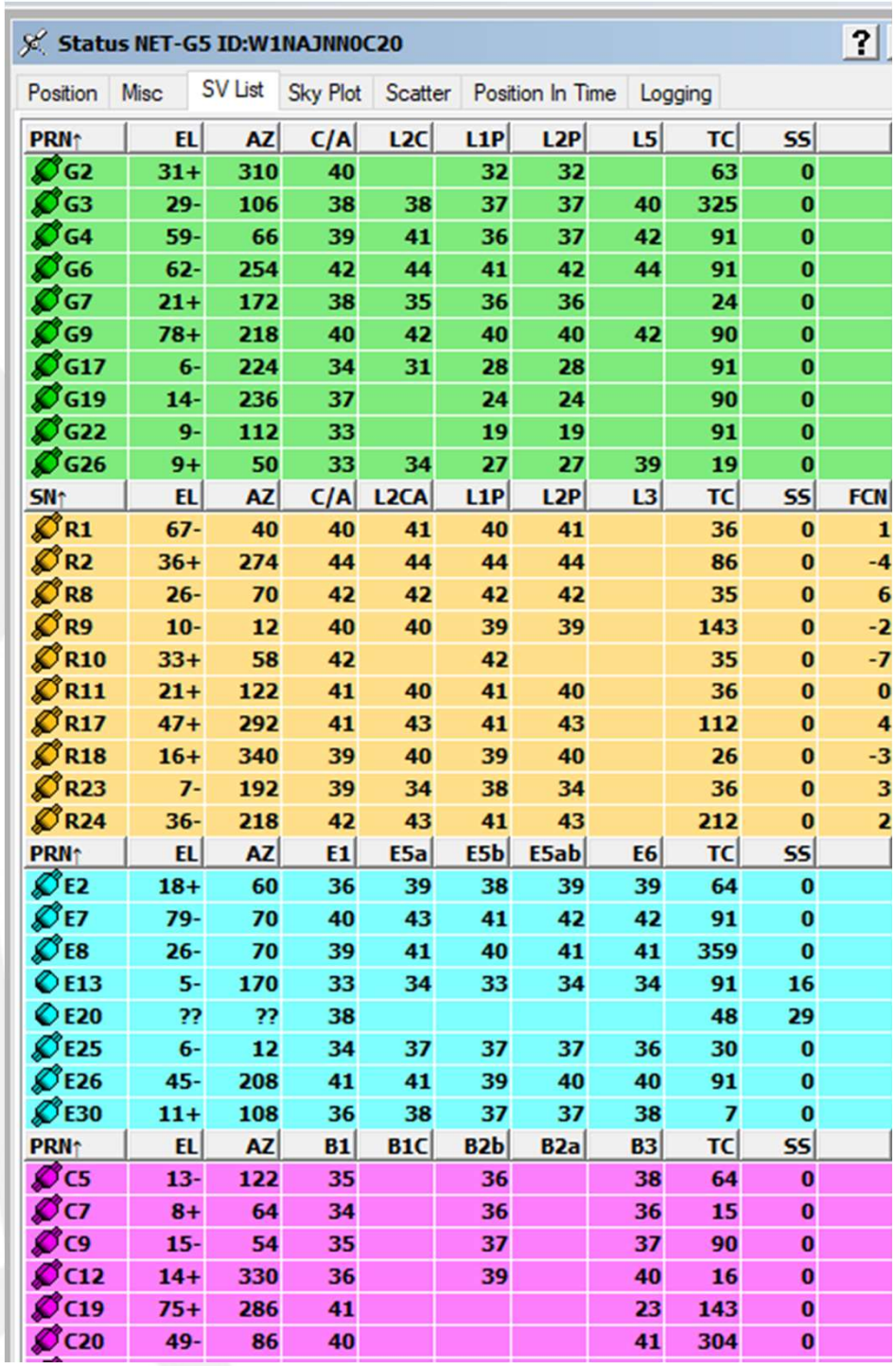
Case 1: mobile network provider

Story of GNSS interference caused by new signals in telecommunication

Discovering radio interference

- Important to know the normal values
- Looking for the unexpected in station data especially after maintenance of datacenter
- Affected Site: Ref. Station Ede
  - Topcon NET-G5 receiver stated to show low SNR at GPS
  - Septentrio PolaRx5 receiver was still showing normal SNR at GPS

Unexpected SNR values at the receiver interface.



PRN	EL	AZ	C/A	L2C	L1P	L2P	L5	TC	SS	
G2	31+	310	40		32	32		63	0	
G3	29-	106	38	38	37	37	40	325	0	
G4	59-	66	39	41	36	37	42	91	0	
G6	62-	254	42	44	41	42	44	91	0	
G7	21+	172	38	35	36	36		24	0	
G9	78+	218	40	42	40	40	42	90	0	
G17	6-	224	34	31	28	28		91	0	
G19	14-	236	37		24	24		90	0	
G22	9-	112	33		19	19		91	0	
G26	9+	50	33	34	27	27	39	19	0	
SN	EL	AZ	C/A	L2CA	L1P	L2P	L3	TC	SS	FCN
R1	67-	40	40	41	40	41		36	0	1
R2	36+	274	44	44	44	44		86	0	-4
R8	26-	70	42	42	42	42		35	0	6
R9	10-	12	40	40	39	39		143	0	-2
R10	33+	58	42		42			35	0	-7
R11	21+	122	41	40	41	40		36	0	0
R17	47+	292	41	43	41	43		112	0	4
R18	16+	340	39	40	39	40		26	0	-3
R23	7-	192	39	34	38	34		36	0	3
R24	36-	218	42	43	41	43		212	0	2
PRN	EL	AZ	E1	E5a	E5b	E5ab	E6	TC	SS	
E2	18+	60	36	39	38	39	39	64	0	
E7	79-	70	40	43	41	42	42	91	0	
E8	26-	70	39	41	40	41	41	359	0	
E13	5-	170	33	34	33	34	34	91	16	
E20	??	??	38					48	29	
E25	6-	12	34	37	37	37	36	30	0	
E26	45-	208	41	41	39	40	40	91	0	
E30	11+	108	36	38	37	37	38	7	0	
PRN	EL	AZ	B1	B1C	B2b	B2a	B3	TC	SS	
C5	13-	122	35		36		38	64	0	
C7	8+	64	34		36		36	15	0	
C9	15-	54	35		37		37	90	0	
C12	14+	330	36		39		40	16	0	
C19	75+	286	41				23	143	0	
C20	49-	86	40				41	304	0	

Comparing Topcon NET-G5 at various sites

With interference

Status NET-G5 ID:W1NAJNN0C20

Position | Misc | SV List | Sky Plot | Scatter | Position In Time | Logging

PRN↑	EL	AZ	C/A	L2C	L1P	L2P	L5	TC	SS	
G1	6-	150	32	32	26	27	38	8	0	
G2	17+	316	38		25	25		8	0	
G3	44-	94	40	41	40	40	43	289	0	
G4	74-	90	40	42	38	38	42	27	0	
G6	57+	290	41	42	40	41	43	128	0	
G9	59+	216	39	41	39	39	42	85	0	
G17	20-	234	39	37	28	29		26	0	
G19	28-	248	39		32	32		26	0	
G22	23-	102	38		28	28		26	0	
G31	10-	30	36	33	31	32		8	0	
SN↑	EL	AZ	C/A	L2CA	L1P	L2P	L3	TC	SS	FCN
R1	30	262	41	40	41	40		27	6	1
R7	46-	56	43	45	43	45		244	0	5
R8	71+	298	41	43	41	43		144	0	6
R9	25+	84	40	41	40	42		26	0	-2
R10	6+	130	37		37			3	0	-7
R16	21-	30	39	38	38	38		24	0	-1
R22	16-	186	39	30	38	31		287	0	-3
R23	58-	262	41	42	41	41		150	0	3
R24	38+	318	44	44	44	44		28	0	2
PRN↑	EL	AZ	E1	E5a	E5b	E5ab	E6	TC	SS	
E4	54+	236	42	44	43	44	45	128	0	
E11	55+	282	40	43	41	42	43	26	0	
E12	44-	188	41	41	39	40	41	26	0	
E18	??	??	36	39	38	38	38	2	6	
E19	64-	68	40	41	39	40	41	26	0	

Without interference

Status NET-G5 ID:W1H2 V FYG

Position | Misc | SV List | Sky Plot | Scatter | Position In Time | Logging

PRN↑	EL	AZ	C/A	L2C	L1P	L2P	L5	TC	SS	
G1	4-	152	37	34	30	31	40	385	16	
G2	18+	316	43		28	28		36	0	
G3	44-	98	48	46	50	50	52	293	0	
G4	74-	92	48	53	45	44	57	189	0	
G6	57+	286	51	49	55	55	56	134	0	
G7	5+	176	37	33	25	30		3	0	
G9	59+	21	52	50	57	57	56	119	0	
G17	19-	234	41	38	29	29		238	0	
G19	26-	248	45		35	34		195	0	
G22	23-	104	43		30	31		346	0	
G25	1-	346	34	31	12	13	37	50	16	
G31	10-	30	38	35	35	35		182	0	
SN↑	EL	AZ	C/A	L2CA	L1P	L2P	L3	TC	SS	FCN
R1	30	264	47	43	46	43		63	6	1
R7	46-	58	54	52	52	52		245	0	5
R8	72+	300	53	56	52	55		152	0	6
R9	27+	84	50	49	49	48		61	0	-2
R10	7+	130	43		42			6	0	-7
R16	22-	28	43	42	42	41		114	0	-1
R22	14-	188	42	34	41	33		289	0	-3
R23	57-	260	57	48	56	48		153	0	3
R24	39+	316	54	50	53	49		79	0	2
PRN↑	EL	AZ	E1	E5a	E5b	E5ab	E6	TC	SS	
E4	53+	238	48	53	54	54	52	140	0	
E11	55+	280	46	48	49	49	51	176	0	
E12	42-	190	43	47	49	47	49	330	0	
E19	64-	70	45	49	49	49	50	269	0	

Analyzing interference:

Theoretical steps:

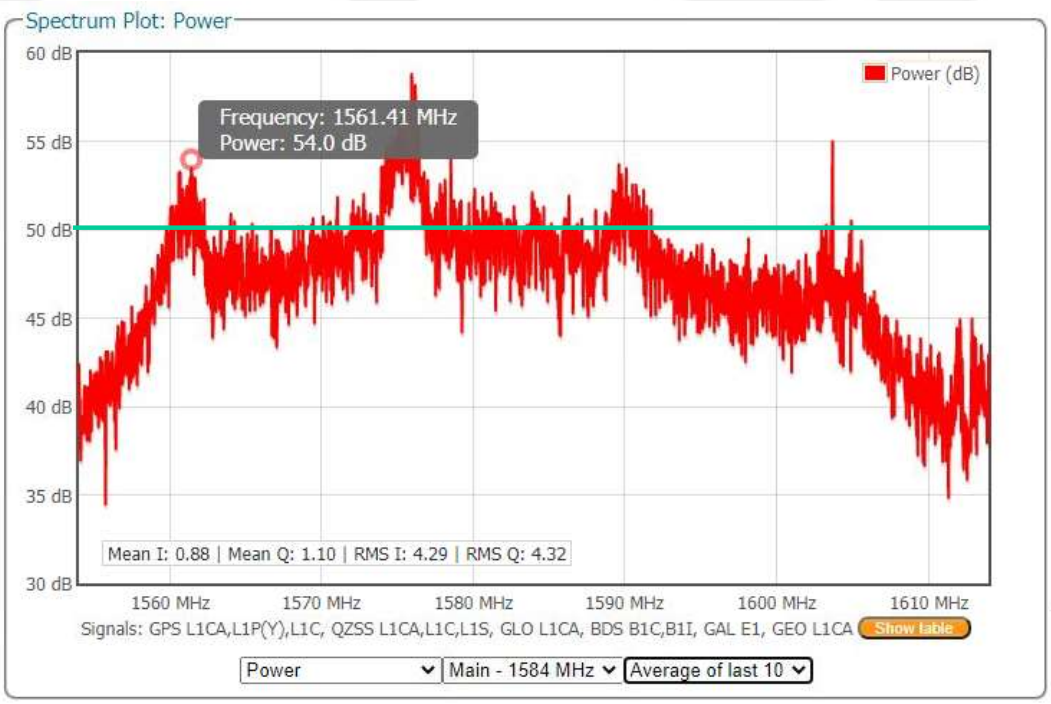
1. Spectrum analyses
2. Temporal analyses
3. Geographical analyses

Practical implementation

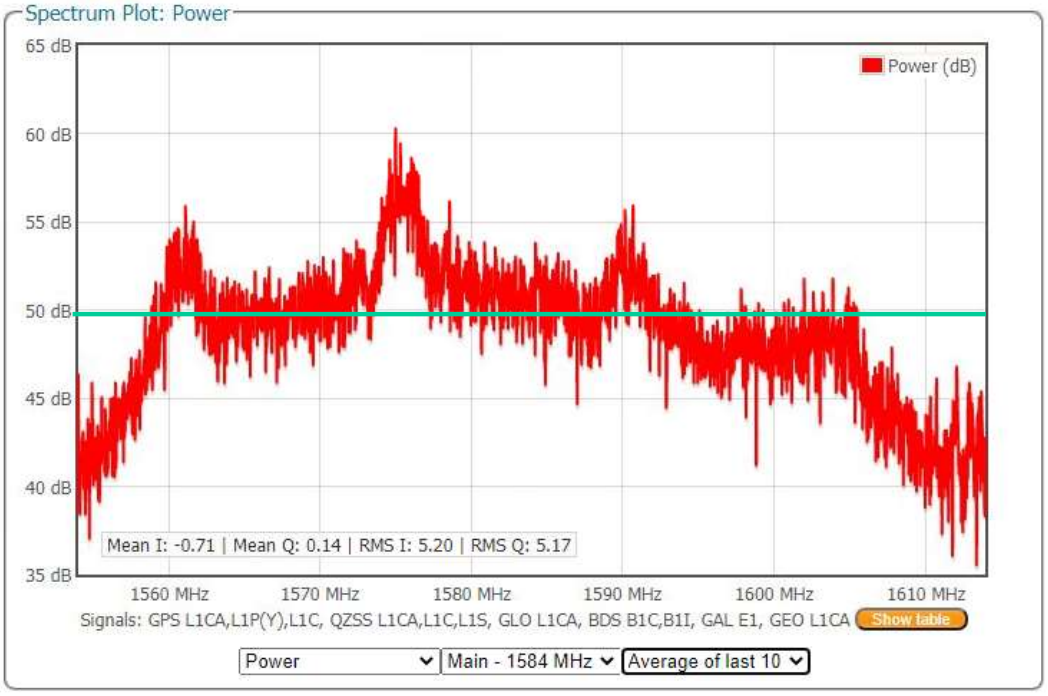
1. Spectrum plot of PolaRx5
2. Search in RINEX-log
3. Plotting RINEX-log of all stations

1. Spectrum analysis

With interference



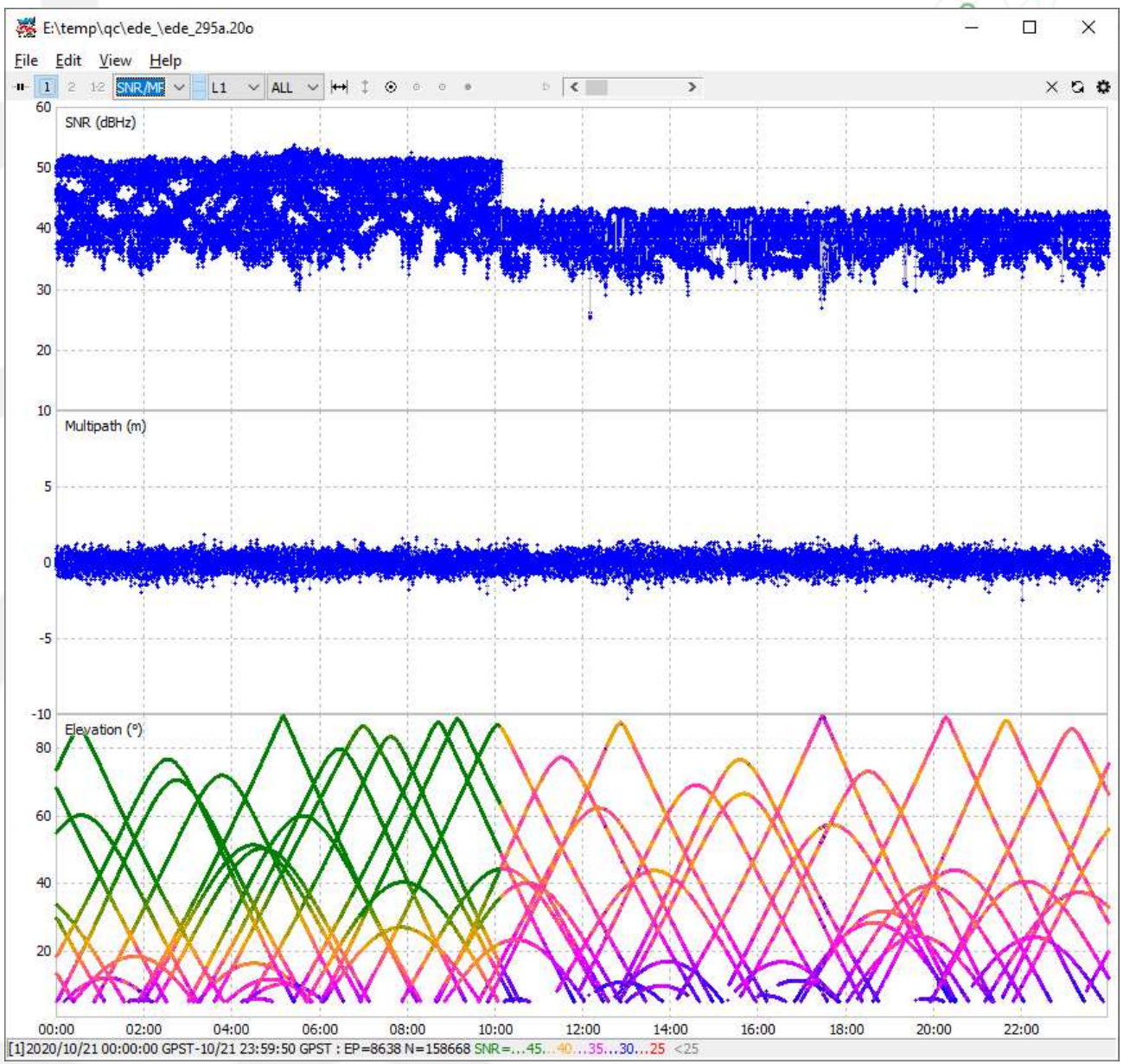
Without interference



2. Temporal analyses

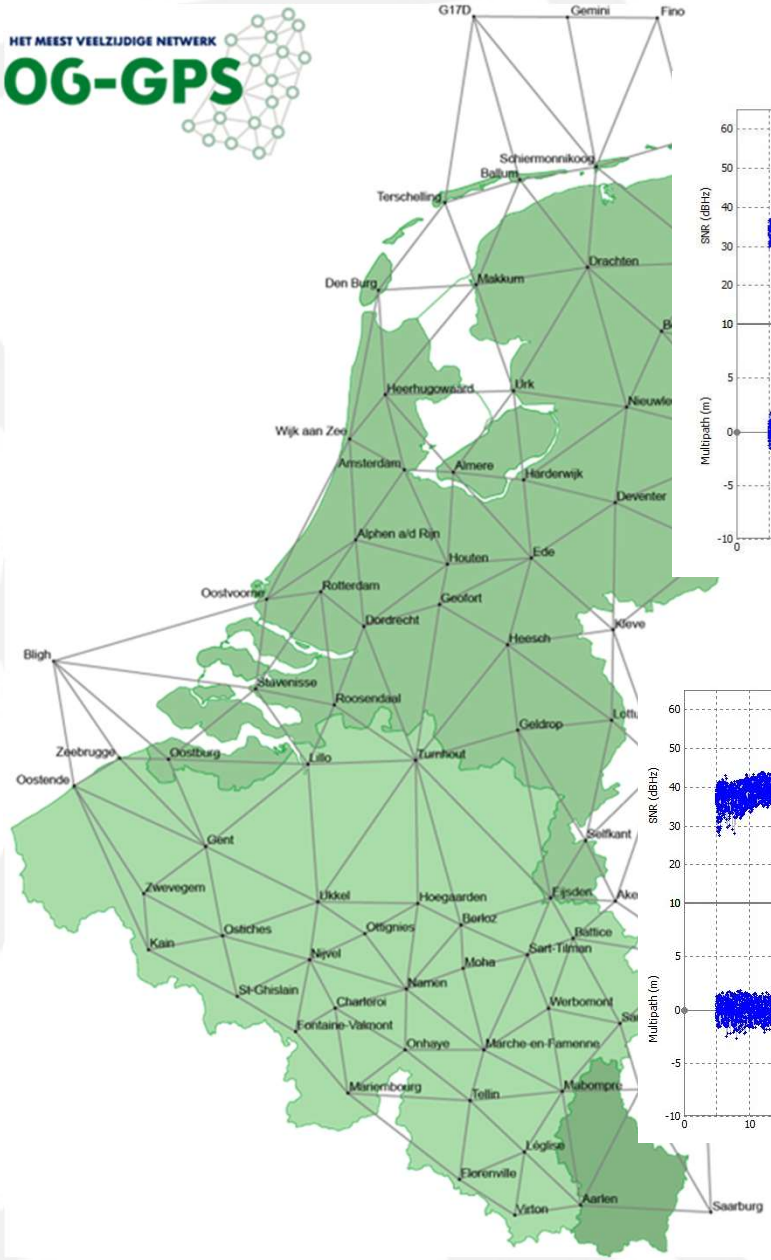
- Browsing the data to find the origin of the interference
- Use RTK-LIB to plot RINEX-log
- Interference started during the day as if a stationary signal was turned on
- 10 dB decrease (20%) !
- Station has 2 receivers on 1 antenna but only 1 receiver was affected.
- Only Topcon NET-G5 affected
- Septentrio PolaRX5 stayed unaffected

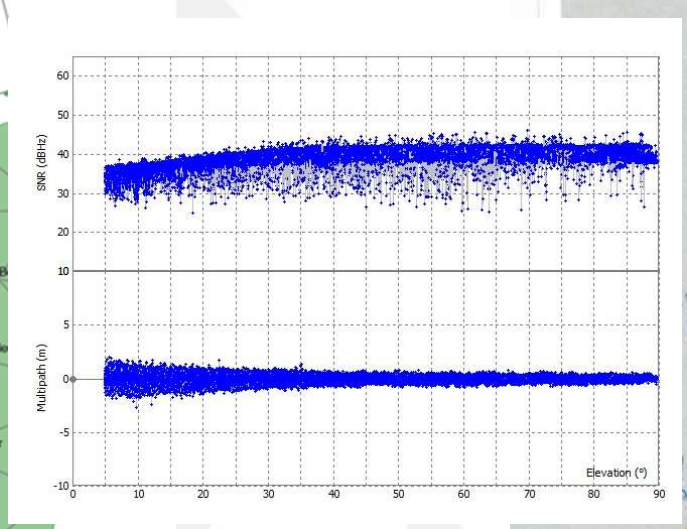
Ede

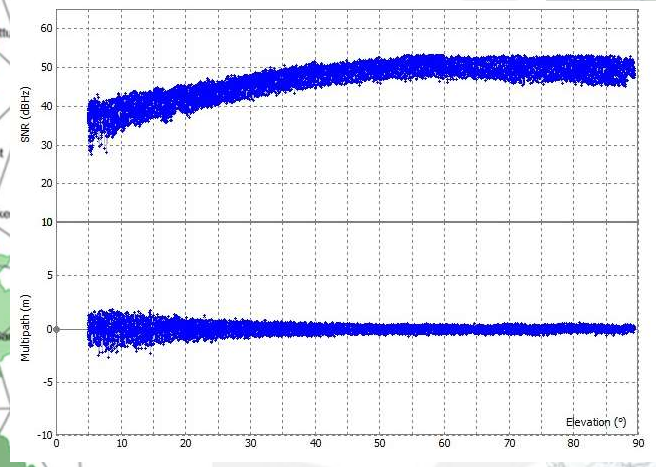


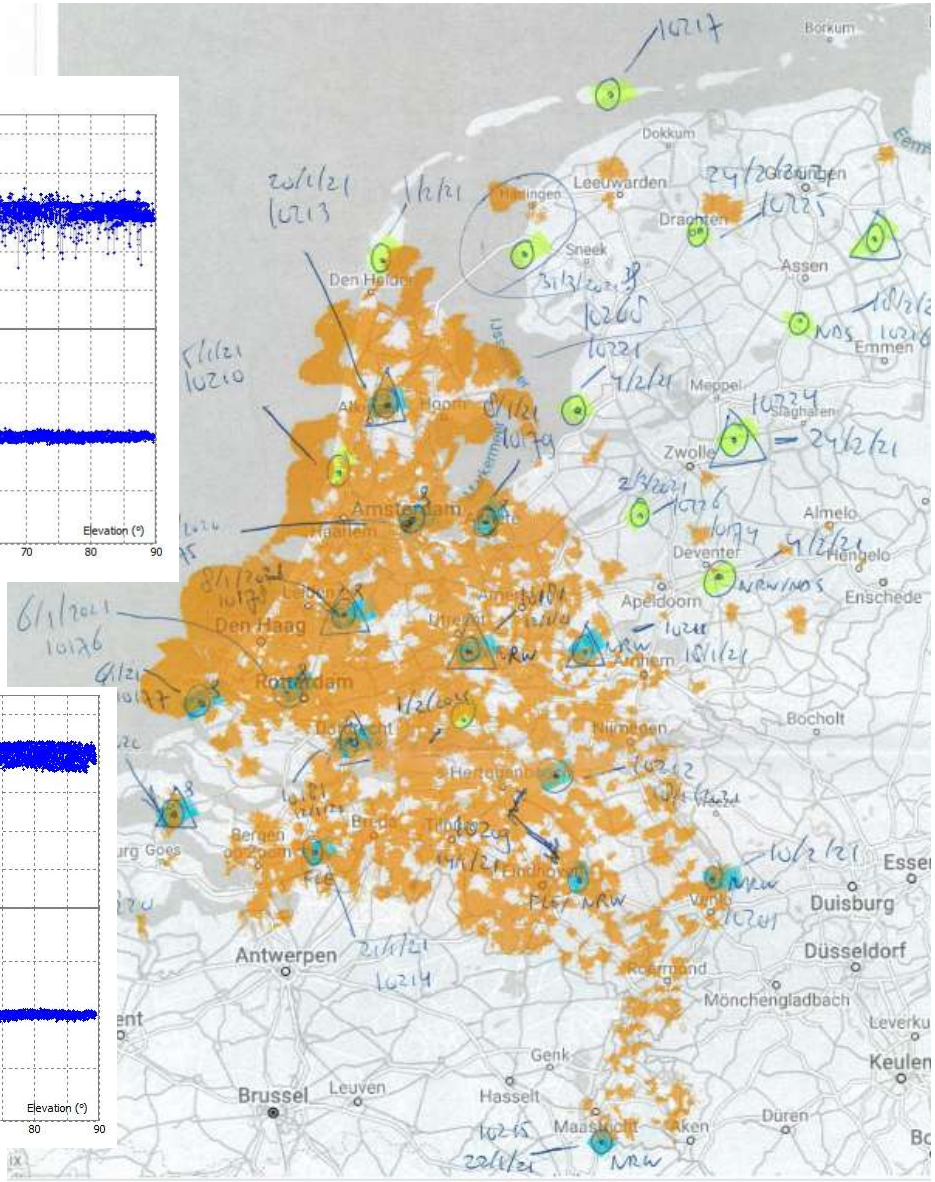
Geographical analyses

A manual analysis show that KPN 5G-internet is directly correlated with the interference



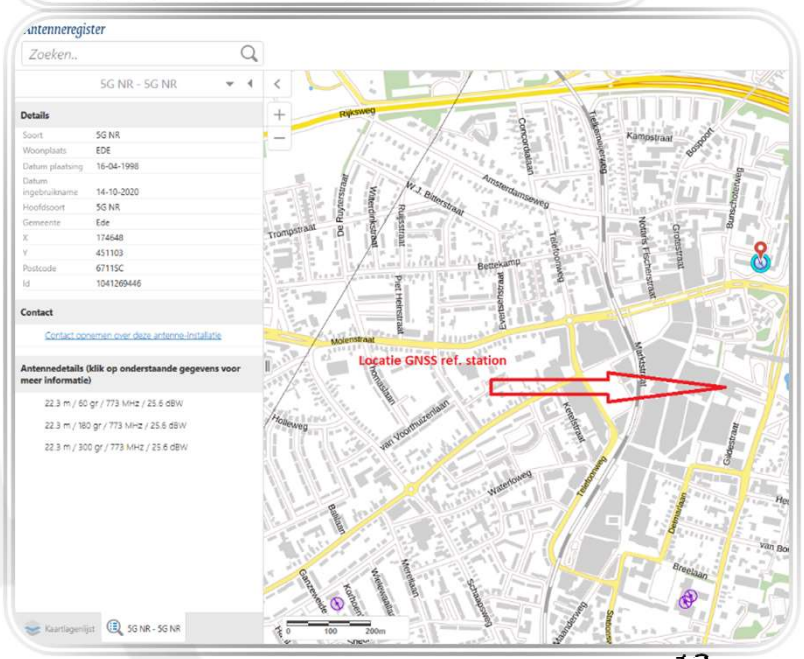






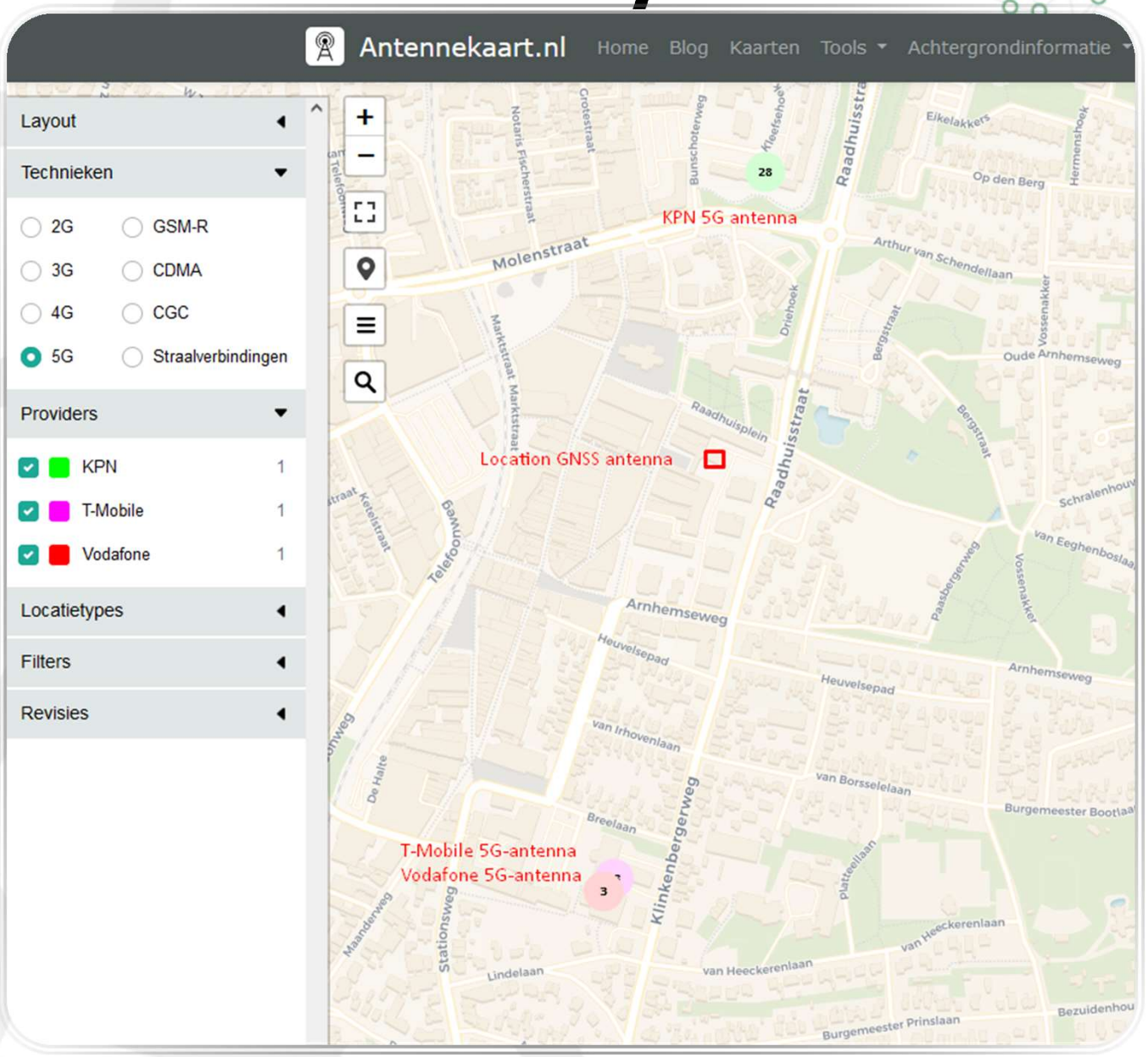
Temporal fit with the case Ede

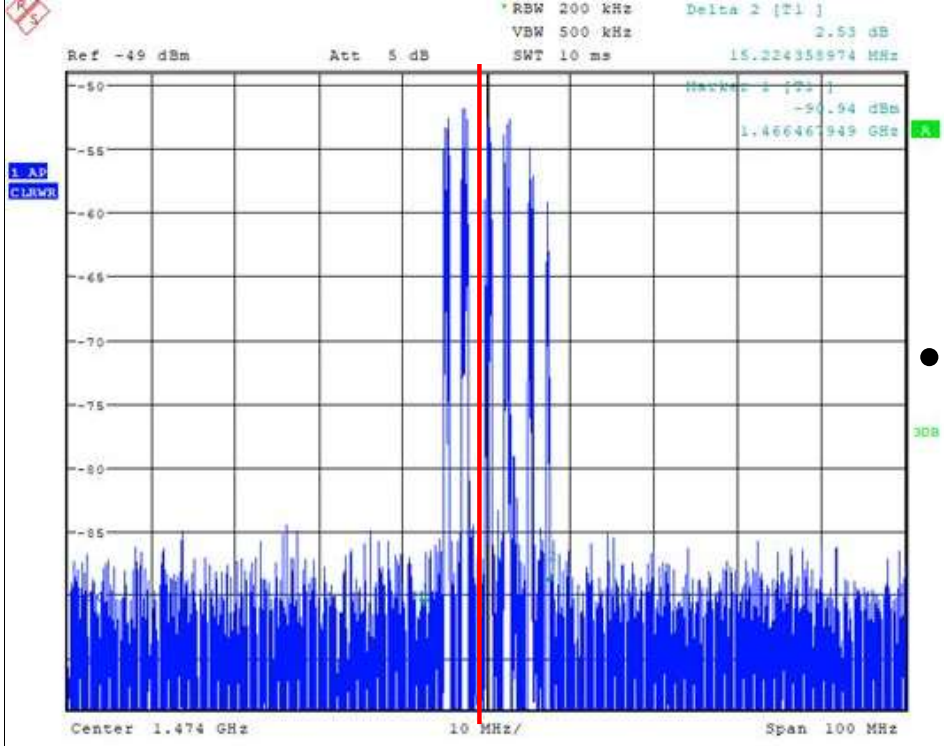
- Using two different sources:
  - List from KPN with maintenance date, time and location
  - Dutch antenna registry map
- Mobile network maintenance and interference had an **exact fit**
- Mobile network antenna pointed to our GNSS antenna.
- During maintenance, 5G was also implemented
- 5G: 784 MHz -> 2nd harmonic: 1.568 MHz (close to GPS L1 1.575 MHz)



Inconsistancies within the theory

- Other networkproviders turned on 5G-internet without causing interference.
- Only at KPN-antennas interference was found, Vodafone and T-Mobile have almost equal 5G-internet
  700 MHz frequencies.





Collaborating to find problem

- Agentschap Telecom
  - Only KPN turned 4G+ signal on
  - 4G+ at 1.475 MHz
  - Only downlink due to possible interference of mobile-phone GPS
  - Field tests with 1.475 MHz radiator proved theory
- KPN
  - Took almost 3 months to get a technical response
  - 5G didn't cause interference
  - 4G LTE+ caused interference at frequency of 1.475 MHz
- Topcon
  - Conducted their own tests to find the issues with their equipment

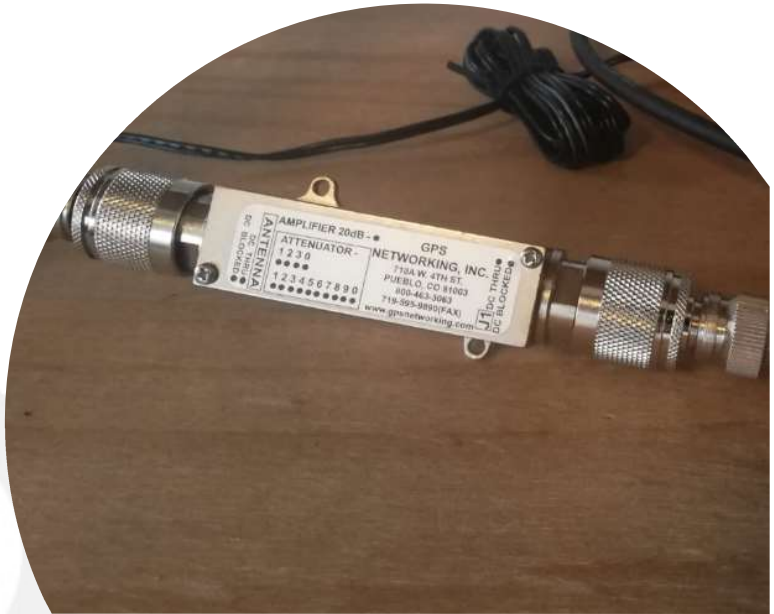
Looking into possible solutions

- Two types of attenuator
  - -20dB amplifier DC blocked
  - -40dB amplifier DC blocked

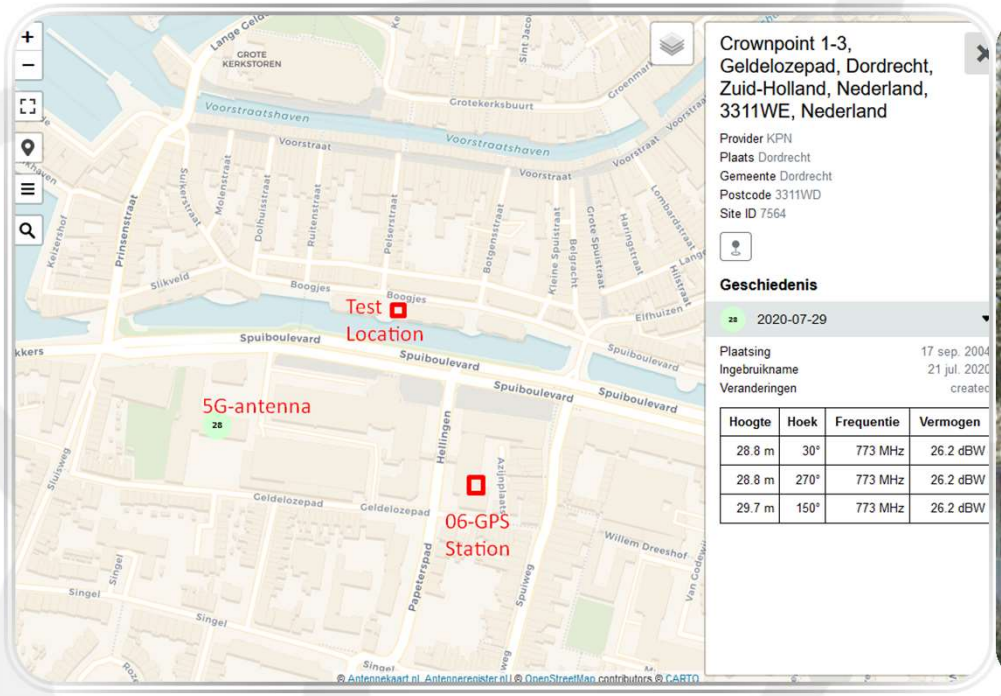
- Proposed new antenna
  - CR.G5C choke ring with cavity filter

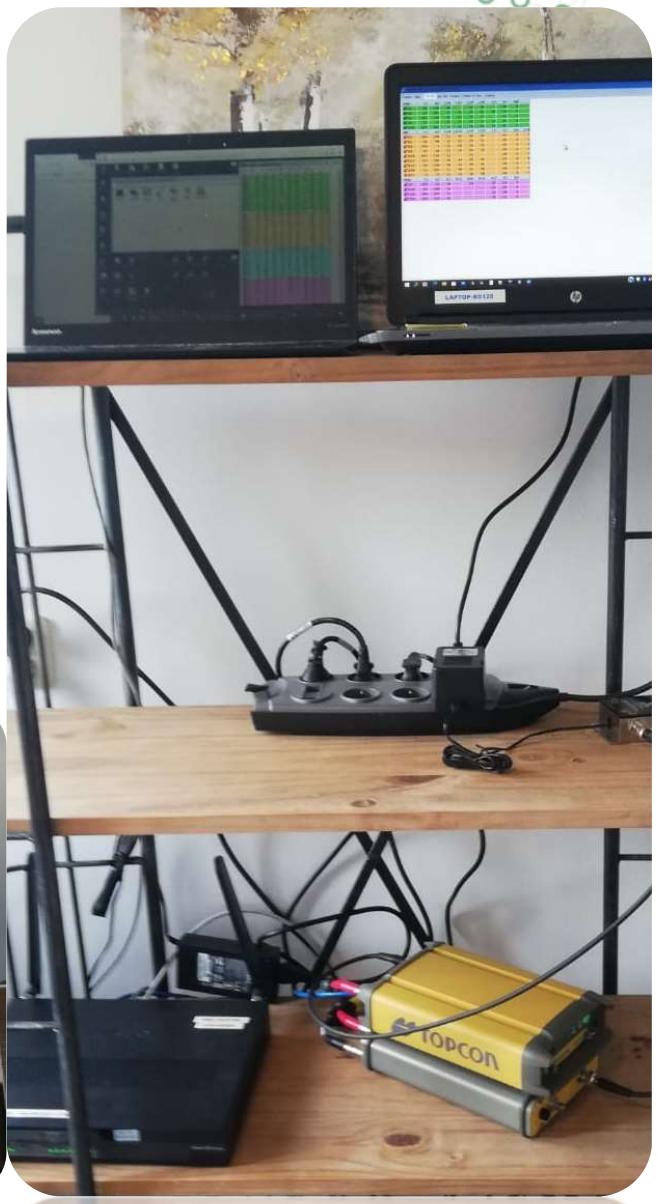
Attenuator -40dB with cooling

Attenuator -20dB



Testing solution using temporal station





Test-scenarios:

1. Replication of 06-GPS station Dordrecht
2. Replication without antenna splitter
3. Replication with addition of band filter compact
4. Replication with addition of band filter cooled
5. Replication with non-amplified antenna splitter
6. Replication with new antenna “TPSCR.G5C TPSH”

Only the proposed antenna by Topcon could mitigate the interference!

Antenna TPSCR.G5C TPSH

Cavity filter mitigates near band jamming

TPS CR.G5C

Out of Band Rejection

- <1050 MHz : -80 dB
- 1051 – 1090 MHz : -60 dB (39 MHz)
- 1160 – 1300 MHz : - 0 dB (140 MHz) (L2/L3/L5)
- 1370 – 1510 MHz : -60 dB (140 MHz)
- 1540 – 1610 MHz : - 0 dB (70 MHz) (L1)
- 1670 – 1699 MHz : -60 dB (29 MHz)
- > 1700 MHz : -80 dB

TPS CRG5

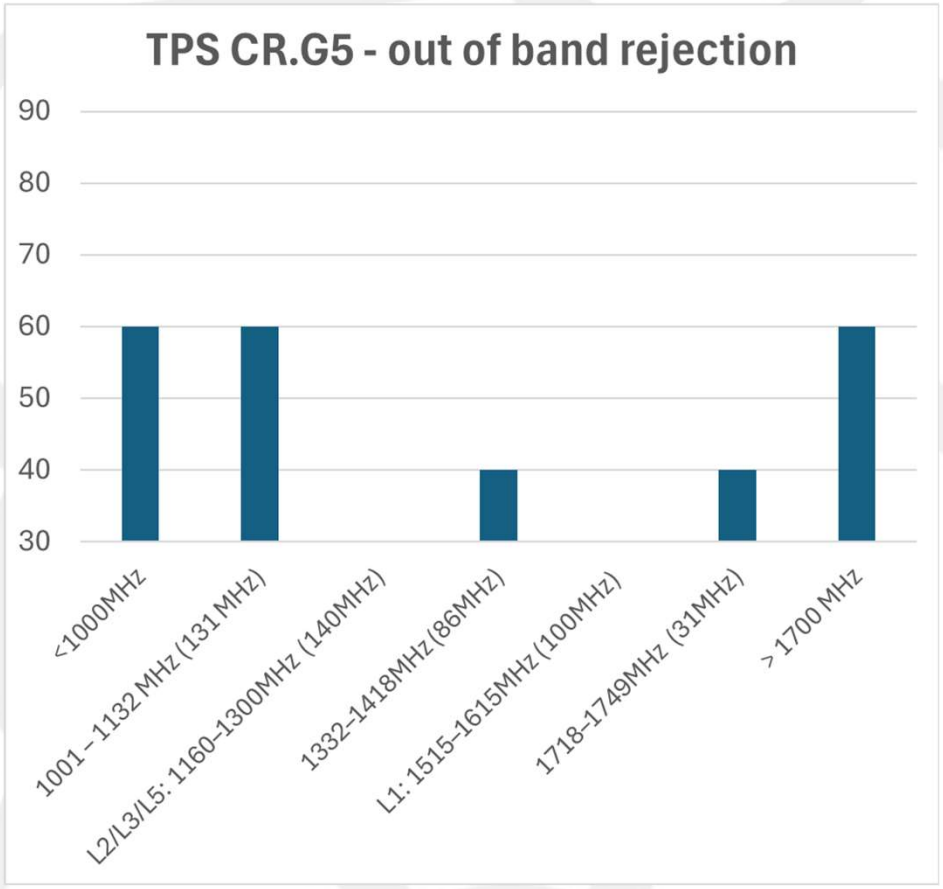
Out of Band Rejection

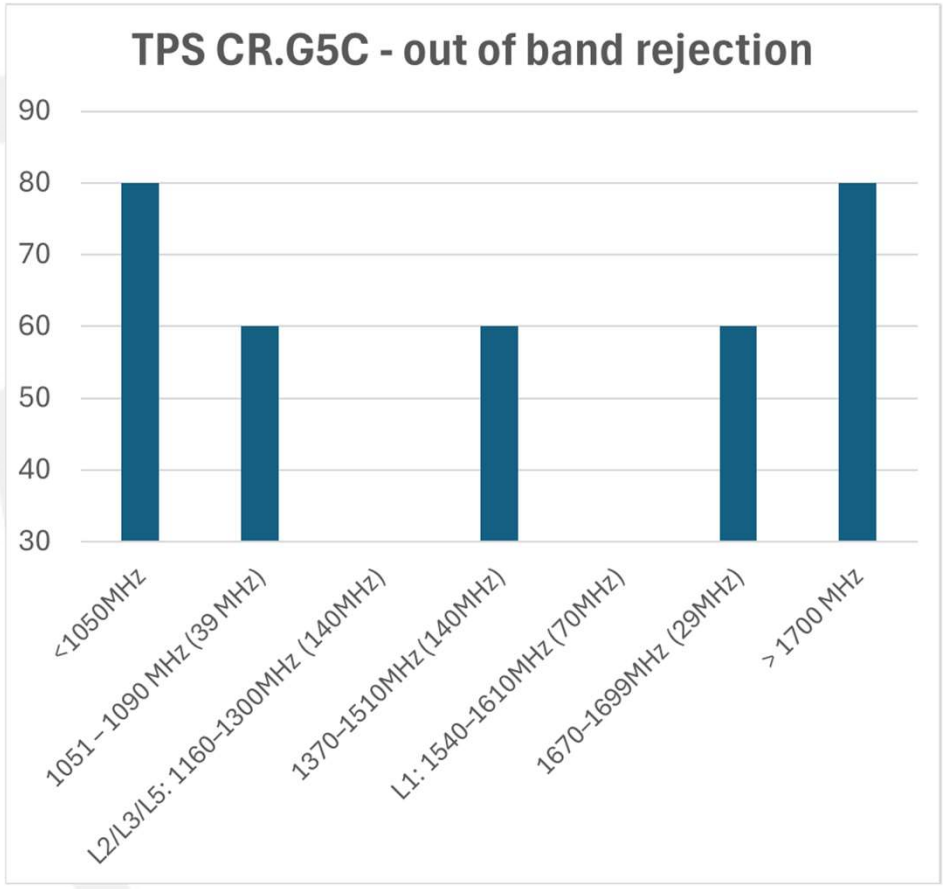
- <1000 MHz : -60 dB
- 1001 – 1132 MHz : -60 dB (131 MHz)
- 1160 – 1300 MHz : - 0 dB (140 MHz) (L2/L3/L5)
- 1332 – 1418 MHz : -40 dB (86 MHz)
- 1515 – 1615 MHz : - 0 dB (100 MHz) (L1)
- 1718 – 1749 MHz : -40 dB (31 MHz)
- > 1750 MHz : -60 dB

Too broad Out of band rejection

Smaller rejection

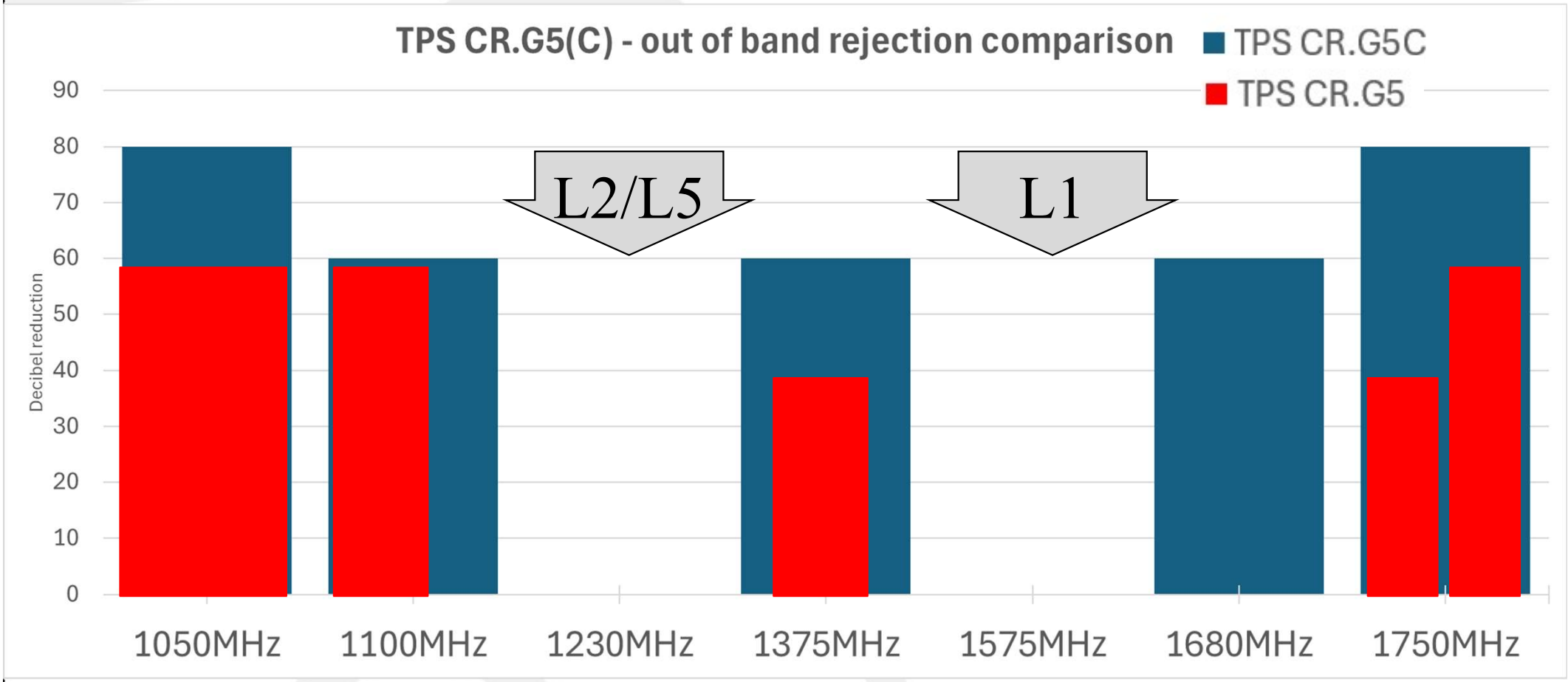
Cavity filter mitigates near band jamming





TPS CR.G5 has a too broad Out of band rejection,
and a 20dB weaker rejection filter.

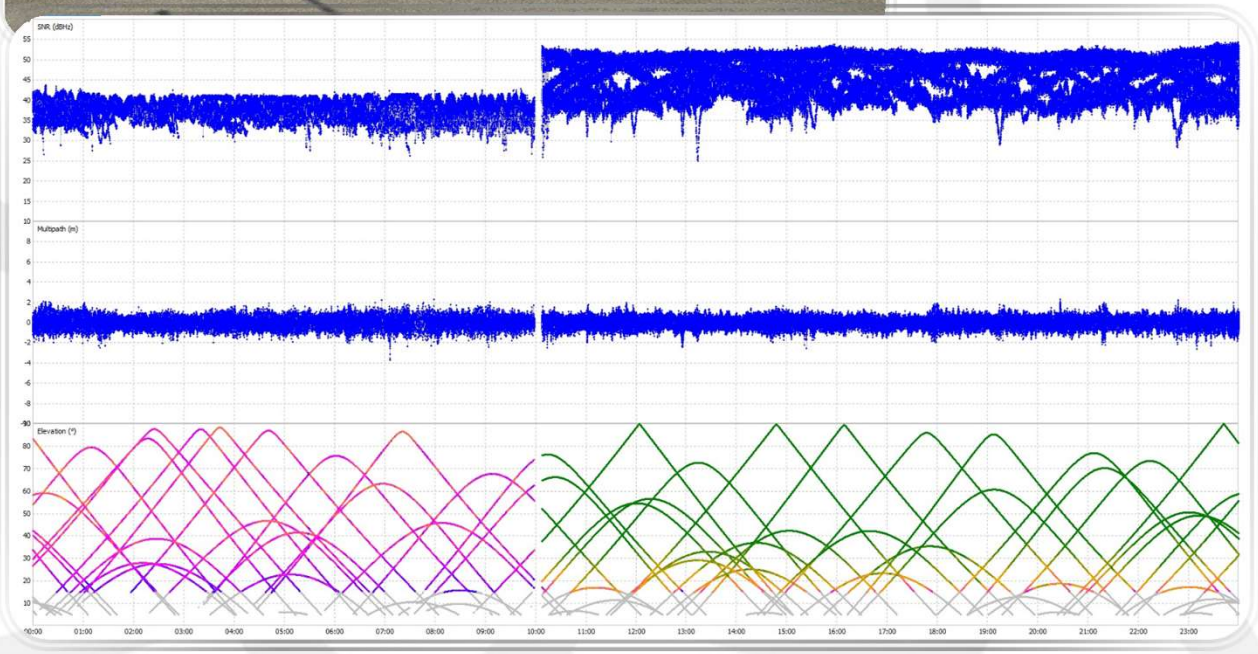
Cavity filter mitigates near band jamming

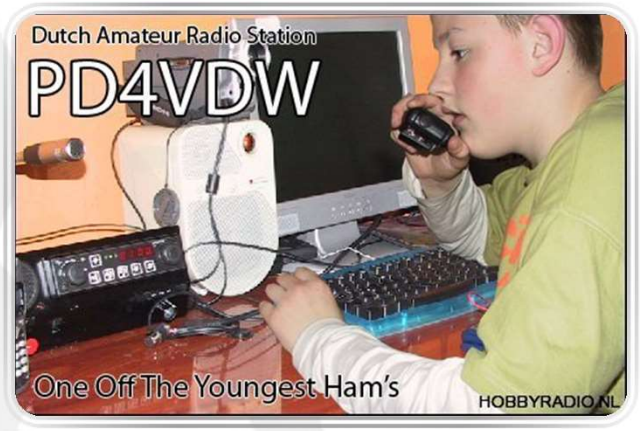


TPS CR.G5C has a broader Out of band rejection,
and a 20dB stronger rejection filter.

Implementing solution

- Antenna change at 28 stations
- Change logs to partners

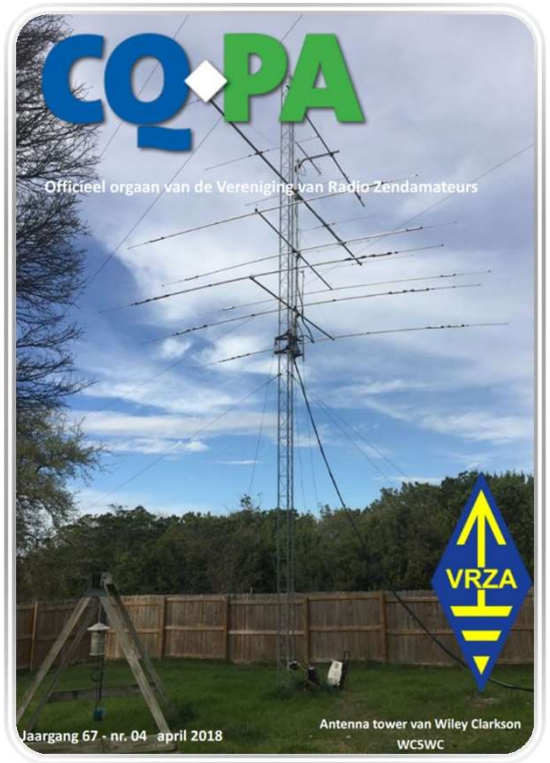




HET MEEST VEELZIJDIGE NETWERK
OG-GPS

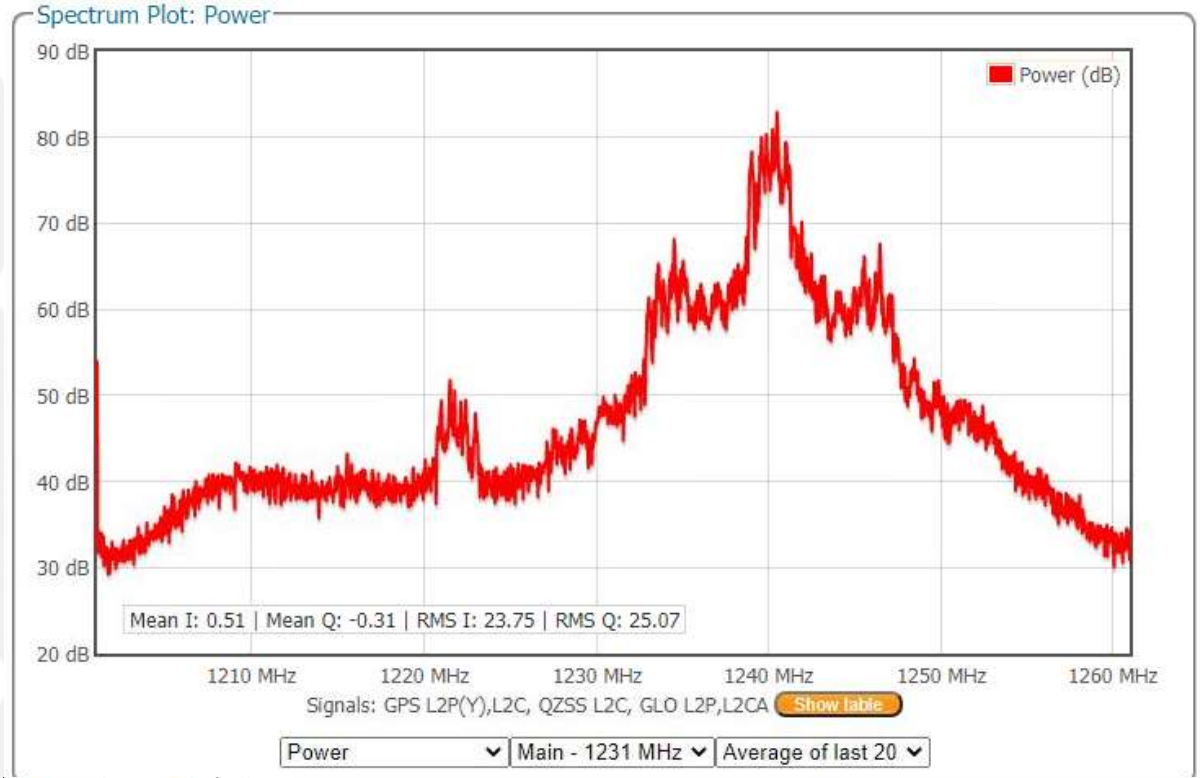
Case 2: Radio Amateur interference

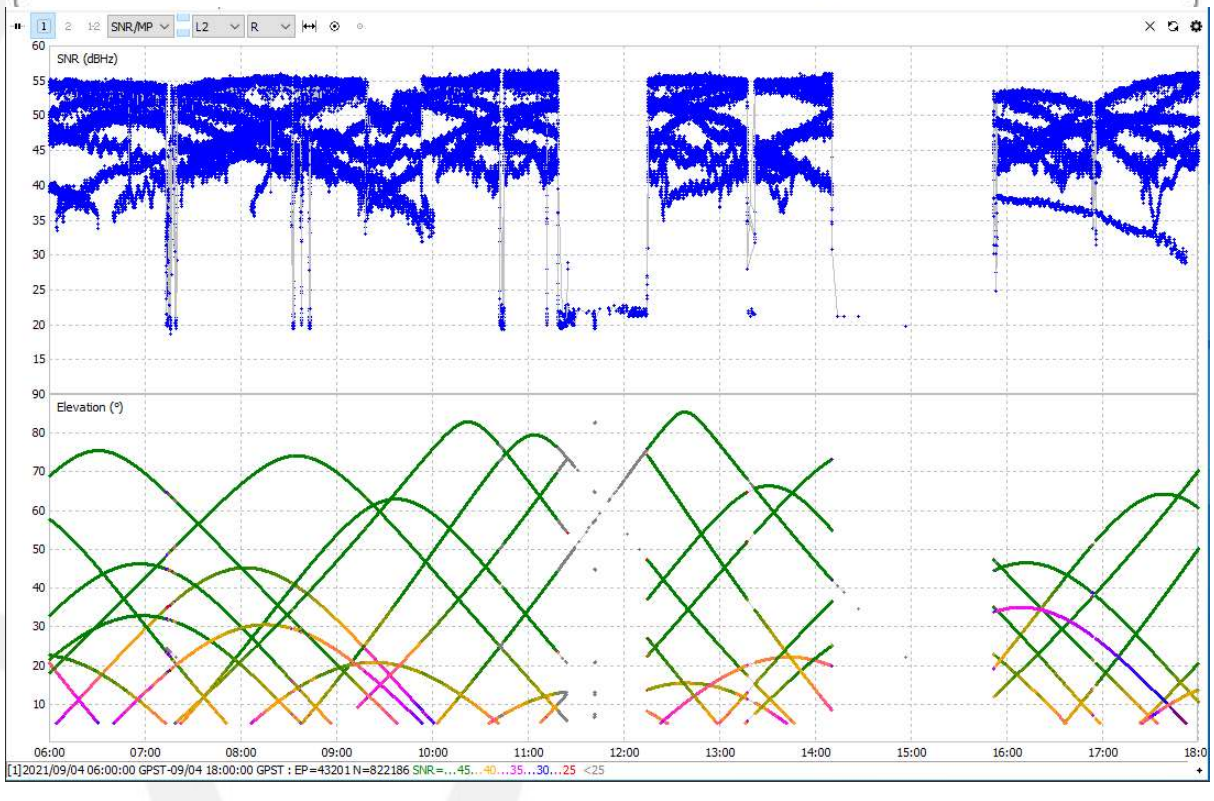
Single station Radio Interference



Discovery of interference

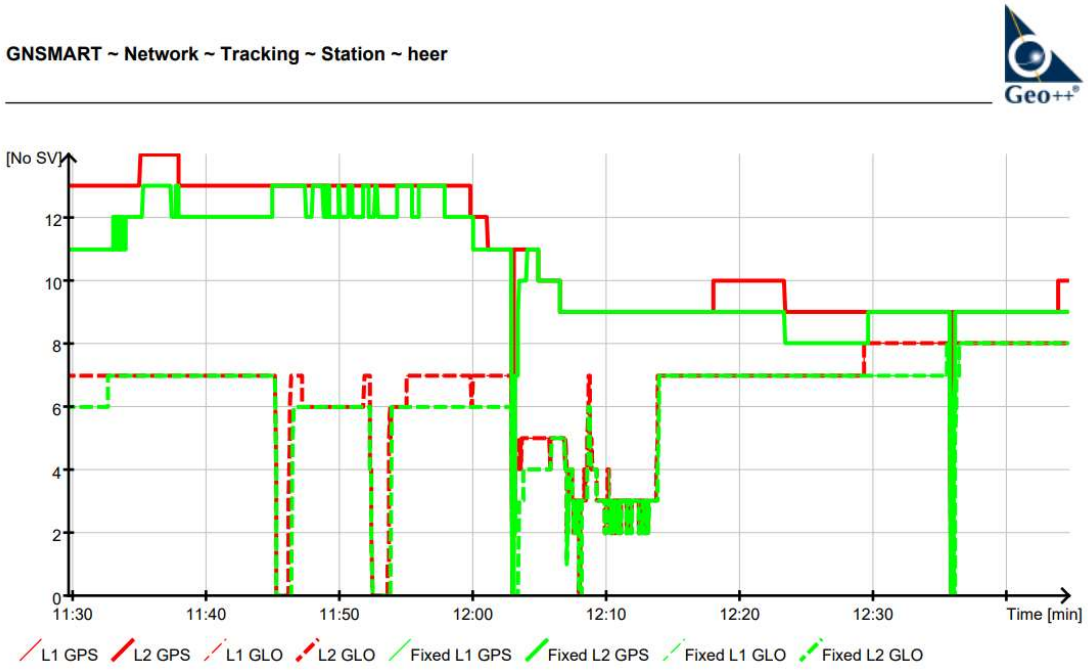
- Station Heerhugowaard
- Loss of fix in GNNET/GPPNET (GNSMART Geo++)
- Time depended, no exact schedule
- Only L2 of GPS & GLO affected



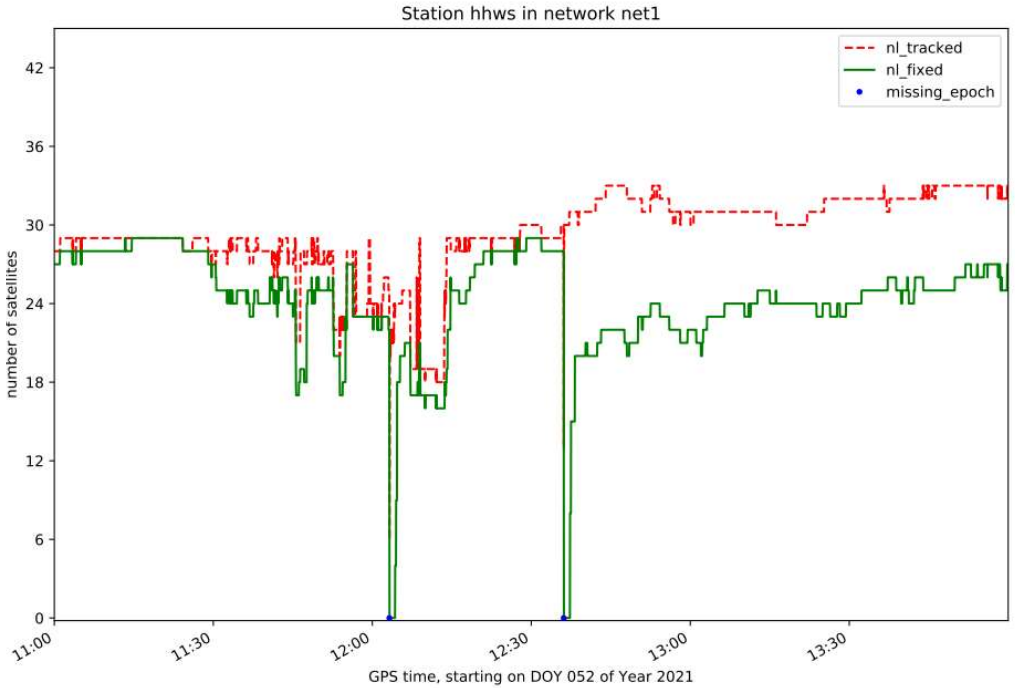


Effect on RTK-corrections

GNNET



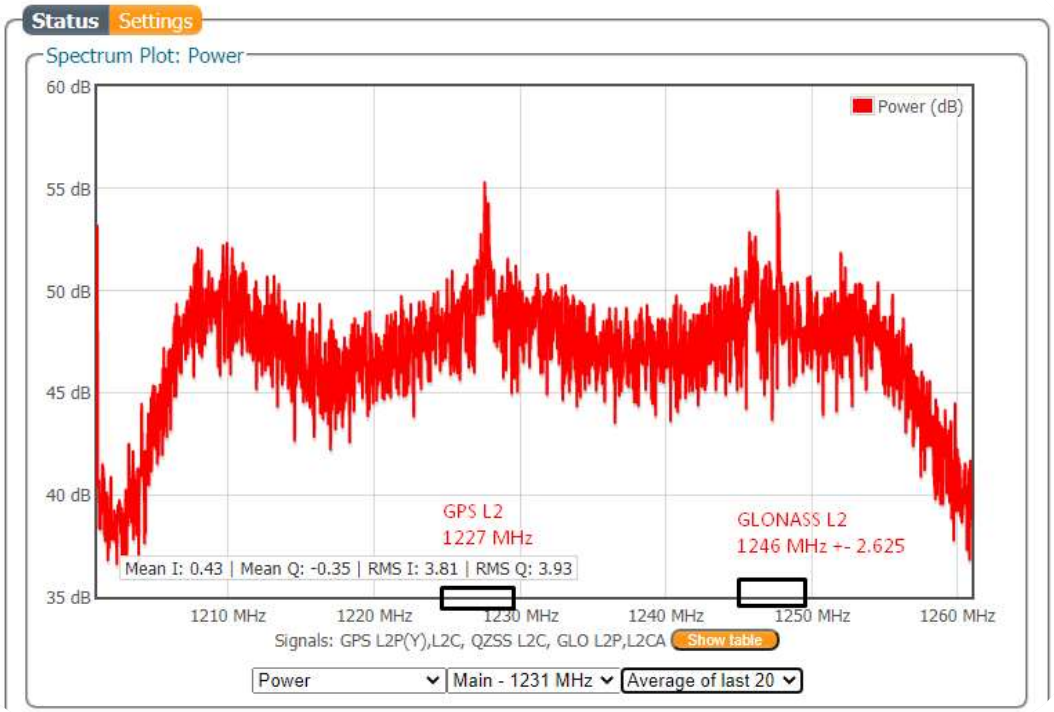
GPPNET

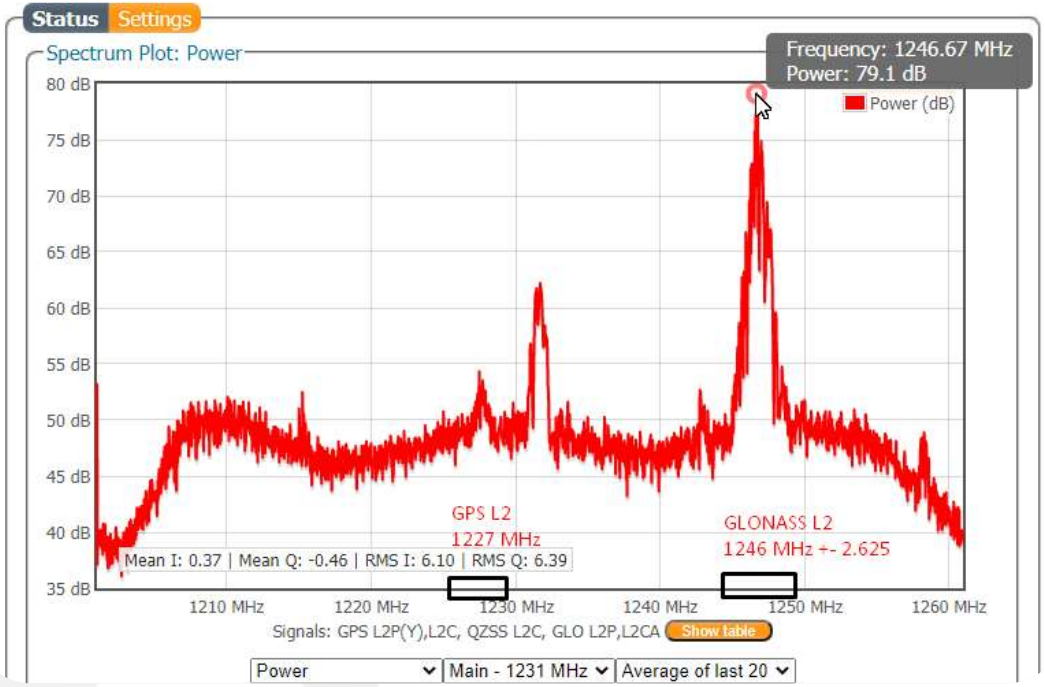


Spectrum analyses

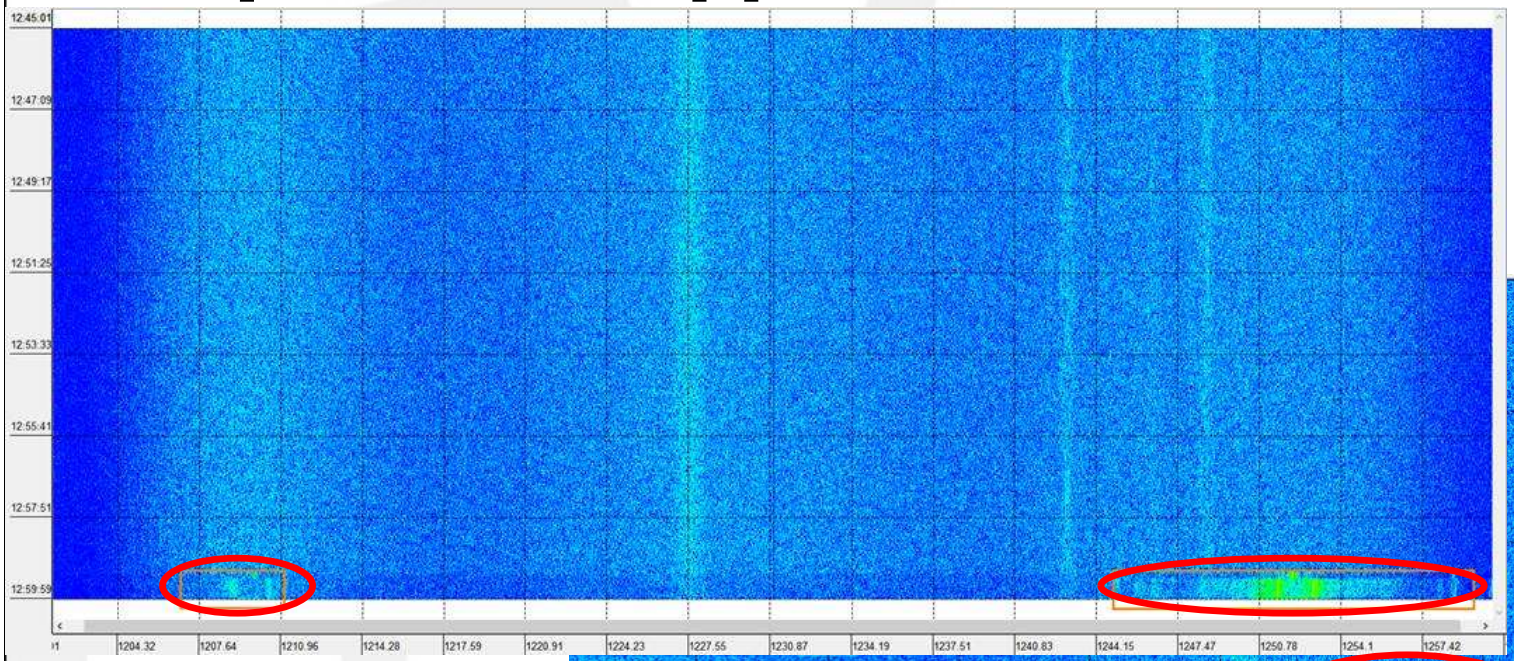
Kanaal	GLO L1 MHz	GLO L2 MHz	PRN
-7	1598.063	1242.938	10, 14
-6	1598.625	1243.375	
-5	1599.188	1243.813	
-4	1599.750	1244.250	02, 06
-3	1600.313	1244.688	18, 22
-2	1600.875	1245.125	09, 13
-1	1601.438	1245.563	12, 16
0	1602.000	1246.000	11, 15
1	1602.563	1246.438	01, 05
2	1603.125	1246.875	20, 24
3	1603.688	1247.313	01, 23
4	1604.250	1247.750	17, 21
5	1604.813	1248.188	03, 07
6	1605.375	1248.625	04, 08
7	1605.938	1249.063	

Signaal	Freq. MHz
GPS L1	1575.42
GPS L2	1227.60
GPS L5	1176.45
GAL E1	1575.42
GAL E5a	1176.45
GAL E5b	1207.14
GAL E6	1278.75
BDS B1	1561.10
BDS B2	1207.14
BDS B3	1268.52



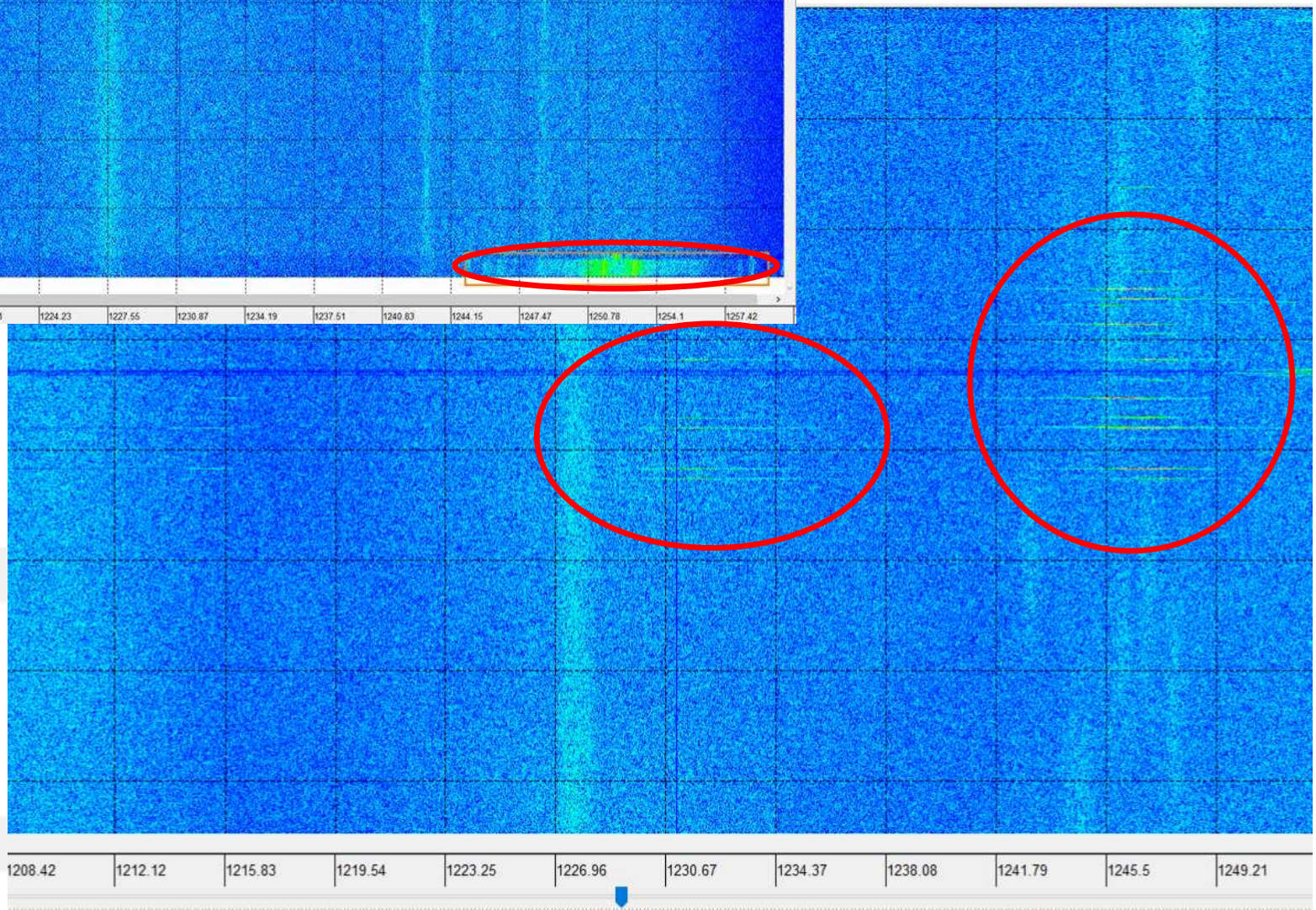


Spectrum analyses with Septentrio support



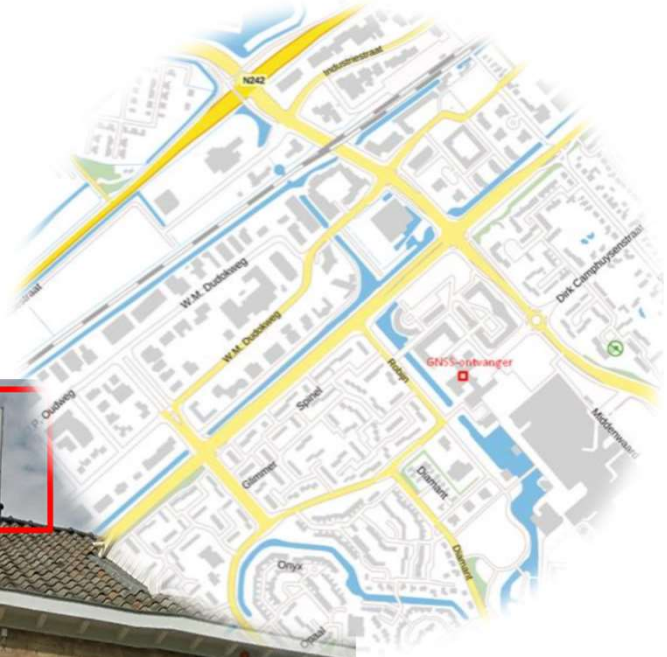
Frequency

Time

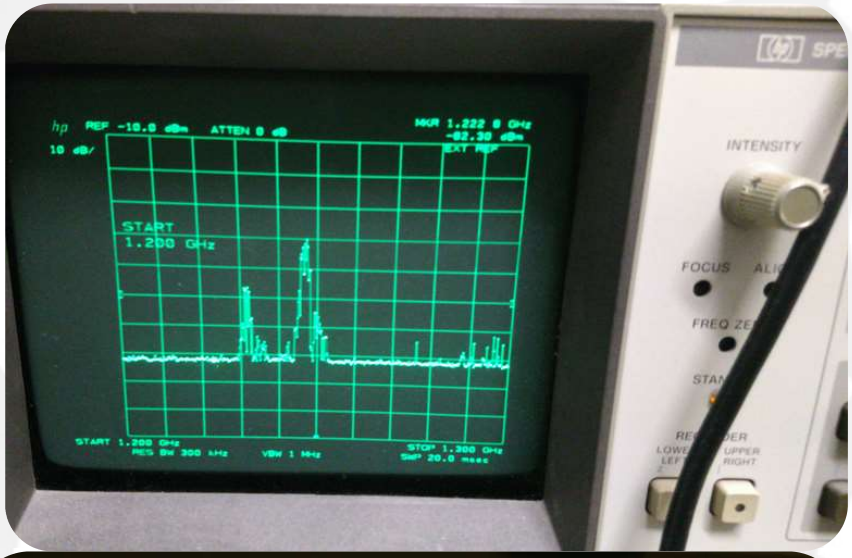


Spatial analyses

- Using antenna registry and street view to find radio amateurs
- Contact regional radio amateur association
- Email contact and plan a meeting



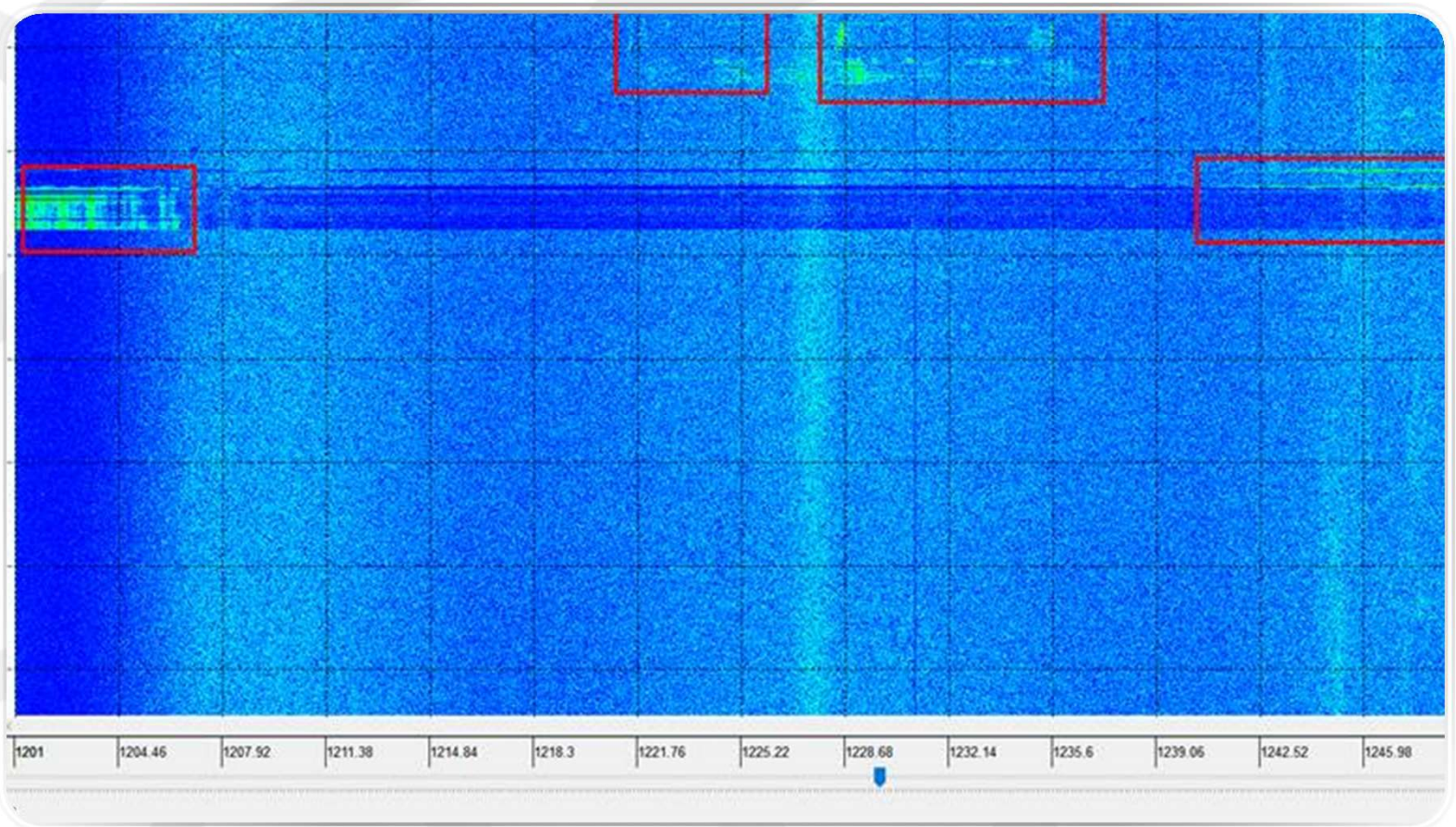
Radio amateur association specialized in video broadcast



- Joining their meeting for interactive spectrum testing.
- Share screen with members Radio amateur association.
- Every user tests their frequency and signal strength
- Life feedback, amount of interference shared

Analysis and conclusion

- During life feedback session the amateurs tested their broadcast limitation
  - 1 amateur used exactly GPS L2
  - 3 amateurs used GLONASS L2 to communicated
- Time-spectrum plot was shared afterwards

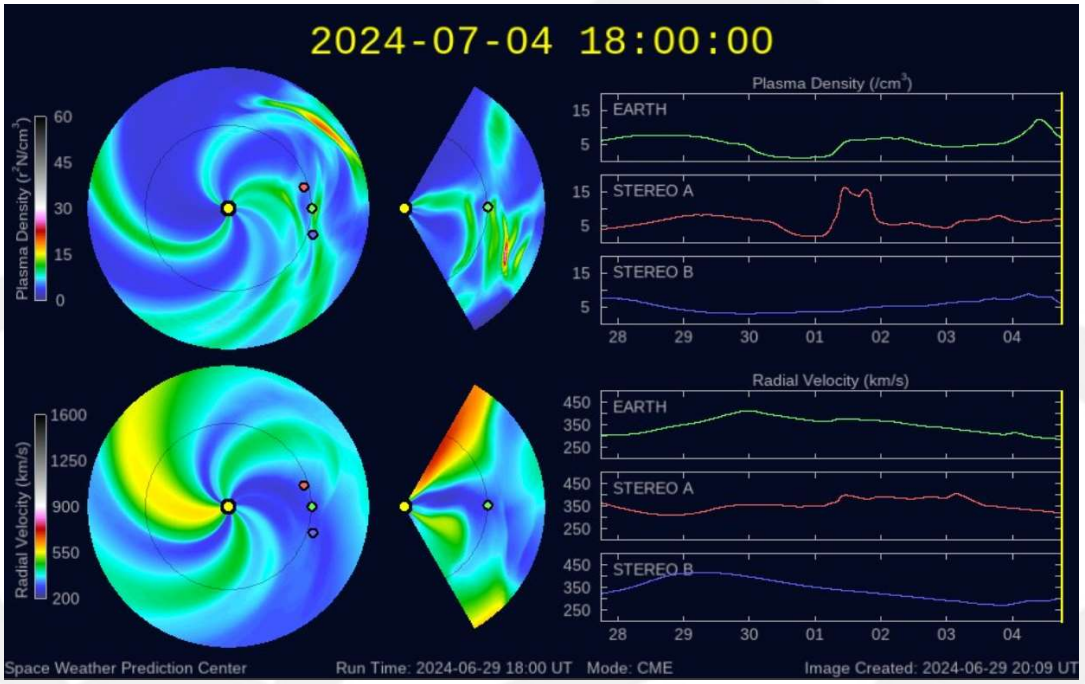


Interference stopped

- Informing various radio amateur asociations
- At one radio amateur television station there was a single user sending at 1252MHz exactly over the GNSS antenna.
- No Agentschap Telecom involved
- Monitoring performance GNSS-station with RINEX logs and network-performance

Conclusions

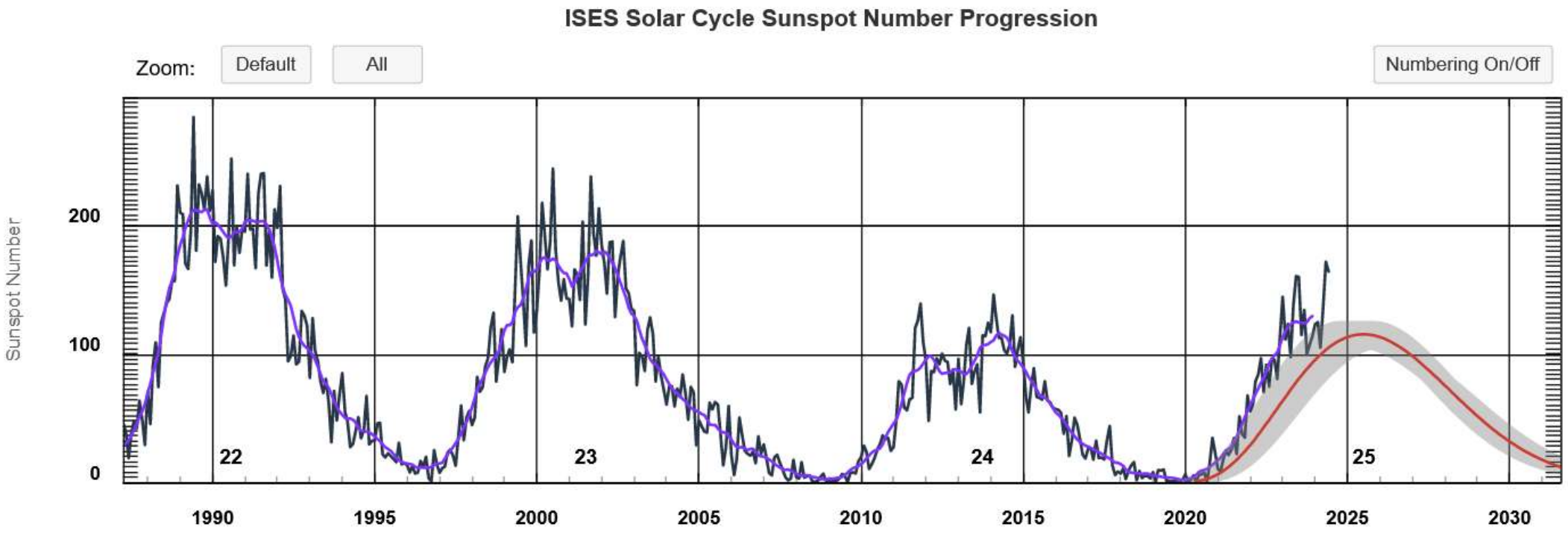
- Know normal GNSS values and monitor receiver performance
- There is always some interference, only focus on problematic interference
- Use social network while investigating problem.



HET MEEST VEELZIJDIGE NETWERK
OG-GPS

Case 3: ionospheric activity

Solar activity cycle

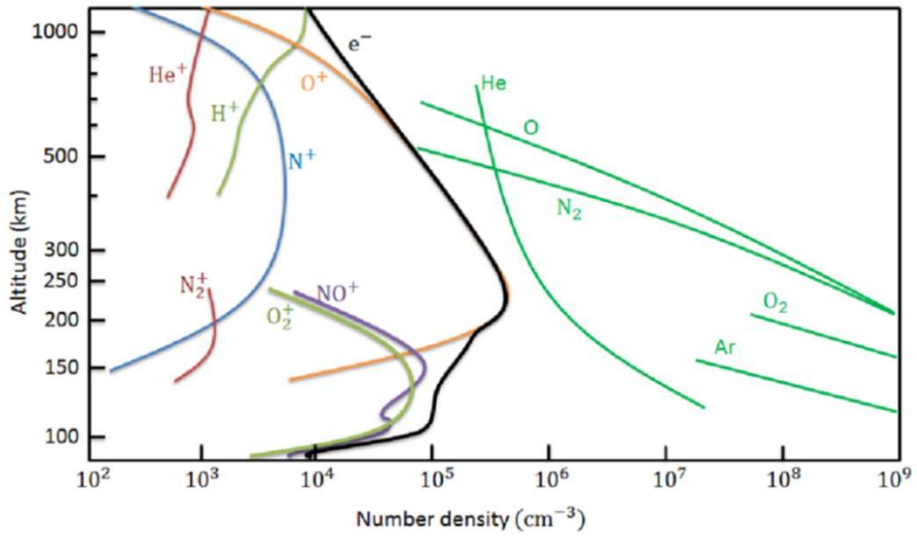


- Monitor iono-activity:
  - VTEC
  - I95
  - IPI
  - Monitor GNSS
- Mitigation strategies:
  - Multi frequency GNSS
  - Geodetic antenne
  - Ref.station density
    - FKP distance

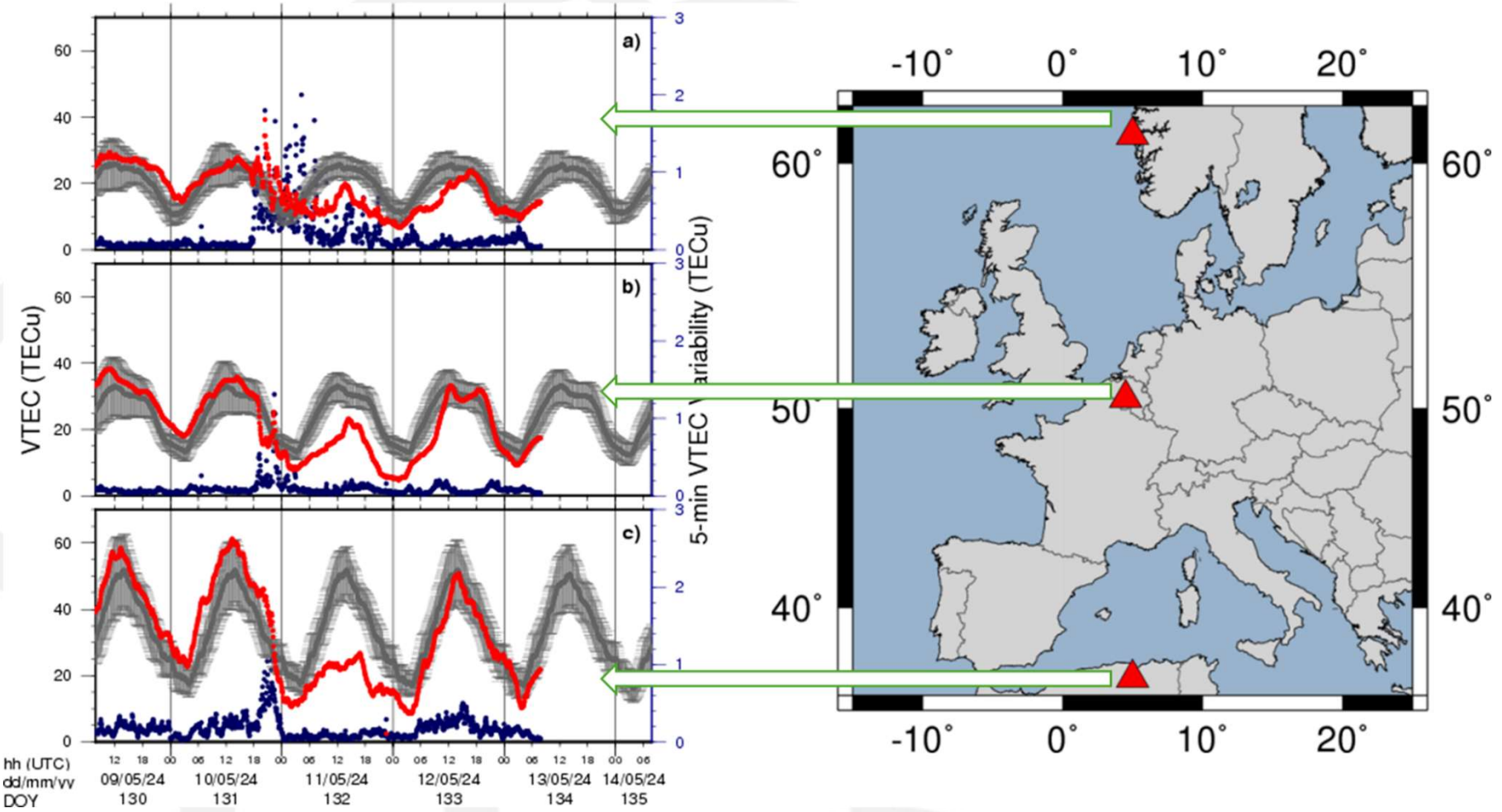
Ionospheric storm at 10-May-2024

Royal observatorium Ukkel (Brussels)

Optical Telescopes in Uccle



Vertical Total Electron Content



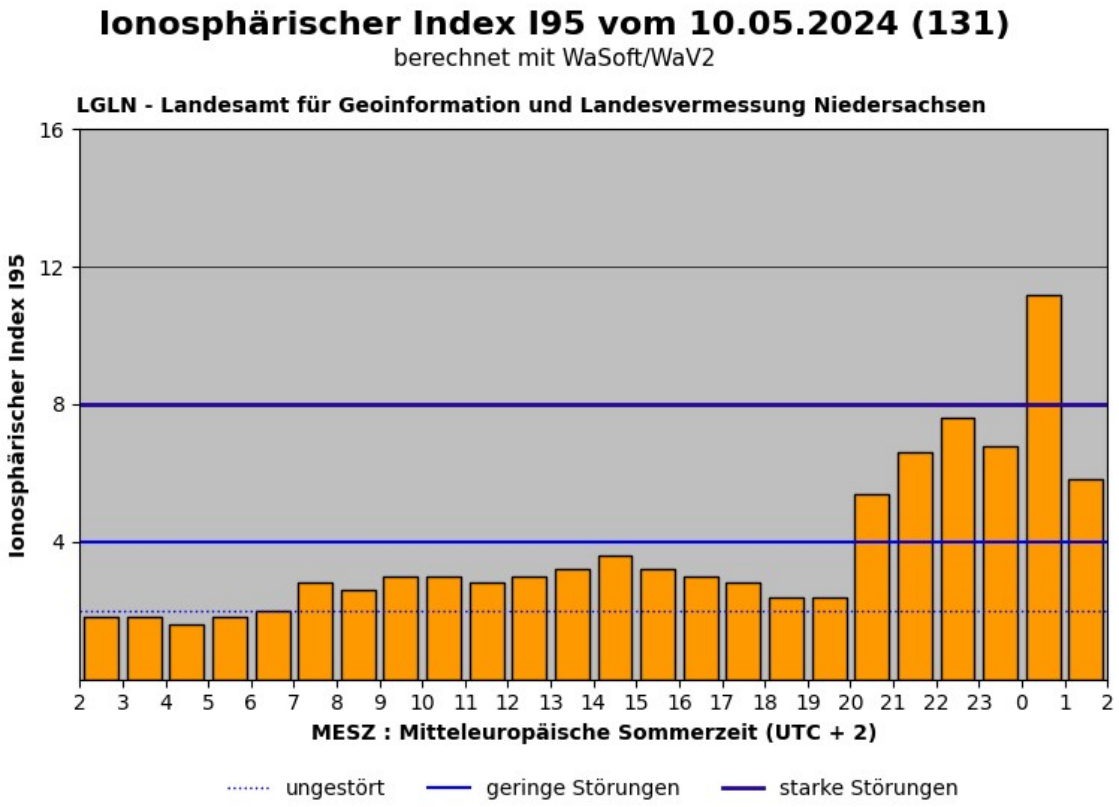
VTEC in red, VTEC variability in blue, expected VTEC in gray

i95 monitoring

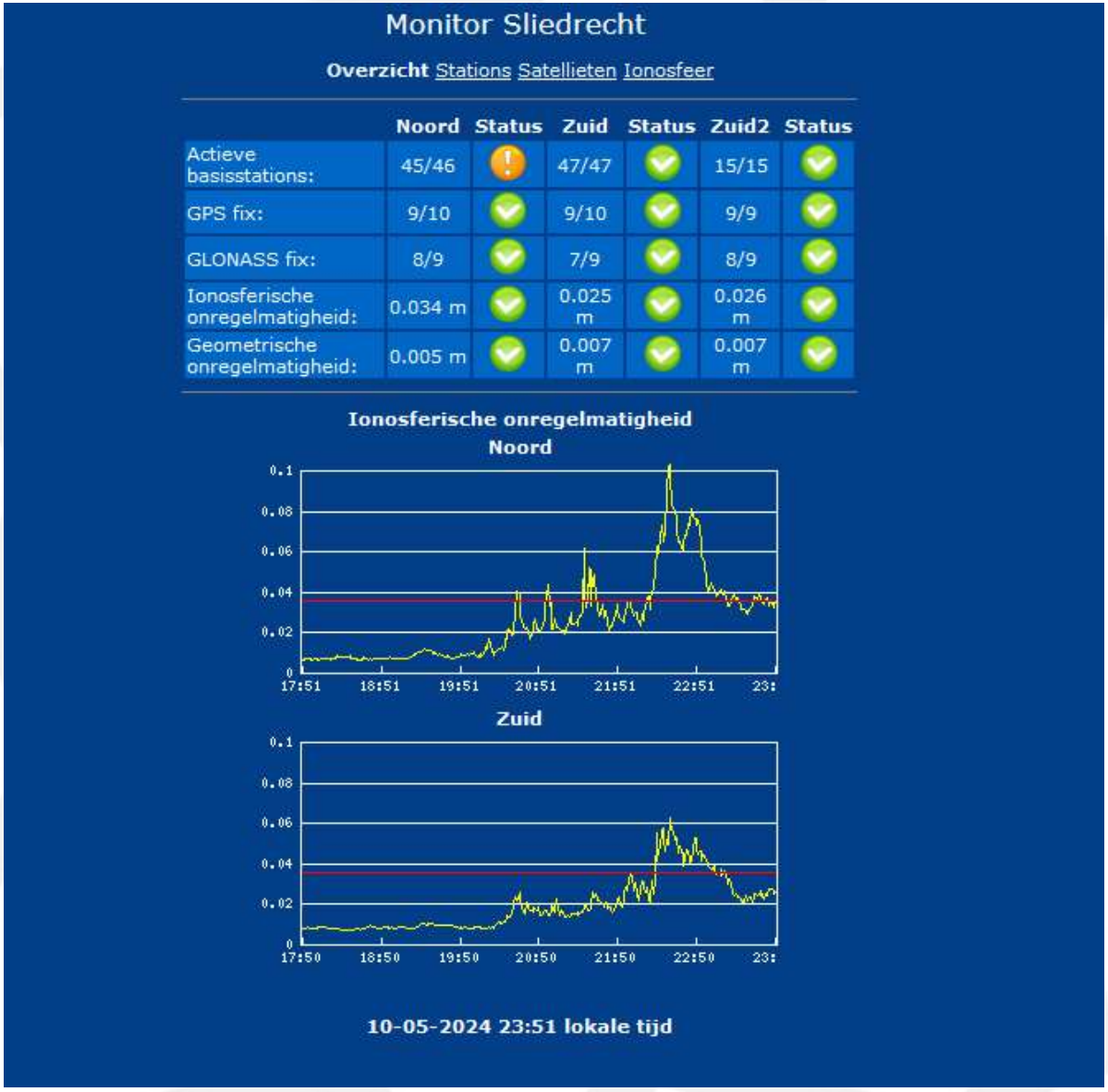
Assumption that rover and ref.station within 20 km experience equal ionospheric base level (relative satellite differences only of interest)

I95 index: 95% margin of ΔI reflects generic ionospheric disturbance:

$$\Delta I = \sqrt{\Delta I_{LAT}^2 + \Delta I_{LON}^2}$$



Ionospheric storm at 10-may-2024



The measure of the interpolation quality of the state information (how well the network predicts the distance dependent errors) is displayed (in meters) separately for the ionospheric (**IPI**) and the geometric (**IP0**) part.
They are computed by 2nd order FKP std. using the std from all stations and satellites with a distance dependent weighting.

A RTK network user's equipment has to account for these residual errors in the field. The ionospheric part IPI can normally be eliminated by dual frequency receivers, if the rover could solve its ambiguities. The geometric part IP0 is mainly influenced by tropospheric irregularities.

Ionospheric storm at 10-may-2024

HET MEEST VEELZIJDIGE NETWERK OG-GPS

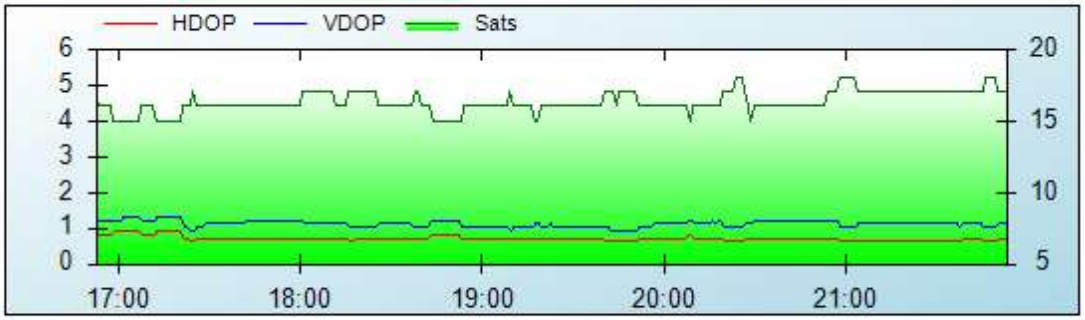
Network Status

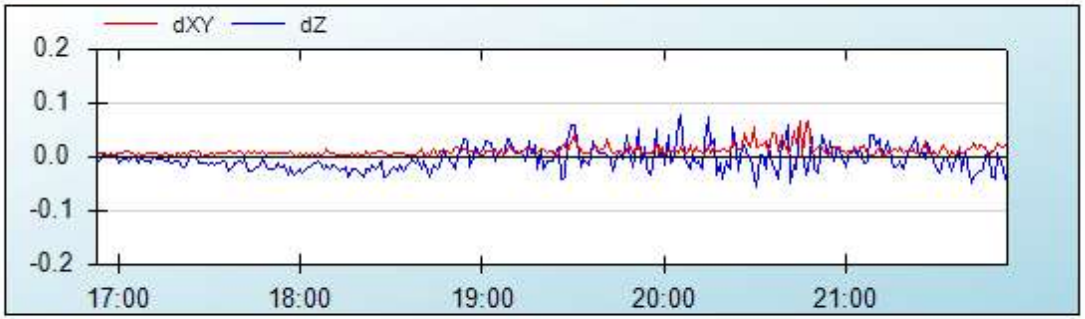
Local Time	10-05-2024 23:53:21
UTC Time	10-05-2024 21:53:21
Monitor Online	142-23:10:29
Active Stations	56 (of 56)
GPS Satellites Tracked	11
GPS Satellites Fixed	10
GLONASS Satellites Tracked	9
GLONASS Satellites Fixed	9
Atmospheric Conditions	Moderate (IR=0.03)

Monitors

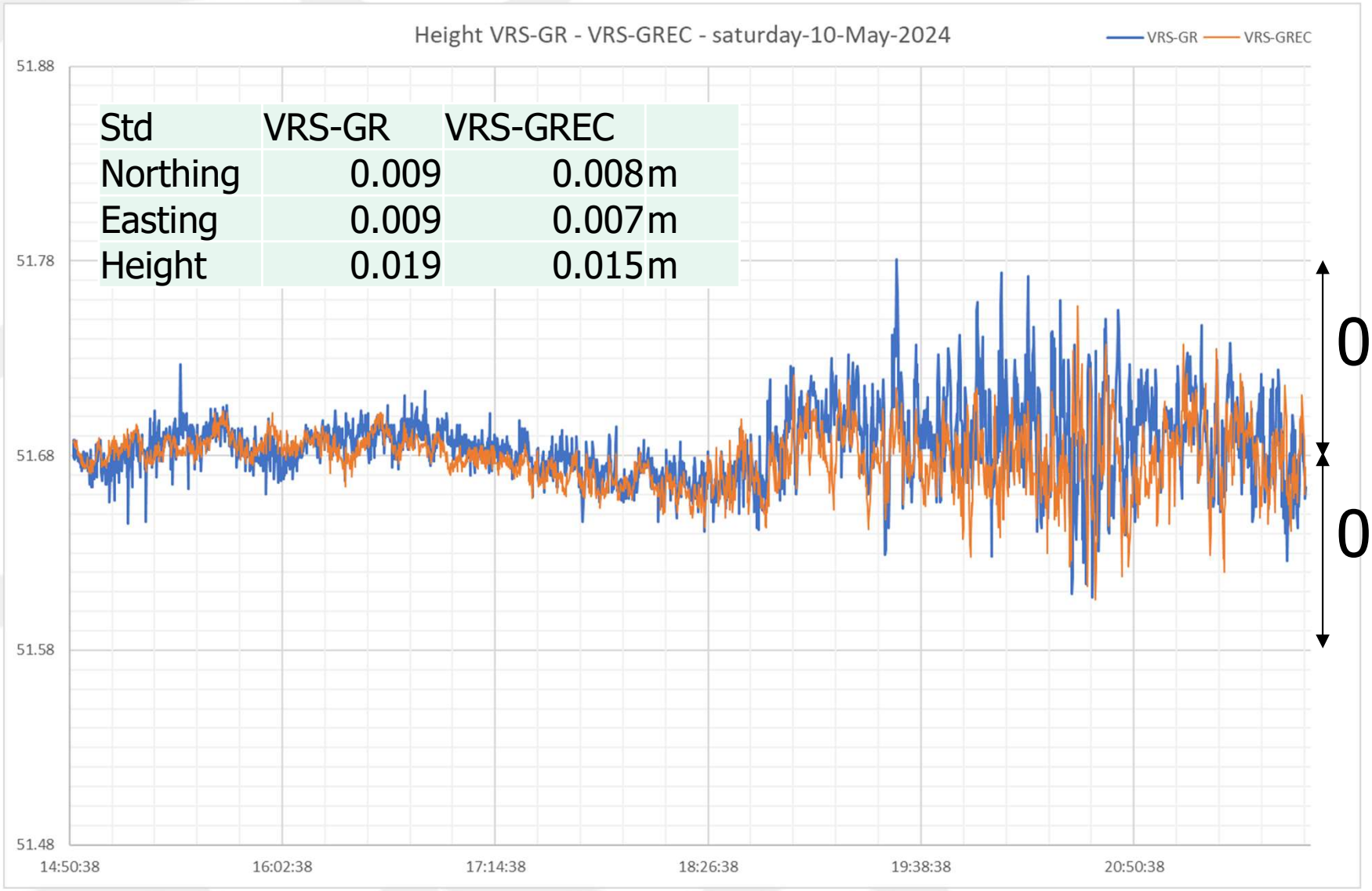
BUNSCHOTEN2

		HDOP	0.70	Satellites	17
Status	RTK Fixed	In fix (last hr)	100.00%	VDOP	1.10
dXY	0.026	2Σ (last 10 min)	0.014	In fix (last 6 hr)	100.00%
dZ	-0.008	2Σ (last 10 min)	0.037	2Σ (last hour)	0.016
				2Σ (last hour)	0.044





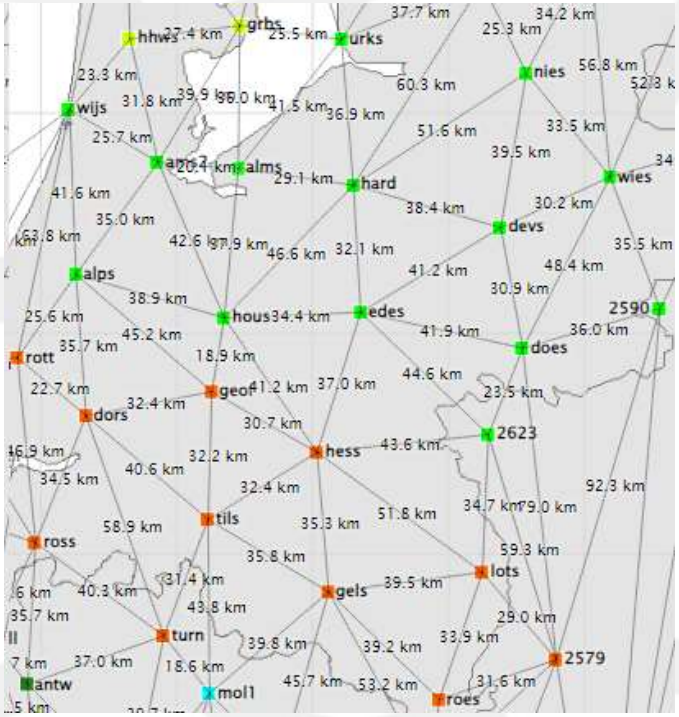
Iono-storm GR-RTK vs. GREC-RTK



Std	VRS-GR	VRS-GREC	
Northing	0.009	0.008	m
Easting	0.009	0.007	m
Height	0.019	0.015	m

Mitigation measures:

- Mitigations strategies:
  - Multi freq. GNSS
  - Geodetic antenne
  - Ref.station density
    - FKP distance



THANK YOU FOR YOUR ATTENTION

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