

Ympyräpolarisaatio – teoriaa ja mittauksia

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Sisälllys

Taustaa:

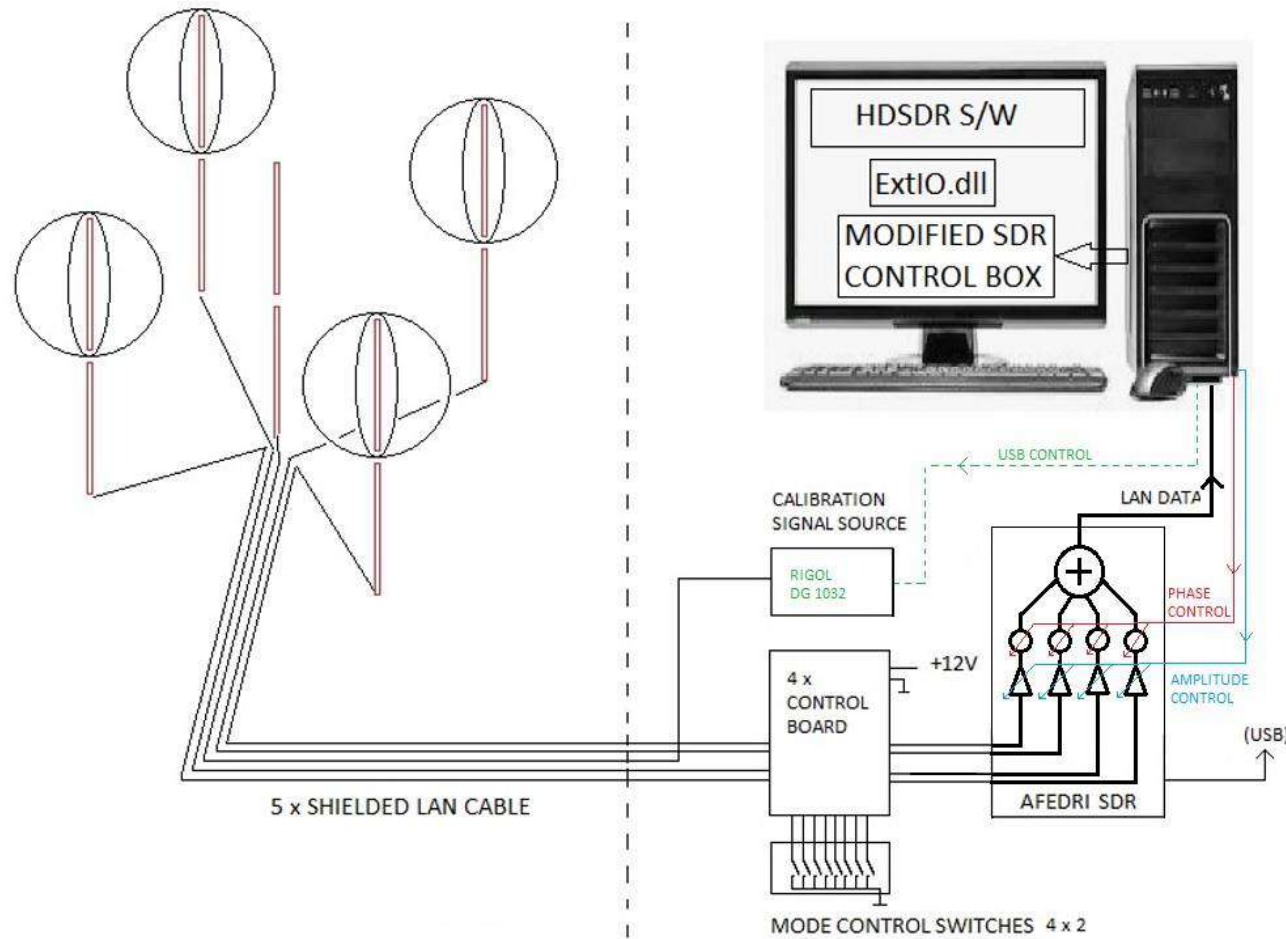
1. Hardware
2. 4-square-antenni
3. Beam- and null-steering
4. Tulokulmien määrittäminen

Polarisaation teoriaa ja mittauksia:

5. Määritelmiä
 6. Ionosfäärin vaikutus
 7. Ympyräpolarisaatioantennit
 8. Ympyräpolarisaatio antenniryhmällä
 9. Joka polarisaation vastaanotin
 10. Polarisaatioparametrit
 11. Yhteenveto
- Viitteet

Tätä ennen tapahtunut:

1. Hardware



[1] SRAL:n Syysleiri, Hankasalmi, 2020

AFEDRI SDR-Net Four Channel SDR by Alex 4Z5LV [2]



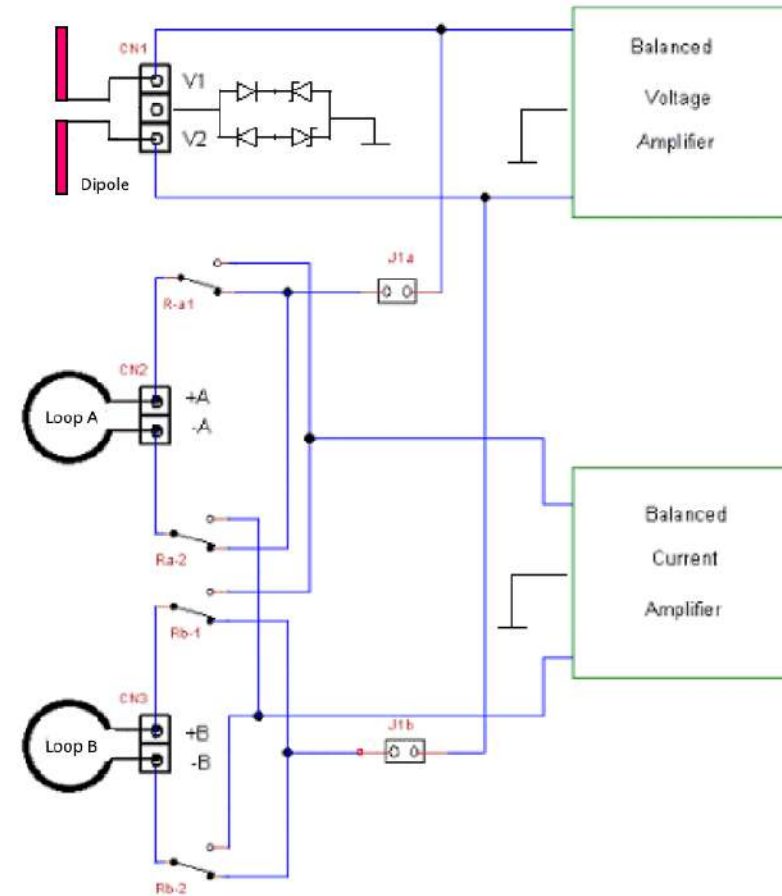
Active Antenna Amplifier AAA-C by LZ1AQ [3]



Fig.1.1 Amplifier



Fig.1.2 Control board

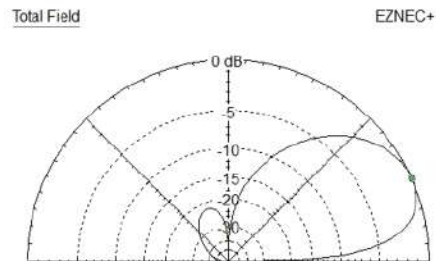


2. 4-square antenni

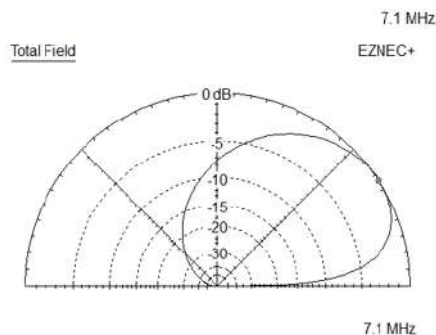
[1] SRAL:n Syysleiri, Hankasalmi, 2020

Laajakaistainen!

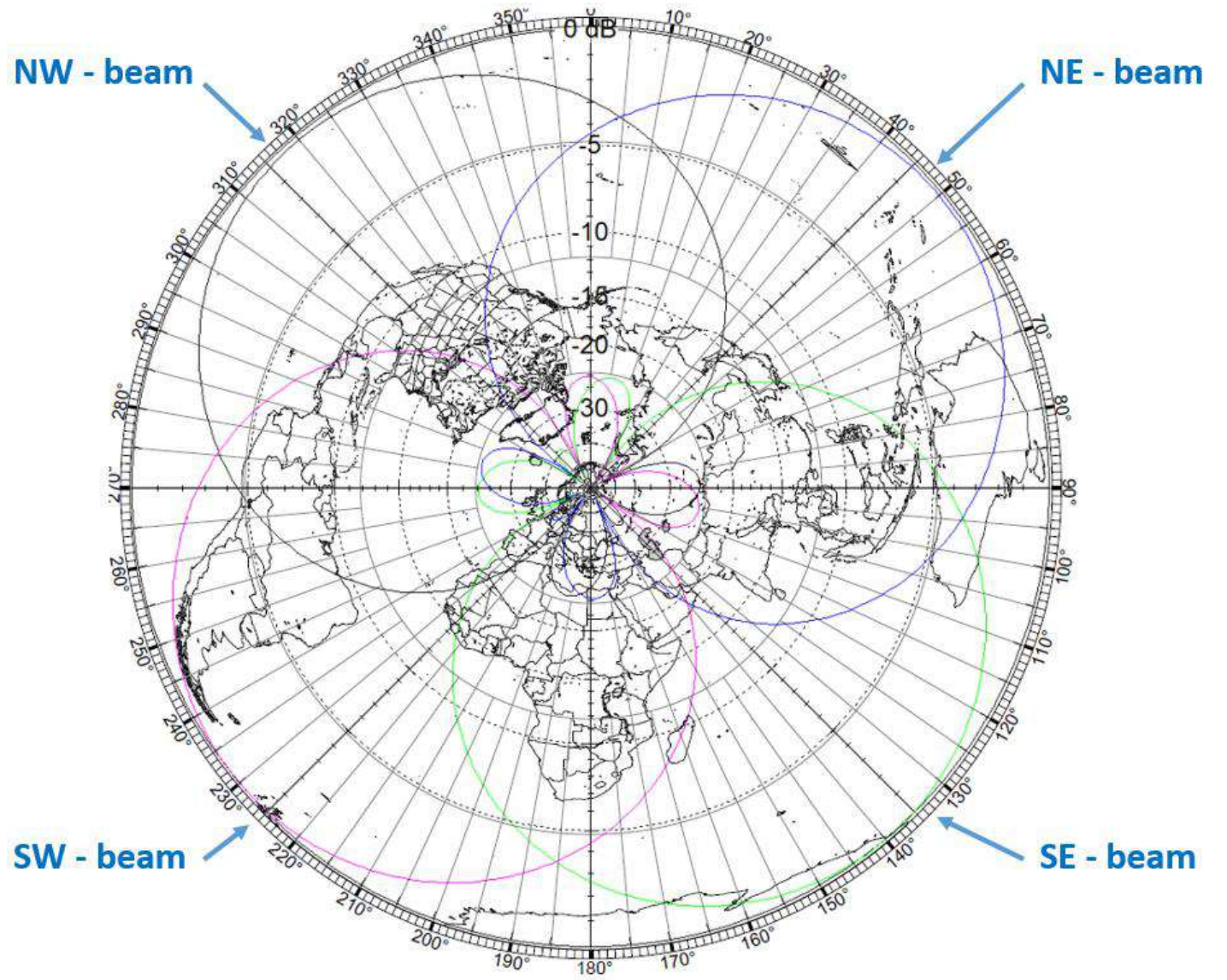
Jokseenkin samat az - säteilykuviot saadaan sekä dipoleilla että luupeilla, erot vertikaalitasossa.



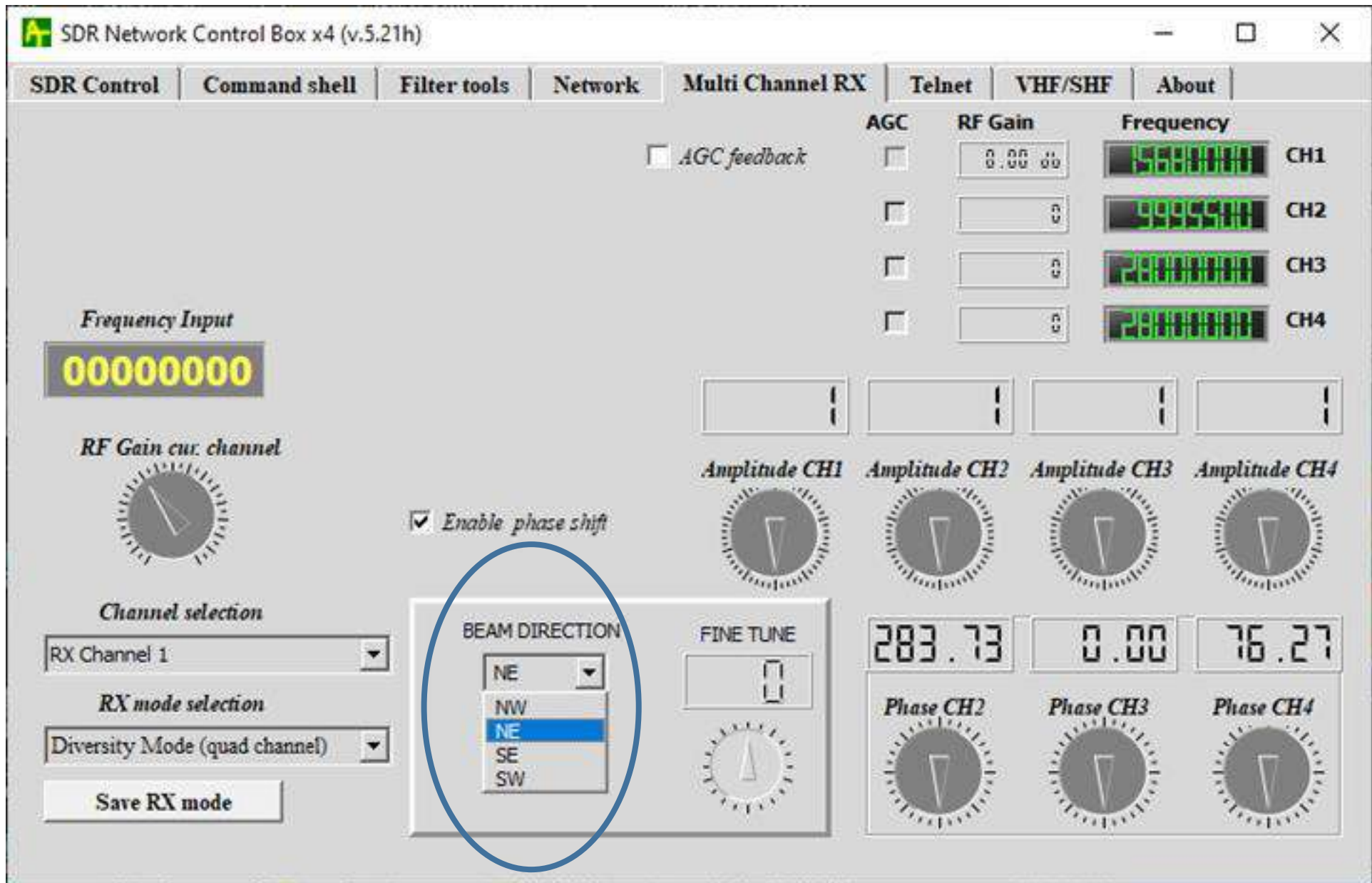
Dipolit



Luupit

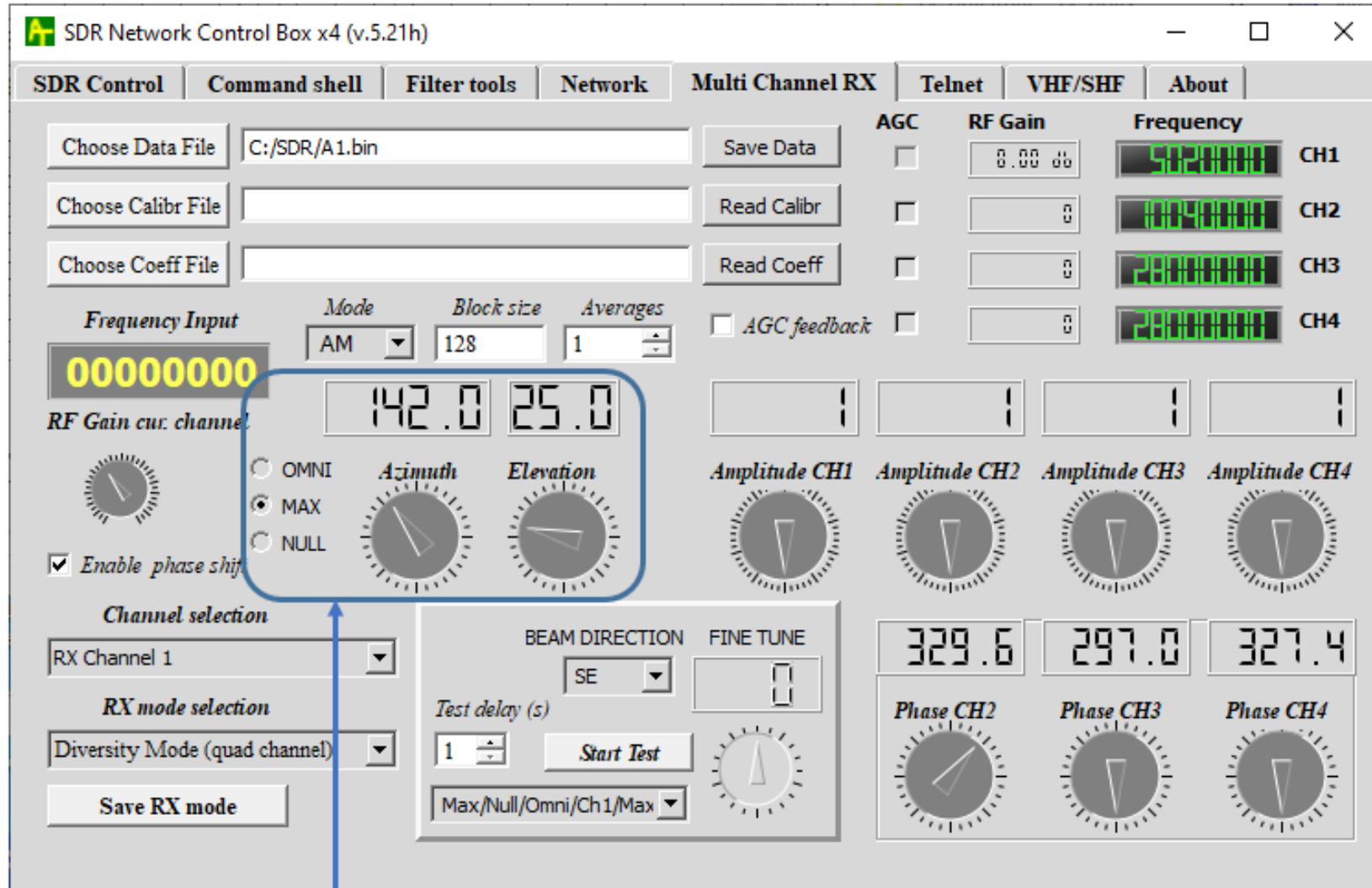


Ref. direction = 320° (T)



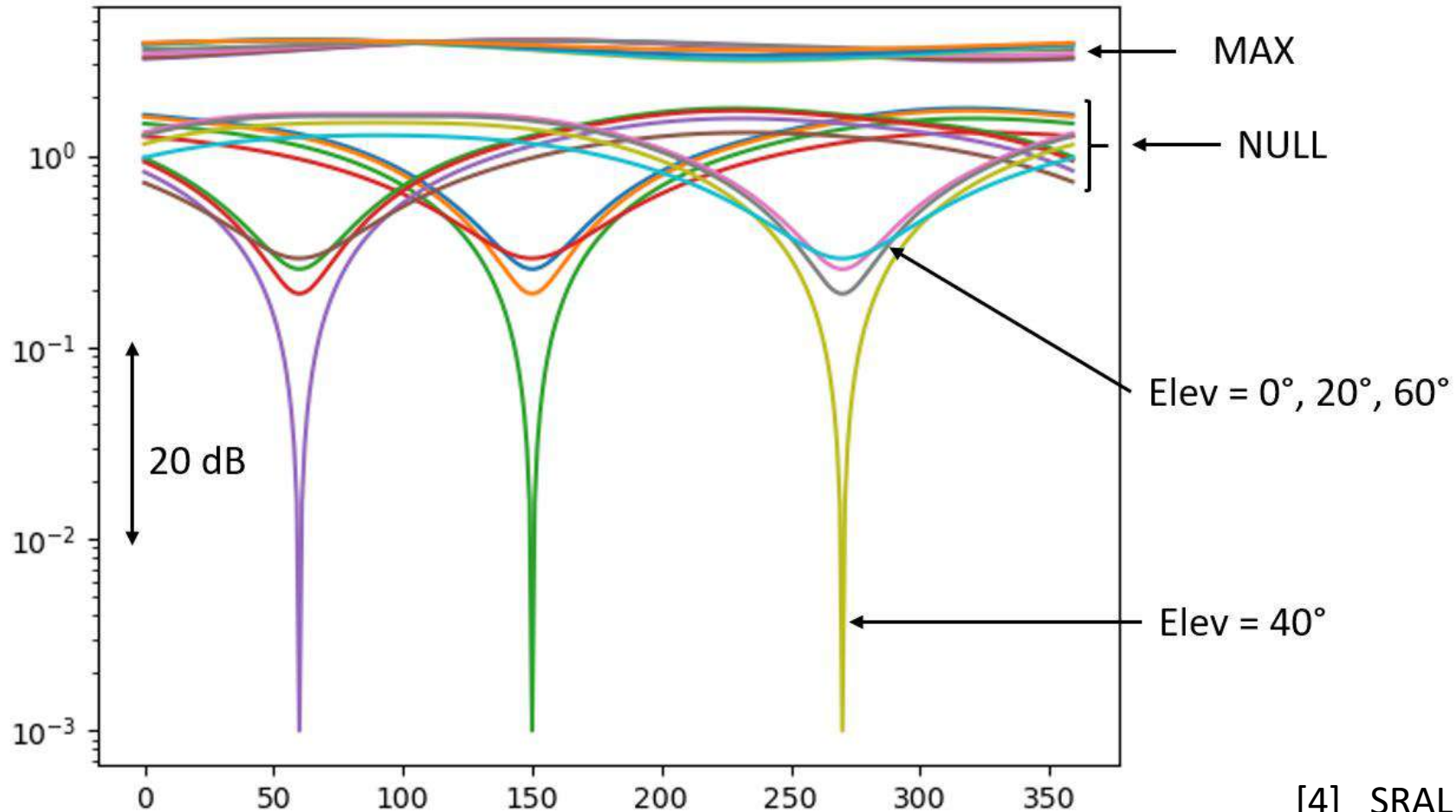
3. Beam- and null-steering

- Säteilysäikeilan maksimi voidaan myös kääntää haluttuun suuntaan
- Samoin nolla-kohta – kuten notch-filter!



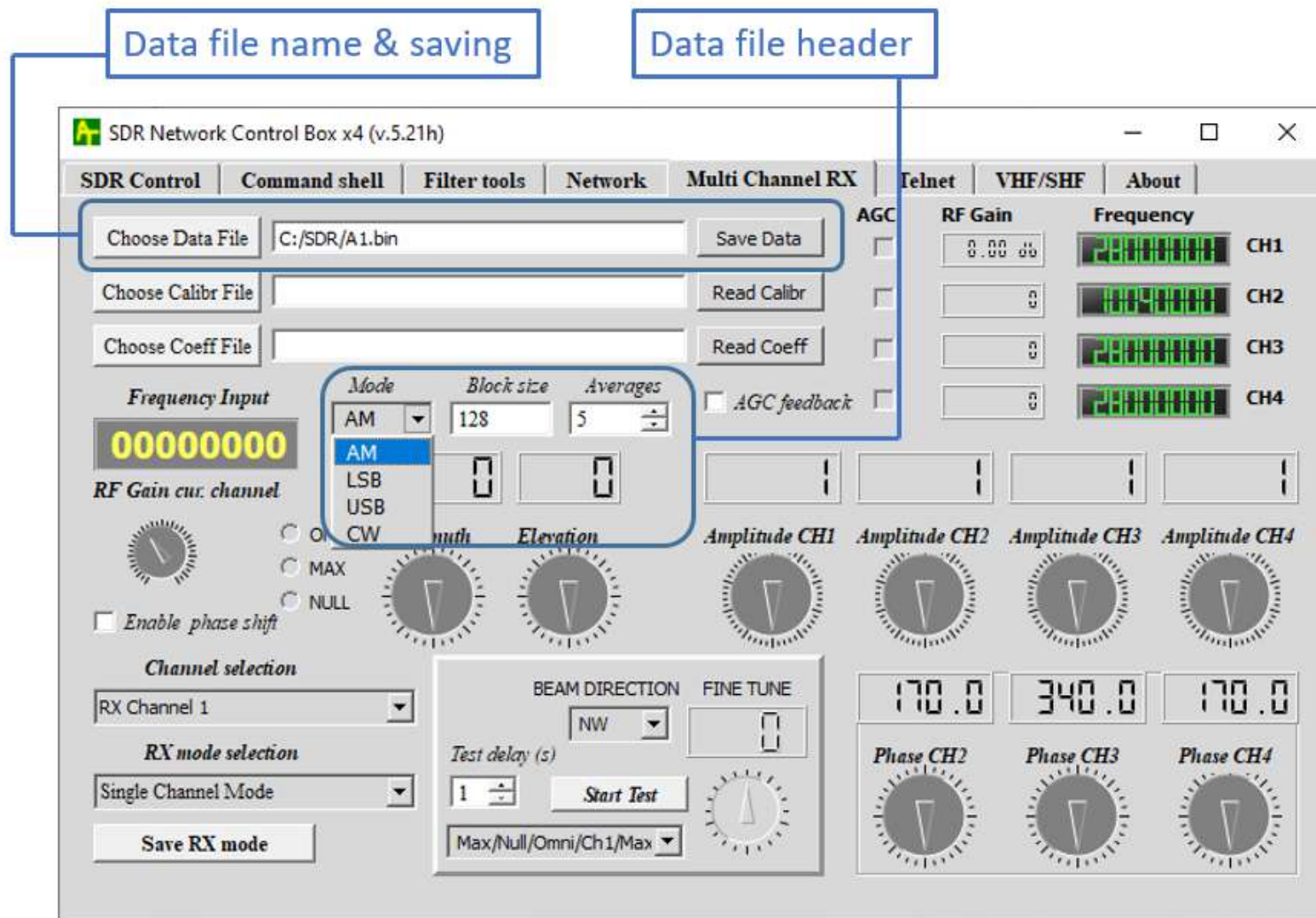
Select Omni, Max or Null & adjust azimuth & elevation

Tuleva signaali: 4.958 MHz az = 60°, 150°, 270°, elev = 40°



[4] SRAL Kesäleiri, Eerikkilä, 2022.

4. Signaalin tulokulmien määrittäminen



Pienen (typ. 641 kB)
datatiedoston talletus (C++).

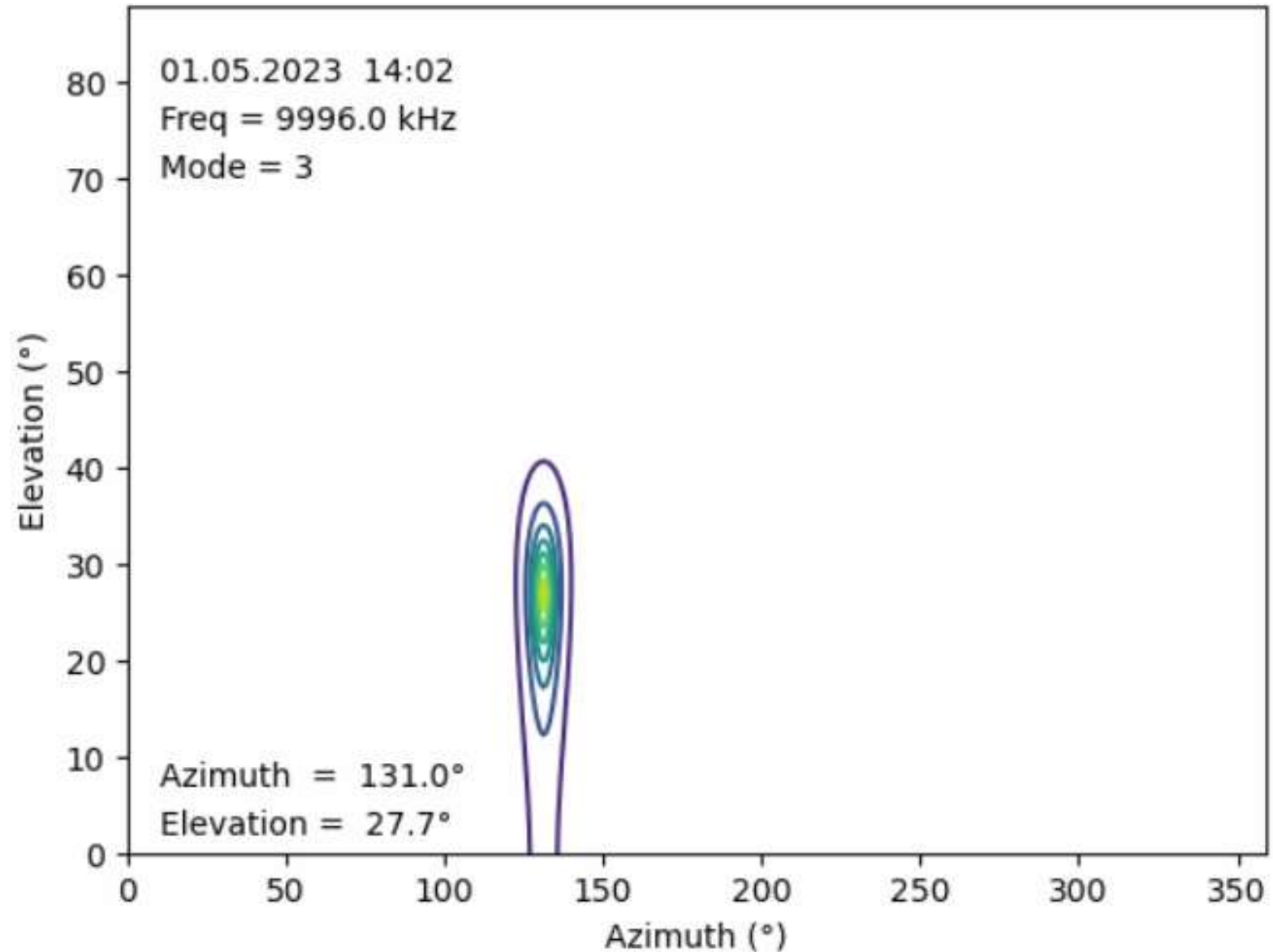
Tiedoston luku, algoritmit ja
tulostus Python-ohjelmalla.

[4] SRAL Kesäleiri, Eerikkilä, 2022.

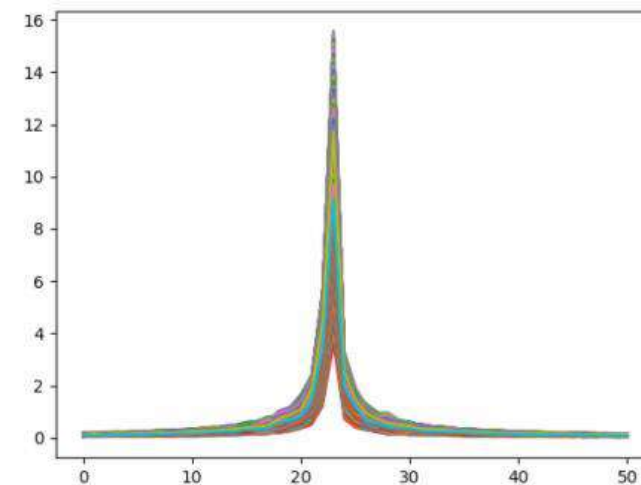
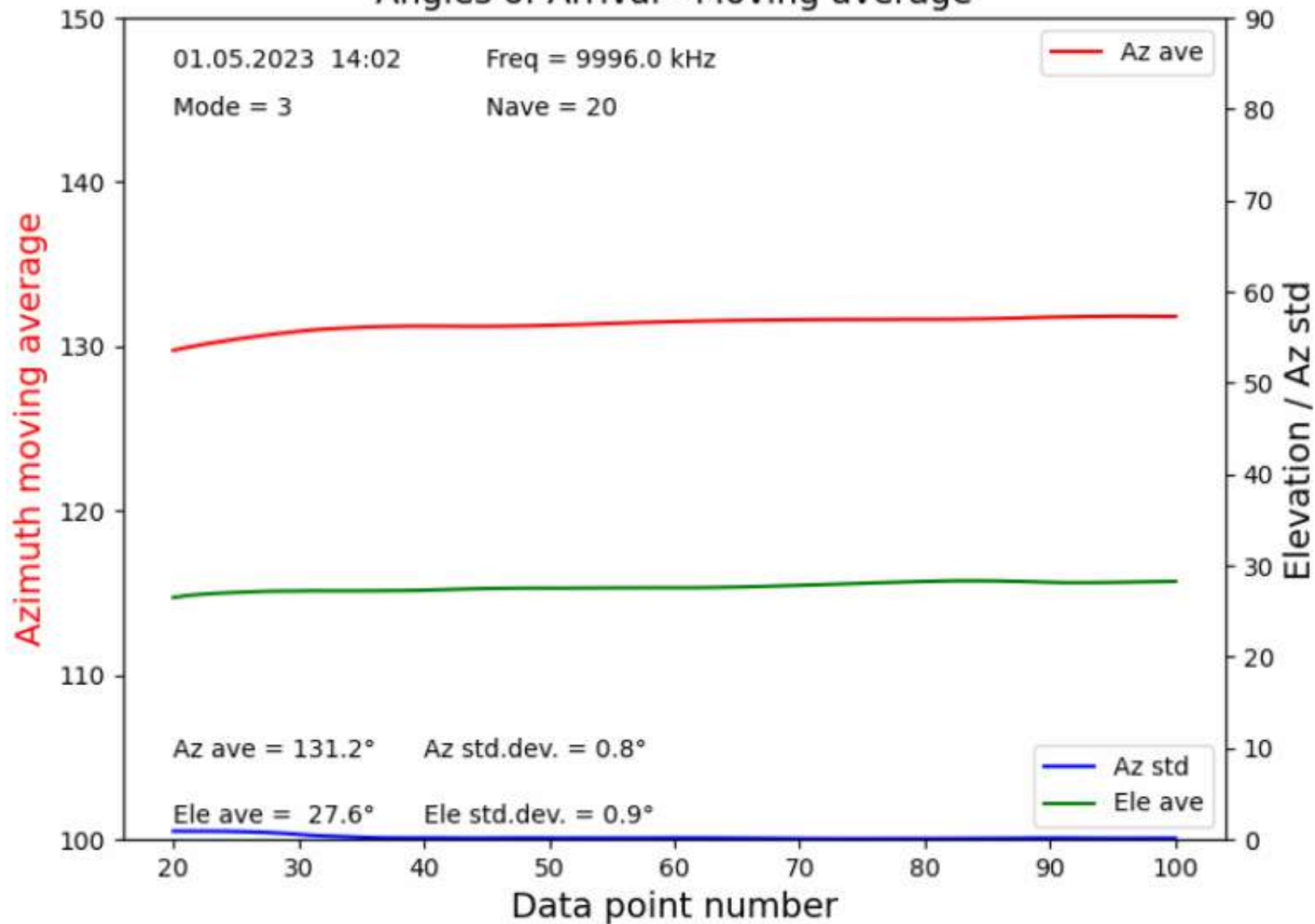
MUSIC- algorithm [6]

Time and std.
frequency station
RWM at Taldom,
Russia.

Direction and
distance from
QTH (Vesanto):
131.9 ° / 941 km
(Google Earth)



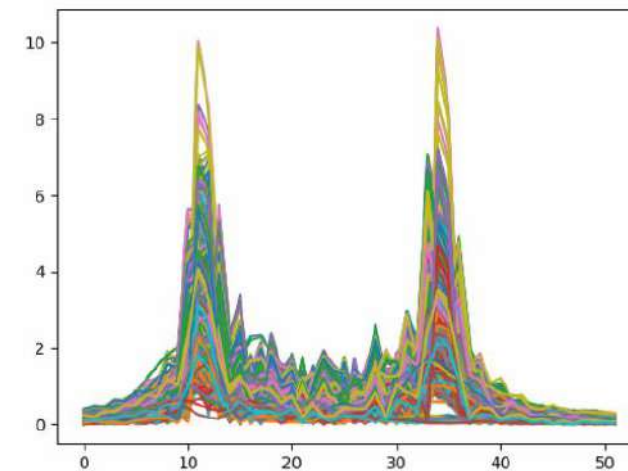
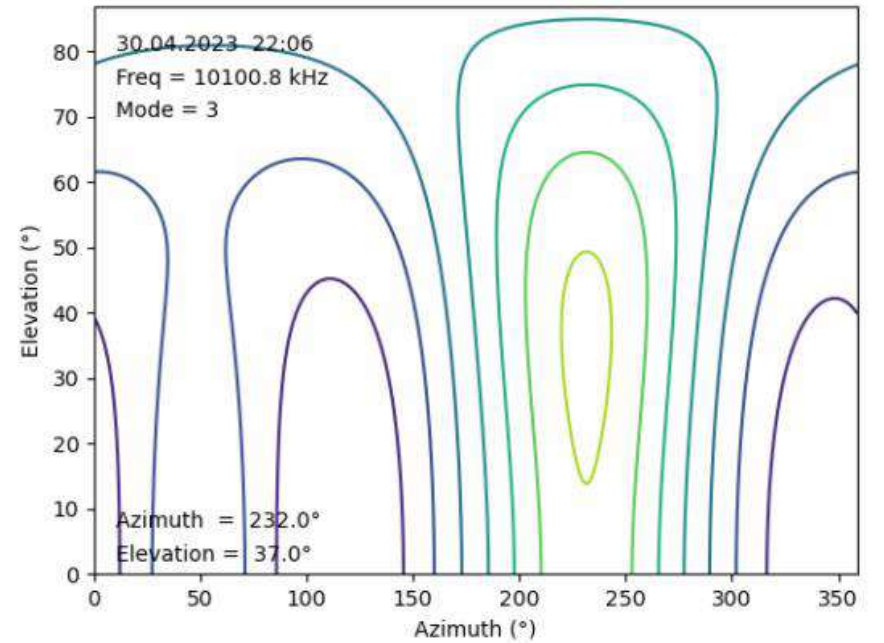
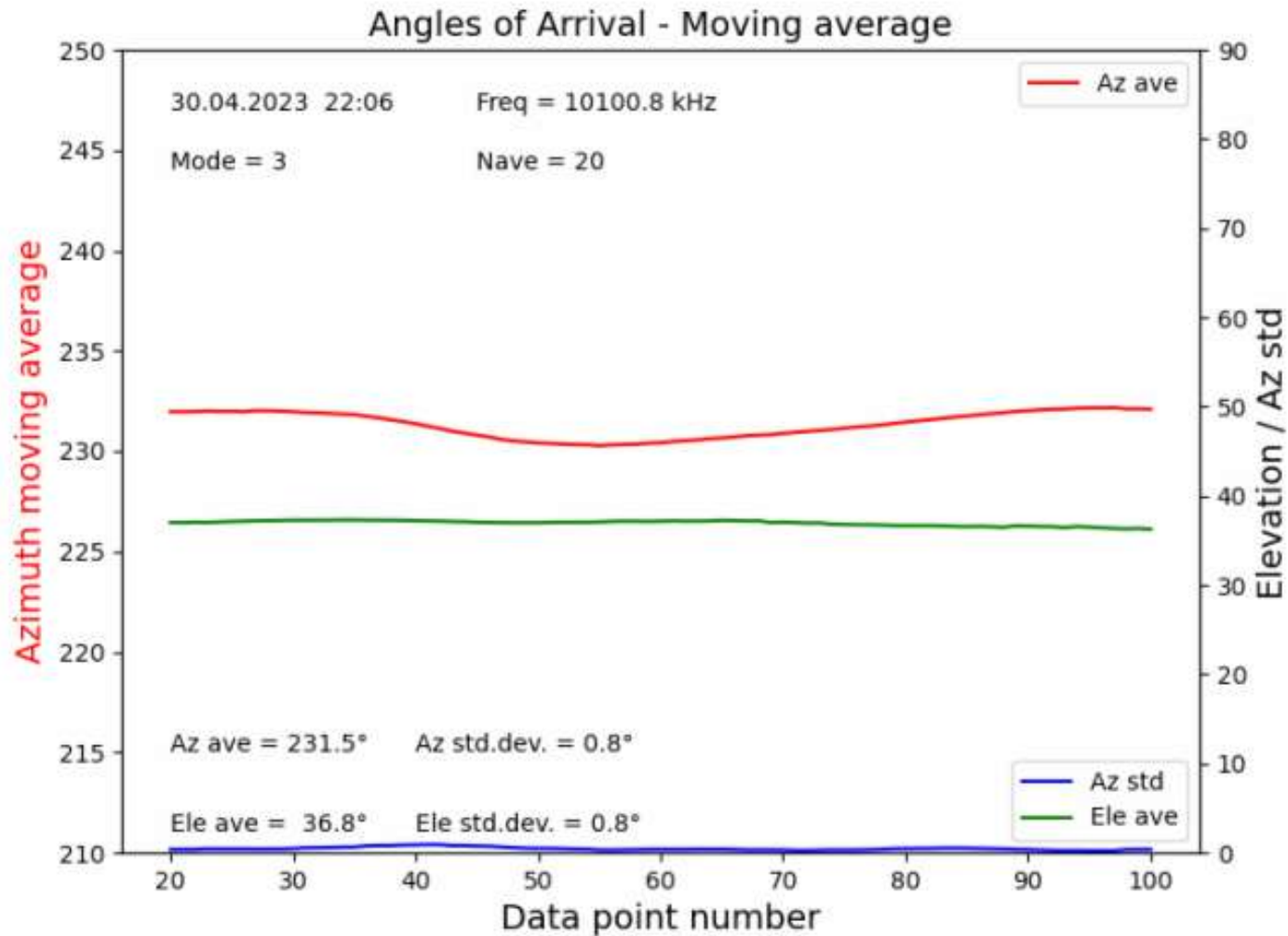
Angles of Arrival - Moving average



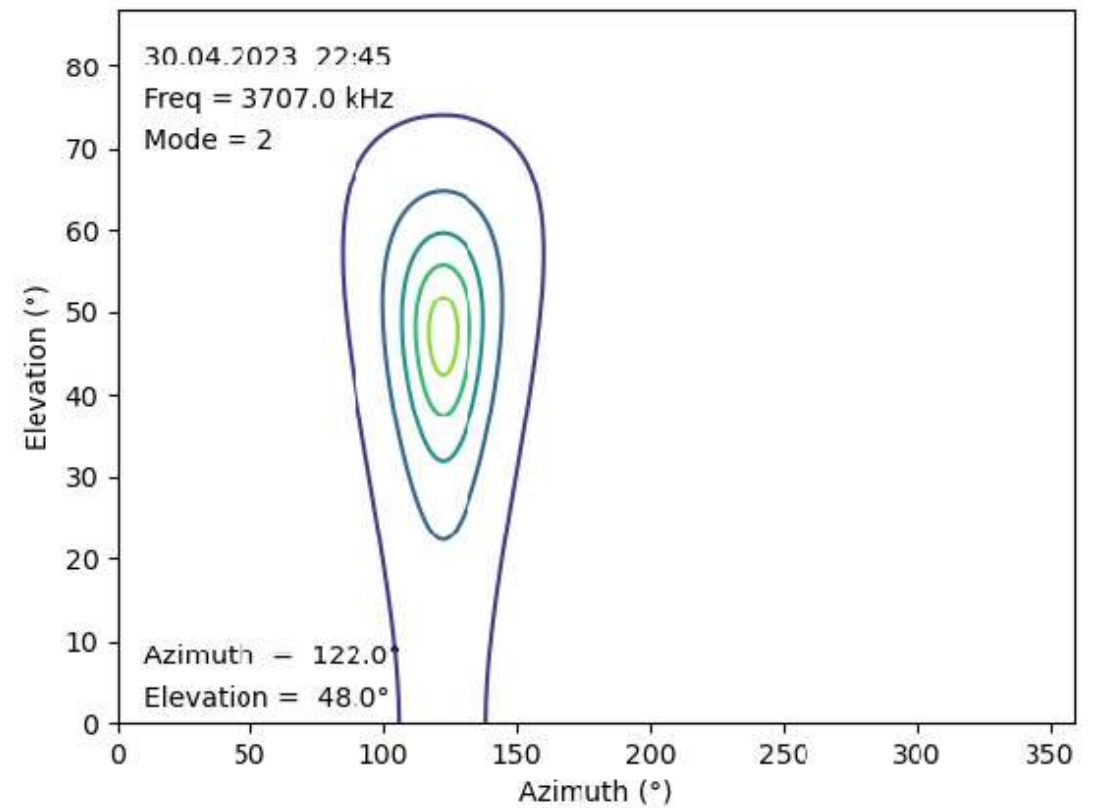
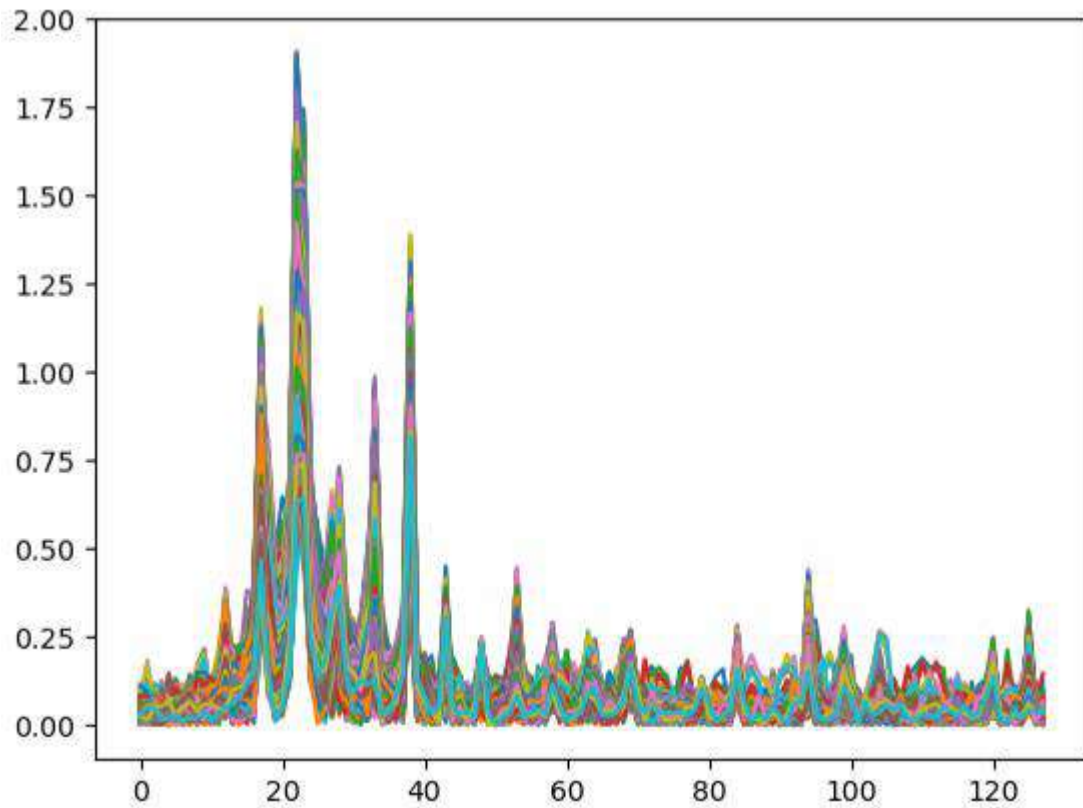
Yhden signaalin tulokset voidaan määrittää analyttisesti (= nopeasti) [7]

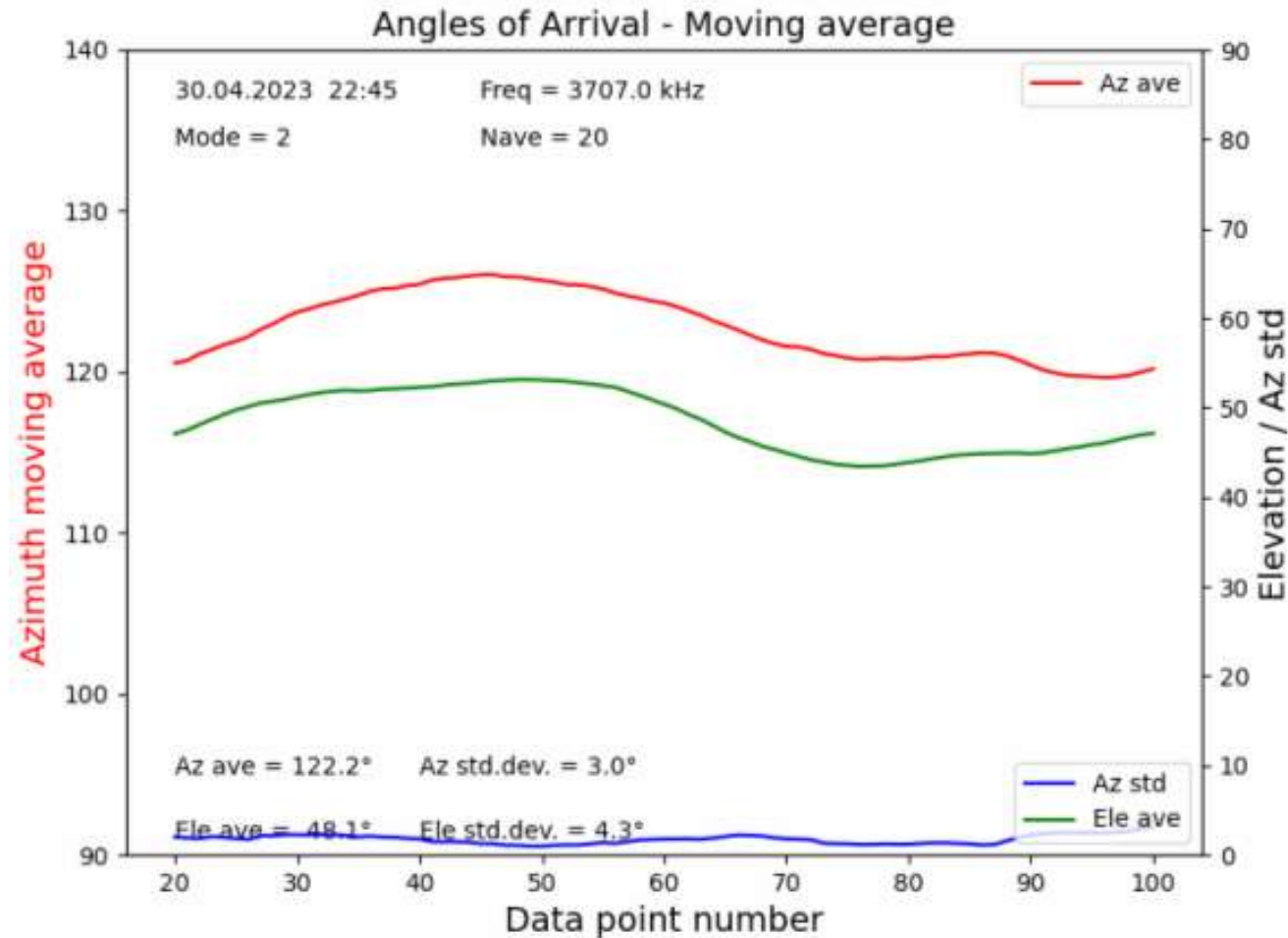
100 Data points \approx 5 s

DWD (Deutsche Wetter Dienst) weather fax tx in Pinneberg
 Direction & distance from QTH (Vesanto): 230.2° / 1399 km



Daily digital QRM @ 3707 kHz(USB) – where is it coming from?





Measured directions from Vesanto:

- Azimuth = 122°
- Elevation = 48°

Height of F2 layer from Moscow ionogram (*):

hmF2 = 317.3 km →

Estimated distance =

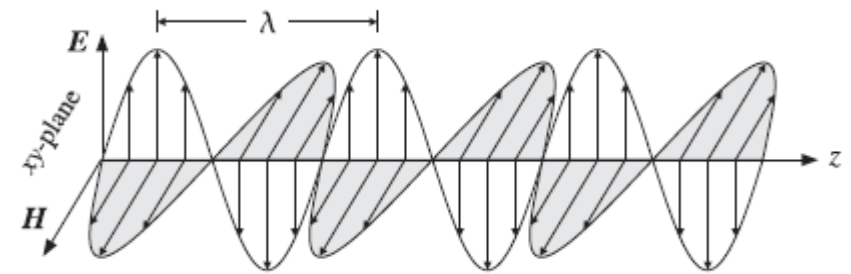
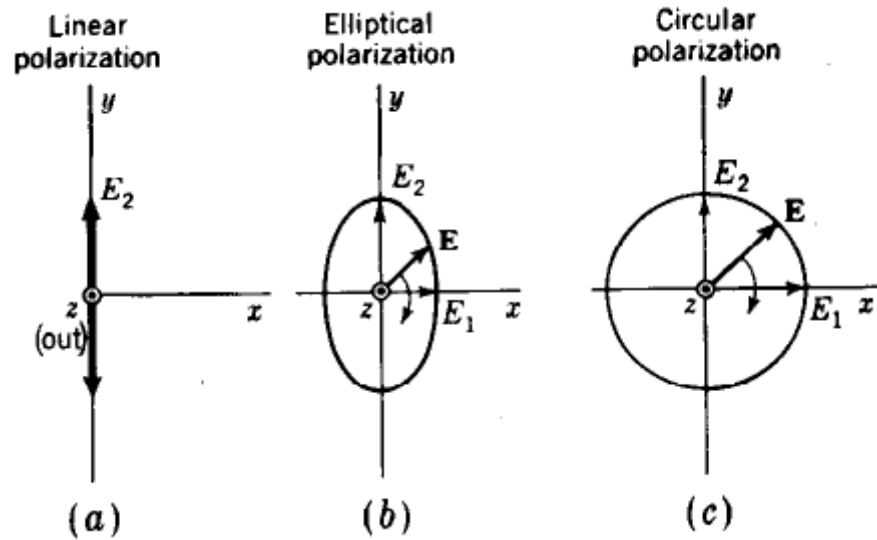
- 541 km (single hop)
- **1083 km (2 hops)**

Severnyi Air Base at Ivanovo?

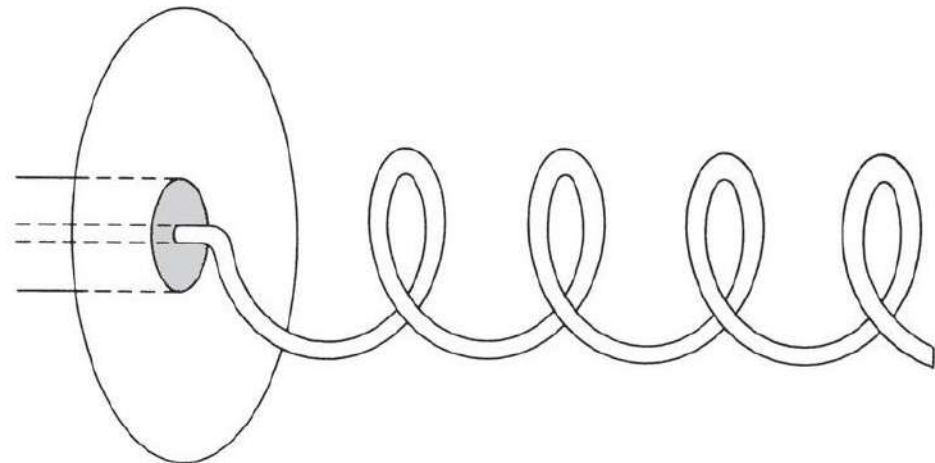
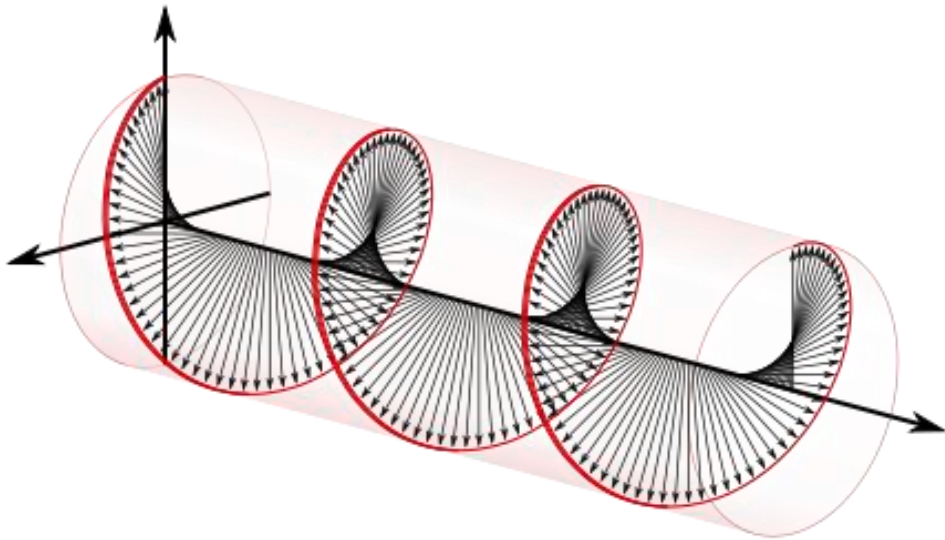
(* <https://www.izmiran.ru/services/moscow.shtml>)

5. Määritelmiä

- Kaukokentässä EM - kenttä etenee tasoaaltona
- Tasoaallossa E - ja H - kenttien vektorit kohtisuorassa
- E - vektorin suunta määrää *polarisaation*:

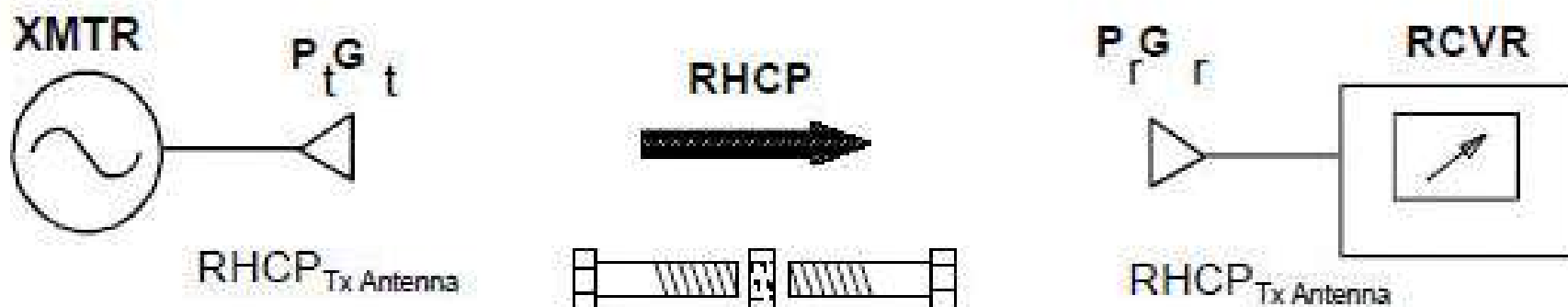
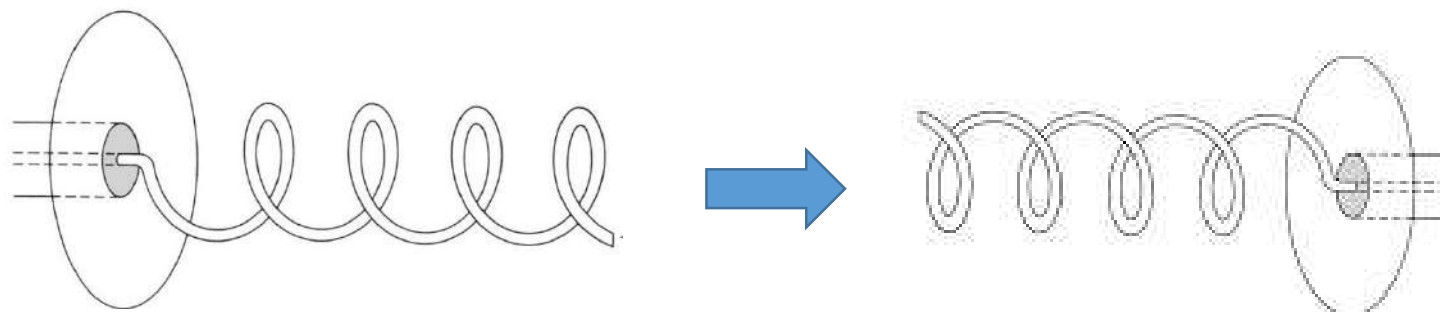


- Kiertopolarisaation käsisyys määritellään etenemisuuntaan nähden.
- Oikeakätisen (RCP) aallon kenttävektori pyörii myötäpäivään (IEEE).
- Voidaan synnyttää oikeakätisellä helix – antennilla. [5]



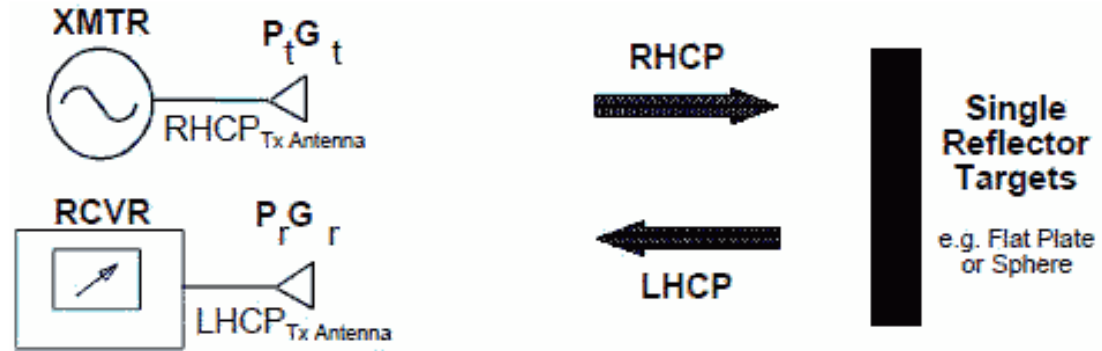
Obs! Huom! Astronomit määrittelevät käsisyyden toisinpäin!

- Jos TX antenni on oikeakätinen (RCP), myös RX antennin on oltava oikeakätinen:



6. Ionosfäärin vaikutus

Heijastuksessa
polarisaation suunta
kääntyy:



- Tämä tapahtuu IONOSFÄÄRISSÄ, missä lineaaripolarisoitu aalto jakaantuu kahteen karakteristiseen aaltoon: **Ordinary (O)** ja **Extra-ordinary (X)**.
- Kahtaistaitto: Etenemiskertoimet, reitit ja rajataajudet ovat eri.
- Magneettikenttä vaikuttaa \rightarrow Meillä $O \sim RCP$ ja $X \sim LCP$ ylös mennessä ja $O \sim LCP$ ja $X \sim RCP$ alas tulevalle signaalille heijastuksen jälkeen.

O - ja **X** - aallot nähdään ionogrammissa.

O: LCP

X: RCP

X-aallon rajataajuus f_{xI} (8.0 MHz) on suurempi kuin

O-aallon rajataajuus f_oF2 (7.338 MHz)



Station YYYY DAY DDD HHMMSS P1 FFS S AXN PPS IGA PS
Dourbes 2014 Jan29 029 075500 RSF 005 2 712 100 05+ @5

foF2	7.338
foF1	2.31
foF1p	N/A
foE	1.73
foEp	1.85
fxI	8.00
foEs	1.80
fmin	1.30

MUF(D)	24.55
M(D)	3.35
D	N/A

h'F	182.8
h'F2	232.0
h'E	114.0
h'Es	123.8

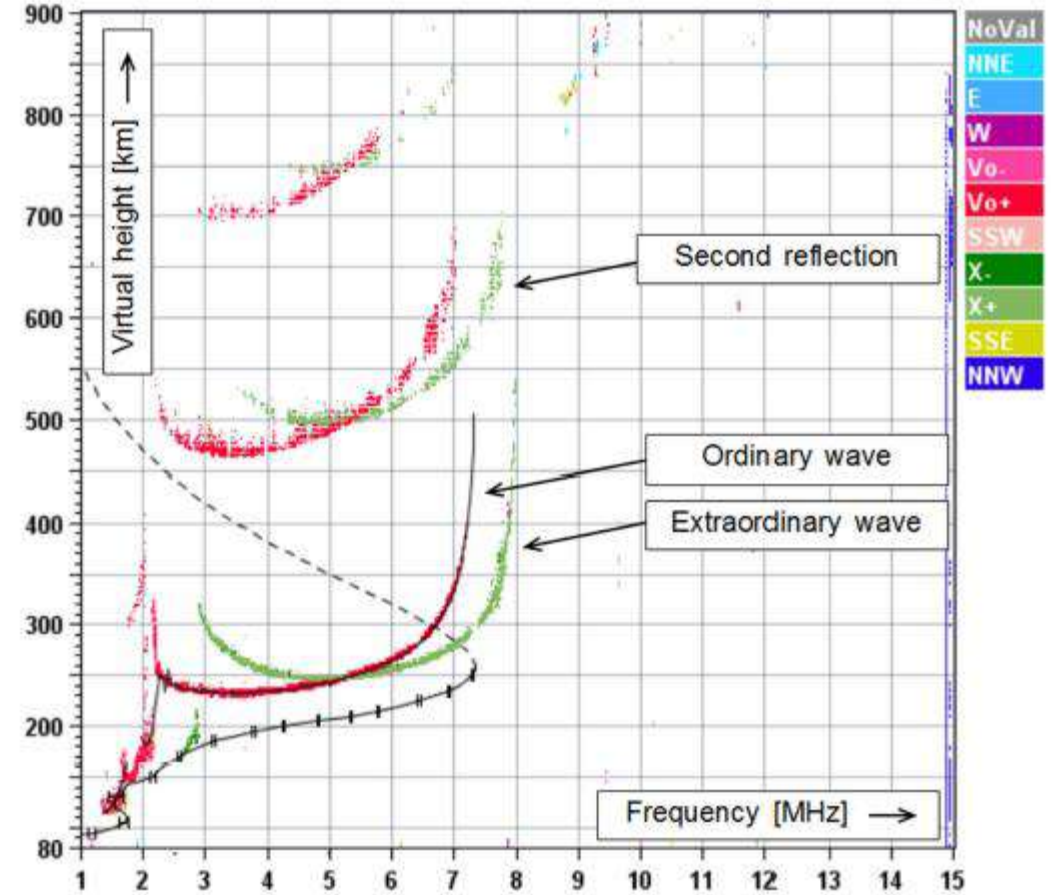
hmF2	257.1
hmF1	159.9
hmE	108.8
yF2	68.1
yF1	26.5
yE	18.7
B0	69.5
B1	2.13

C-level	11
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Auto:

Artist5

500200



D	100	200	400	600	800	1000	1500	3000	[km]
MUF	8.0	8.1	8.4	9.1	9.9	11.2	14.9	24.5	[MHz]

DB049_201402075500.RSF / 560fx512h 25 kHz 2.5 km / DPS-4D DB049 049 / 50.1 N 4.6 E

Ion2Png v. 1.3.17

”Happy hour”

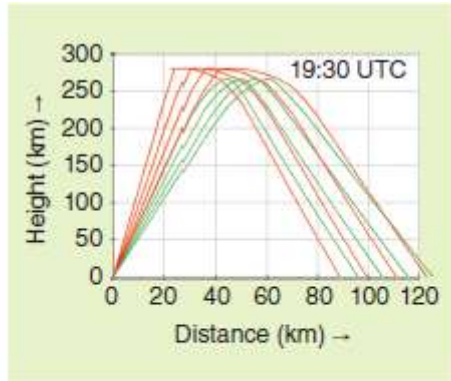


FIGURE 8. After 16:38 UTC (sunset), the ionization decreases. At 19:30 UTC, waves already penetrate much further into the ionosphere and the reflection height increases.

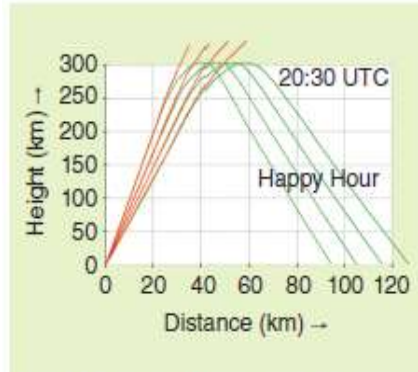


FIGURE 9. At 20:30 UTC, the electron density of the ionosphere has decreased so much that the ordinary wave is no longer reflected, but the extraordinary wave is still supported and the downward wave has circular polarization. This is the evening Happy Hour.

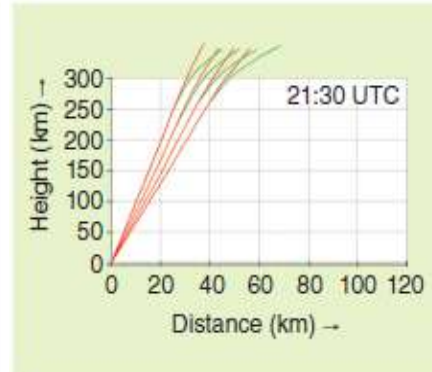


FIGURE 10. At 21:30 UTC, the ionization of the ionosphere has decreased so much that none of the characteristic waves are reflected.

Simulointi PropLab 3:IIa

Witvliet & al, Measuring the Isolation of the Circularly Polarized Characteristic Waves in NVIS Propagation, IEEE Antennas and Propagation Magazine · June 2015

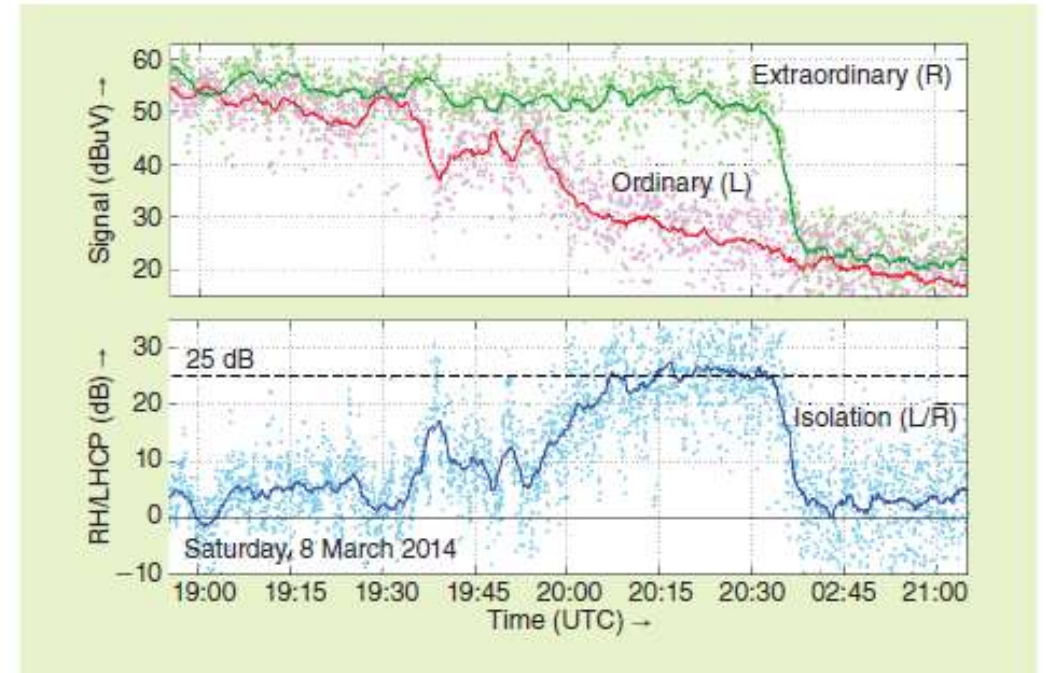
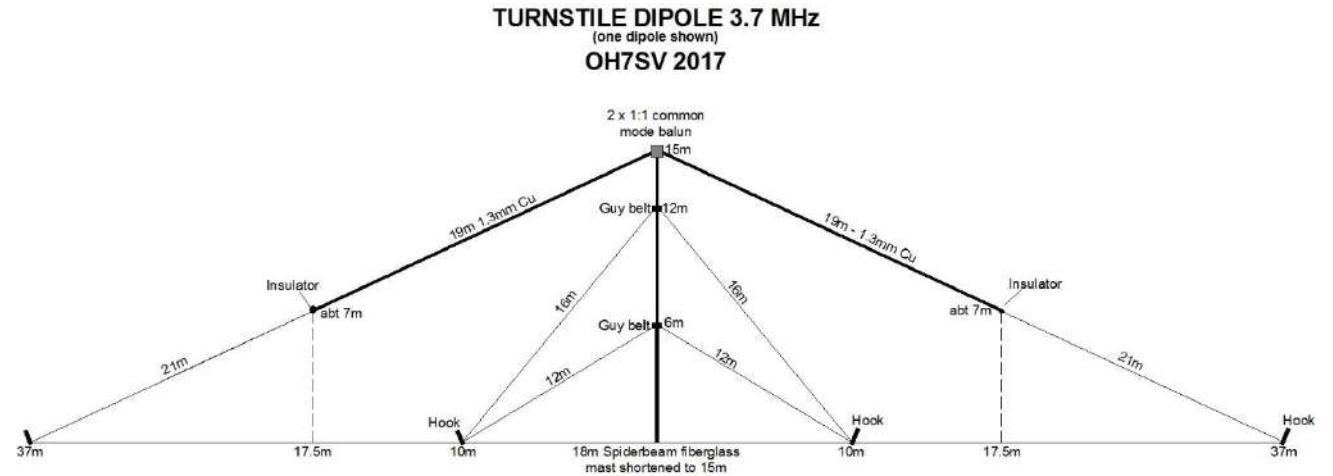
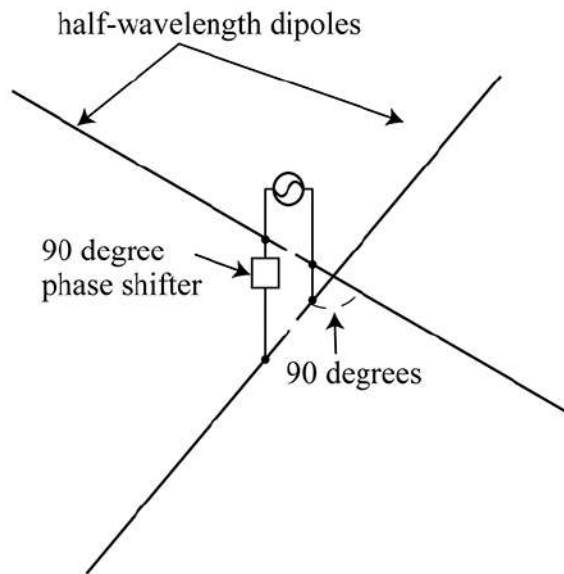
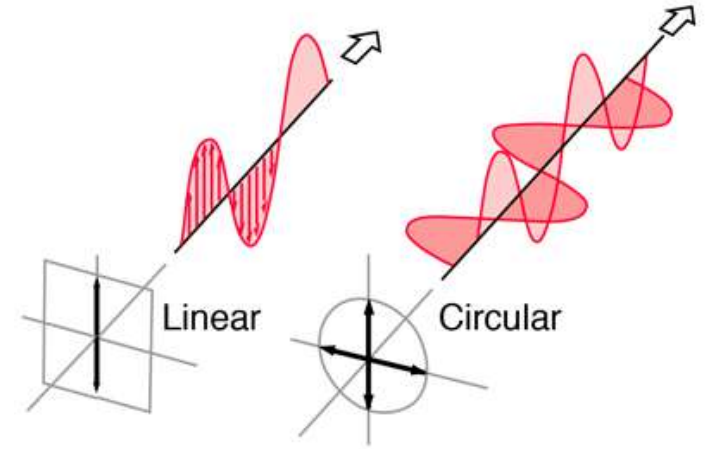


FIGURE 26. The signal strength of the ordinary (red) and extraordinary waves (green) and their ratio (blue), measured during the evening Happy Hour of Saturday, 8 March 2014.

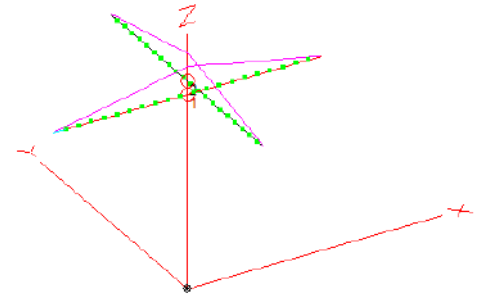
Mittaus

7. Ympyräpolarisaatioantennit

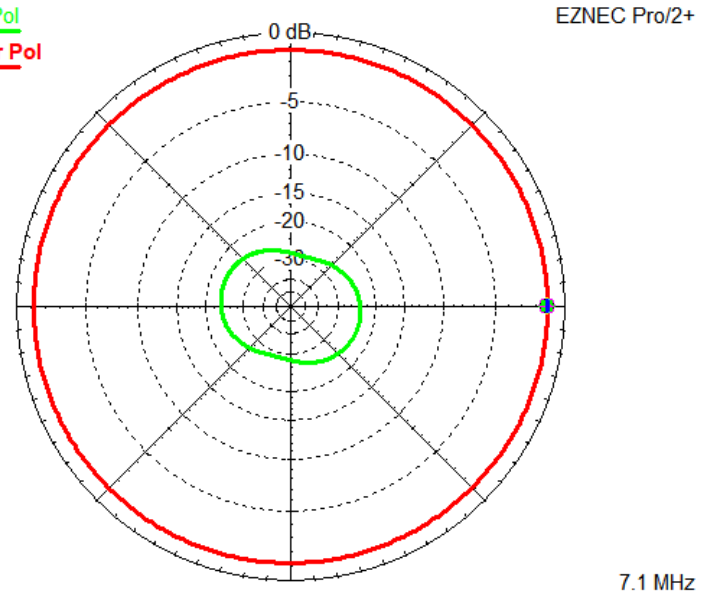
Kaksi $\lambda/2$ dipolia kohtisuorassa, syötetään 90° vaihe-erolla = TURNSTILE antenni.



Turnstile – antennin suuntakuviot:



RH Circular Pol
* LH Circular Pol



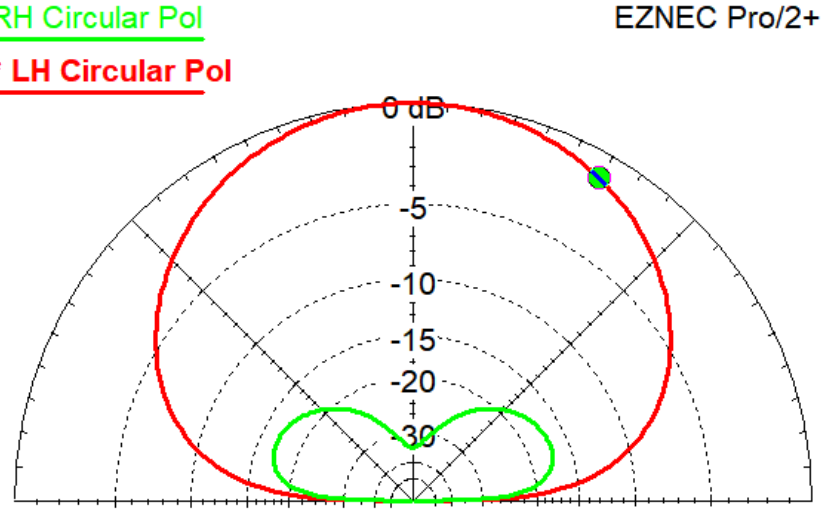
Azimuth Plot
Elevation Angle 60.0 deg.
Outer Ring 1.38 dBic

3D Max Gain 1.38 dBic
Slice Max Gain 0.24 dBic @ Az Angle = 20.0 deg.
Front/Side 0.04 dB
Beamwidth ?
Sidelobe Gain 0.24 dBic @ Az Angle = 200.0 deg.
Front/Sidelobe 0.0 dB

Cursor Az 0.0 deg.
Gain 0.23 dBic
0.0 dBmax
-1.15 dBmax3D

7.1 MHz

RH Circular Pol
* LH Circular Pol



Elevation Plot
Azimuth Angle 0.0 deg.
Outer Ring 1.38 dBic

3D Max Gain 1.38 dBic
Slice Max Gain 1.38 dBic @ Elev Angle = 90.0 deg.
Beamwidth 95.0 deg.; -3dB @ 42.5, 137.5 deg.
Sidelobe Gain < -100 dBic
Front/Sidelobe > 100 dB

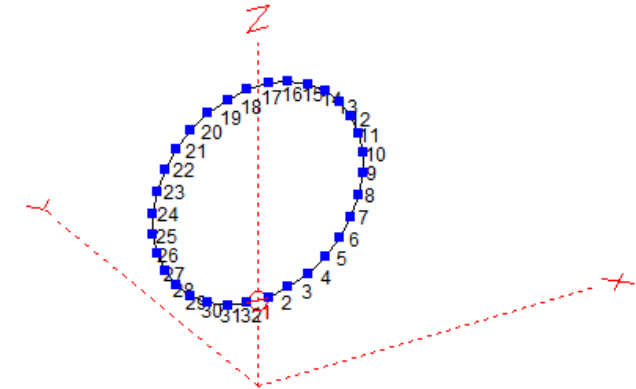
EZNEC Pro/2+

Cursor Elev 60.0 deg.
Gain 0.23 dBic
-1.15 dBmax
-1.15 dBmax3D

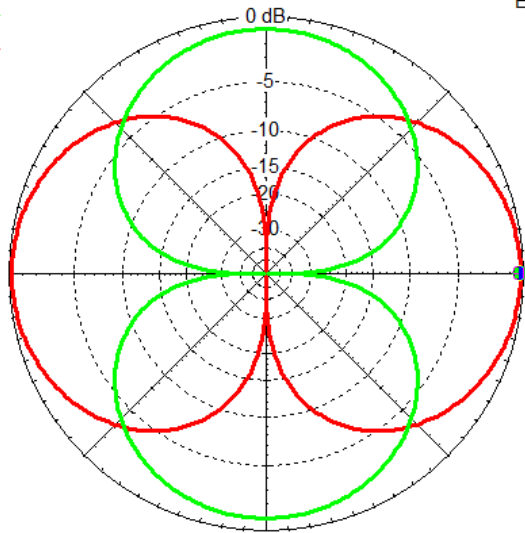
7.1 MHz

Pieni ($d < \lambda / 10$) luuppi, vain RX

- Laajakaistainen: Säteilökuvio ei riipu taajuudesta.
- Impedanssi kylläkin.



Horizontal Pol
* Vertical Pol



EZNEC Pro/2+

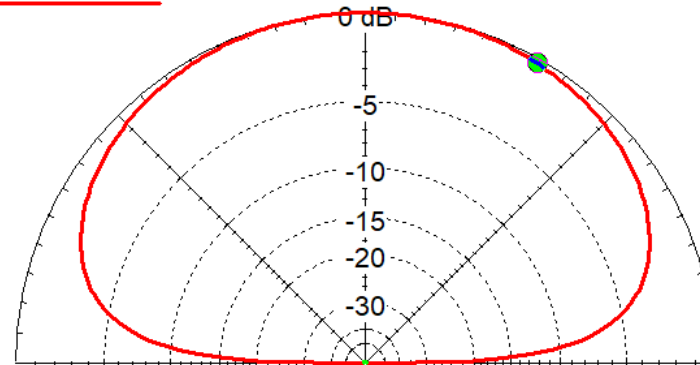
Azimuth Plot
Elevation Angle 60.0 deg.
Outer Ring -5.18 dBi

3D Max Gain -5.18 dBi
Slice Max Gain -5.41 dBi @ Az Angle = 0.0 deg.
Front/Side 94.58 dB
Beamwidth 89.8 deg.; -3dB @ 315.1, 44.9 deg.
Sidelobe Gain -5.41 dBi @ Az Angle = 180.0 deg.
Front/Sidelobe 0.0 dB

Cursor Az 0.0 deg.
Gain -5.41 dBi
0.0 dBmax
-0.23 dBmax3D

7.1 MHz

Horizontal Pol
* Vertical Pol



EZNEC Pro/2+

Elevation Plot
Azimuth Angle 0.0 deg.
Outer Ring -5.18 dBi

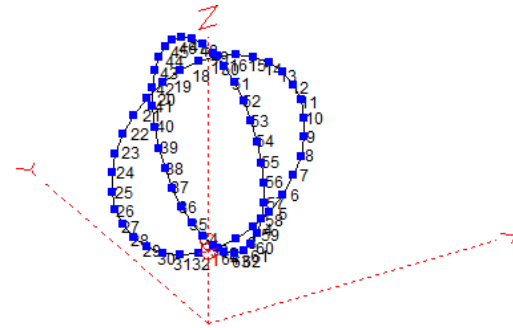
3D Max Gain -5.18 dBi
Slice Max Gain -5.18 dBi @ Elev Angle = 90.0 deg.
Beamwidth 144.6 deg.; -3dB @ 17.7, 162.3 deg.
Sidelobe Gain < -100 dBi
Front/Sidelobe > 100 dB

Cursor Elev 60.0 deg.
Gain -5.41 dBi
-0.23 dBmax
-0.23 dBmax3D

7.1 MHz

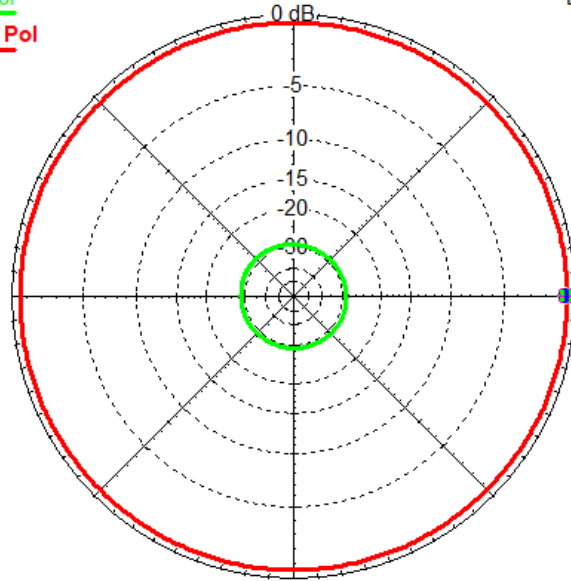
Huom! Obs!
X-polarisaation
säteilökuvio.

Kaksi ristikkäistä luuppia, syötetään
 90° vaihe-erolla = CP antenni.



RH Circular Pol
 * LH Circular Pol

EZNEC Pro/2+



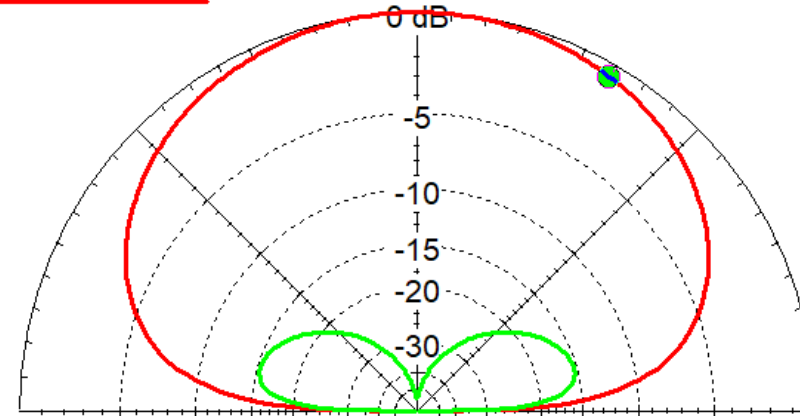
7.1 MHz

Azimuth Plot
 Elevation Angle 60.0 deg.
 Outer Ring -5.18 dBic
 3D Max Gain -5.18 dBic
 Slice Max Gain -5.72 dBic @ Az Angle = 336.0 deg.
 Front/Side 0.01 dB
 Beamwidth ?
 Sidelobe Gain -5.72 dBic @ Az Angle = 156.0 deg.
 Front/Sidelobe 0.0 dB

Cursor Az 0.0 deg.
 Gain -5.72 dBic
 0.0 dBmax
 -0.55 dBmax3D

RH Circular Pol
 * LH Circular Pol

EZNEC Pro/2+



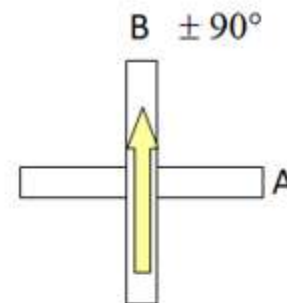
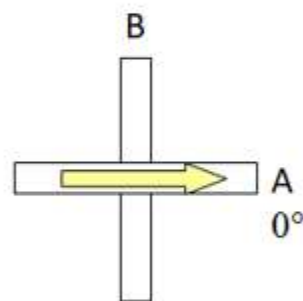
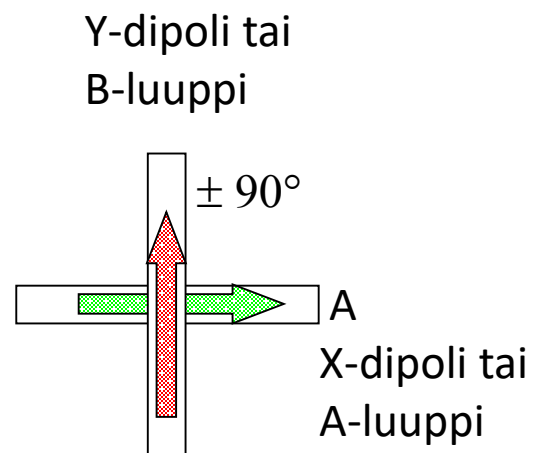
7.1 MHz

Elevation Plot
 Azimuth Angle 0.0 deg.
 Outer Ring -5.18 dBic
 3D Max Gain -5.18 dBic
 Slice Max Gain -5.17 dBic @ Elev Angle = 90.0 deg.
 Beamwidth 121.2 deg.; -3dB @ 29.4, 150.6 deg.
 Sidelobe Gain < -100 dBic
 Front/Sidelobe > 100 dB

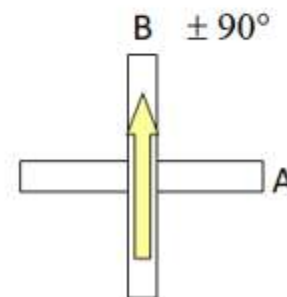
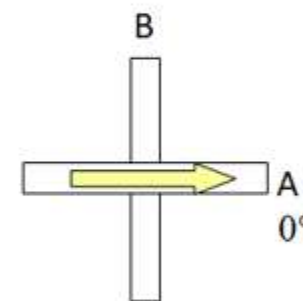
Cursor Elev 60.0 deg.
 Gain -5.72 dBic
 -0.55 dBmax
 -0.55 dBmax3D

8. Ympyräpolarisaatio antenniryhmällä

CP onnistuu myös ristidipoleilla,
ristiluupeilla ja myös
4 ristiluupin ryhmällä.



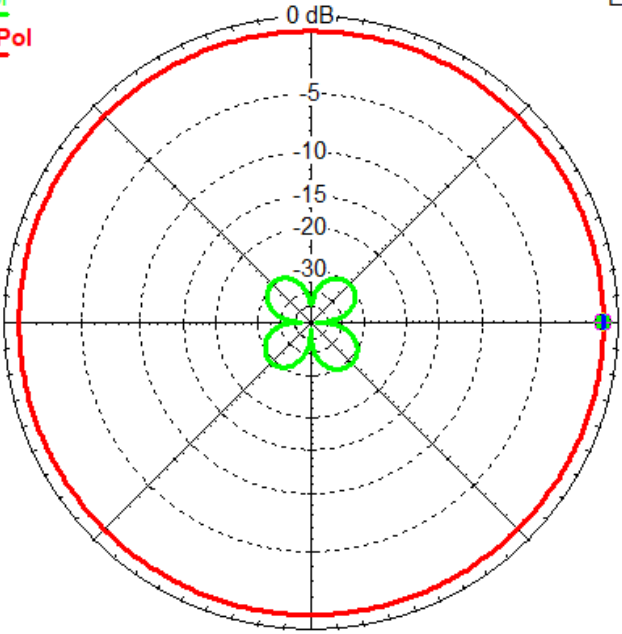
$+ 90^\circ \rightarrow$ LHCP
 $- 90^\circ \rightarrow$ RHCP



+ 90°

LCP neljän ristiluupin ryhmällä

RH Circular Pol
* LH Circular Pol



EZNEC Pro/2+

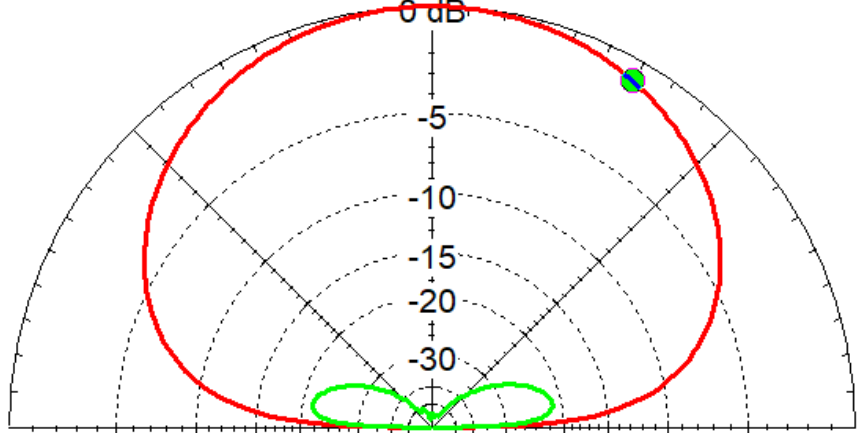
7.1 MHz

Azimuth Plot
Elevation Angle 60.0 deg.
Outer Ring -2.44 dBic

3D Max Gain -2.44 dBic
Slice Max Gain -3.31 dBic @ Az Angle = 311.0 deg.
Front/Back 0.03 dB
Beamwidth ?
Sidelobe Gain < -100 dBic
Front/Sidelobe > 100 dB

Cursor Az 0.0 deg.
Gain -3.33 dBic
-0.02 dBmax
-0.89 dBmax3D

RH Circular Pol
* LH Circular Pol



EZNEC Pro/2+

7.1 MHz

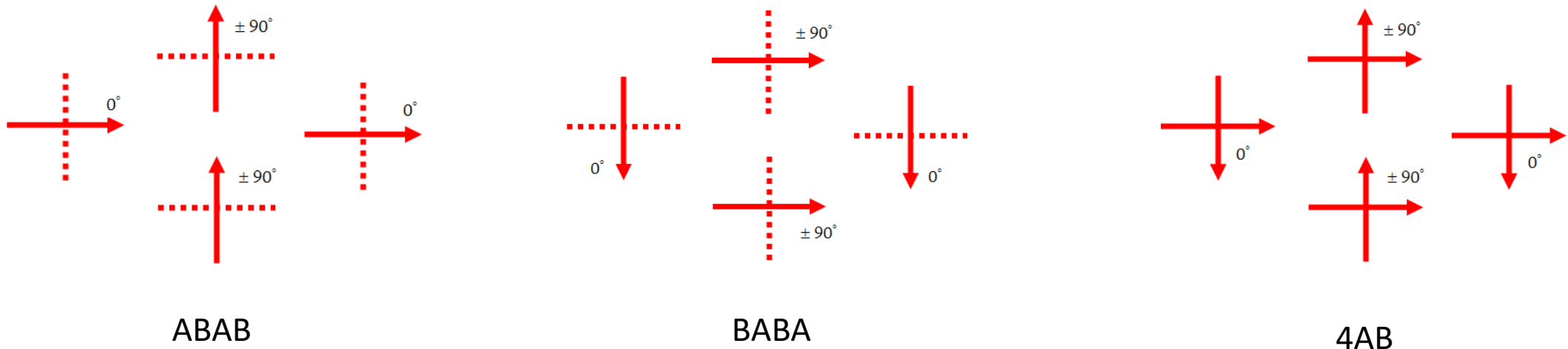
Elevation Plot
Azimuth Angle 0.0 deg.
Outer Ring -2.44 dBic

3D Max Gain -2.44 dBic
Slice Max Gain -2.44 dBic @ Elev Angle = 89.0 deg.
Beamwidth 105.1 deg.; -3dB @ 37.4, 142.5 deg.
Sidelobe Gain < -100 dBic
Front/Sidelobe > 100 dB

Cursor Elev 60.0 deg.
Gain -3.33 dBic
-0.89 dBmax
-0.89 dBmax3D

Antenniryhmällä toteutettu CP – antenni:

- Sama ympärisäteilevä säteilykuvio kuin yhdellä risti-luoppi parilla.
- Hiukan parempi Xpol, hiukan enemmän vahvistusta.
- RCP / LCP voidaan toteuttaa erilaisilla yhdistelmillä → redundanssi mahdollistaa antennien epäideaalisuuden vaikutuksen minimoinnin.



9. Joka polarisaation vastaanotin

Mielivaltainen täysin polarisoitu tasoaalto voidaan esittää:

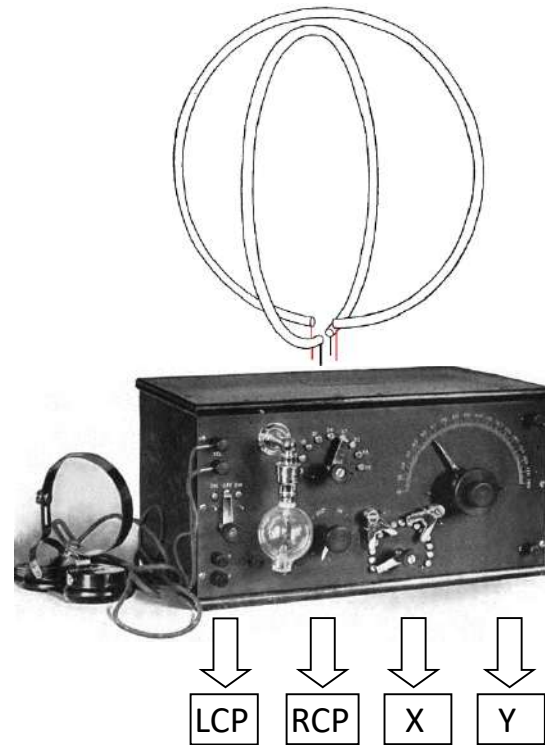
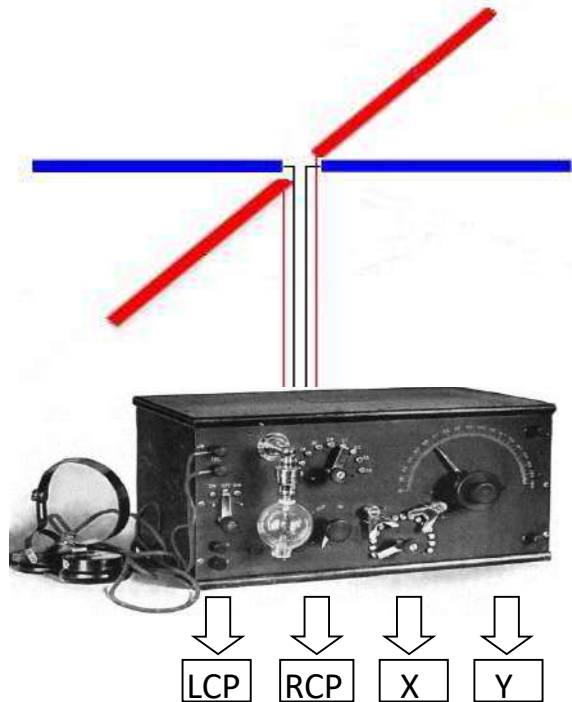
- Kahden lineaaripolarisoidun (E_X ja E_Y) aallon summana, tai
- Kahden ympyräpolarisoidun (E_R ja E_L) summana.

Matemaattisesti:

$$\begin{cases} E_R = (E_X - j E_Y) / \sqrt{2} \\ E_L = (E_X + j E_Y) / \sqrt{2} \end{cases} \quad \rightarrow \quad \begin{cases} E_X = \sqrt{2} (E_L + E_R) / 2 \\ E_Y = -j \sqrt{2} (E_L - E_R) / 2 \end{cases}$$

Eli: Kun vastaanotetaan ympyräpolarisoidut signaalit, vastaavat lineaaripolarisoidut signaalit voidaan laskea.

Joka polarisaation vastaanotin
on mahdollinen!

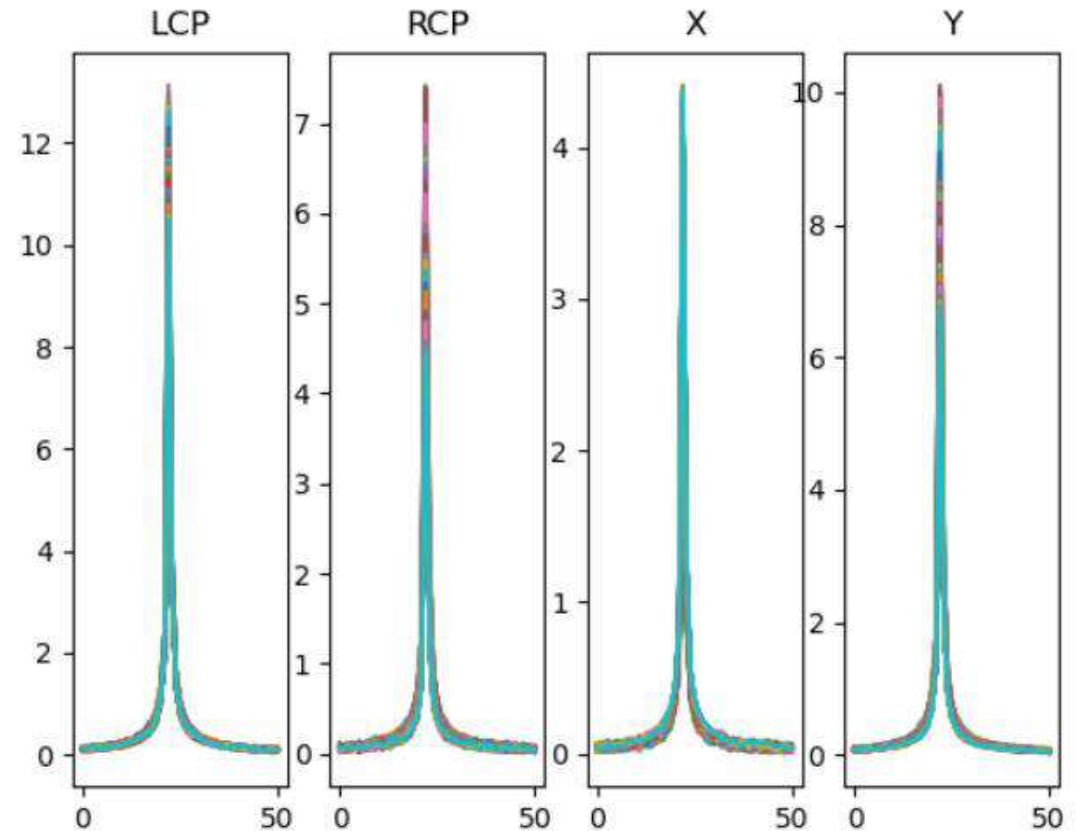
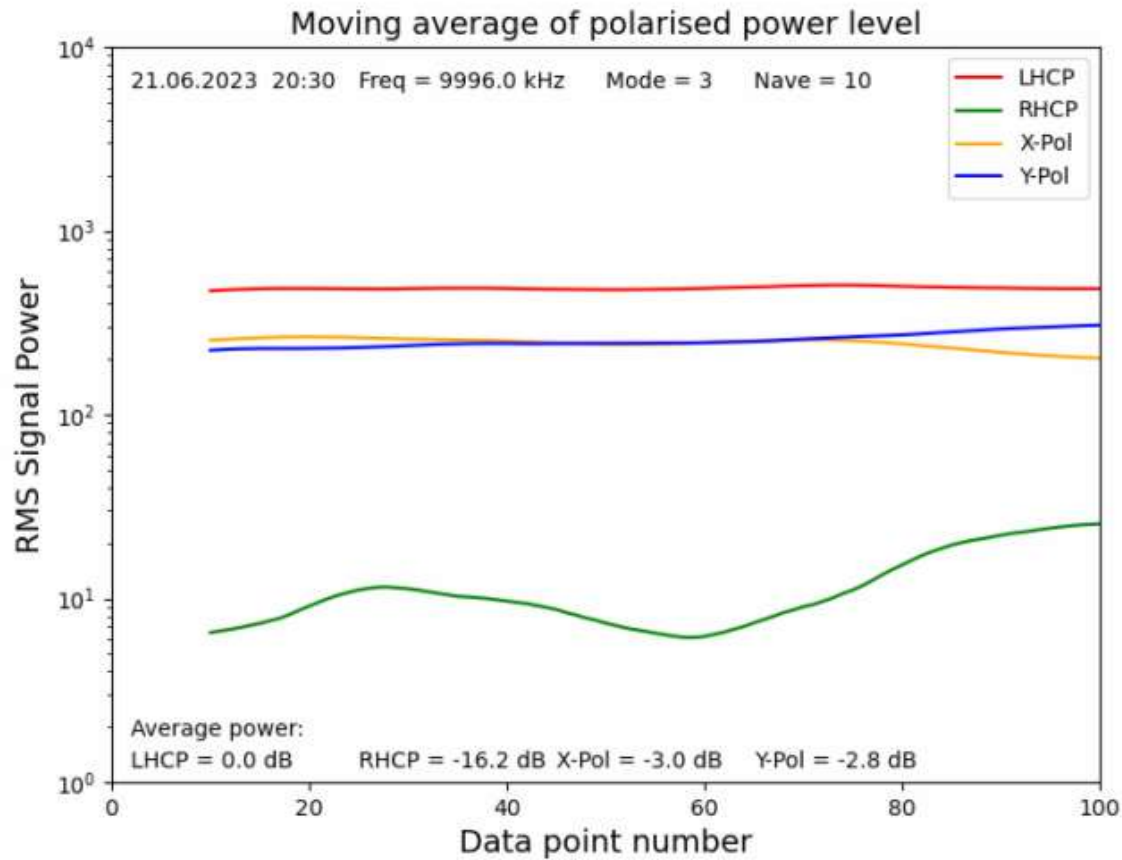


Joka polarisaation vastaanotin

The screenshot shows the SDR Network Control Box x4 (v.5.21h) interface. The 'Multi Channel RX' tab is active. The interface includes several control panels:

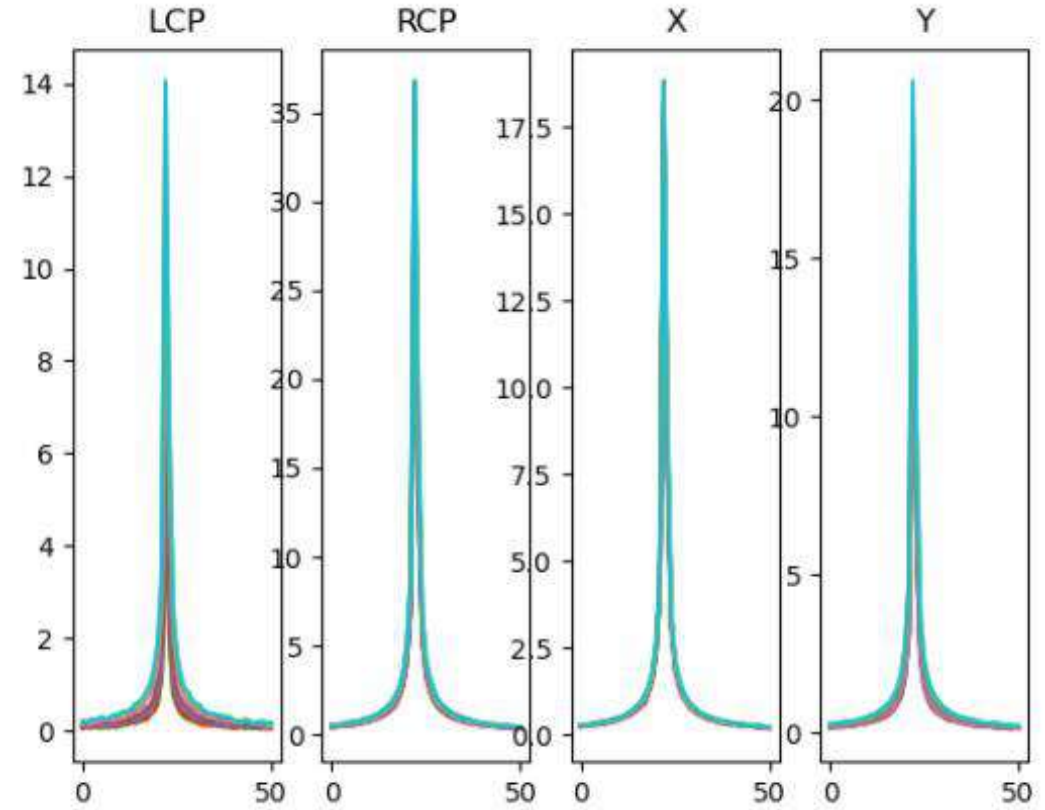
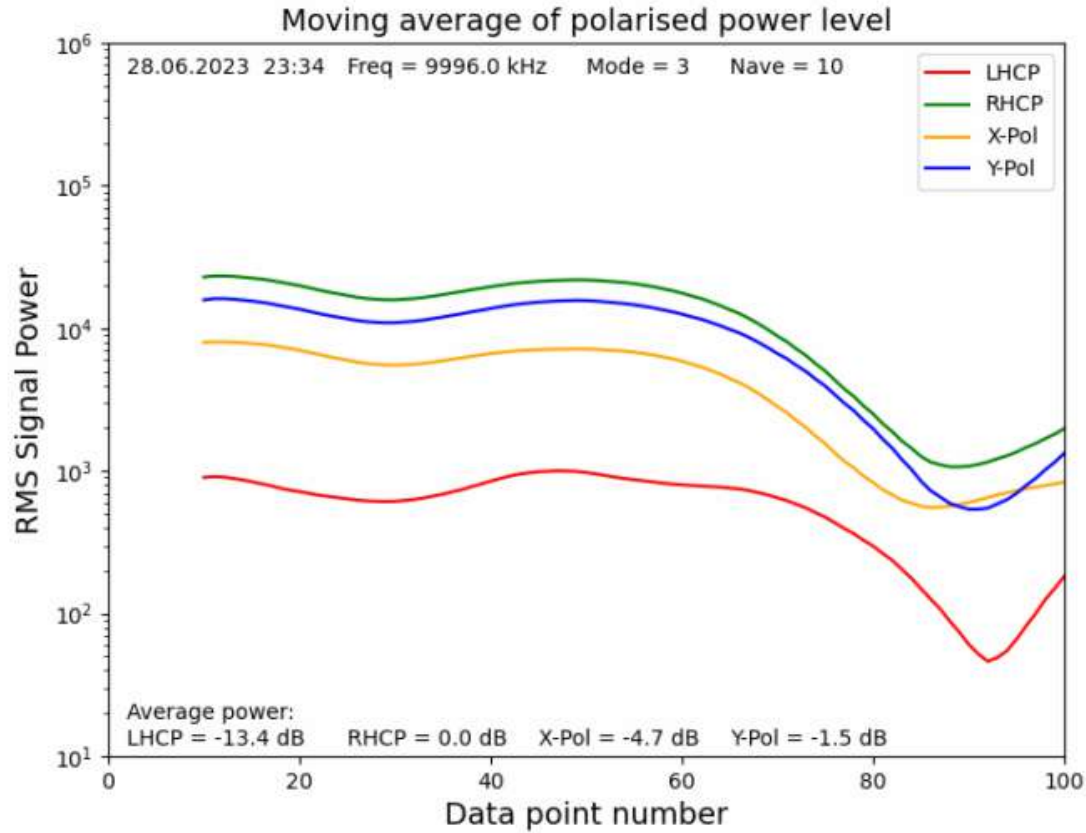
- File Selection:** 'Choose Data File', 'Choose Calibr File', and 'Choose Coeff File' buttons.
- Buttons:** 'Save Data', 'Read Calibr', and 'Read Coeff' buttons.
- Frequency Input:** A large digital display showing '00000000'.
- Mode and FFT Settings:** 'Mode' set to 'CW', 'FFT length' set to '8192', and 'Averages' set to '1'.
- AGC and RF Gain:** 'AGC' and 'AGC feedback' checkboxes are unchecked. 'RF Gain' is set to '0.00 dB'.
- Channels:** Four channels (CH1-CH4) are listed with their respective frequencies: CH1 (100.19931), CH2 (100.19990), CH3 (280000000), and CH4 (280000000).
- Beam/Polarisation:** A dropdown menu is open, showing options: X, NW, NE, SE, SW, LHCP, RHCP, X, and Y. The 'X' option is selected and highlighted.
- Phase Shift:** 'Enable phase shift' checkbox is checked.
- Channel Selection:** 'RX Channel 1' is selected in the dropdown.
- RX Mode Selection:** 'Diversity Mode (quad channel)' is selected.
- Save RX mode:** A button to save the current settings.
- Amplitude and Phase Controls:** Four amplitude meters (CH1-CH4) and three phase meters (CH2-CH4) are visible.

ORDINARY WAVE STRONGEST ('Päivä - polarisaatio')



RWM Taldom 9.996 MHz

EXTRA-ORDINARY WAVE STRONGEST ('Yö-polarisaatio')



RWM Taldom 9.996 MHz

10. Polarisaatioparametrit

POLARISAATIOELLIPSI

Yleisessä tapauksessa polarisaatio on

ELLIPTINEN

(Etenevän aallon E-vektorin kärki piirtää ellipsin)

Kaksi parametria määrittää

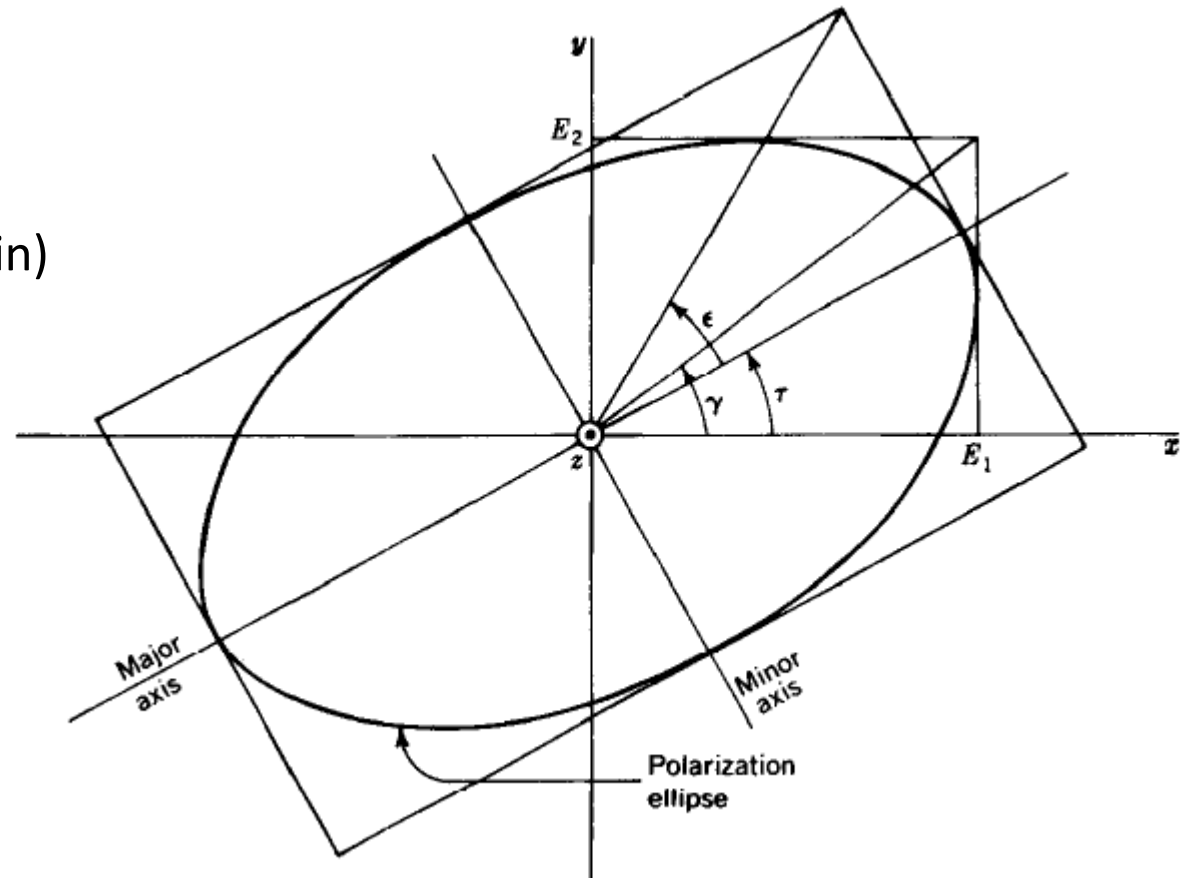
POLARISAATIOELLIPSIN:

- Akselisuhde ($A/B = \cot \varepsilon$), ja
- Ellipsin kallistuskulma (τ)

tai:

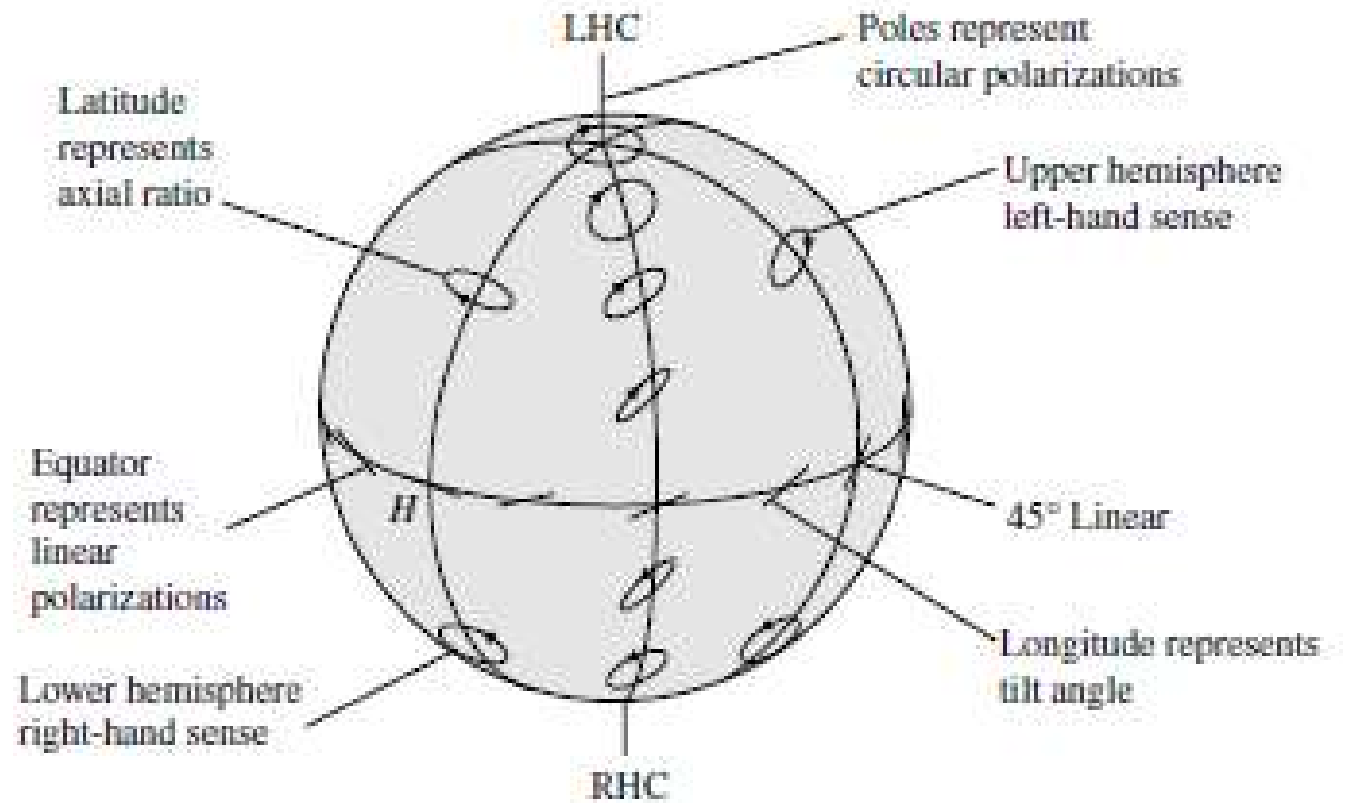
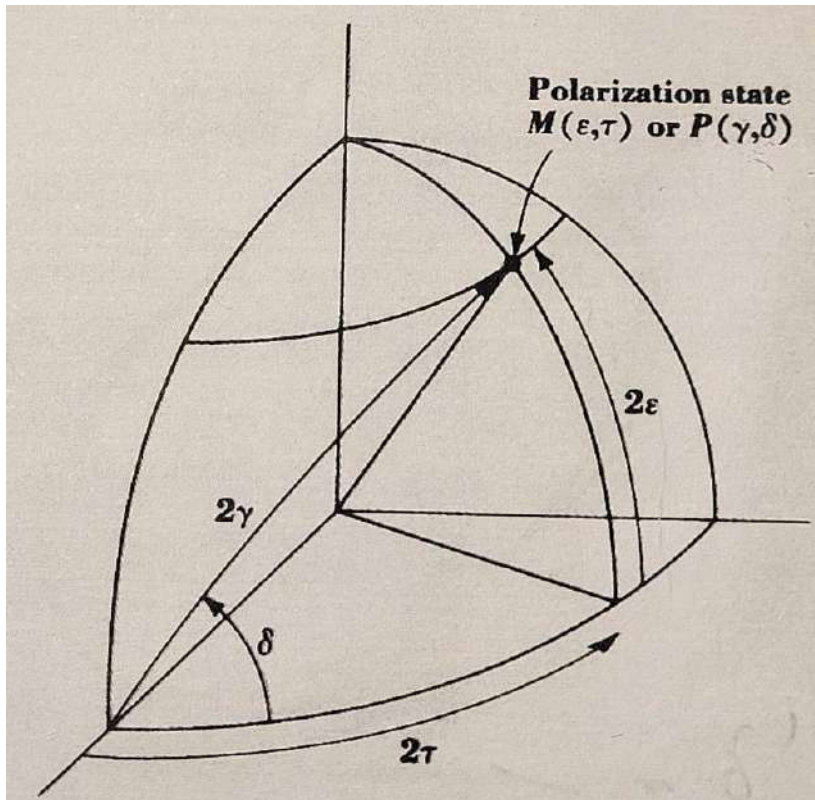
x- ja y-suuntaisten kenttien:

- Amplitudien suhde ($\tan \gamma = E_2/E_1$), ja
- Vaihe-ero (δ)



POINCARÉ PALLO

Aallon (ja antennin!) polarisaatiotila $M(\varepsilon, \tau)$ voidaan esittää pallokoordinaatistossa:

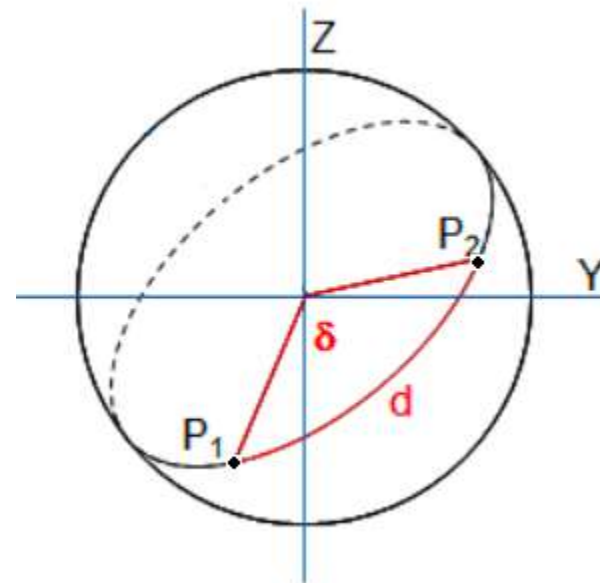


POLARISATION MISMATCH LOSS

Jos tulevan aallon ja rx antennin polarisaatiot eivät ole samat:

$$\text{Vaimennus: } L = \cos^2 (\delta / 2)$$

Alignment angle	Polarization mismatch (dB)
0	0
±15	0.301
±30	1.249
±45	3.010
±60	6.020
±75	11.740
±90	∞



POLARISAATIOPARAMETRIEN MITTAAMINEN

- Riittää, että on kaksi ORTOGONAALISTA rx antennia, jos niiden signaalien vaihe-ero voidaan mitata.
- Esim. H - ja V - dipolit tai LCP- ja RCP- antennit.
- Monet signaalit ovat satunnaisia, kohinaisia ja (erityisesti radioastronomiassa) vain osittain polarisoituneita.
- Näiden mittauksiin on parasta keskiarvoistaa (integroida) ja korreloida vastaanotetut signaalit.
- Määritellään STOKESIN PARAMETRIT:

STOKESIN PARAMETRIT voidaan mitata:

Tehomittauksilla
X ja Y –kentistä
H- ja V- antenneilla:

Tai:

Tehomittauksilla
LCP ja RCP – kentistä
CP – antenneilla:

$$\left[\begin{array}{l} I = \langle |E_X|^2 \rangle + \langle |E_Y|^2 \rangle \\ Q = \langle |E_X|^2 \rangle - \langle |E_Y|^2 \rangle \\ U = 2 \operatorname{Re} \{ E_X E_Y^* \} \\ V = 2 \operatorname{Im} \{ E_X E_Y^* \} \end{array} \right.$$

$$\left[\begin{array}{l} I = \langle |E_R|^2 \rangle + \langle |E_L|^2 \rangle \\ Q = 2 \operatorname{Re} \{ E_R E_L^* \} \\ U = -2 \operatorname{Im} \{ E_R E_L^* \} \\ V = \langle |E_L|^2 \rangle - \langle |E_R|^2 \rangle \end{array} \right.$$

Lisäksi tarvitaan kenttäkomponenttien välisen korrelaation
reaali- ja imaginaariarvot.

Polarisaatioparametrit lasketaan Python ohjelmalla

Average of 100 samples (n. 5 s)

21.06.2023 20:33 ('Päivä - polarisaatio')

Frequency (kHz) = 9996.0

I = 3.439 Q/I = -0.620 U/I = 0.474 V/I = 0.600 LCP

Degree of polarisation = 0.984

Degree of linear polarisation = 0.780

Degree of circular polarisation = 0.600

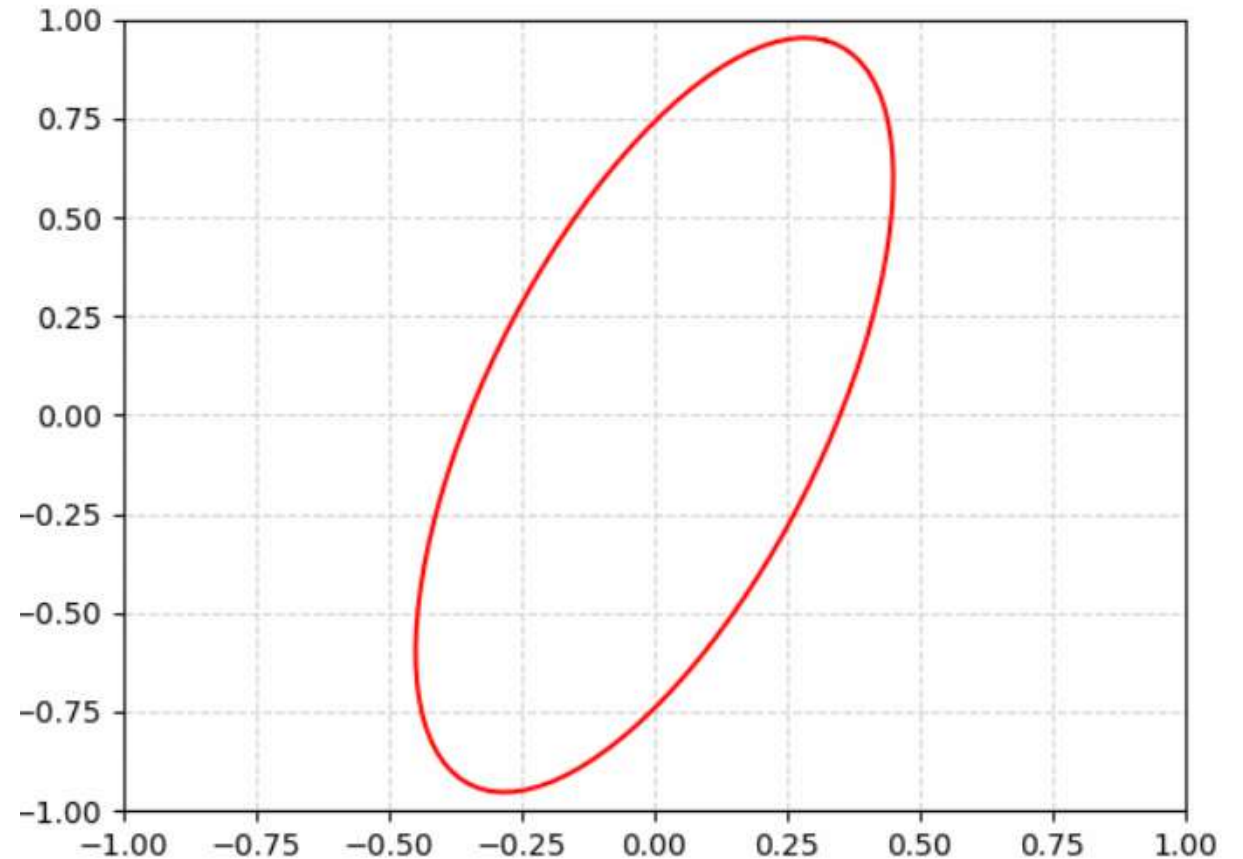
Polarisation ellipse:

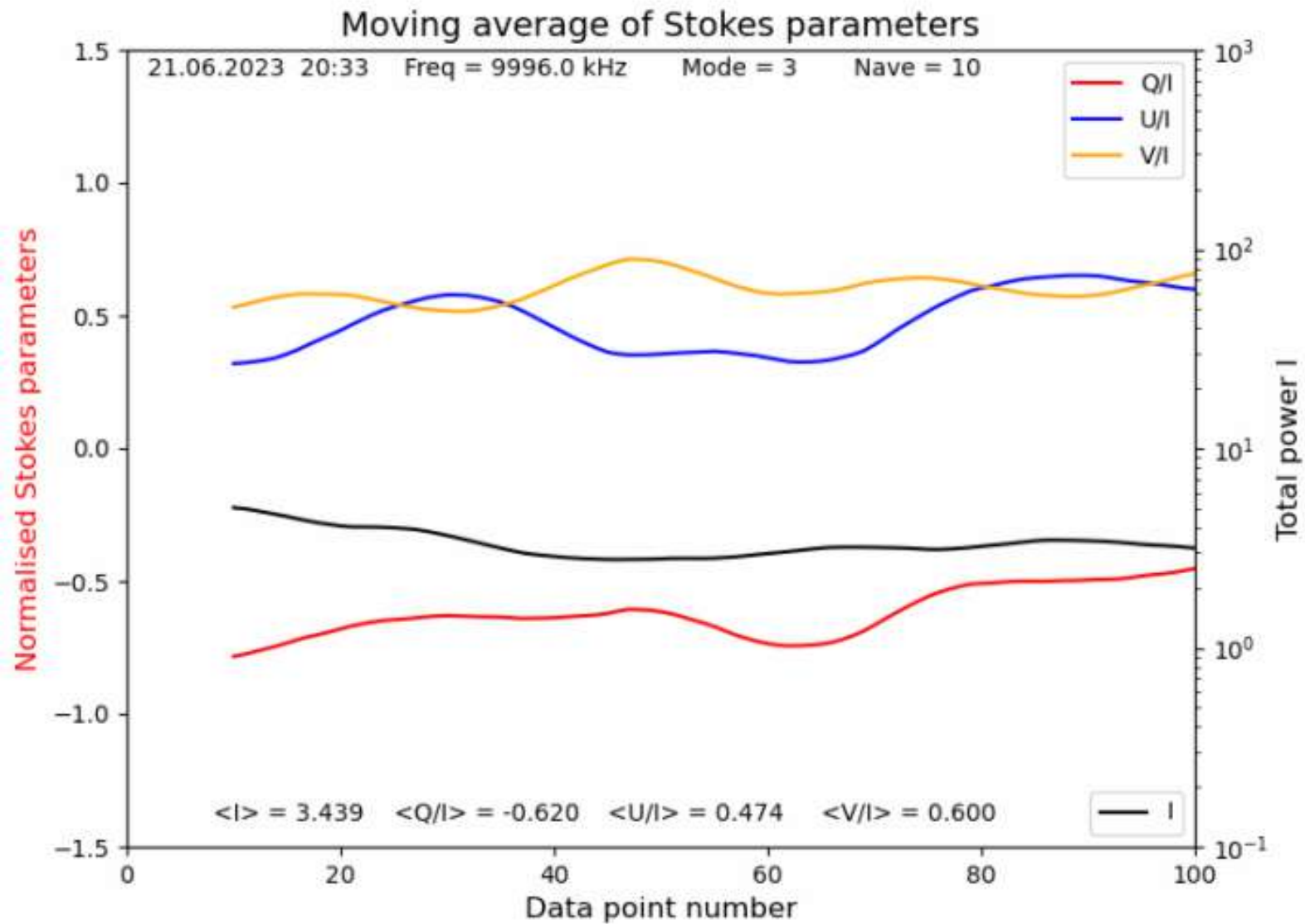
Axial ratio = 3.00 eps = 18.4°

Tilt angle = 71.3°

Ey/Ex = 2.12 Phase shift = 51.0°

Elcp/Ercp = 1.50 Phase shift = 142.6°





Average of 100 samples (n. 5 s)

21.06.2023 00:00 ('Yö – polarisaatio')

Frequency (kHz) = 9996.0

I = 61.776 Q/I = -0.362 U/I = 0.113 V/I = -0.925 RCP

Degree of polarisation = 1.000

Degree of linear polarisation = 0.379

Degree of circular polarisation = 0.925

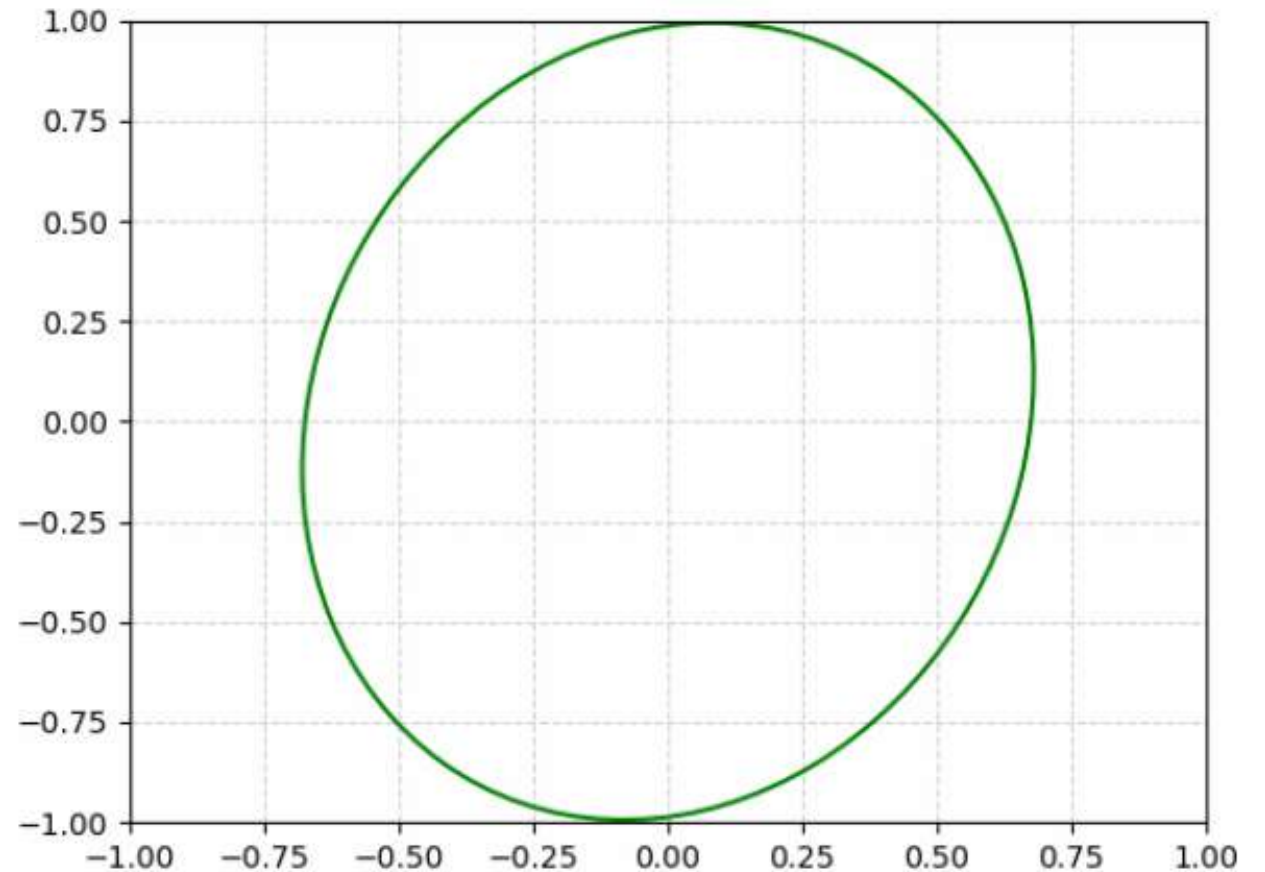
Polarisation ellipse:

Axial ratio = 1.49 $\epsilon_{ps} = -33.8^\circ$

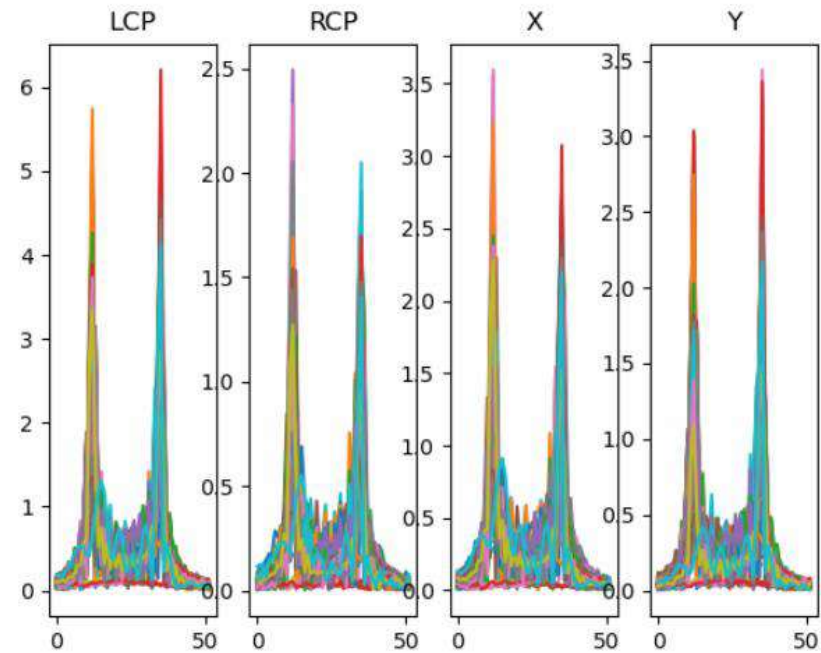
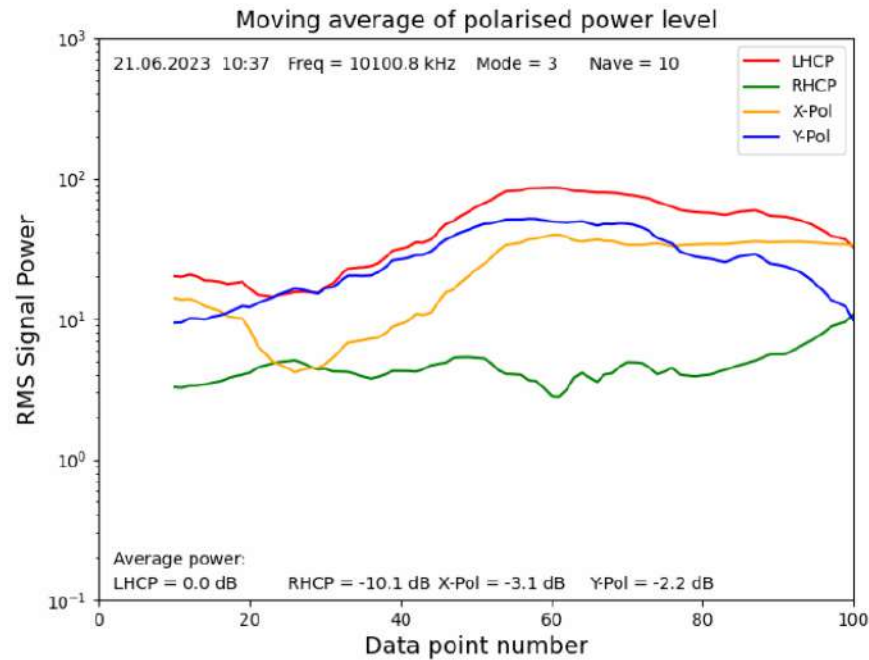
Tilt angle = 81.4°

Ey/Ex = 1.46 Phase shift = -83.1°

Elcp/Ercp = 0.60 Phase shift = 162.7°



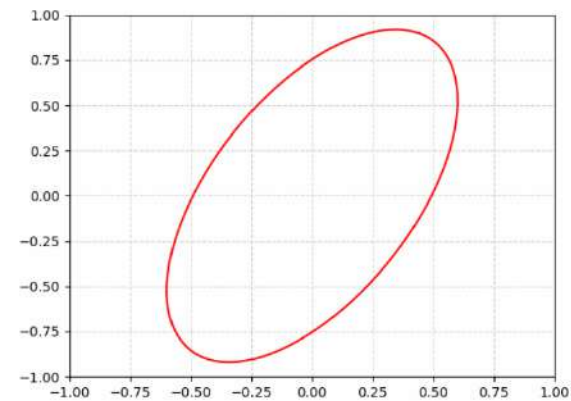
DWD – 'Päivä - polarisaatio'



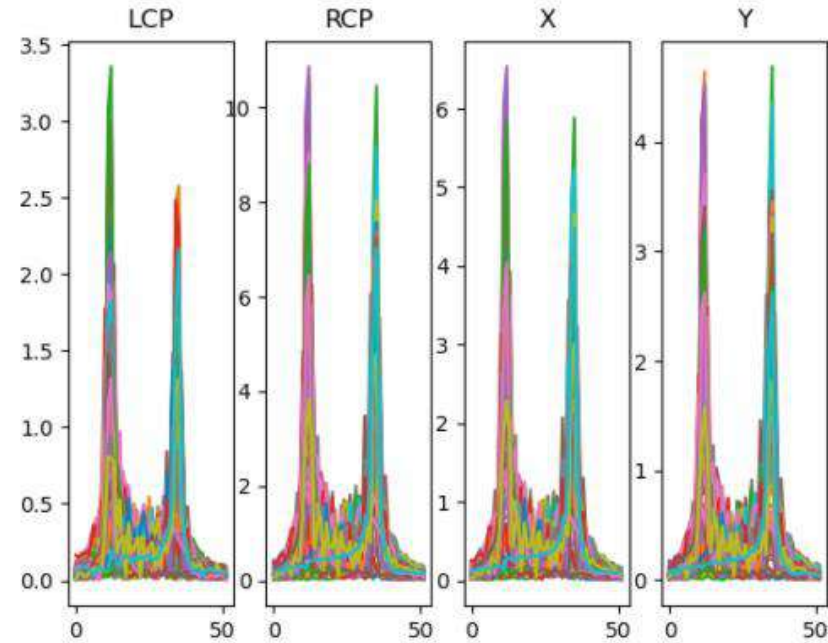
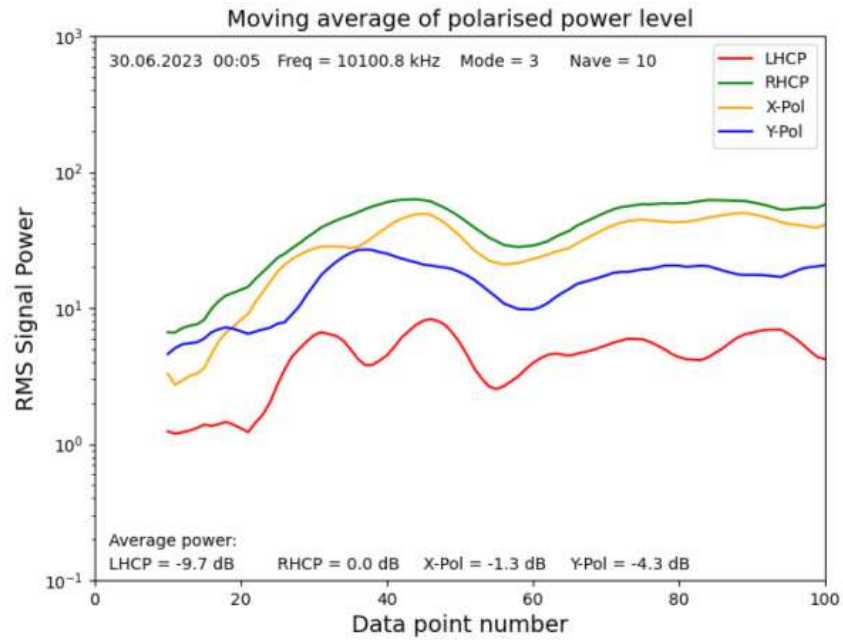
Frequency (kHz) = 10100.8
 $I = 0.800$ $Q/I = 0.106$ $U/I = -0.139$ $V/I = 0.751$ LCP
 Degree of polarisation = 0.771
 Degree of linear polarisation = 0.175
 Degree of circular polarisation = 0.751

Polarisation ellipse:
 Axial ratio = 2.21 $\epsilon_{ps} = 24.3^\circ$
 Tilt angle = 63.8°

 $E_y/E_x = 1.53$ Phase shift = 55.1°
 $E_{lcp}/E_{rcp} = 1.83$ Phase shift = 127.5°



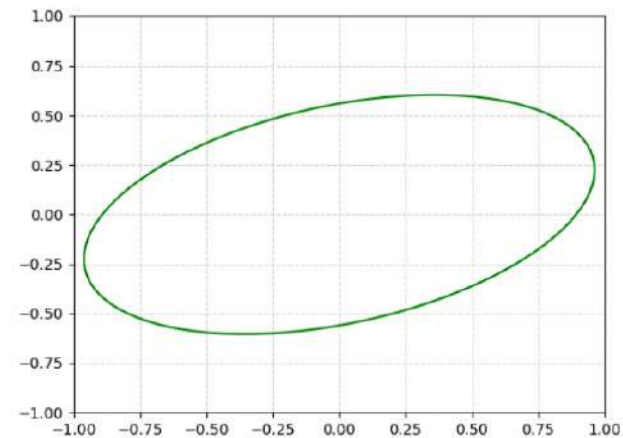
DWD – 'Yö - polarisaatio'



Frequency (kHz) = 10100.8
 $I = 2.294$ $Q/I = 0.393$ $U/I = 0.304$ $V/I = -0.836$ RCP
 Degree of polarisation = 0.972
 Degree of linear polarisation = 0.497
 Degree of circular polarisation = 0.836

Polarisation ellipse:
 Axial ratio = 1.85 $\epsilon_{ps} = -28.4^\circ$
 Tilt angle = 18.8°

 $E_y/E_x = 0.63$ Phase shift = -68.1°
 $E_{lcp}/E_{rcp} = 0.65$ Phase shift = 37.7°



11. CONCLUSION

- Phase-steered antenna array of 4 identical antennas (each consisting of two crossed loops and a vertical dipole), connected to a phase-coherent 4-channel HF-receiver (Afedri), has been studied experimentally.
- Attractive properties have already been demonstrated earlier:
 - Switched-beam (4-square) operation, as well as continuous (manual) beam- and null-steering.
 - Determination of the angles of arrival (both azimuth and elevation) of the incoming HF-signal.
- Novel feature is the capability of receiving circular-polarised signals, and a receiver/antenna for all polarisations has been demonstrated.
- Determination of the polarisation state or Stokes parameters for the incoming signal has been demonstrated.

VIITTEET

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- [2] <http://afedri-sdr.com/index.php>
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- [4] Tapani Närhi, "Vaiheohjatun SDR - RX - antennin kehitys", SRAL 101 Kesäleiri, Eerikkilä, 14-17/7/2022. (<https://sites.google.com/view/oh7eag>)
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- [7] Yuntao Wu, H. C. So, "Simple and accurate two-dimensional angle estimation for a single source with uniform circular array, IEEE Antennas and Wireless Propagation Letters, vol. 7, 2008, pp. 78 – 80.