UNIVERSITY of OULU
Sodankylä Geophysical Observatory

Optical-riometric comparisons of high-energy auroral electron precipitation

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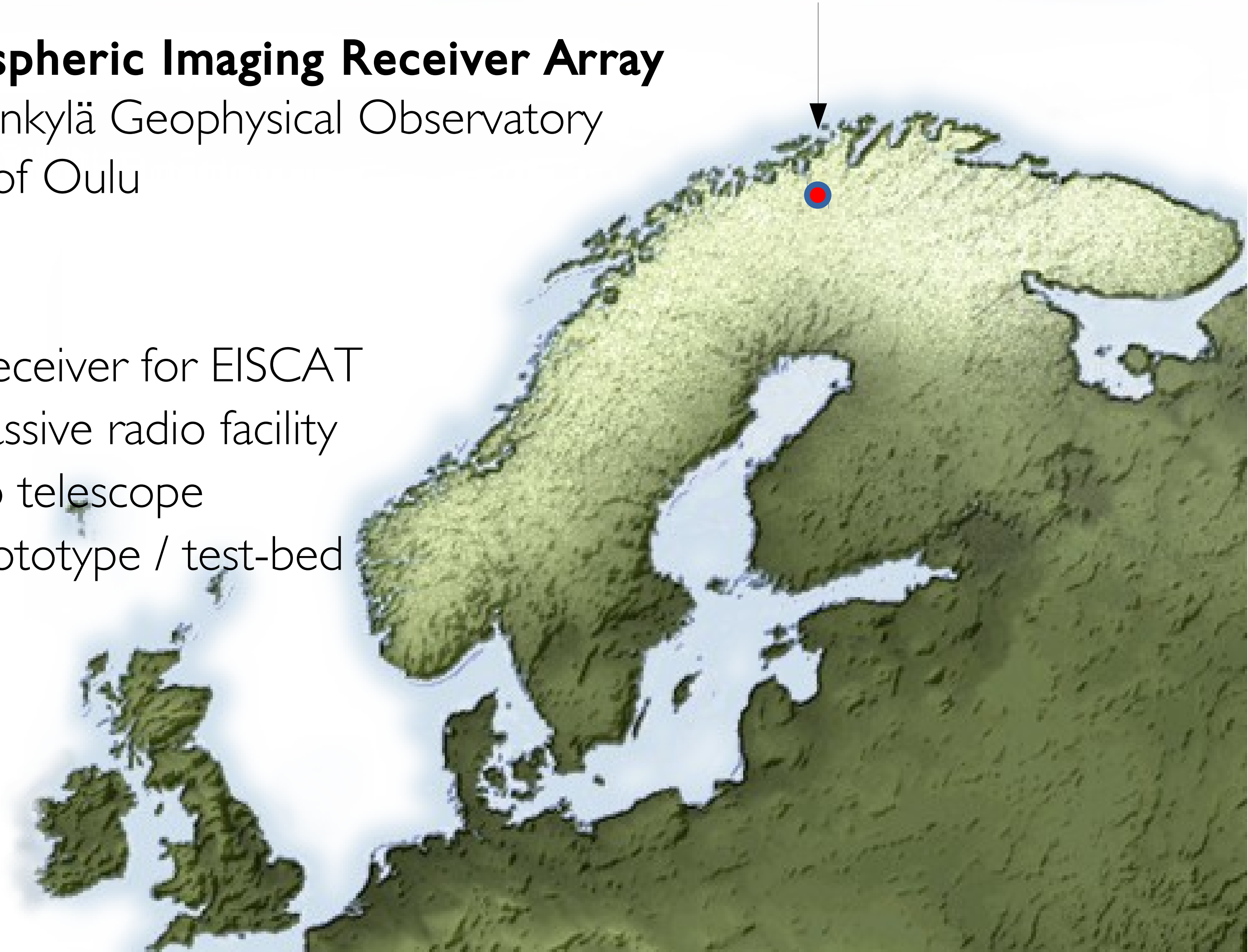
With thanks to Noora Partamies, UNIS; and Kirsti Kauristie, FMI.

LOFAR Science Meeting, Zandvoort, NETHERLANDS, 05-Apr-2016 / DMcKB-0131-LOFAR2016

KAIRA

Kilpisjärvi Atmospheric Imaging Receiver Array
Operated by Sodankylä Geophysical Observatory
for the University of Oulu

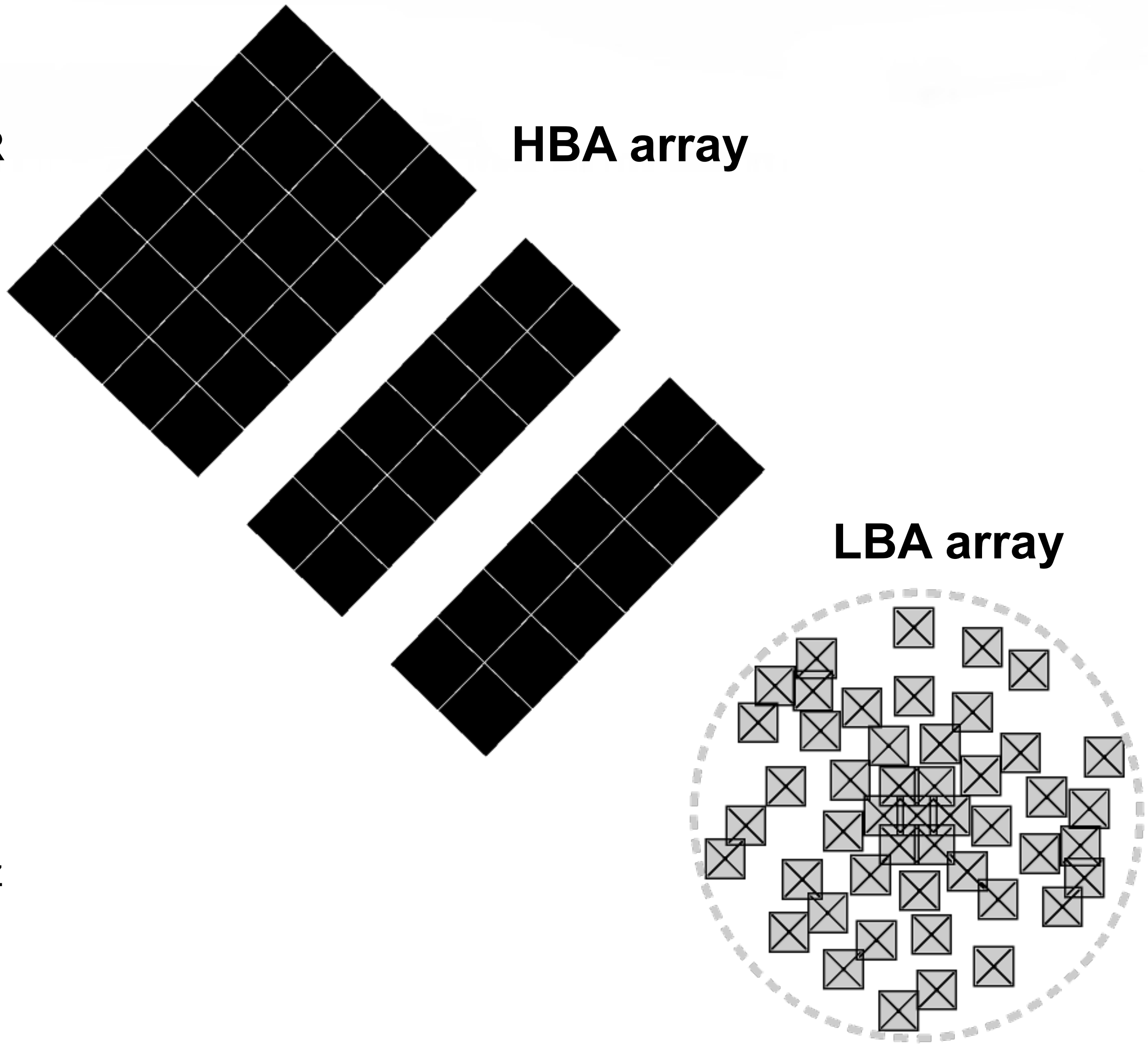


Project

- Bi-static radar receiver for EISCAT
- Atmospheric passive radio facility
- HF / VHF Radio telescope
- EISCAT_3D prototype / test-bed
- Operational
  since 2012

What is it?

- **High-Band Antenna (HBA) array**
  - 30x50m, 47 tiles,
  - layout optimised for EISCAT VHF ISR
  - 16-element per tile → 768 antennas
  - Intra-tile analogue beamformer
  - 110-270 MHz
- **Low-Band Antenna (LBA) array**
  - ~34m diameter, 48 aerial,
  - equivalent to a LOFAR “RS inner”
  - inverted-V dipoles
  - 10-90 MHz
- **Beamlets**
  - 244 (pseudo 16-bit mode) = ~48 MHz
  - 488 (8-bit mode) = ~96 MHz
  - 976 (4-bit mode) = ~191 MHz



SOFTWARE

KAIRA Software (KSW)

– Written and maintained by the author to provide a complete stand-alone, single-LOFAR-station observing system

Running since 2012

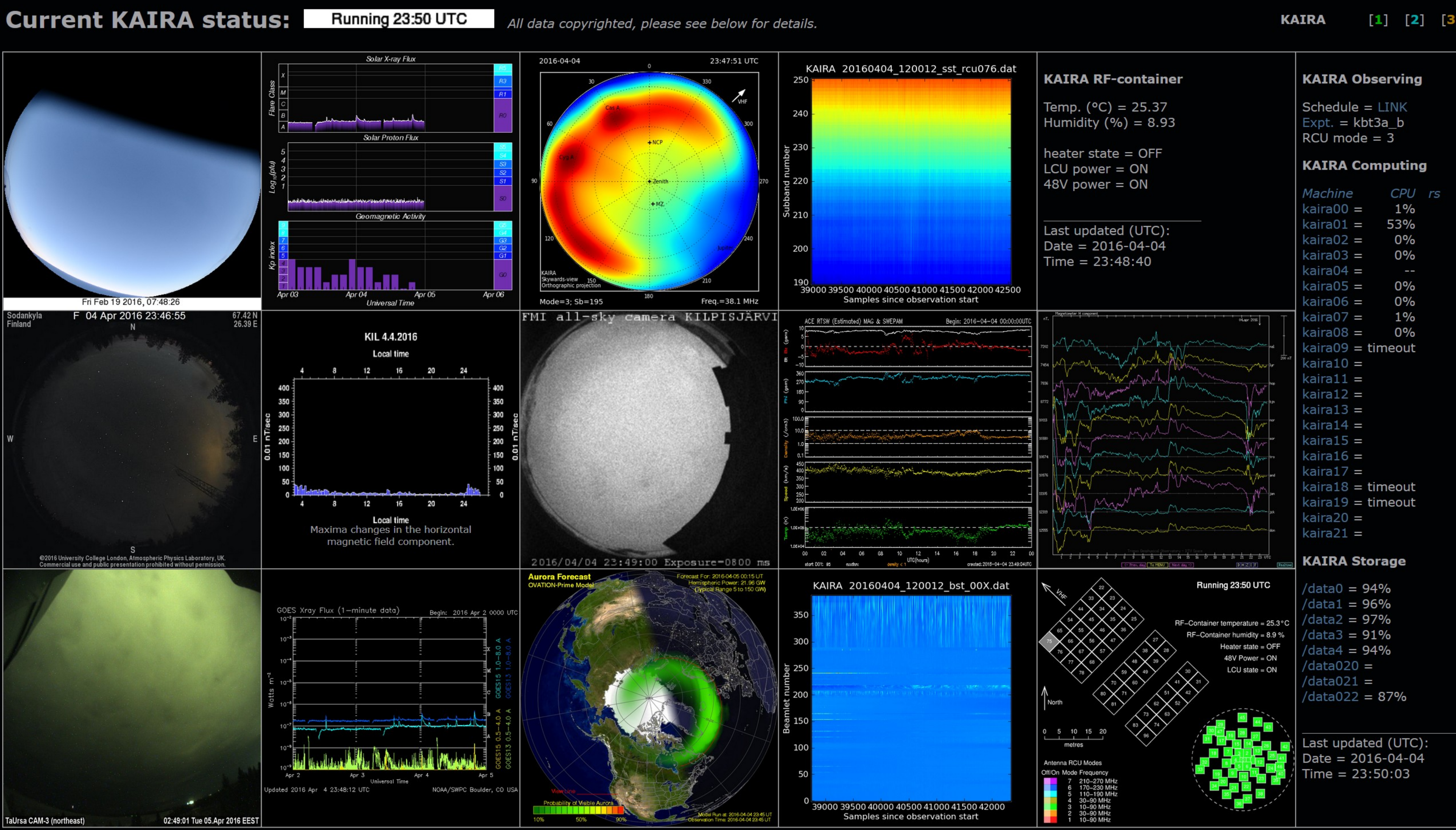
Experiment scheduler/recovery system

– KAIRA Background Task (KBT)

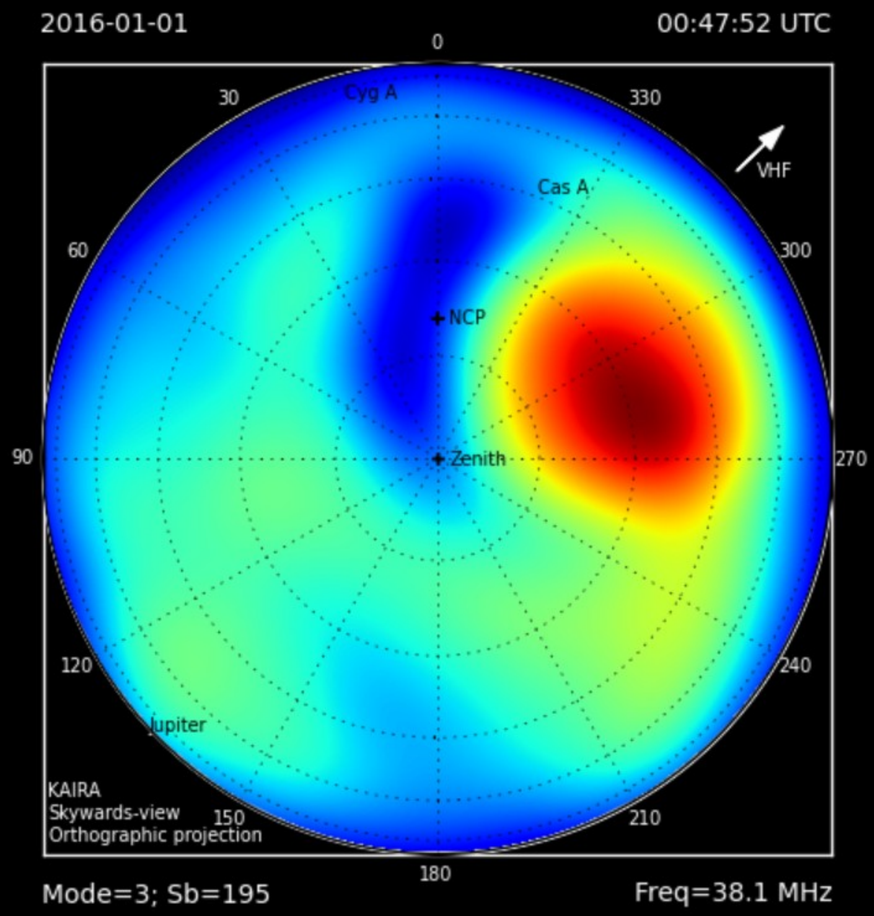
Comprehensive monitoring system

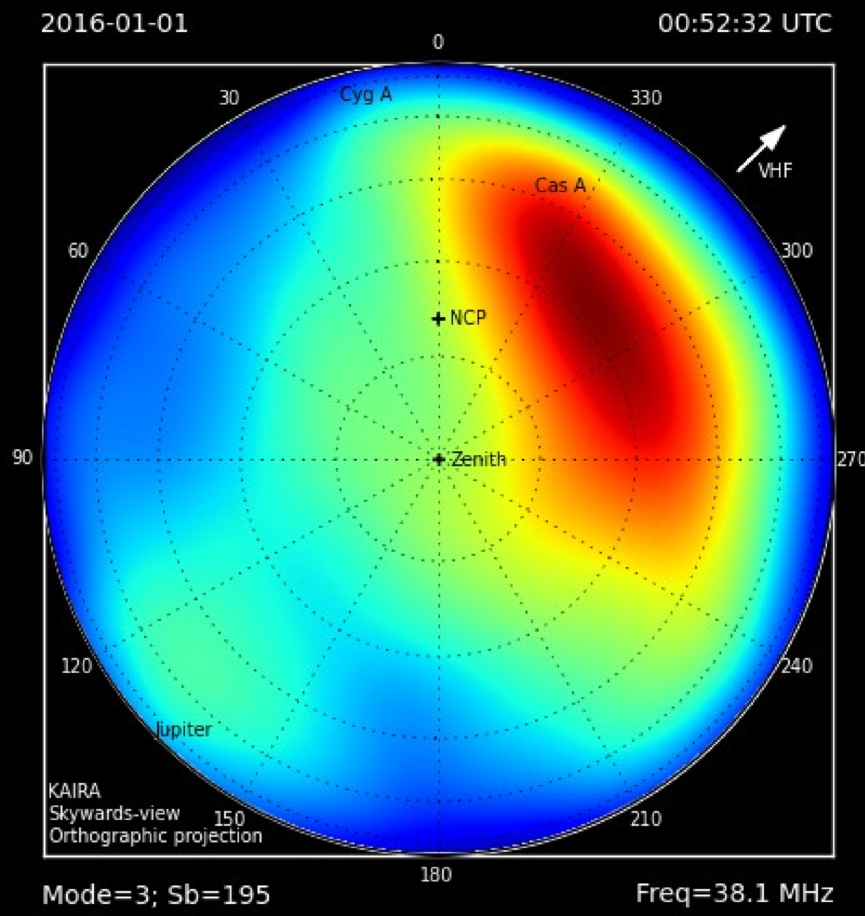
– (KMH, KSS, KMB, KMS, etc., web interface and reporting) – e.g. http://www.sgo.fi/~djm45/KAIRA

KAIRA MONITORING SYSTEM

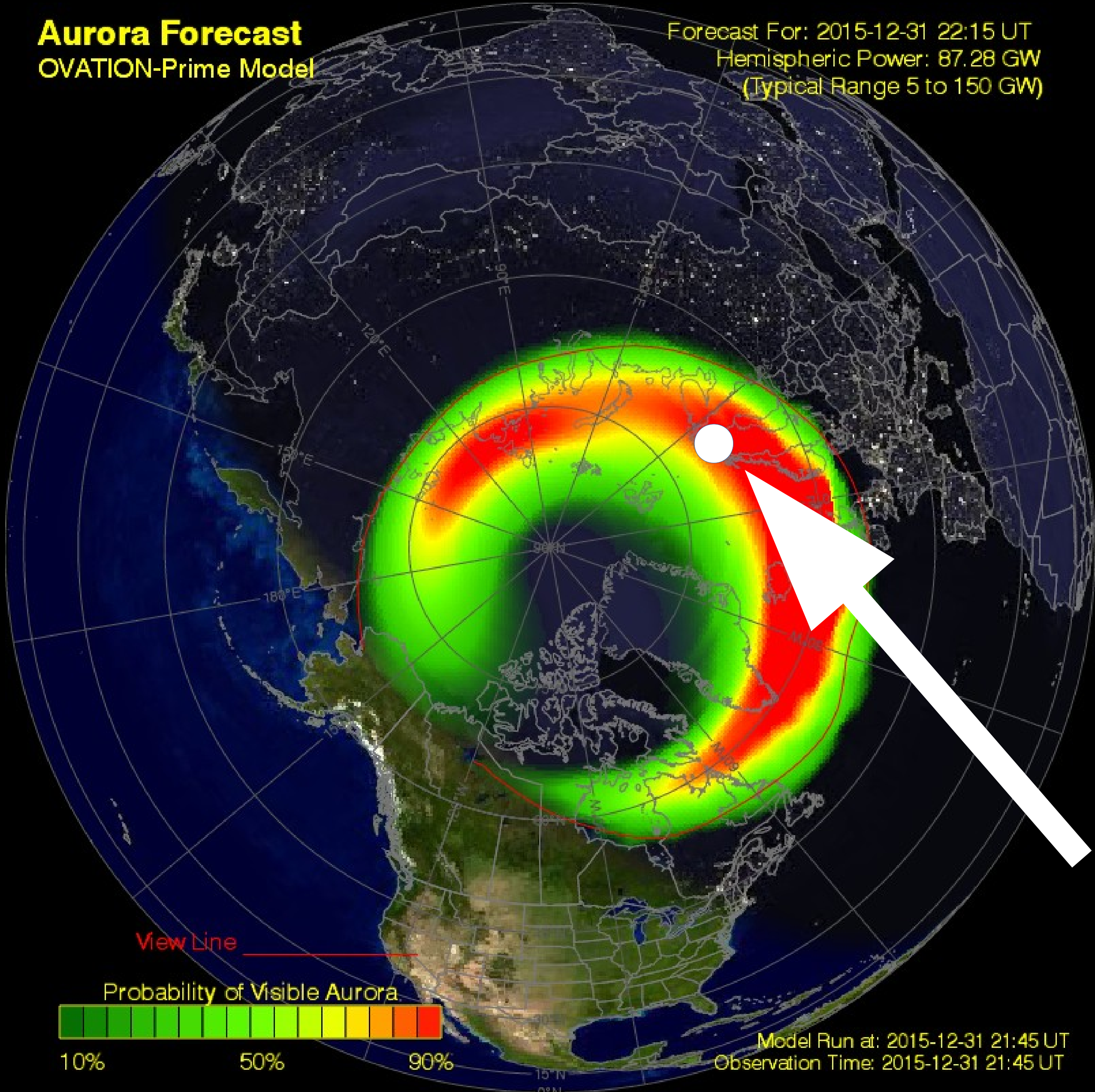


Unusual all-sky image





Auroral oval



Kjell Henriksson Observatory, UNISc

ABSORPTION

- **D-region, free electrons**
- **Collisional plasma, chemically complicated**
- **Multiple sources of ionisation**
  - Ly_{α} ionises NO
  - EUV ionises $O_2(^1\Delta g)$
  - Hard X-ray and EUV ionise O_2 and N_2
  - Galactic cosmic rays
  - Solar particle and auroral precipitation

J. K. Hargreaves. The Solar-Terrestrial Environment. Cambridge University Press,

$$n^2 = 1 - \frac{X}{1 - iZ} = 1 - \frac{\omega_{\mathrm{N}}^2}{\omega(\omega - i\nu)}$$

Complex $$n = \mu - i\chi$$

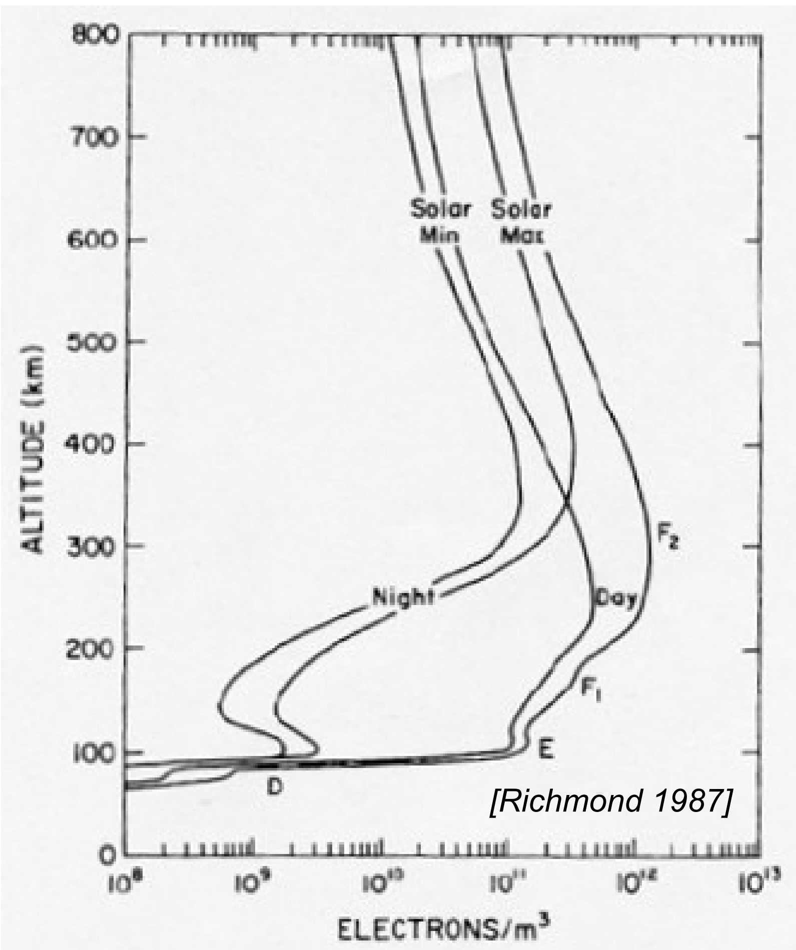
Exp. decay $$\exp(-x\chi\omega/c)\cos\omega(t - x\mu c)$$

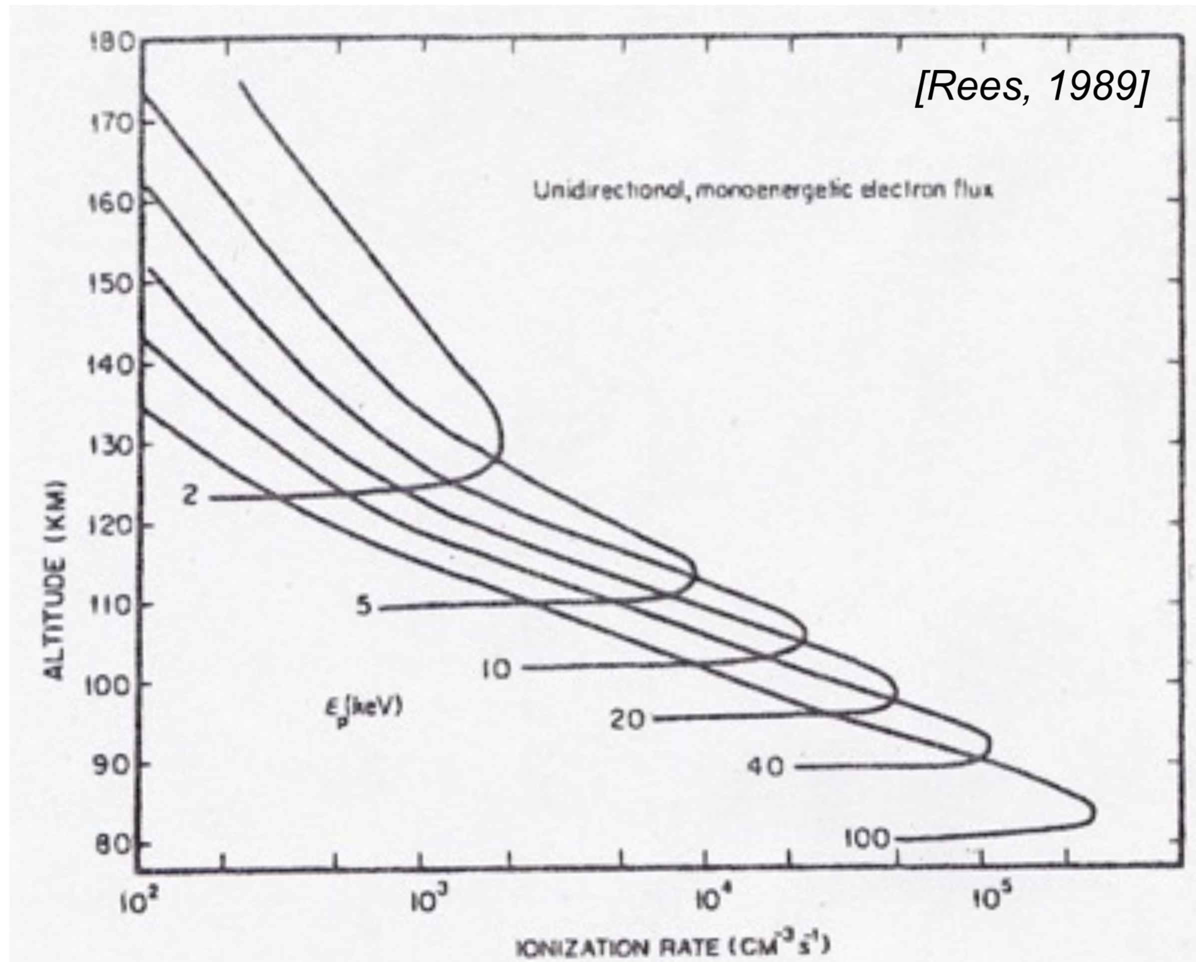
Abs. coeff $$\kappa = \frac{\omega}{c} \cdot \frac{1}{2\mu} \cdot \frac{XZ}{1 + Z^2} = \frac{e^2}{2\epsilon_0 mc} \cdot \frac{1}{\mu} \cdot \frac{N_{\mathrm{e}}\nu}{\omega^2 + \nu^2}$$

Riometry Eqn. $$A = 4.5 \times 10^{-5} \int \frac{N_{\mathrm{e}}\nu}{\omega^2 + \nu^2}\, dx \ (\mathrm{dB})$$

J. K. Hargreaves. The Solar-Terrestrial Environment. Cambridge University Press,

IONOSPHERE


800
700
600
500
400
300
200
100
0
ALTITUDE (km)
Solar Min
Solar Max
Night
Day
F_2
F_1
E
D
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
ELECTRONS/m^3
[Richmond 1987]


[Rees, 1989]
Unidirectional, monoenergetic electron flux
180
170
160
150
140
130
120
110
100
90
80
ALTITUDE (KM)
2
5
10
20
40
100
E_p(keV)
10^2
10^3
10^4
10^5
IONIZATION RATE ($CM^{-3}s^{-1}$)

ALL-SKY RIOMETRY

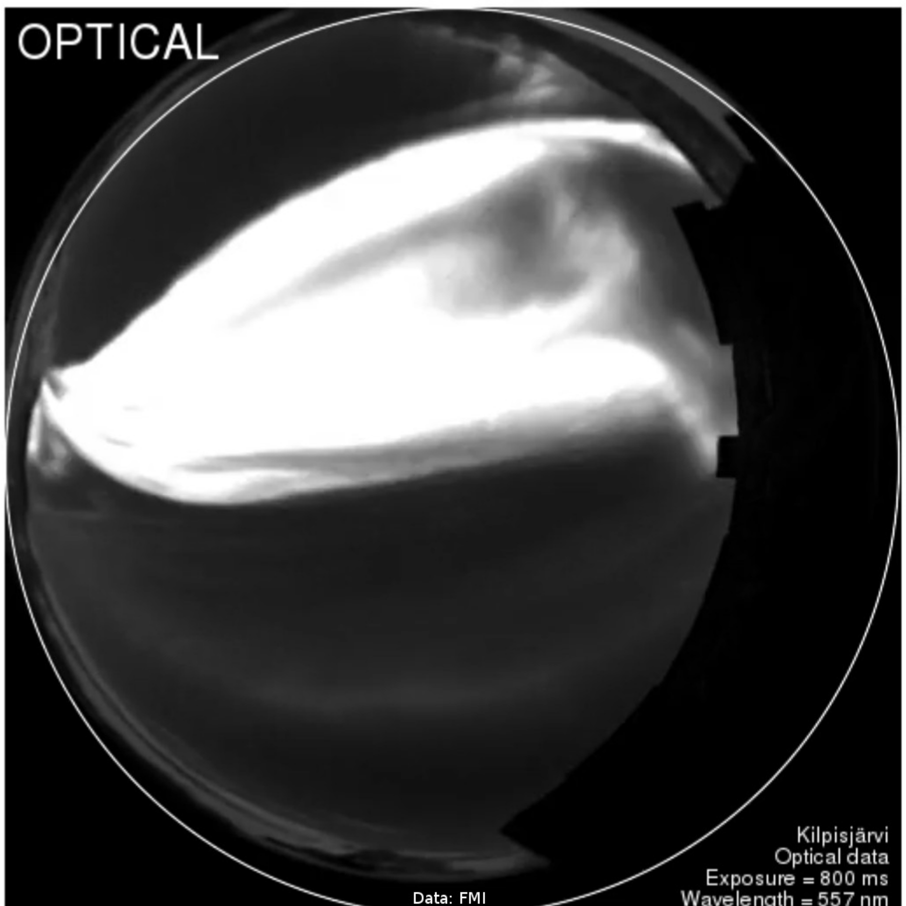
- If you can measure all-sky power, at the right frequency, you can do riometry

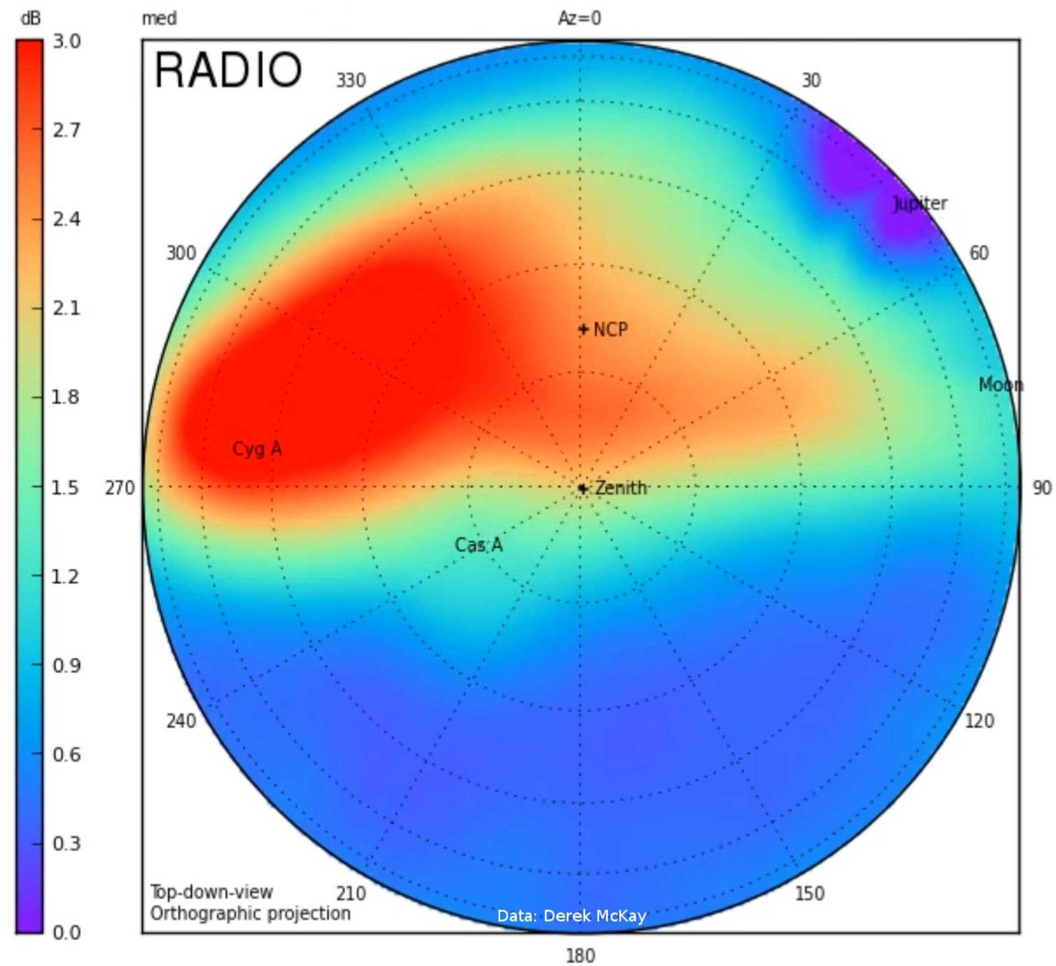
$$A = 4.5 \times 10^{-5} \int \frac{N_\mathrm{e}\nu}{\omega^2 + \nu^2} \; dx \;\; (\mathrm{dB})$$

$$A = 10 \log_{10}(P_\mathrm{q}/P)$$

McKay, *et al.* (2015)

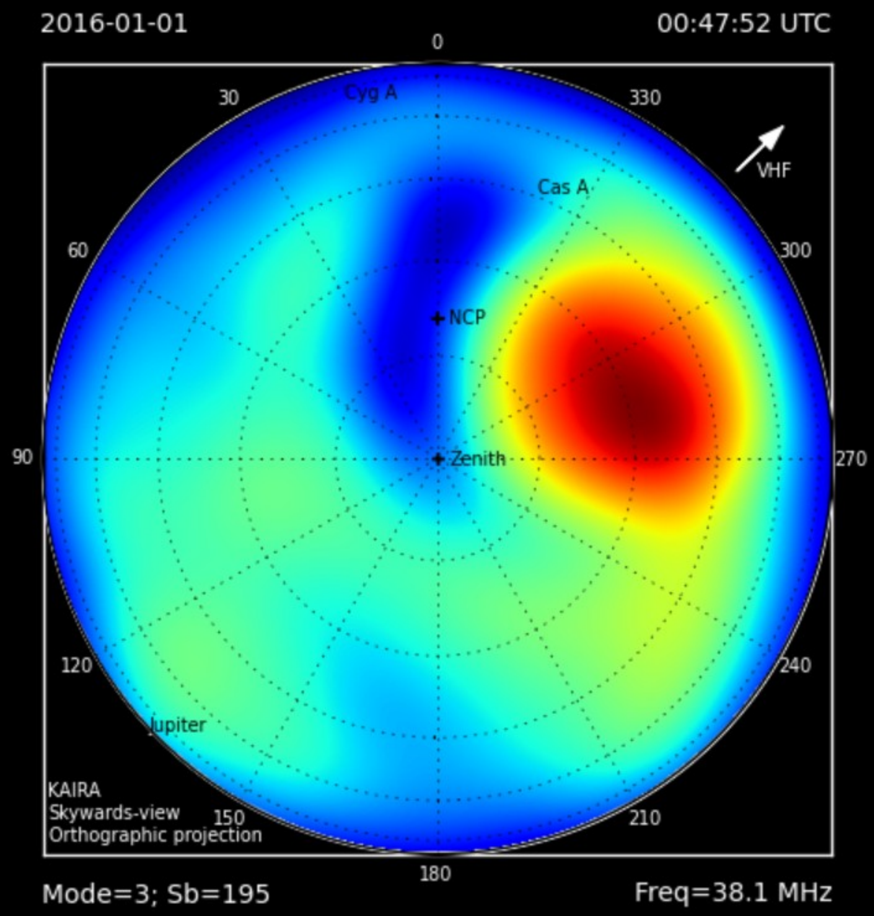
OPTICAL-RIOMETRIC COMPARISON

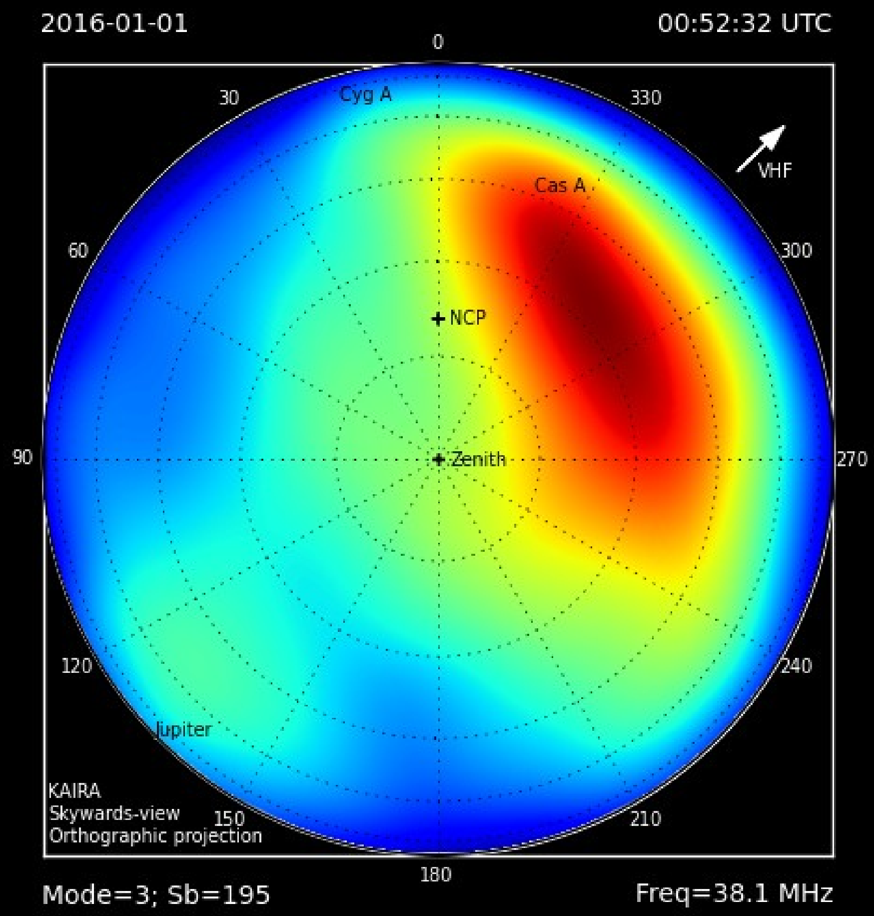




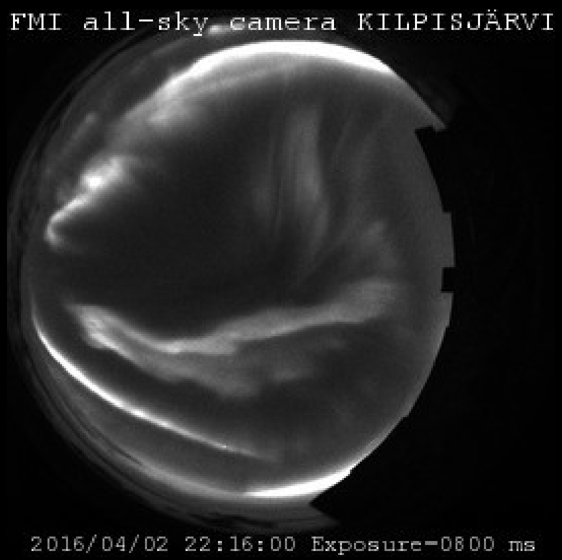
OPTICAL AND RIOMETRIC IMAGING OF POLAR MAGNETOSPHERIC SUBSTORMS

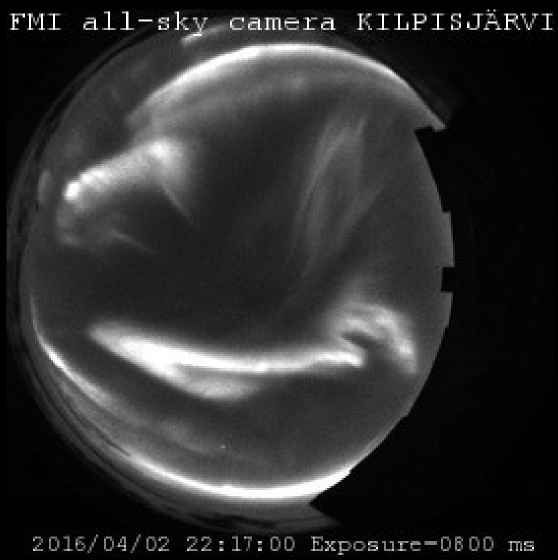
Unusual all-sky image

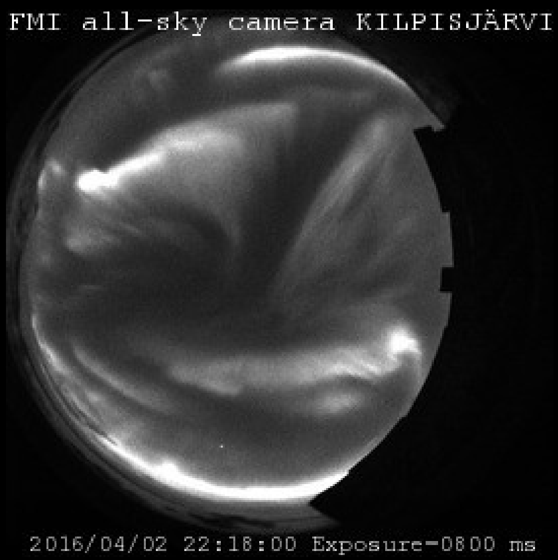




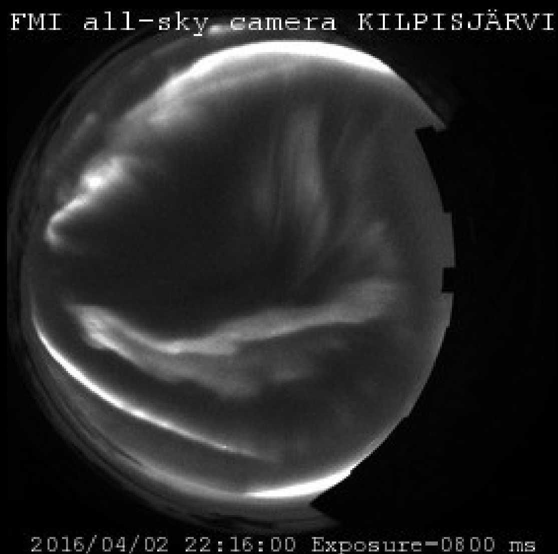
Keogram

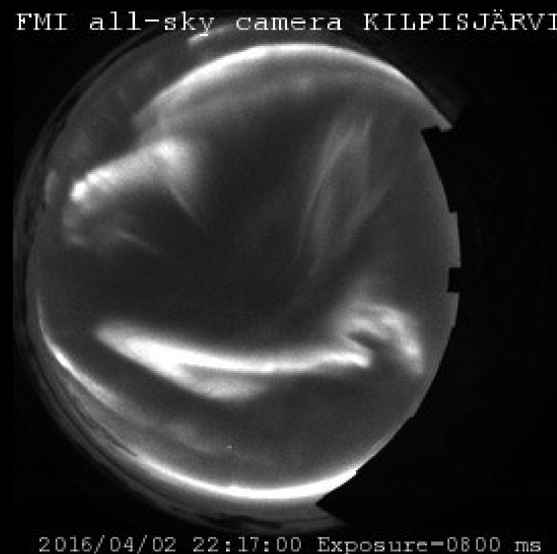

FMI all-sky camera KILPISJÄRVI
2016/04/02 22:16:00 Exposure=0800 ms

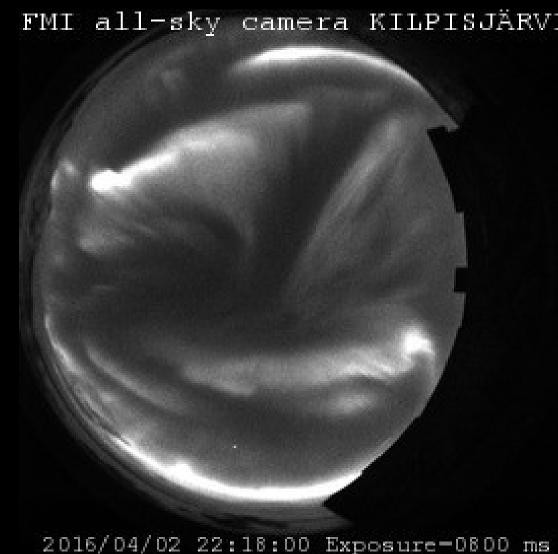

FMI all-sky camera KILPISJÄRVI
2016/04/02 22:17:00 Exposure=0800 ms


FMI all-sky camera KILPISJÄRVI
2016/04/02 22:18:00 Exposure=0800 ms

Keogram


FMI all-sky camera KILPISJÄRVI
2016/04/02 22:16:00 Exposure=0800 ms


FMI all-sky camera KILPISJÄRVI
2016/04/02 22:17:00 Exposure=0800 ms

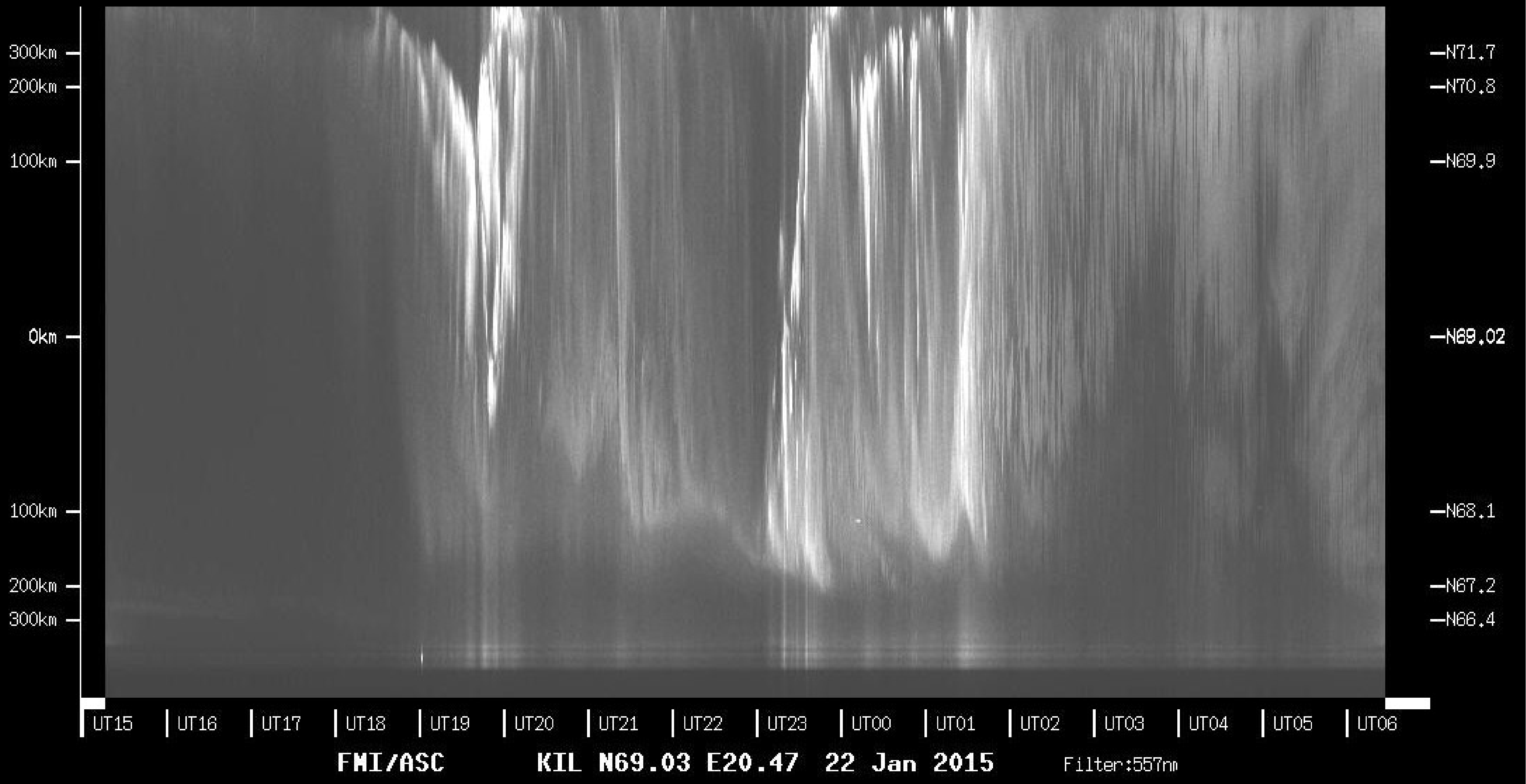

FMI all-sky camera KILPISJÄRVI
2016/04/02 22:18:00 Exposure=0800 ms


ame

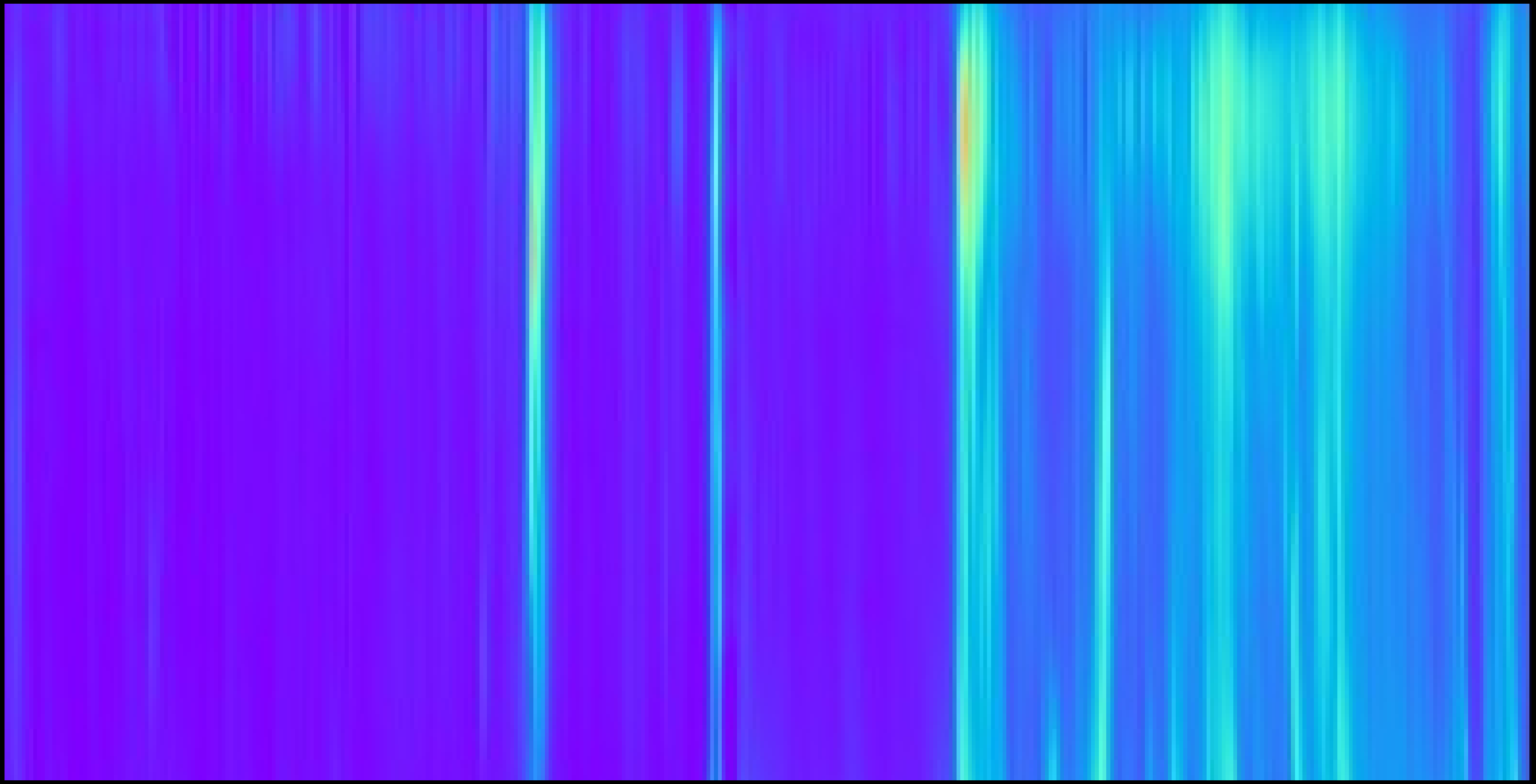

ame

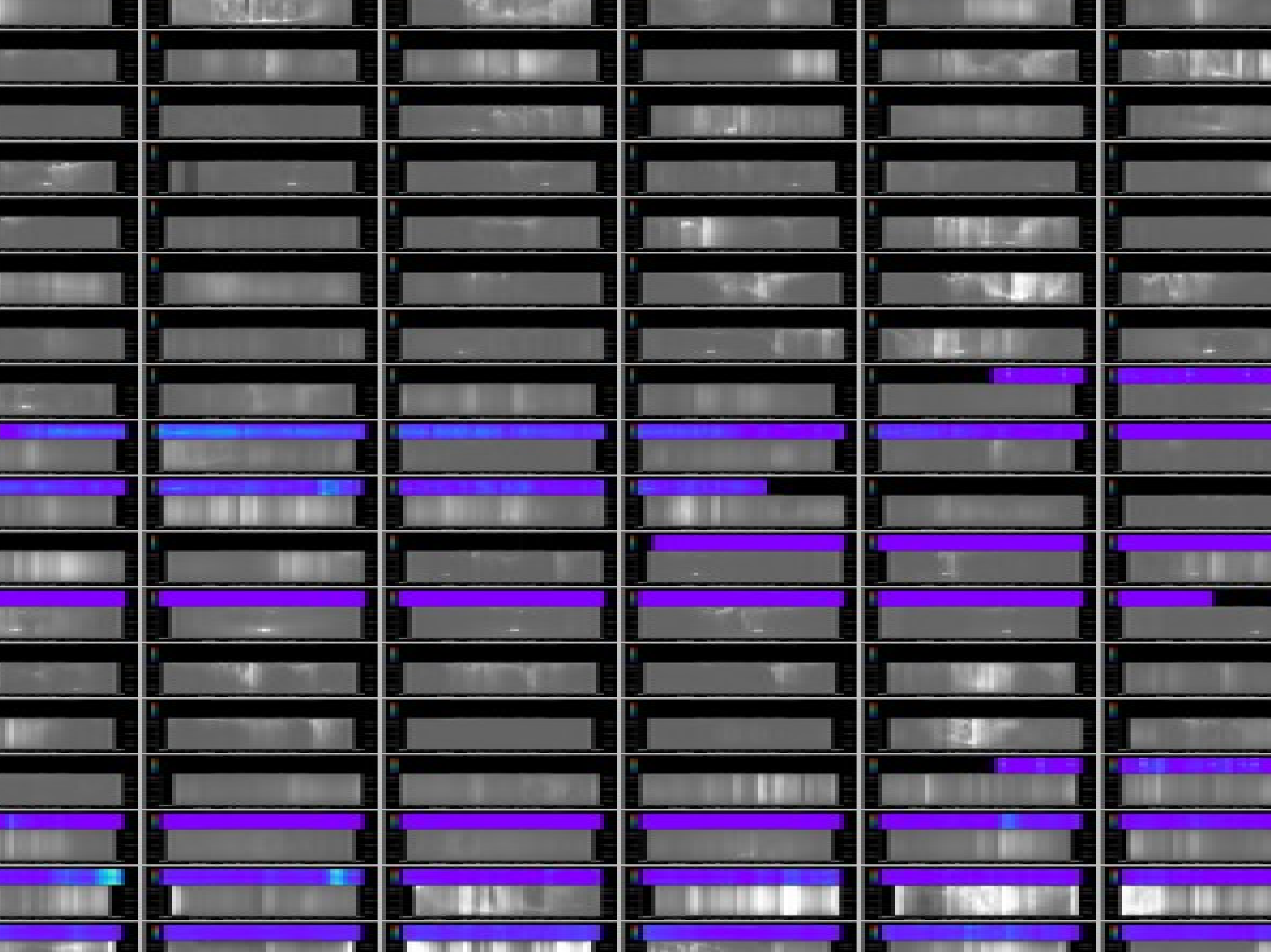

ame

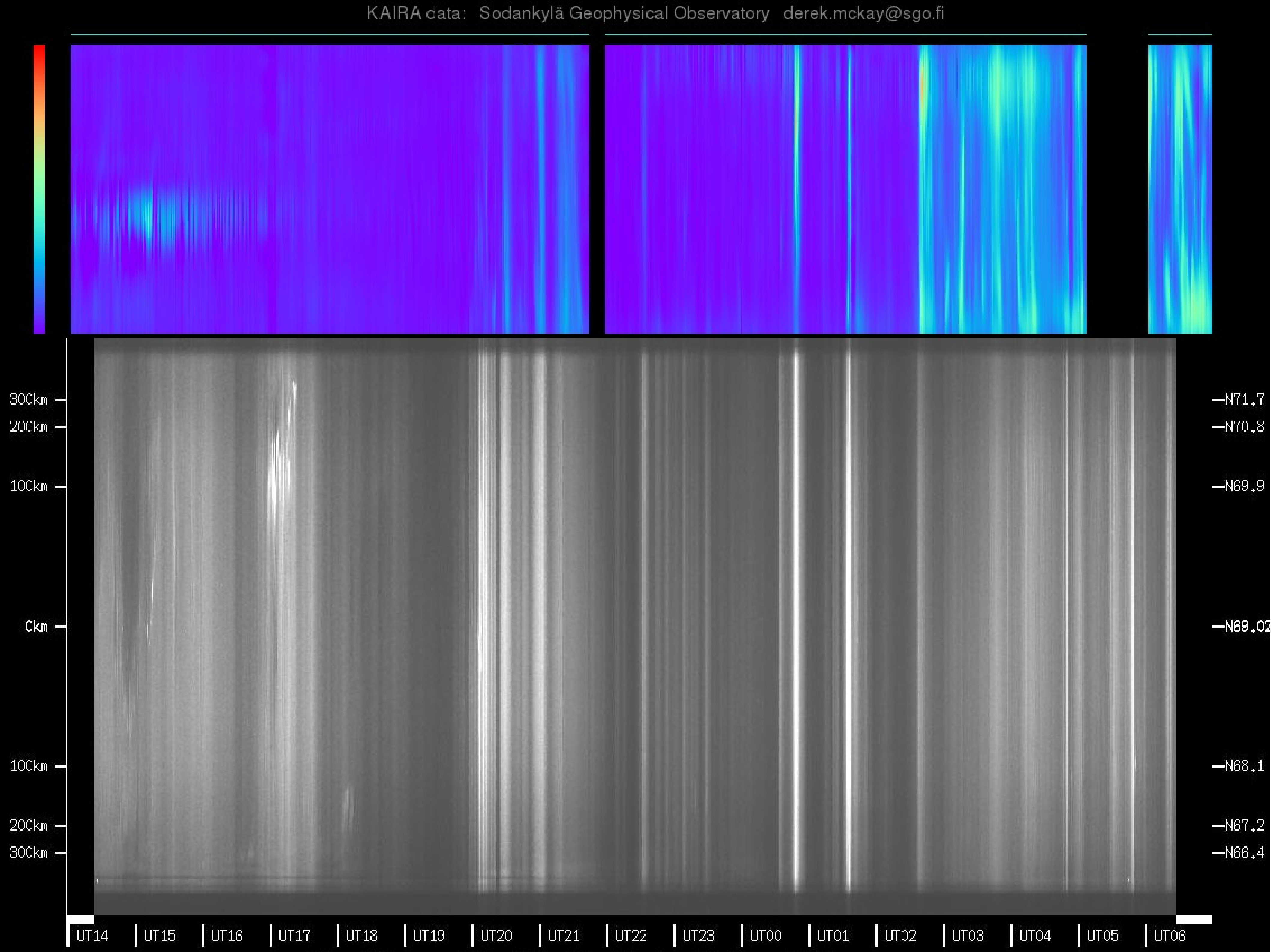
Keogram


300km
200km
100km
0km
100km
200km
300km
N71.7
N70.8
N69.9
N69.02
N68.1
N67.2
N66.4
UT15 UT16 UT17 UT18 UT19 UT20 UT21 UT22 UT23 UT00 UT01 UT02 UT03 UT04 UT05 UT06
FMI/ASC
KIL N69.03 E20.47 22 Jan 2015
Filter:557nm

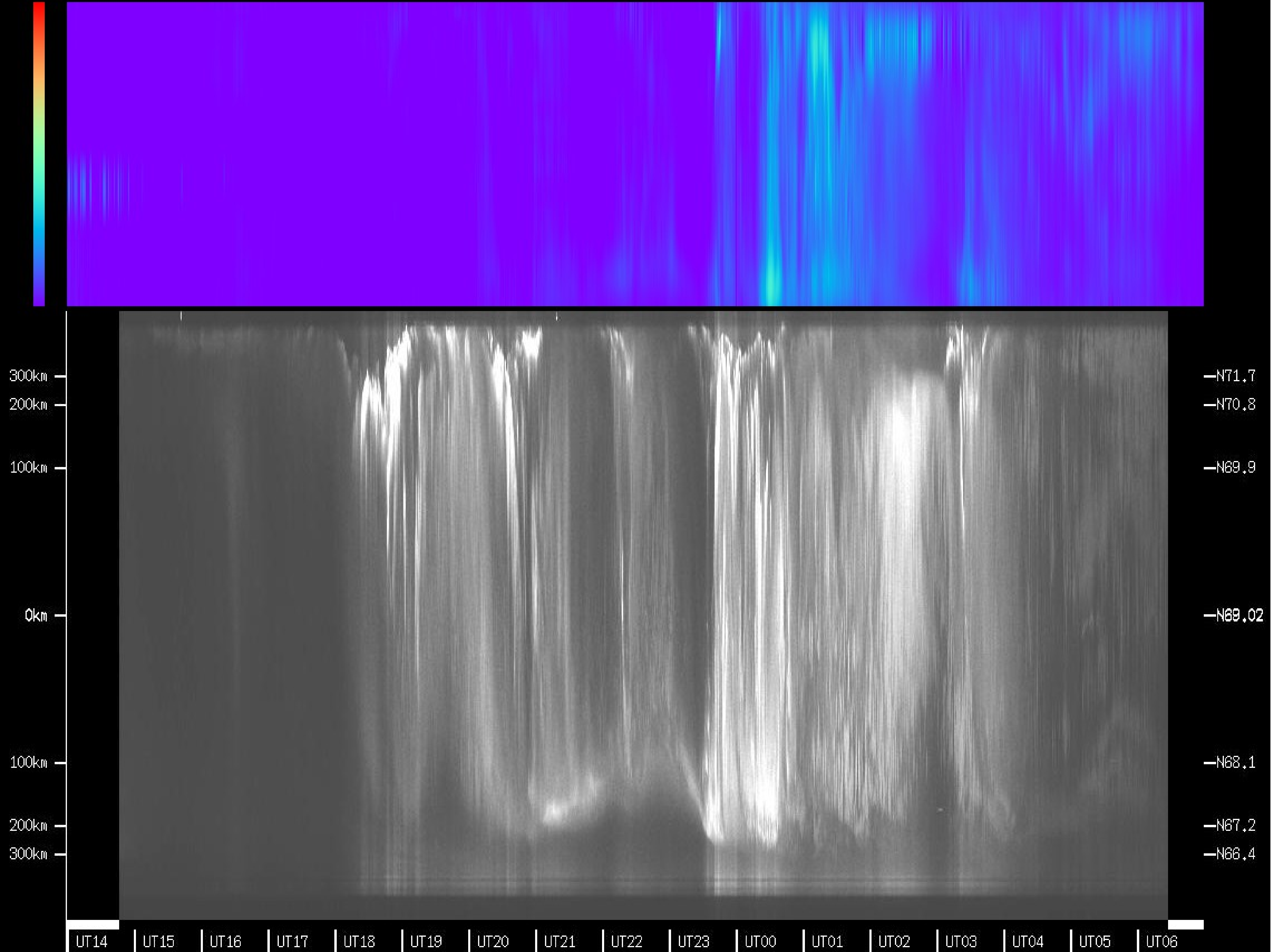
Riometric keogram







KAIRA data: Sodankylä Geophysical Observatory derek.mckay@sgo.fi
300km
200km
100km
0km
100km
200km
300km
N71.7
N70.8
N69.9
N69.02
N68.1
N67.2
N66.4
UT14
UT15
UT16
UT17
UT18
UT19
UT20
UT21
UT22
UT23
UT00
UT01
UT02
UT03
UT04
UT05
UT06


300km
200km
100km
0km
100km
200km
300km
N71.7
N70.8
N69.9
N69.02
N68.1
N67.2
N66.4
UT14
UT15
UT16
UT17
UT18
UT19
UT20
UT21
UT22
UT23
UT00
UT01
UT02
UT03
UT04
UT05
UT06

CURRENTS

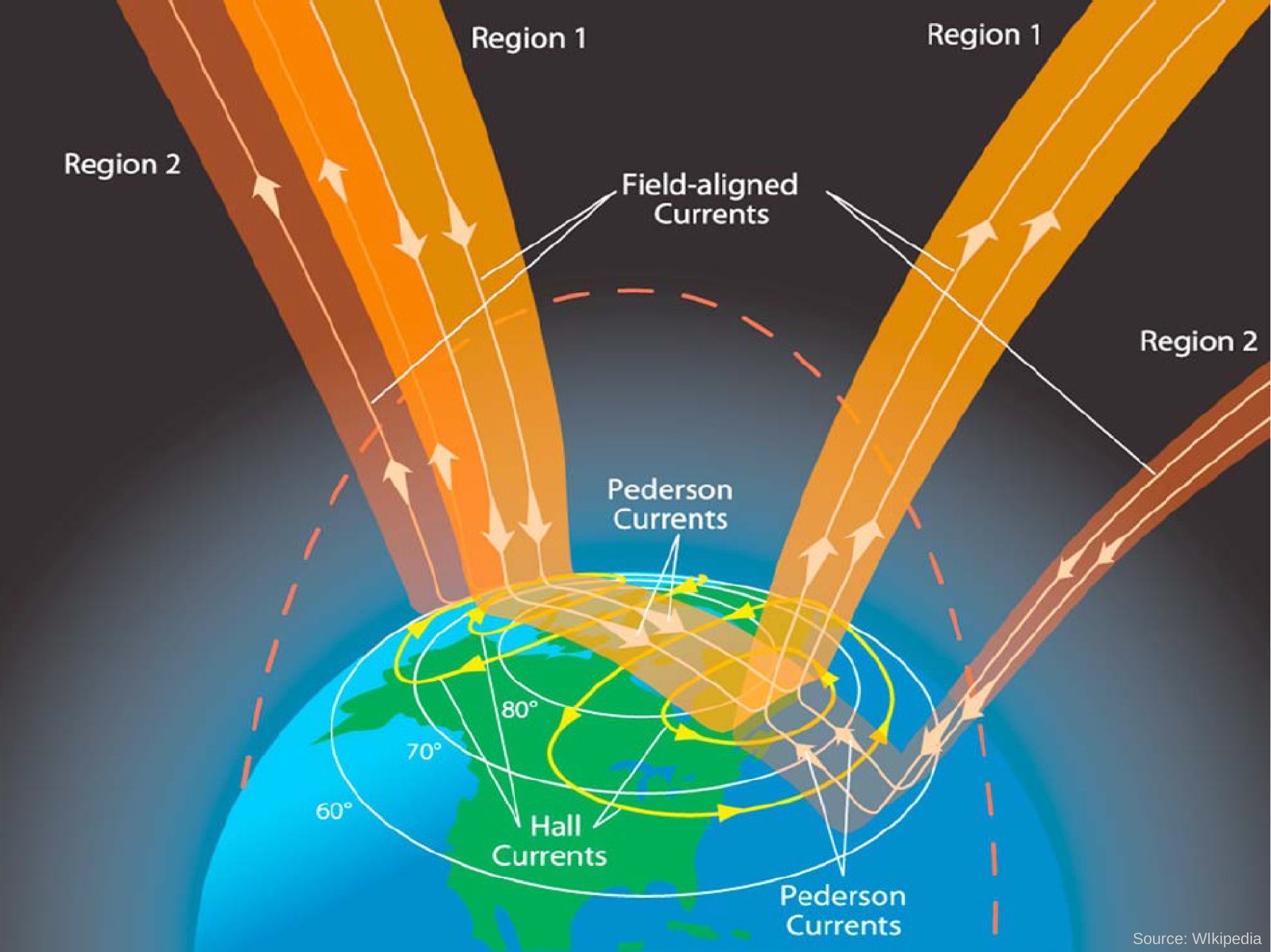
D-region Pedersen currents

First observed by Hosokawa & Ogawa

EISCAT VHF observations

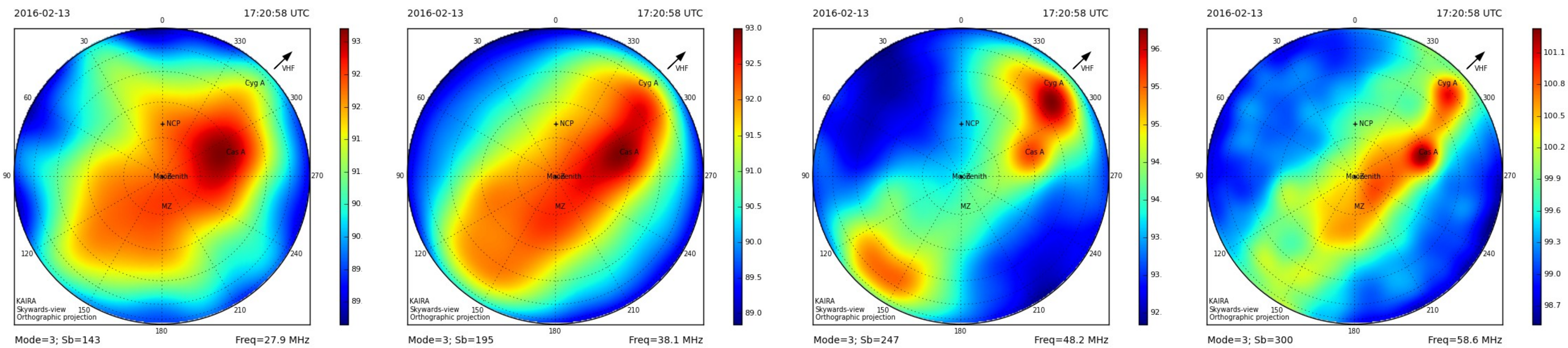
Associated with pulsating auroral events

Coupled-drivers



Source: WIkipedia

MULTI-FREQUENCY



Multi-frequency, interferometric riometry

4 Subbands all-sky imaging operational

12-15 Subbands needed for Ne inversion

FUTURE

Multi-frequency, interferometry (4 → 12+)

Ongoing large-data statistics

Improved Inverse Problem algorithms

Improved ionospheric models

Investigation of pulsating aurorae

CONCLUSIONS

All-sky inteferometric riometry

Detected pre-/post- substorm bias

Related to Pedersen currents

Continued post substorm energy inflow

Associated pulsating aurorae

Thank you!

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Sodankylä Geophysical Observatory

Thank you!

http://www.sgo.f/KAIRAi
@KairaProject
kaira@sgo.fi

* REFERENCES

+ Hargreaves, J. K. (1995), The Solar-Terrestrial Environment, Cambridge Univ. Press.
+ Hosokawa and Ogawa (2010), "Pedersen current carried by electrons in auroral D-region", GRL, Vol 37 L18103, doi:10.1029/2010GL044746
+ Kero, A., J. Vierinen, D. McKay-Bukowski, C.-F. Enell, M. Sinor, L. Roininen, and Y. Ogawa (2014), Ionospheric electron density profiles inverted from a spectral riometer measurement, Geophys. Res. Lett., 41, 5370–5375, doi:10.1002/2014GL060986.
+ Little, C. G., and H. Leinbach (1959), The riometer—A device for continuous measurement of ionospheric absorption, Proc. IRE, 47, 315–320.
+ McKay-Bukowski, D., et al. (2015), KAIRA: The Kilpisjärvi Atmospheric Imaging Receiver Array — system overview and first results, IEEE Trans. Geosci. Remote Sens., 53, 1440–1451, doi:10.1109/TGRS.2014.2342252.
+ McKay, D., R. Fallows, M. Norden, A. Aikio, J. Vierinen, F. Honary, S. Marple, and T. Ulich (2015), All-sky interferometric riometry, Radio Sci., 50, 1050–1061, doi:10.1002/2015RS005709.
+ van Haarlem, M. P., et al. (2013), Lofar: The low-frequency array, Astron. Astrophys., 556(A2), 53, doi:10.1051/0004-6361/201220873.
+ Virtanen, I. I. (2012), Station Data Cookbook.