Basic radiometry and SNR equations for CCD, ICCD and EMCCD imagers

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Presentation at:

http://alis.irf.se/˜urban/AGF351/Braendstroem-UNIS.pdf

In memoriam

Professor Ingrid Sandahl (1949-2011)

This is about taking pictures of darkness, or. . .

“Hunting photons with a spoon”

Radiometry

Radiometry vs. photometry

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Unfortunately the term photometry is often used instead of radiometry

Radiometry

“Mathematics is often called the queen of the sciences. Radiometry should then be called the waiting maid or servant. It is not especially elegant; it is not very popular, has not been trendy; but it is essential in almost every part of optical engineering.” *Wolfe [1998]*

Solid angle

The solid angle Ω sweeps out the area A on the unit sphere (4π)

$$\Omega = \frac{A}{r^2}\,[\mathrm{sr}]$$

Think of it as a 3D generalisation of the radian (arc length on the unit circle)

Flux

Photon flux:

$$\Phi_\gamma = \frac{\partial N}{\partial t} \left[\frac{\text{photons}}{\text{s}}\right]$$

in energy units:

$$\Phi_E = \frac{hc}{\lambda}\,\frac{\partial N}{\partial t}\,[\text{W}]$$

Radiance

Also known as radiant sterance

In energy units:

$$L_E = \frac{\partial^2 \Phi(\lambda)}{\partial A_s \partial \Omega} \left[\frac{\mathrm{W}}{\mathrm{m}^2\ \mathrm{sr}} \right]$$

In quantum units:

$$L_\gamma = \frac{\lambda}{hc} L_E \left[\frac{\mathrm{photons}}{\mathrm{s\ m}^2\ \mathrm{sr}} \right]$$

Spectral radiance

Also known as spectral radiant sterance

In energy units:

$$L_{\lambda E} = \frac{\partial L}{\partial \lambda} \left[\frac{\mathrm{W}}{\mathrm{m}^2\ \mu\mathrm{m\ sr}} \right]$$

In quantum units:

$$L_{\lambda\gamma} = \frac{\lambda}{hc} L_{\lambda E} \left[\frac{\mathrm{photons}}{\mathrm{s\ m}^2\ \mu\mathrm{m\ sr}} \right]$$

Spectral radiant emittance

Also known as spectral radiant exitance

$$M_{\lambda\gamma} = \frac{\partial\Phi}{\partial A_s} = \left[\frac{\text{photons}}{\text{s}\ m^2}\right]$$

Flux per source area.
What you get from a calibration source.
In energy units:

$$M_{\lambda E} = \frac{hc}{\lambda} M_{\lambda\gamma} \left[\frac{\text{W}}{\text{m}^2\ \mu\text{m sr}}\right]$$

Spectral irradiance

Also known as spectral radiant incidance

$$E_{\lambda e} = \frac{\partial \Phi}{\partial A} = \left[\frac{\text{photons}}{\text{s}\ m^2}\right]$$

Flux per detector area.
What you get on a detector (or whatever)
In energy units:

$$E_{\lambda E} = \frac{hc}{\lambda} E_{\lambda\gamma} \left[\frac{\text{W}}{\text{m}^2\ \mu\text{m sr}}\right]$$

Transmittance

$$T = \prod_{\forall X} T_X(\lambda) = T_a T_o T_f \dots$$

Irradiance

At apperture:

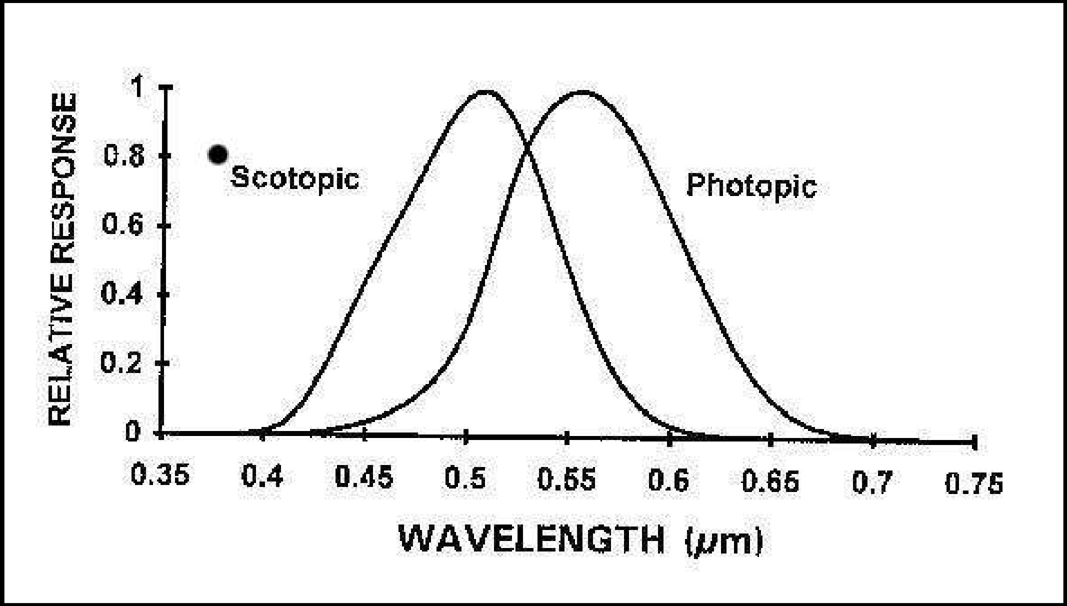
$$E_{\gamma_{app}} = \frac{\Phi_{\gamma_{app}}}{A_{app}} = \frac{L_\gamma A_s T_a \Omega_{ds}}{A_{app}} = \left[\frac{\text{photons}}{\text{s}\ m^2}\right]$$

At image plane (assuming circular apperture):

$$E_{\gamma_i} = \frac{\Phi_{\gamma_{app}}}{A_i} = L_\gamma \frac{A_s}{A_i} T \frac{\pi d_{app}^2}{4 r_s^2} = \left[\frac{\text{photons}}{\text{s}\ m^2}\right]$$

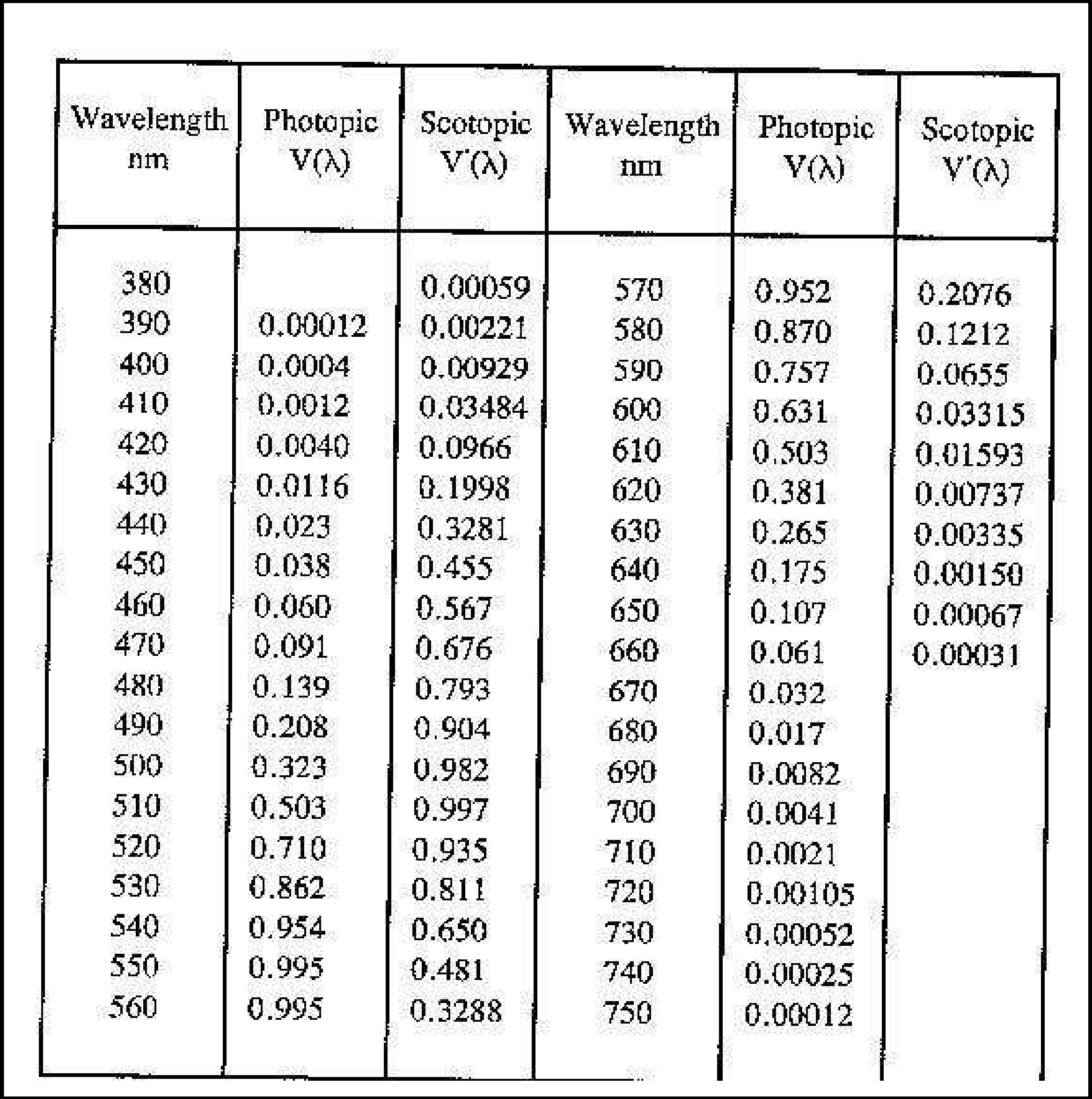
Photometric units

$$\Phi_v = K_M \int_{380\text{nm}}^{750\text{nm}} V(\lambda) M_p(\lambda) d\lambda \, [\text{lm}]$$



scoptic—rods photoptic—cones After *Holst* [1998]

Photometric units



Wavelength nm	Photopic V(λ)	Scotopic V'(λ)	Wavelength nm	Photopic V(λ)	Scotopic V'(λ)
380		0.00059	570	0.952	0.2076
390	0.00012	0.00221	580	0.870	0.1212
400	0.0004	0.00929	590	0.757	0.0655
410	0.0012	0.03484	600	0.631	0.03315
420	0.0040	0.0966	610	0.503	0.01593
430	0.0116	0.1998	620	0.381	0.00737
440	0.023	0.3281	630	0.265	0.00335
450	0.038	0.455	640	0.175	0.00150
460	0.060	0.567	650	0.107	0.00067
470	0.091	0.676	660	0.061	0.00031
480	0.139	0.793	670	0.032	
490	0.208	0.904	680	0.017	
500	0.323	0.982	690	0.0082	
510	0.503	0.997	700	0.0041	
520	0.710	0.935	710	0.0021	
530	0.862	0.811	720	0.00105	
540	0.954	0.650	730	0.00052	
550	0.995	0.481	740	0.00025	
560	0.995	0.3288	750	0.00012	

scoptic—rods ($K_M = 1746\ \mathrm{lm/W}$) photoptic—cones ($K$ 683 lm/W) After [illegible] [1998]

Photometric units

Φ_v	lm	luminous flux
L_v	$\mathrm{cd/m^2}$ or nits	luminance
M_v	lux or $\mathrm{lm/m^2}$	luminous emmitance
E_v	lux or $\mathrm{lm/m^2}$	illumniance

The foot-lambert

A foot-lambert or footlambert (fL, sometimes fl or ft-L) is a unit of luminance in U.S. customary units and some other unit systems. A foot-lambert equals $1/\pi$ candela per square foot, or 3.426 candela per square meter (the corresponding SI unit).

$$1 \ [\mathrm{ftL}] = \frac{1}{\pi} \left[\frac{\mathrm{cd}}{\mathrm{ft}^2}\right] \approx 3.426 \left[\frac{\mathrm{cd}}{\mathrm{m}^2}\right]$$

The Rayleigh

The Rayleigh (1)

Consider a cylindrical column of cross-sectional area 1 m^2 extending away from the detector into the source.

The volume emission rate from a volume element of length dl at distance l is $\epsilon(l, t, \lambda)$ photons $\mathrm{m}^{-3}\,\mathrm{s}^{-1}$. The contribution to L_γ is given by:

$$dL_\gamma = \frac{\epsilon(l, t, \lambda)}{4\pi}\, dl \quad \left[\frac{\text{photons}}{\text{s m}^2\text{ sr}}\right]$$

The Rayleigh (2)

Integrating along the line of sight $l\ [m]$:

$$4\pi L_\gamma = \int_0^\infty \epsilon(l,t,\lambda)dl$$

This quantity is the column emission rate, which *Hunten et al.* [1956] proposed as a radiometric unit for the aurora and airglow.

The Rayleigh (3)

In SI-units the Rayleigh becomes [*Baker and Romick*, 1976]:

$$1\ [\mathrm{Rayleigh}] \equiv 1\ [\mathrm{R}] \triangleq 10^{10} \left[\frac{\mathrm{photons}}{\mathrm{s\ m^2\ (column)}} \right]$$

The word *column* denotes the concept of an emission-rate from a column of unspecified length, as discussed above. It should be noted that the Rayleigh is an apparent emission rate, not taking absorption or scattering into account.

The Rayleigh (4)

However (unfortunately. . .)

> “the Rayleigh can be used as defined without any commitment as to its physical interpretation, even though it has been chosen to make interpretation convenient.” *Hunten et al. [1956]*

And then there is the clarifications by: *Baker* [1974]; *Baker and Romick* [1976]; *Chamberlain* [1995]

By now you should realized that. . .

. . . God said:

Go to, let us go down, and there confound their language, that they may not understand one another’s speech. *[Bible Gen11:7]*

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And there was: stilb, Rayleighs, footlamberts, Irradiance, spectral-radiant sterance, lumens, lux, candela, radiometry, nit, luminance, illuminance, emittance, apostilb, phot, skot, lambert, foot-candle, photometry, DIN, ASA, ISO. . .

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—Help! We are sinking!

and now. . .

The 4π confusion

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Therefore, we propose that photometric measurements of the airglow and aurora be reported in terms of $4\pi B$ rather than the surface brightness B itself. Further, we suggest that $4\pi B$ be given the unit “rayleigh” (symbol R), where B is in units of $10^6\ \mathrm{quanta\ cm^{-2}\ s^{-1}\ sr^{-1}}$. Hence $1\ \mathrm{R} = 10^6\ \mathrm{quanta\ cm^{-2}\ (column)^{-1}\ s^{-1}}$.

Hunten et al. [1956]

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Hunten et al. [1956]

So does both *Hunten et al.* [1956] and *Chamberlain* [1995] claim that $4\pi \times 10^6 = 10^6$???

Can we agree on this?

The apparent radiance (L_γ) can be obtained from the column emission rate I (in Rayleighs) according to *Baker and Romick* [1976]:

$$L_\gamma = \frac{10^{10} I}{4\pi} \left[\frac{\text{photons}}{\text{s m}^2\text{ sr}}\right]$$

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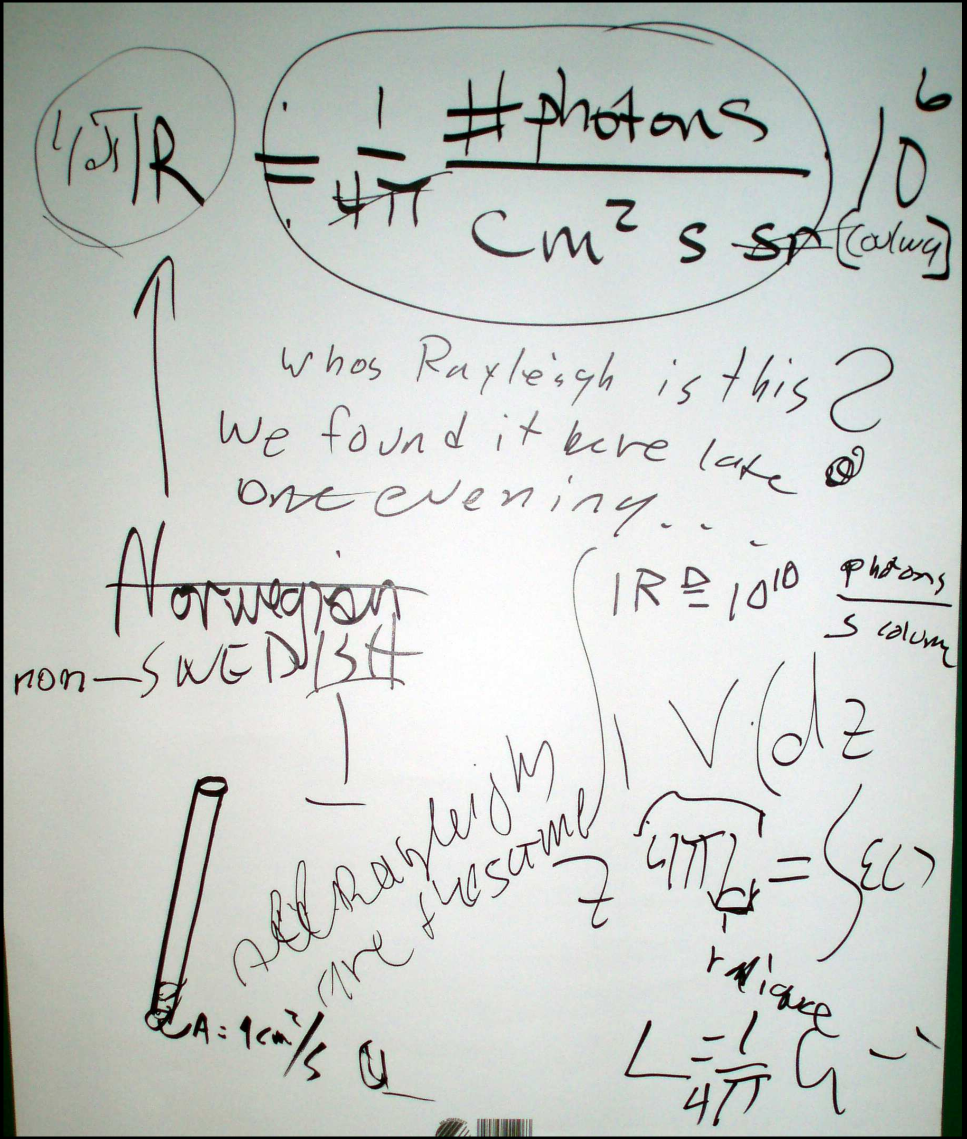
Or is it:

$$L_\gamma = 10^{10} I \left[\frac{\text{photons}}{\text{s m}^2 \text{ sr}}\right]$$

Still confused. . .



. . . but at a different level.

Signal

Where are my photons?

- Transmittance (atmosphere, optics, filters. . .)

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$$\overline{n}_{e^-_\gamma} = \mathsf{Q_E}(\lambda) E_{\gamma_i} t_{int} A_{pix} \left[e^-\right]$$

$$\overline{n}_{e^-_\gamma} \approx \mathsf{Q_E}(\lambda) T t_{int} A_{pix} \frac{10^{10} I}{16 f_{\#}^2} \left[e^-\right]$$

Noise

What is noise?

Some peoples noise are other peoples signal

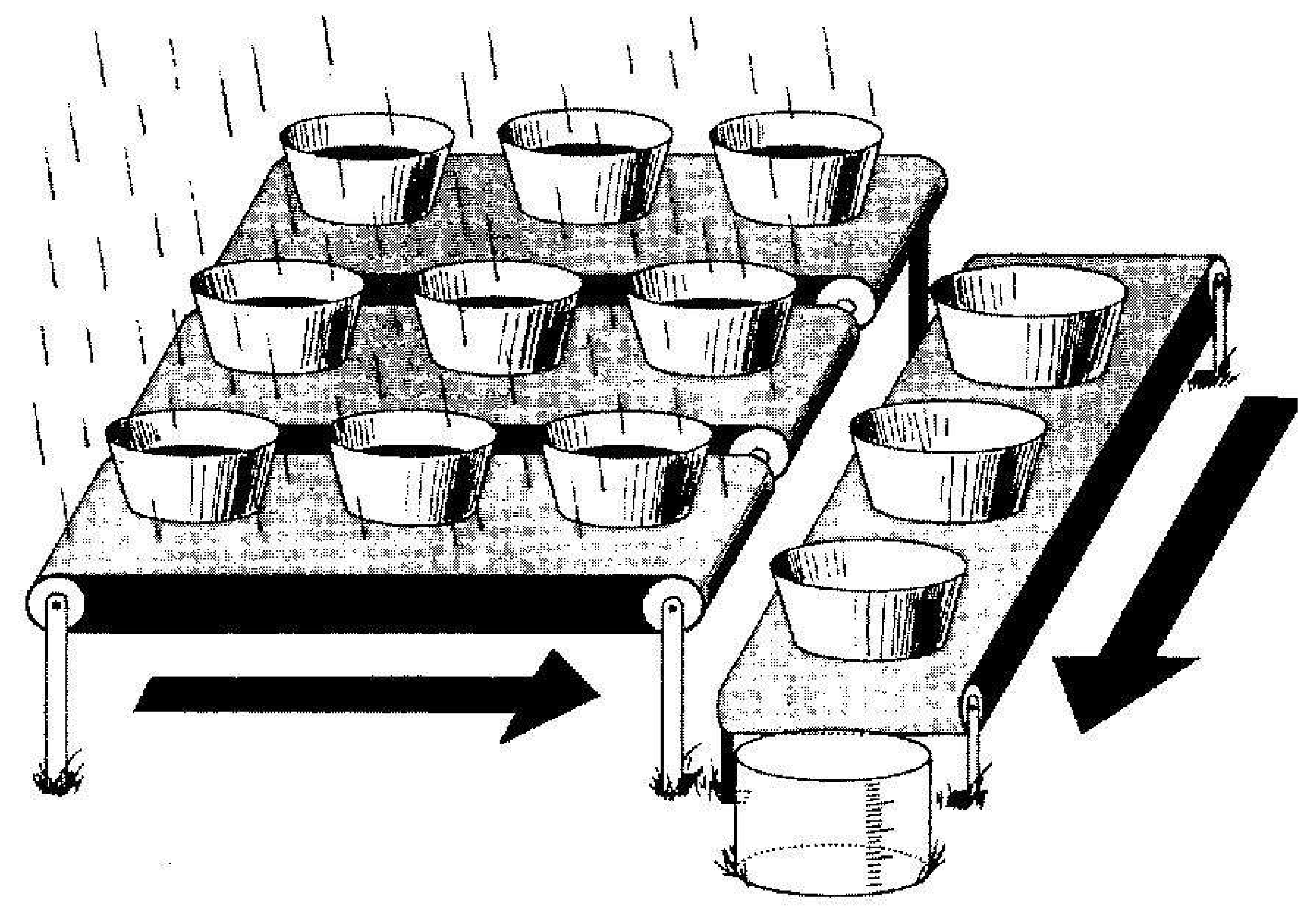
Notation

$\langle X\rangle^2$	variance of X
$\langle X\rangle$	standard deviation of X
$\overline{X}$	mean value of X

Photon arrival is Poisson distributed

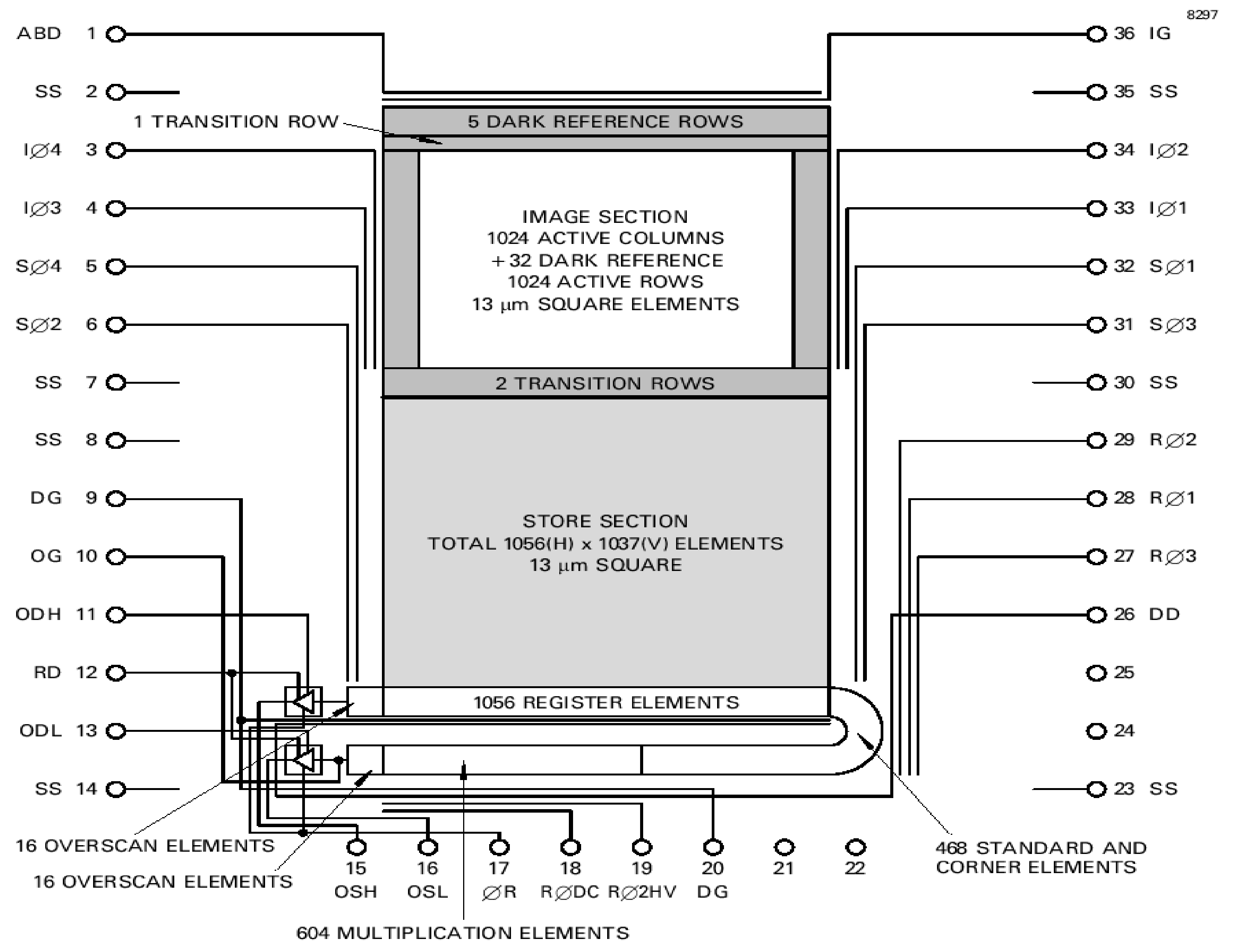
It can be shown that for a Poisson distributed signal variance is equal to the mean

CCD principle of operation



After *Janesick et al.* [1987]

E2V TECH CCD201



What is the SNR of an ideal photon detector?

CCD-noise sources

CCD noise

$$\langle n_{e^-_{CCD}} \rangle = \sqrt{\langle n_{e^-_s} \rangle^2 + \langle n_{e^-_r} \rangle^2 + \langle n_{e^-_p} \rangle^2} \;\; [e^-_{RMS}]$$

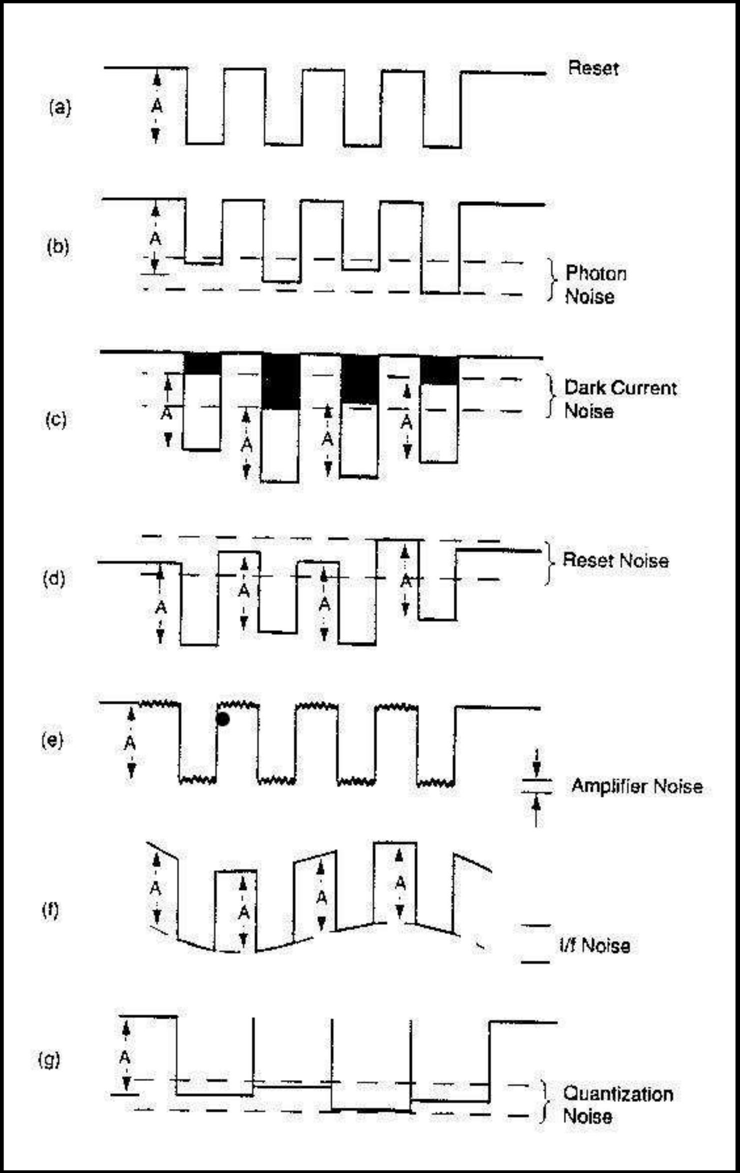
Shot Noise

$$\langle n_{e_s^-} \rangle = \sqrt{CTE^N \left(\langle n_{e_\gamma^-} \rangle^2 + \langle n_{e_d^-} \rangle^2 \right)} =$$

$$= \sqrt{CTE^N \left(\overline{n}_{e_\gamma^-} + \overline{n}_{e_d^-} \right)} \approx$$

$$\approx \sqrt{\overline{n}_{e_\gamma^-} + \overline{n}_{e_d^-}}$$

CCD Noise sources



After *Holst* [1998]

Pattern Noise

$$\langle n_{e^-_p} \rangle = \sqrt{\langle n_{e^-_{FPN}} \rangle^2 + \langle n_{e^-_{PRNU}} \rangle^2} \approx \langle n_{e^-_{PRNU}} \rangle \approx$$

$$\approx U \overline{n}_{e^-_\gamma} \approx \frac{\overline{n}_{e^-_\gamma}}{\sqrt{n_{e^-_{max}}}} \ \left[e^-_{RMS} \right]$$

CCD Noise

$$\langle n_{e^-_{CCD}} \rangle \approx \sqrt{\overline{n}_{e^-_\gamma} + \overline{n}_{e^-_d} + \langle n_{e^-_r} \rangle^2} \quad [e^-_{RMS}]$$

Signal-to-noise ratio for a CCD

- Measured signal-to-noise ratio:

$$SNR_{CCD} = \frac{DN_{signal}}{DN_{noise}} \approx \frac{\overline{n}_{e^-_{\gamma}}}{\langle n_{e^-_{CCD}} \rangle}$$

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- and for an ideal photon detector:

$$SNR_{\gamma\mathrm{ideal}} = \sqrt{\overline{n}_{e^-_\gamma}}$$

IRF

Threshold of detection

The threshold of detection is usually defined as $SNR = 2$ while the Noise Equivalent Exposure NEE, is obtained when $SNR = 1$. For a CCD the maximum signal, or Saturation Equivalent Exposure, SEE is obtained when the charge well capacity $n_{e^-_{max}}\ [e^-]$, is reached. This occurs when:

$$n_{e^-_{\gamma}} \geq n_{e^-_{max}} - n_{e^-_{d}}$$

In most cases the maximum charge-well capacity $DN_{SEE}\ [\mathrm{counts}]$, is matched to the maximum ADC output DN_{max}.

Dynamic range (1)

The Dynamic Range is defined as the peak signal divided by the RMS noise and the DC-bias-level, (if any). The minimum ADC output, is subtracted in the case of a signed integer output. DR is usually expressed in decibels.

$$DR = 20\log_{10}\left(\frac{DN_{SEE} - DN_{min}}{DN_{DC} + DN_{NEE} - DN_{min}}\right)[dB]$$

Dynamic range (2)

An approximate theoretical value for DR is obtained by dividing the maximum signal by the total noise

$$DR \approx 20 \log_{10} \frac{n_{e^-_{max}} - n_{e^-_d}}{\langle n_{e^-_{tot}} \rangle} \; [dB]$$

ICCD

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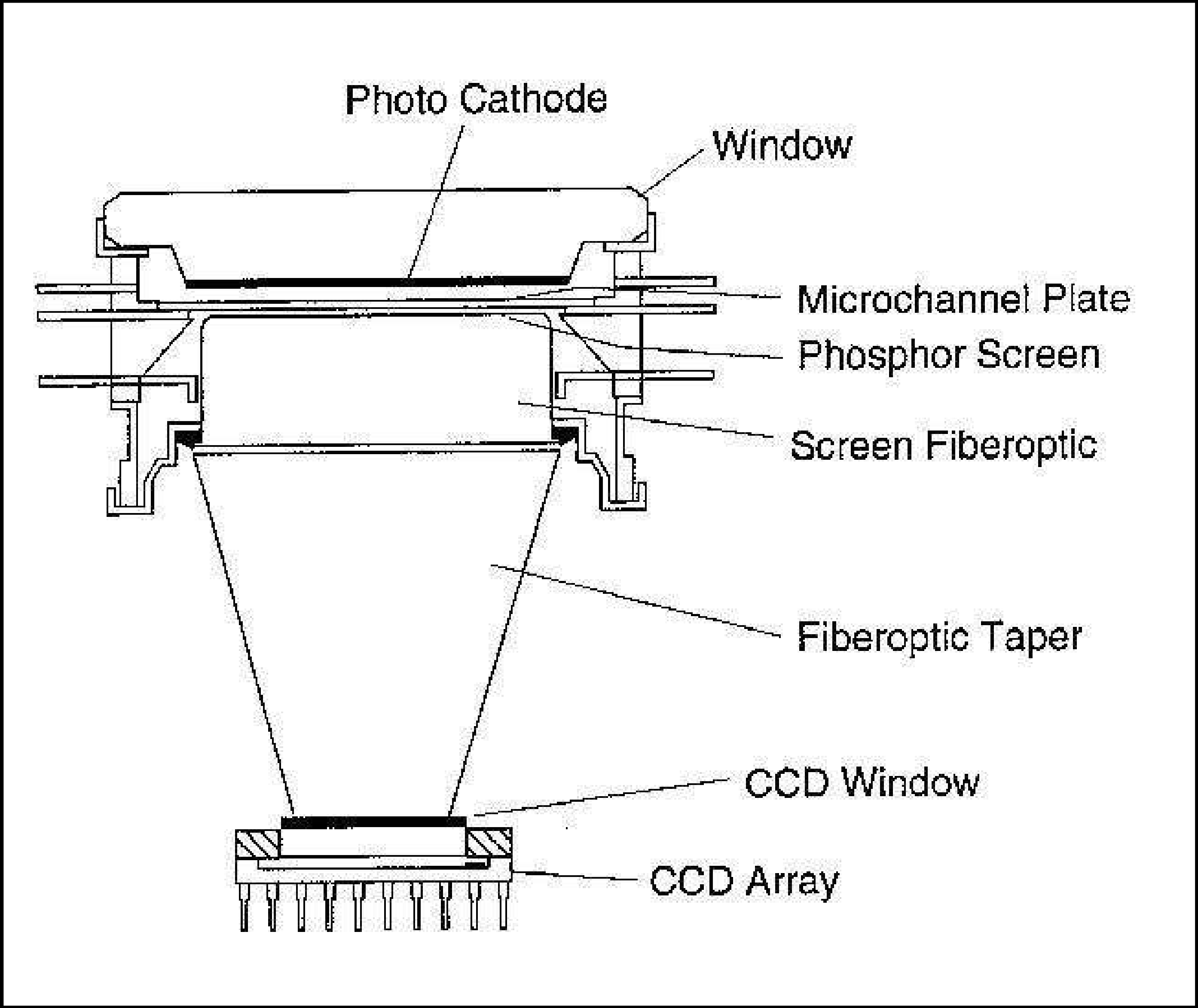

After *Holst* [1998]

SNR for a CCD

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- and for a CCD:

$$SNR_{CCD} \approx \frac{\overline{n}_{e^-_\gamma}}{\sqrt{\overline{n}_{e^-_\gamma} + \overline{n}_{e^-_d} + \langle n_{e^-_r} \rangle^2}}$$

SNR for an ICCD

Noting that for an ICCD:

$$\overline{n}_{e^-_{\gamma,pc}} \approx Q_{E_{pc}}(\lambda) T t_{int} M_{FO}^2 A_{pix} \frac{10^{10} I}{16 f_{\#}^2} \ \left[\mathrm{e}^-_{\mathrm{RMS}}\right]$$

SNR for an ICCD

- The signal-to-noise ratio for an ICCD can be estimated as:

$$SNR_{ICCD} \approx \frac{\overline{n}_{e^-_{\gamma,pc}}}{\sqrt{k^2_{MCP}\left(\overline{n}_{e^-_{\gamma,pc}} + \overline{n}_{e^-_{d,pc}}\right) + \frac{\overline{n}_{e^-_d} + \langle n_{e^-_r} \rangle^2}{\overline{g}^2}}}$$

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- As seen, increasing the gain of the image intensifier makes the CCD noise-sources negligible, but does not increase the SNR beyond that. For very high gain, we see that:

$$SNR_{ICCD} \approx \frac{\overline{n}_{e^-_{\gamma,pc}}}{\sqrt{2(\overline{n}_{e^-_{\gamma,pc}} + \overline{n}_{e^-_{d,pc}})}}$$

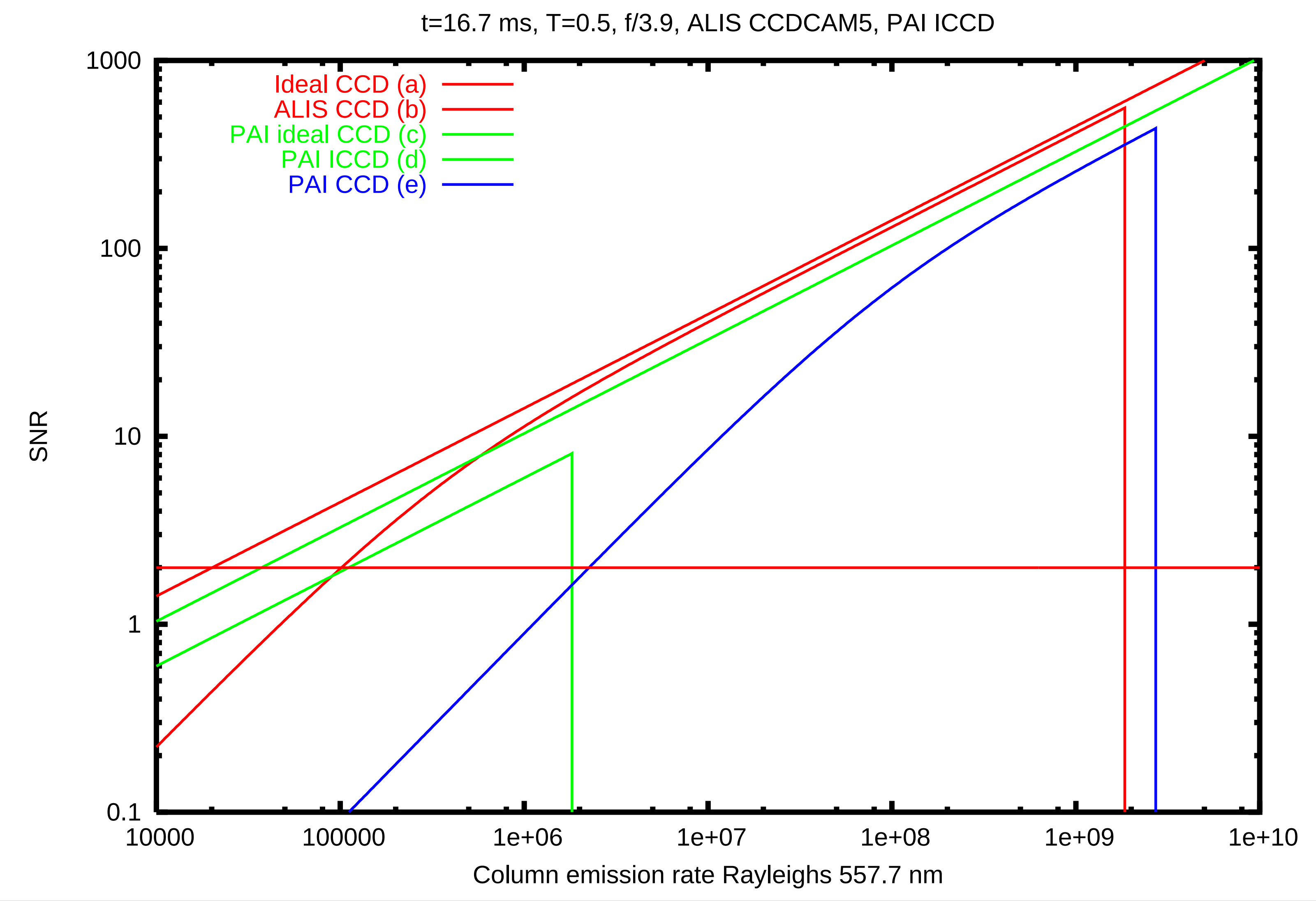
SNR for an emCCD

The signal-to-noise ratio for an electron-multiplication CCD can be estimated as:

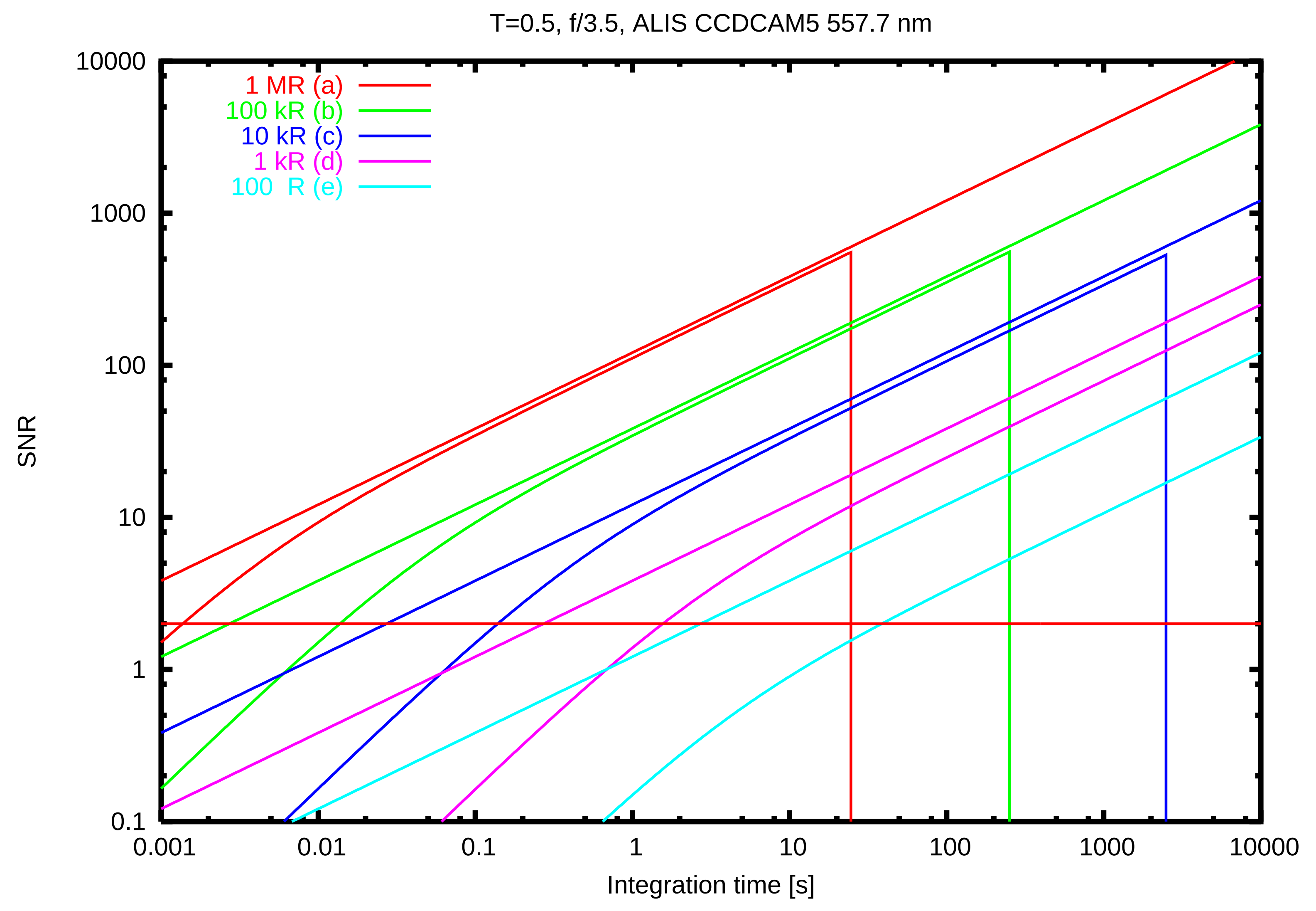
$$SNR_{emCCD} \approx \frac{\overline{n}_{e^-_\gamma}}{\sqrt{k_{em}^2\left(\overline{n}_{e^-_\gamma} + \overline{n}_{e^-_d} + \langle n_{e^-_{cic}} \rangle^2\right) + \frac{\langle n_{e^-_r} \rangle^2}{\overline{g}^2}}}$$

Please note:
For an EMCCD $k_{em} \approx \sqrt{2}$ while k_{MCP} (ICCD) is taken as $\sqrt{2}$ here, which is somewhat too good to be true. In real cases $k_{MCP} \geq 1.6$

SNR example: CCD vs. ICCD



SNR vs. of integration time



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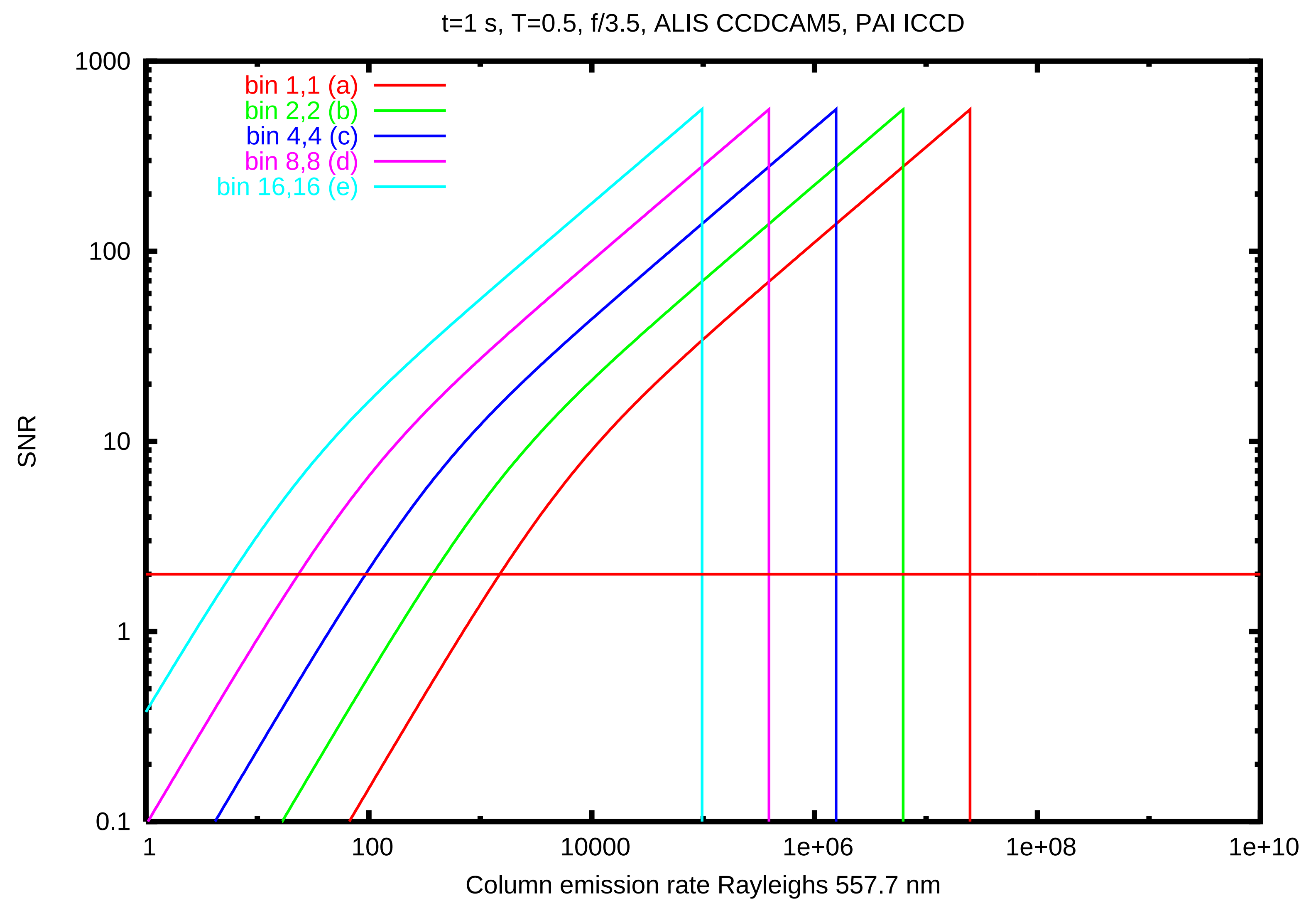
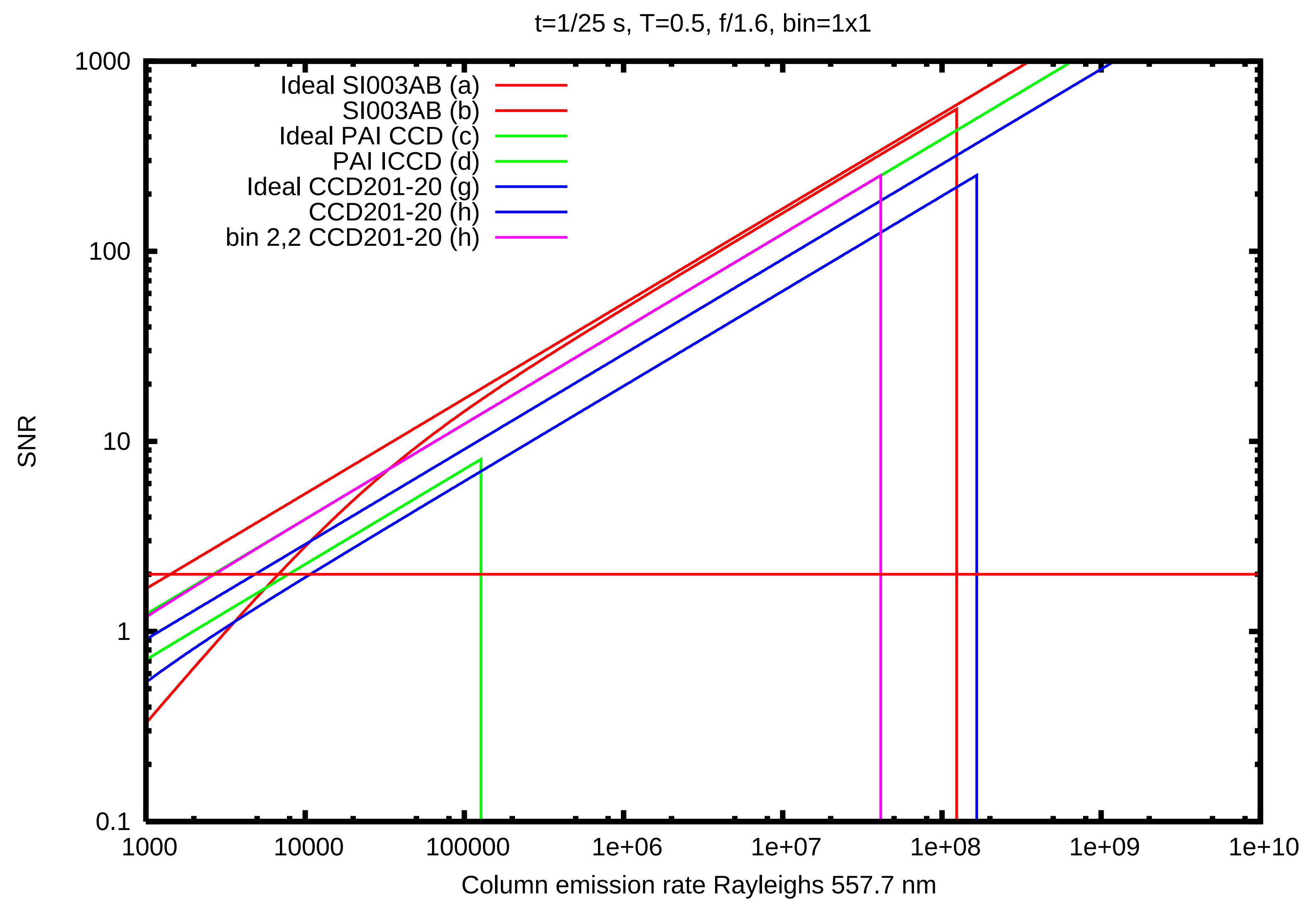
SNR and on-chip binning

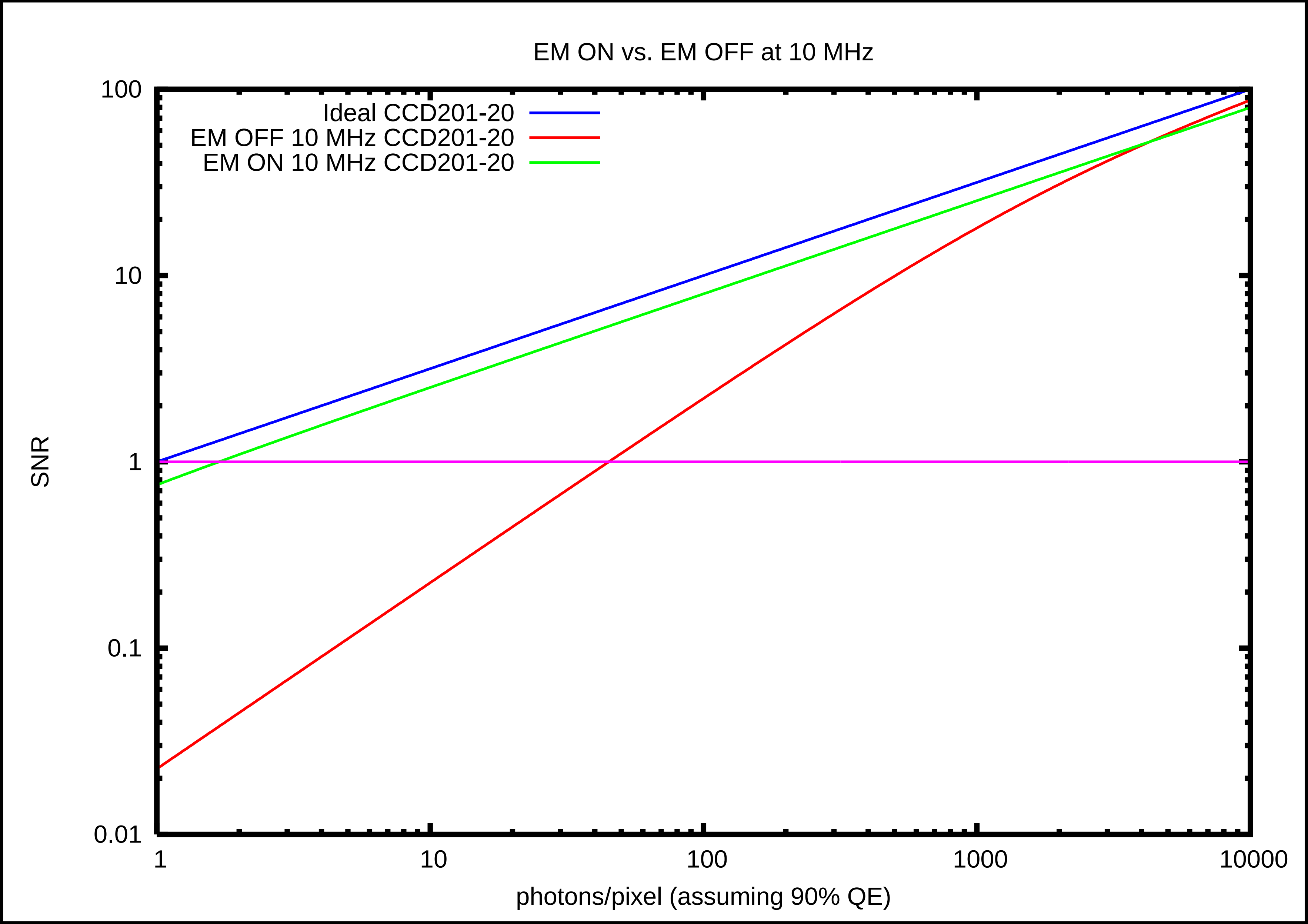


SNR: CCD, ICCD and emCCD



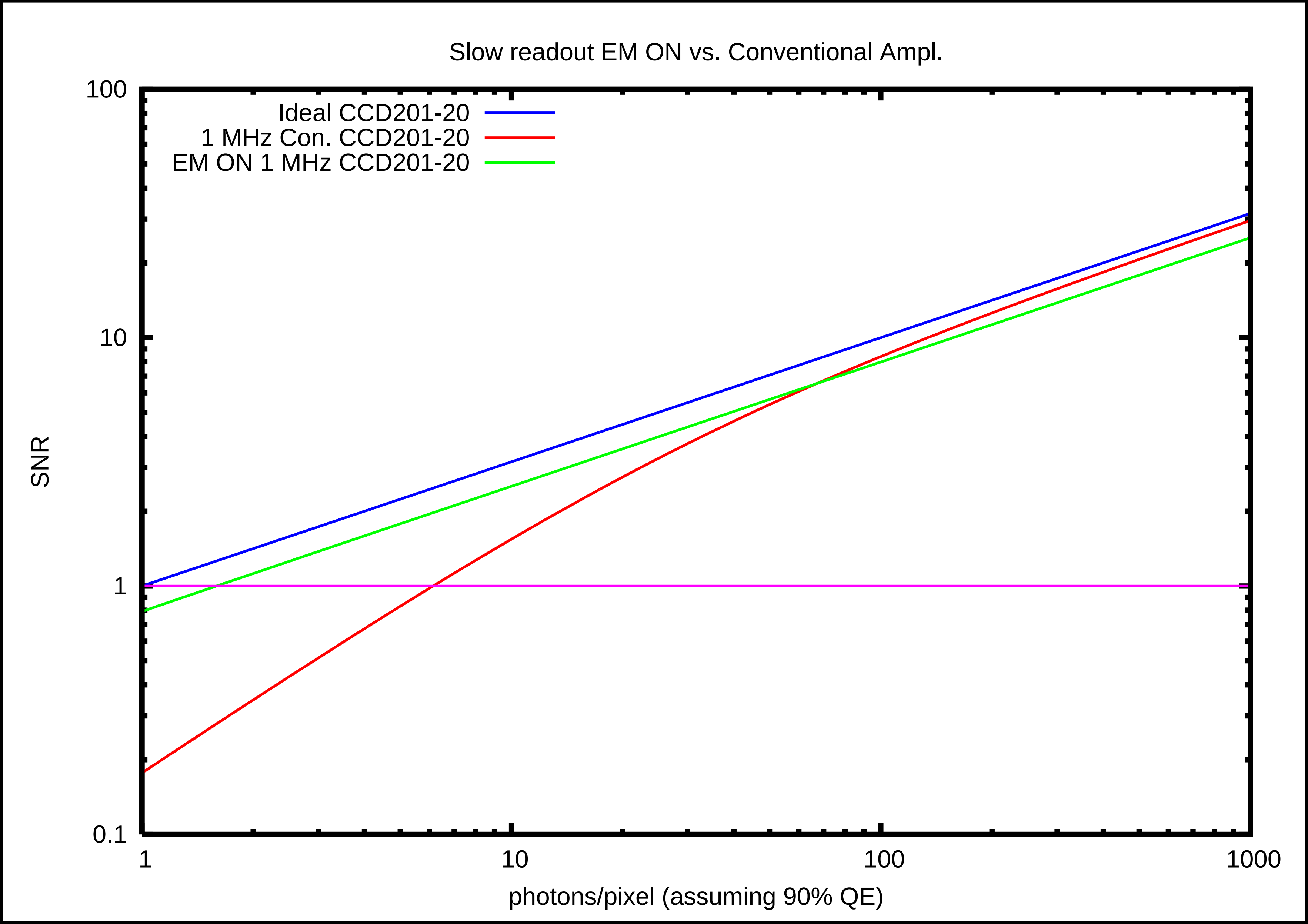
When do we need EM-gain?

Fast: ≈ 2900 photons/pixel



Always for high temporal resolution

Slow: ≈ 42 photons/pixel



Not always for low temporal resolution

Intercalibration

Intercalibration

This is the process of intercalibrating calibration sources and to transfer absolute calibration information between different instruments and research groups.

Hans Lauches intercalibration photometer (responsible person: 1981–1999 Lauche, 1999-2011 Widell, SSC, 2011– Brändström, IRF)

The European Rayleigh

Intercal. procedure

- Calibrators are compared at calibration workshops using a calibration-photometer with 7 filters and a reference source.

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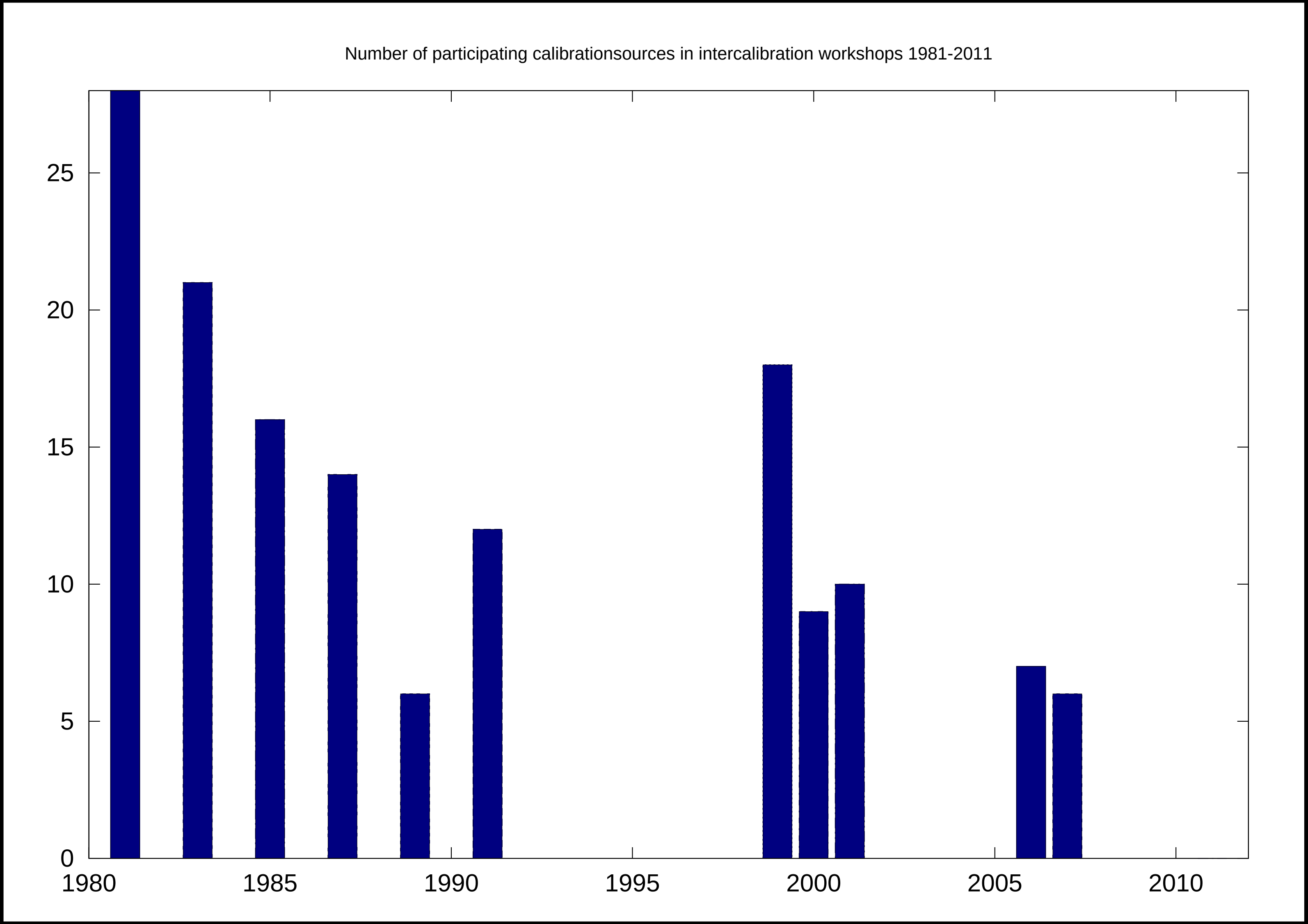
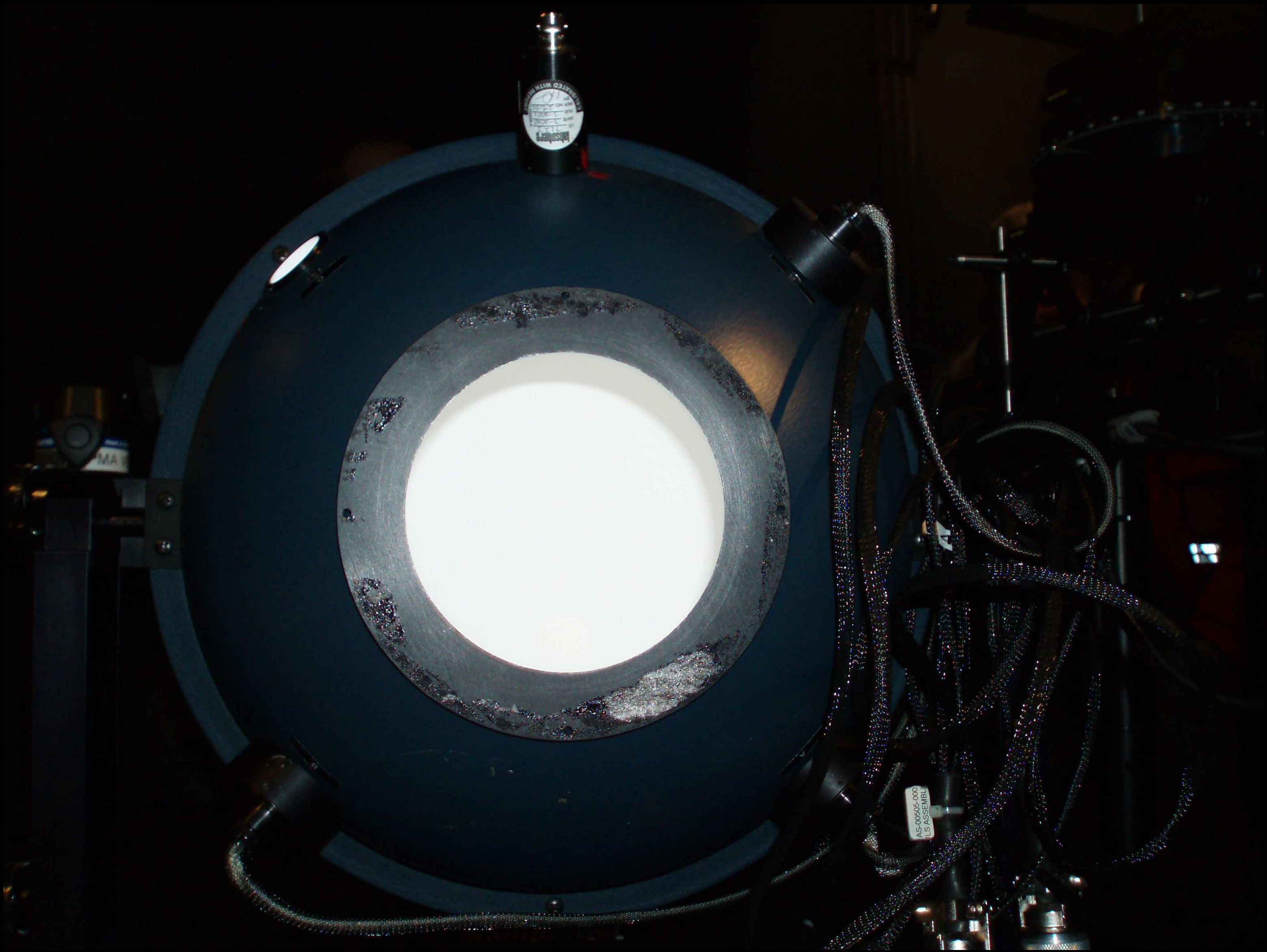
- Known calibration workshops at the optical meetings were: Aberdeen 1981, Lindau 1983, Lysebu 1985, Saskatoon 1987, Lindau 1989, Wien 1991, Lindau 1999, Stockholm 2000, Oulu 2001, Kiruna 2006, Andøya 2007 and Sodankylä 2011.

Intercal. workshops

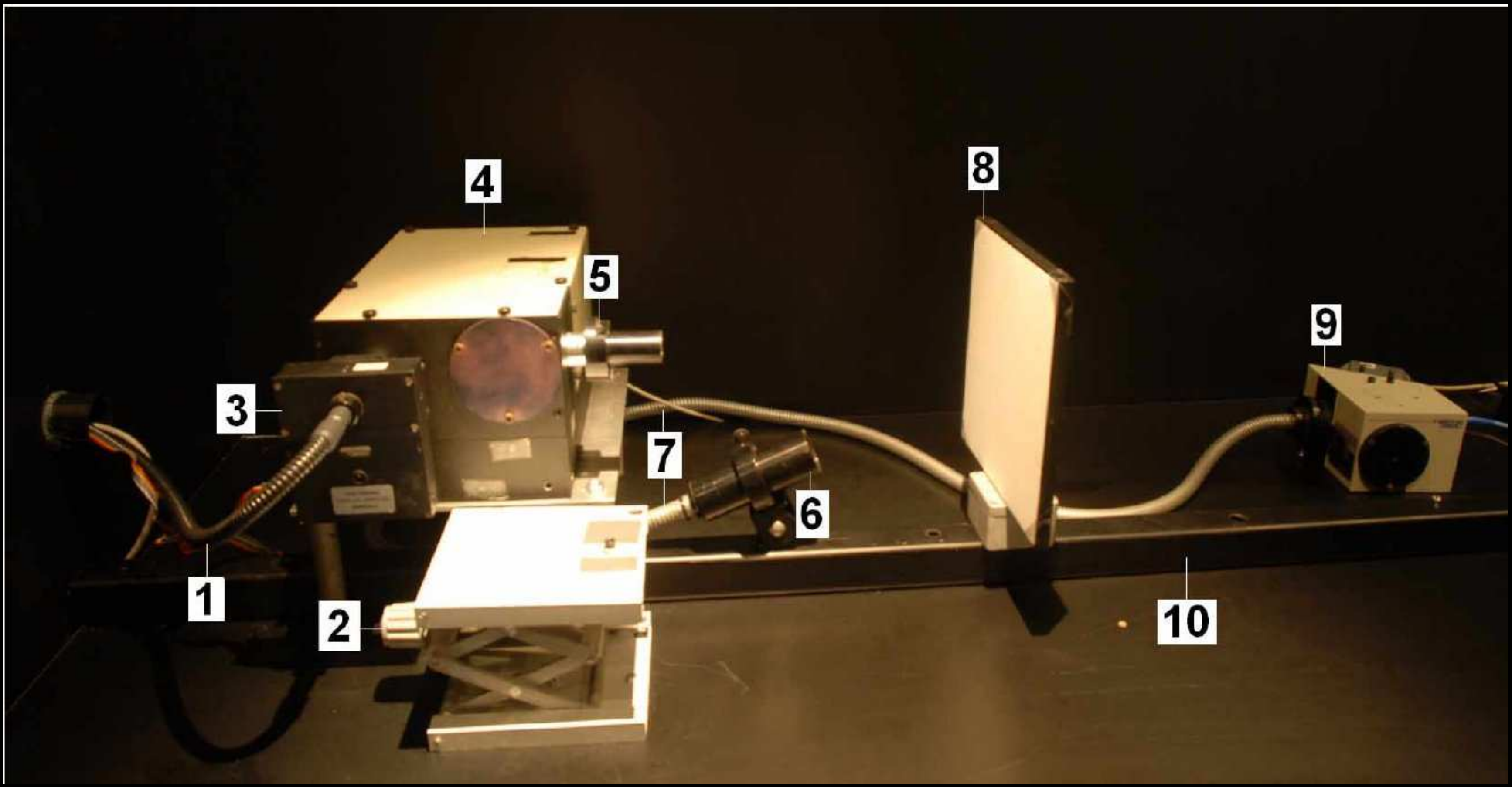


Sodankylä 2011

and the FMI-sphere

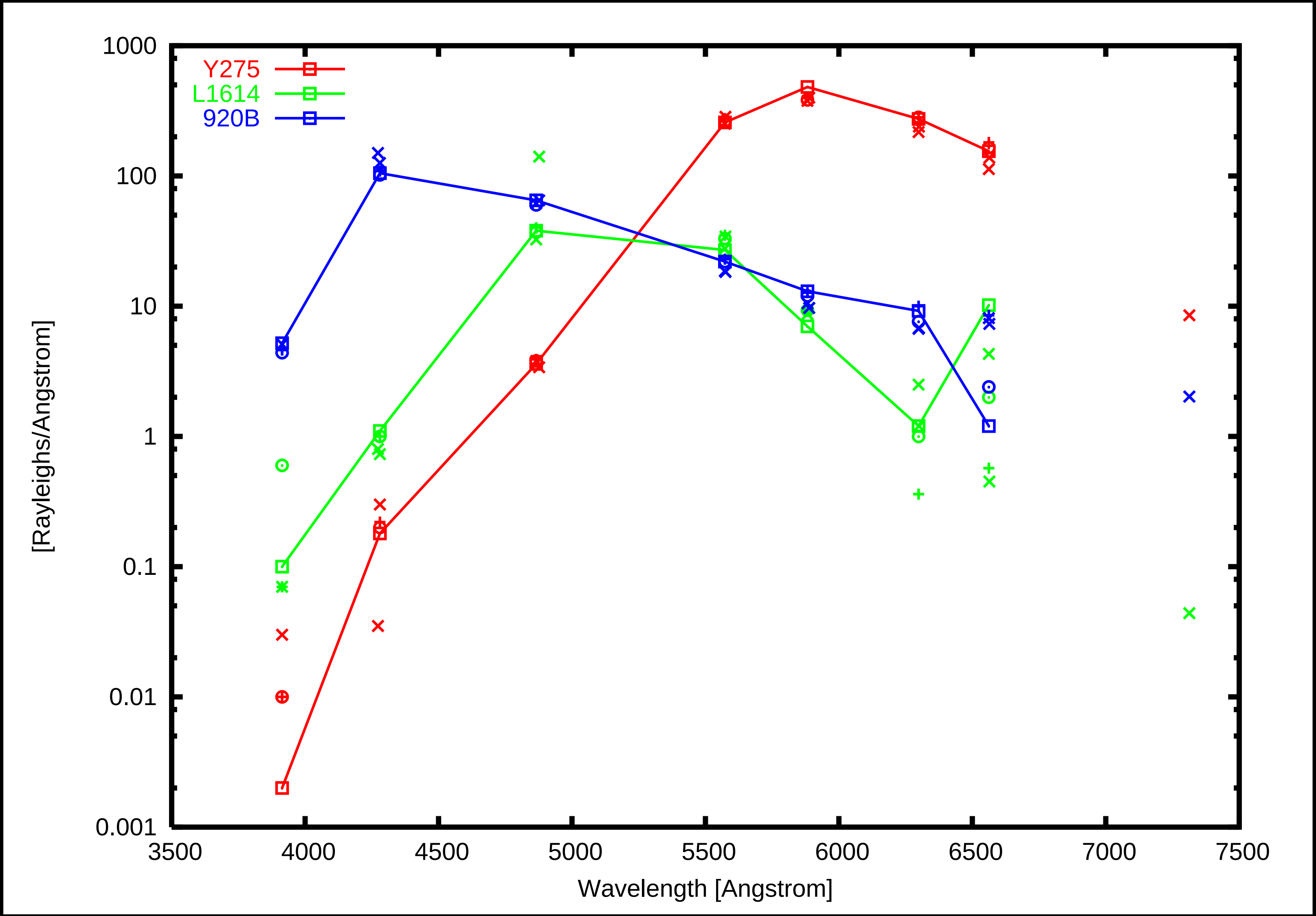


To be done here

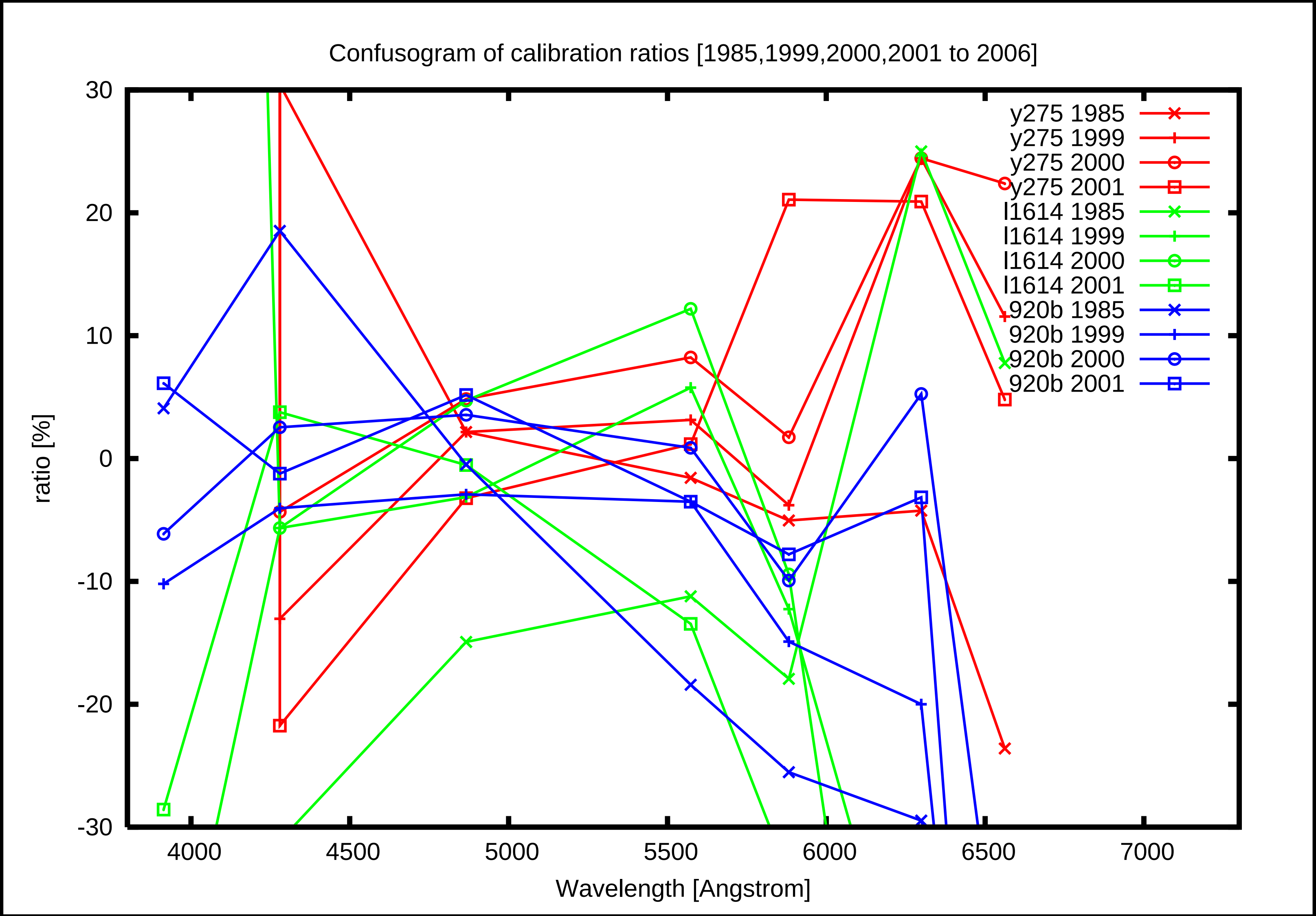


After *Sigernes et al.* [2008]

Intercal. results



Intercal. errors



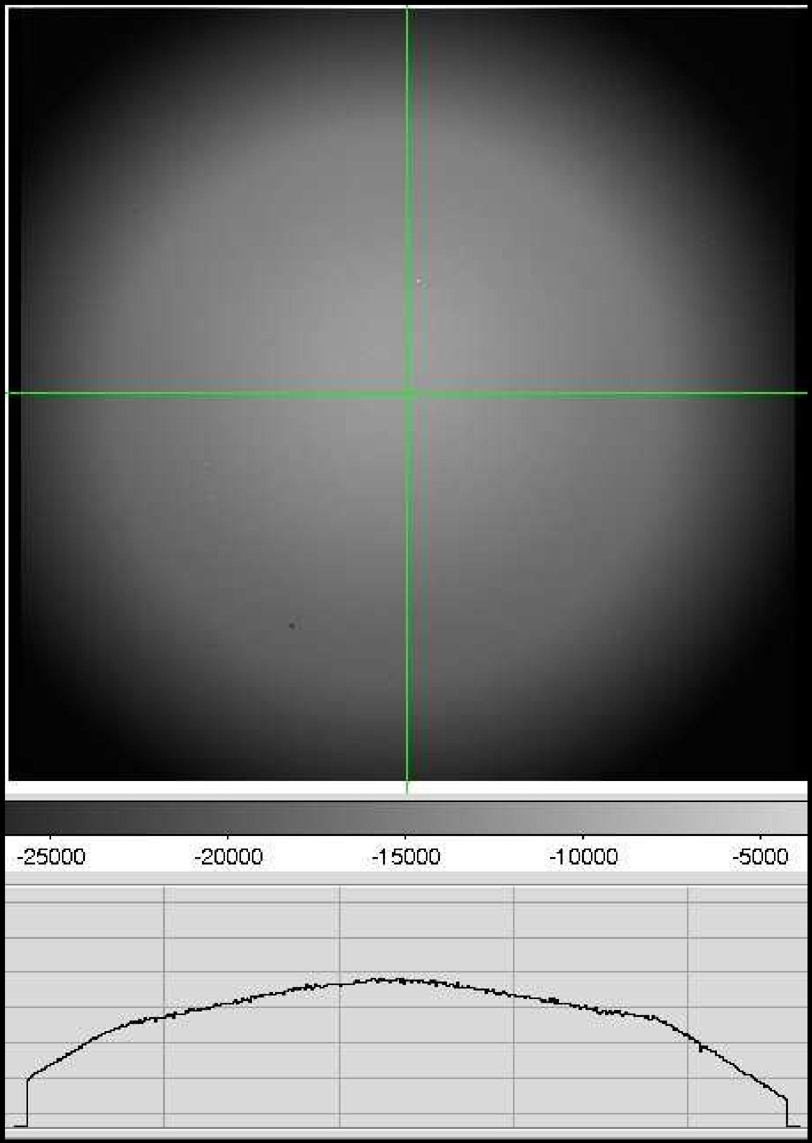
Calibration issues

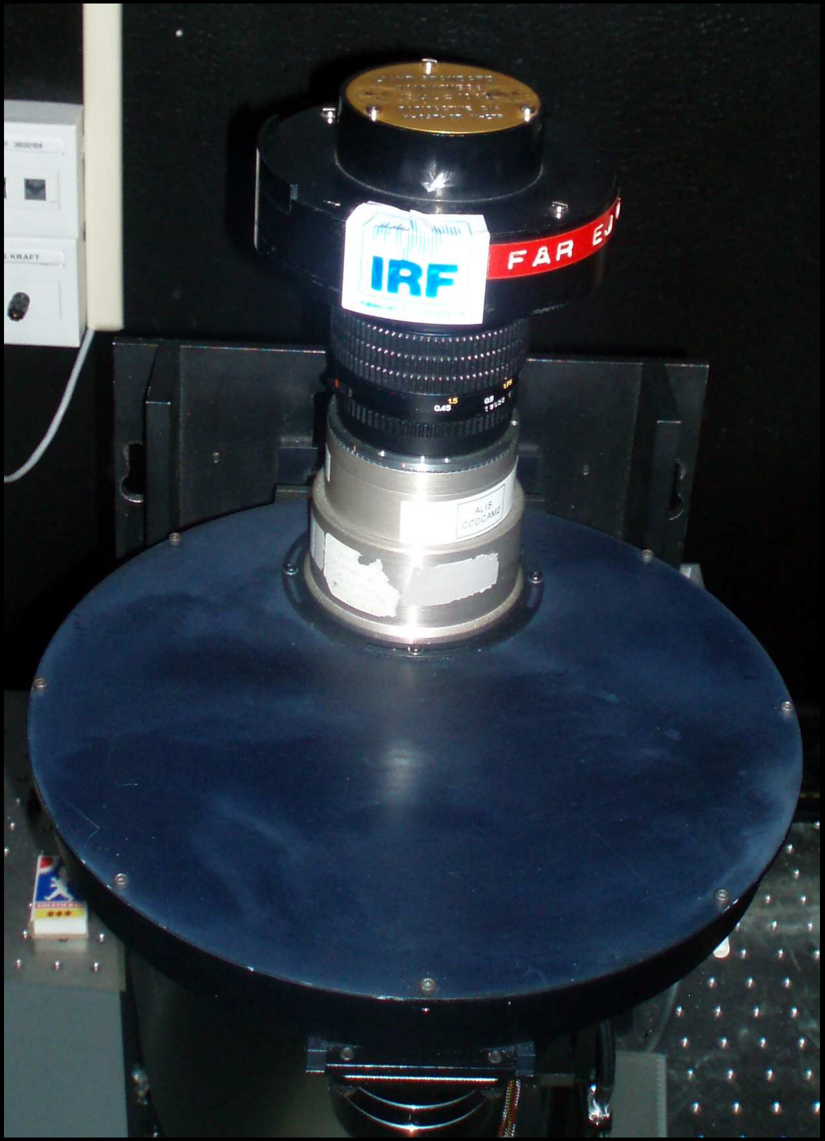
Calibration

Calibration is the process of answering the following two basic questions:

1. What physical value does the pixel represent? (absolute calibration)
2. How is each pixel mapped to the observed object? (geometrical calibration)

Abs. calibration (ALIS)





Challenge

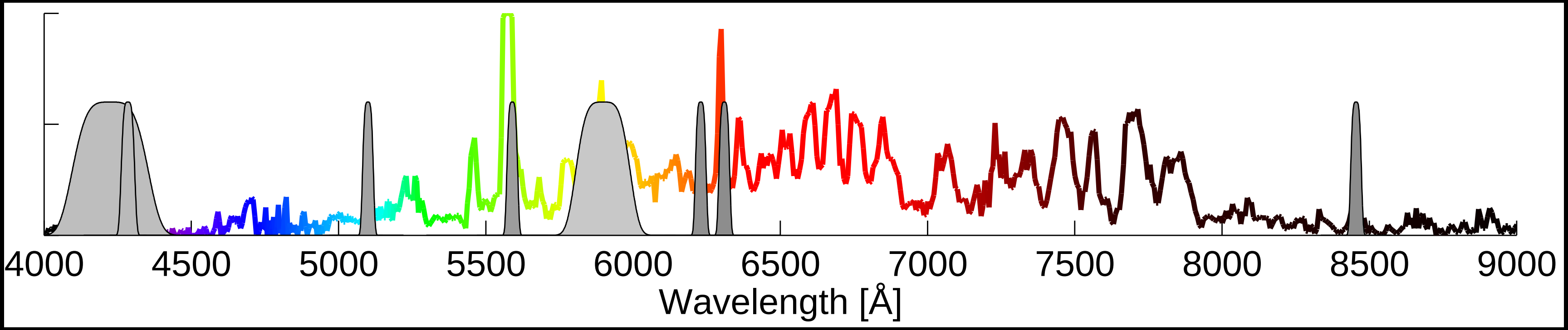
Read the “28. Appendix” and compare to *Sigernes et al.* [2008]. You might also want to compare to *Torr and Espy* [1981]

Calculate $\mathrm{R}/\text{Å}$ for the IRF-UJO-Y275 radioactive source around 5577 Å using the result in “28. Appendix” and compare to latest intercalibration result from Sodankylä. (That source is marked $15\ \mu\mathrm{lm}$

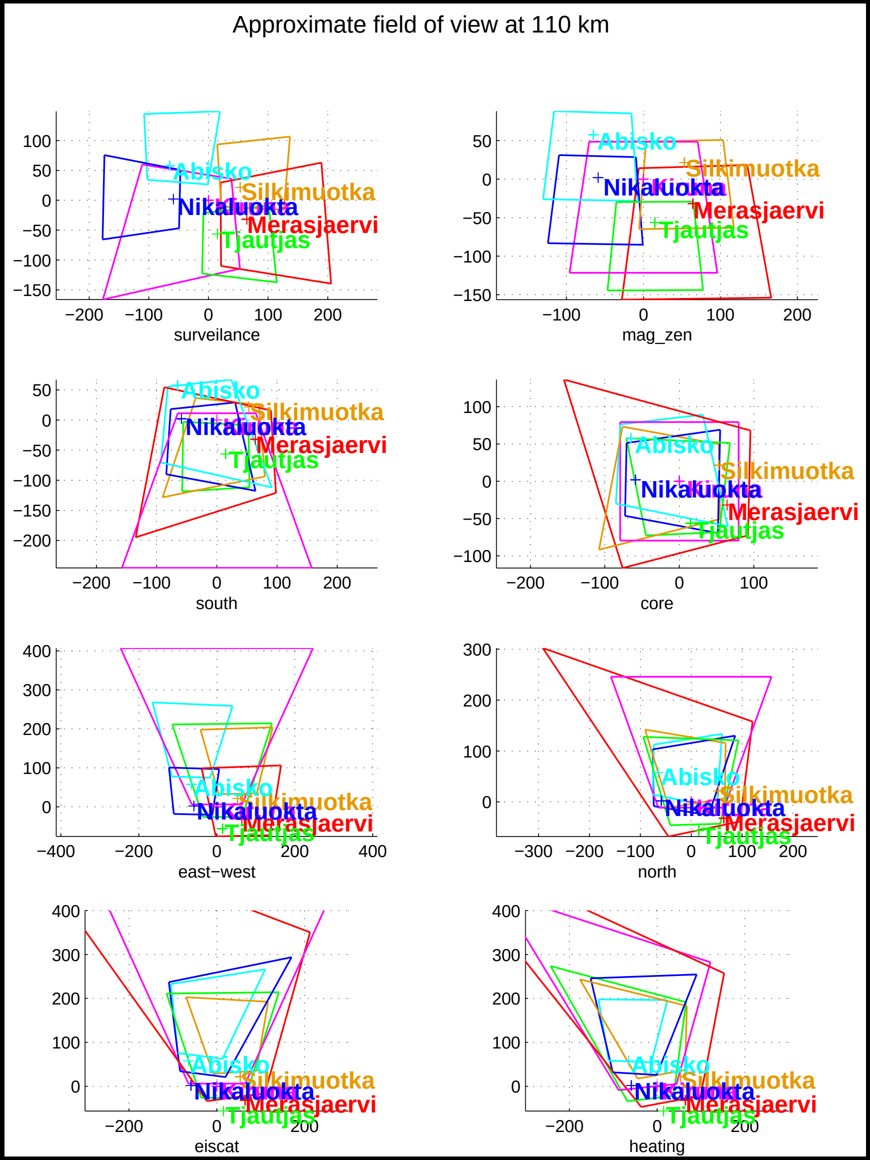
ALIS

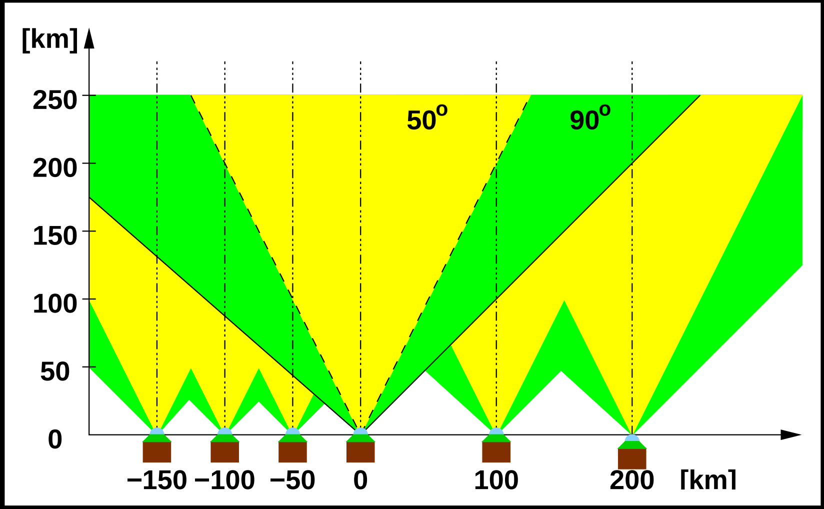
ALIS 2009–2012

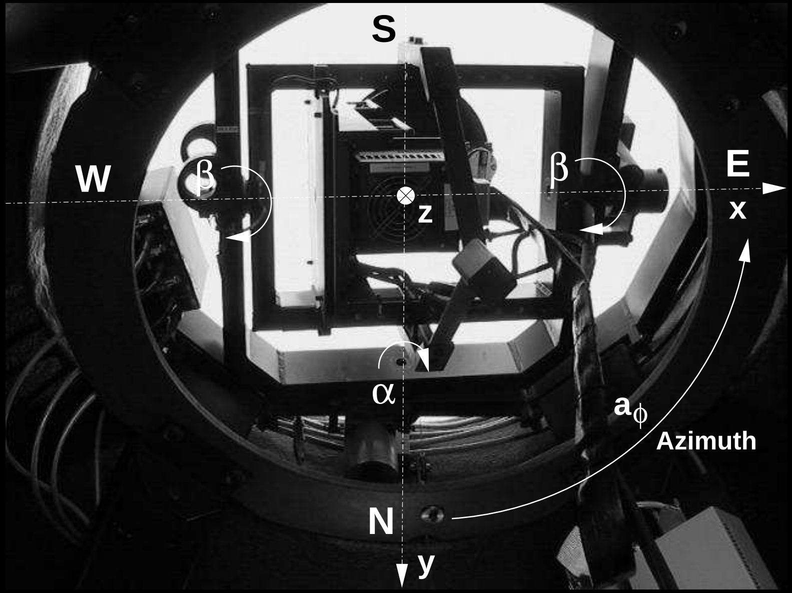
Spectroscopic imaging



Selectable common volumes

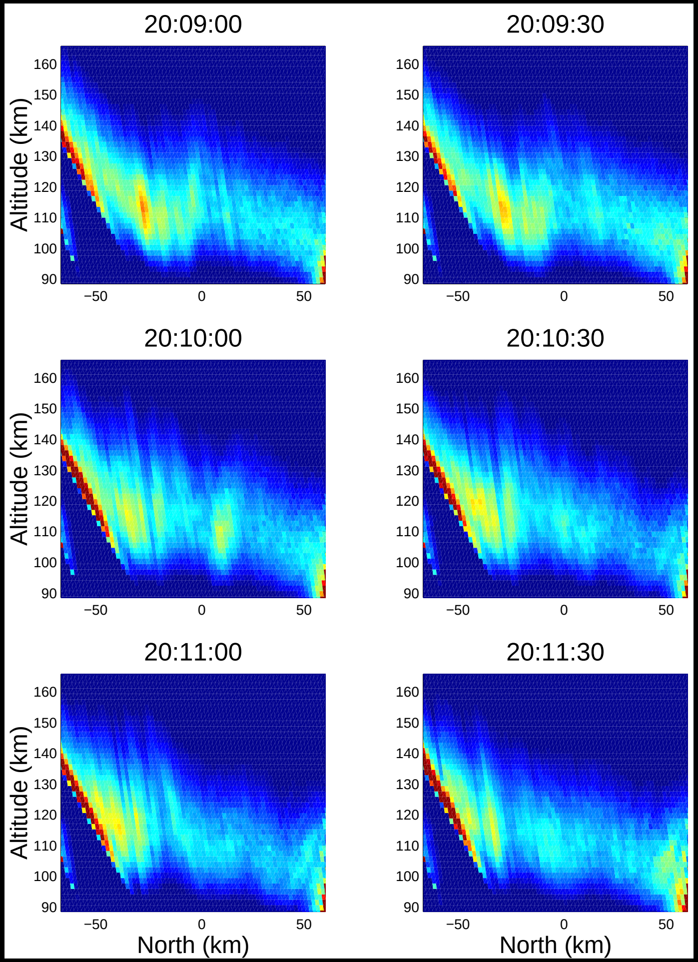




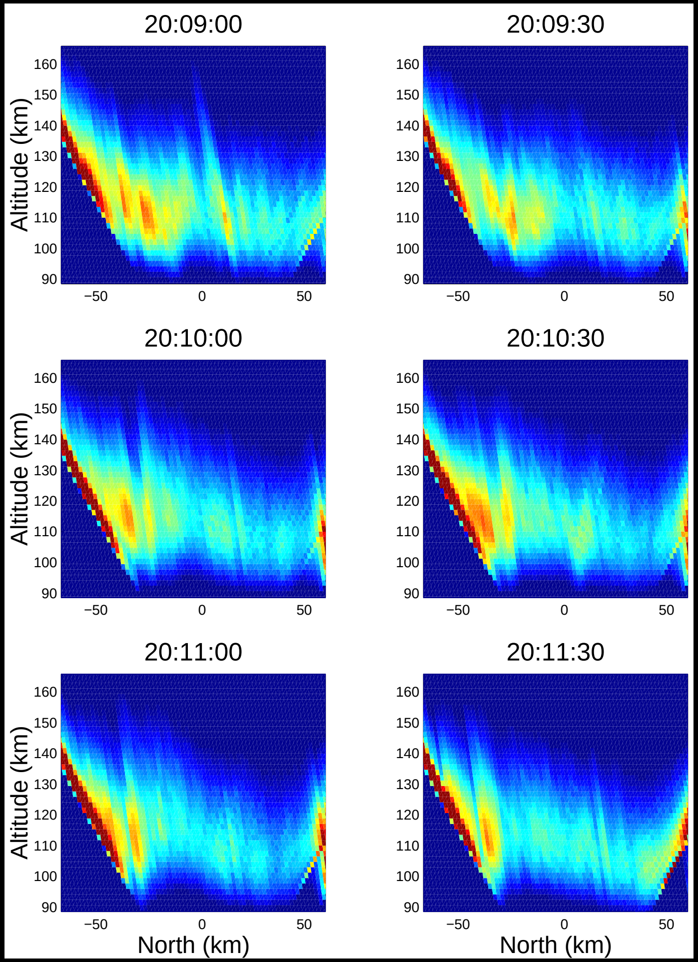


Scientific results and capabilities

Auroral tomography



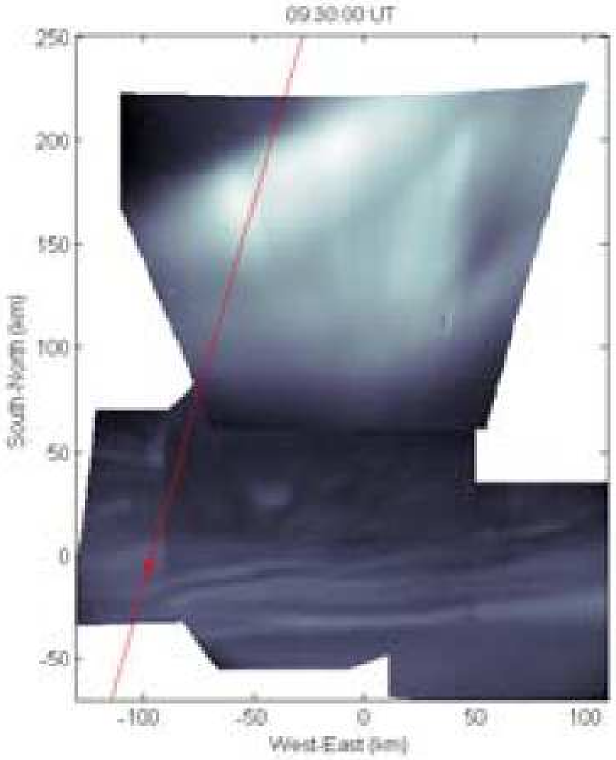
40 km west of Kiruna

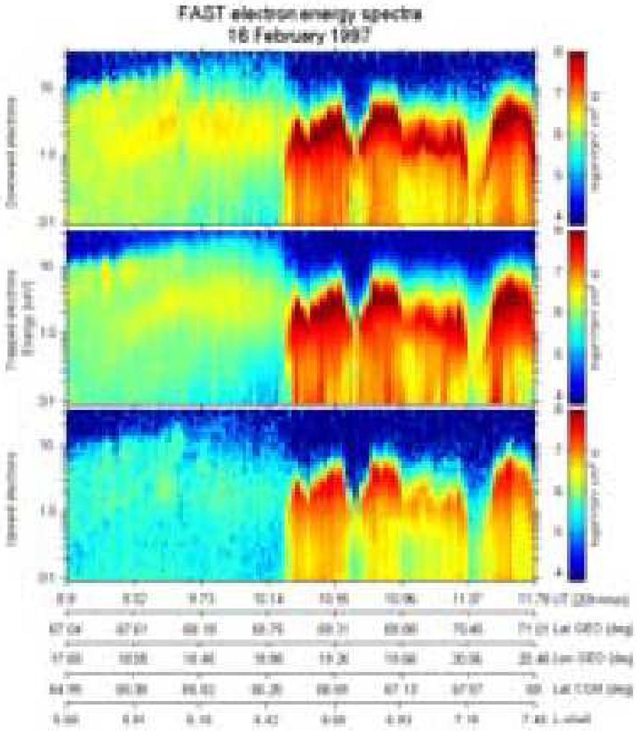


70 km west of Kiruna

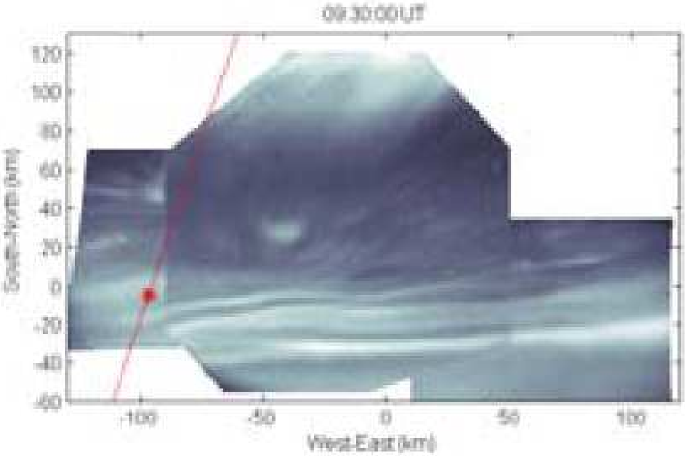
1997-02-16 ALIS/FAST/EISCAT

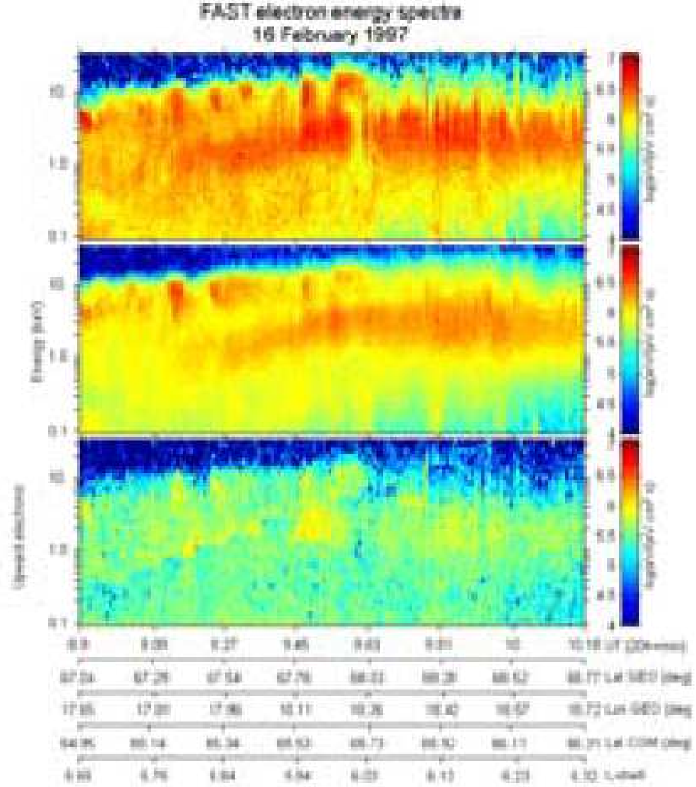
Fine structure of diffuse aurora ALIS-FAST





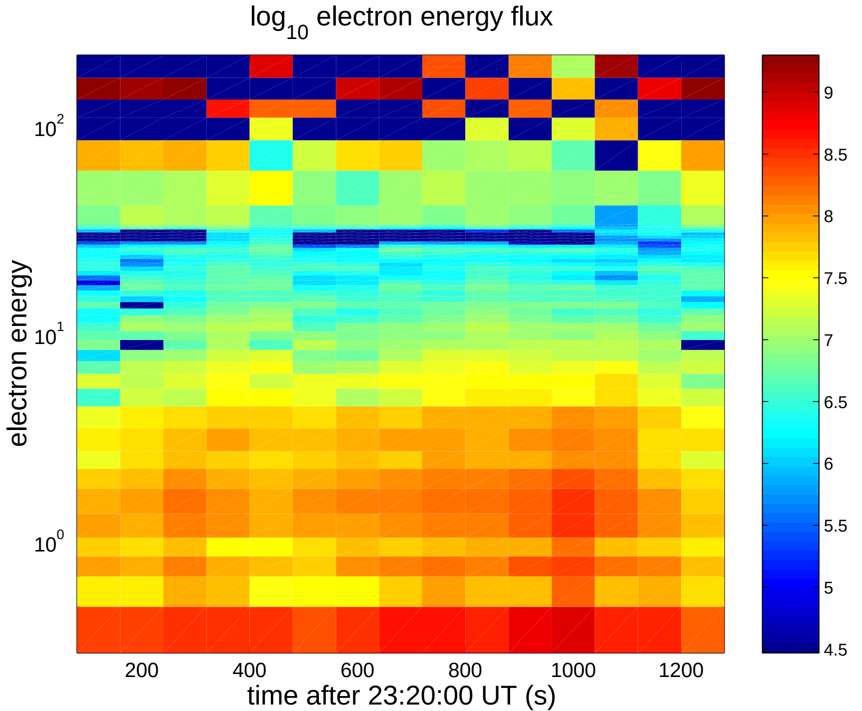
Fine structure of diffuse aurora ALIS-FAST





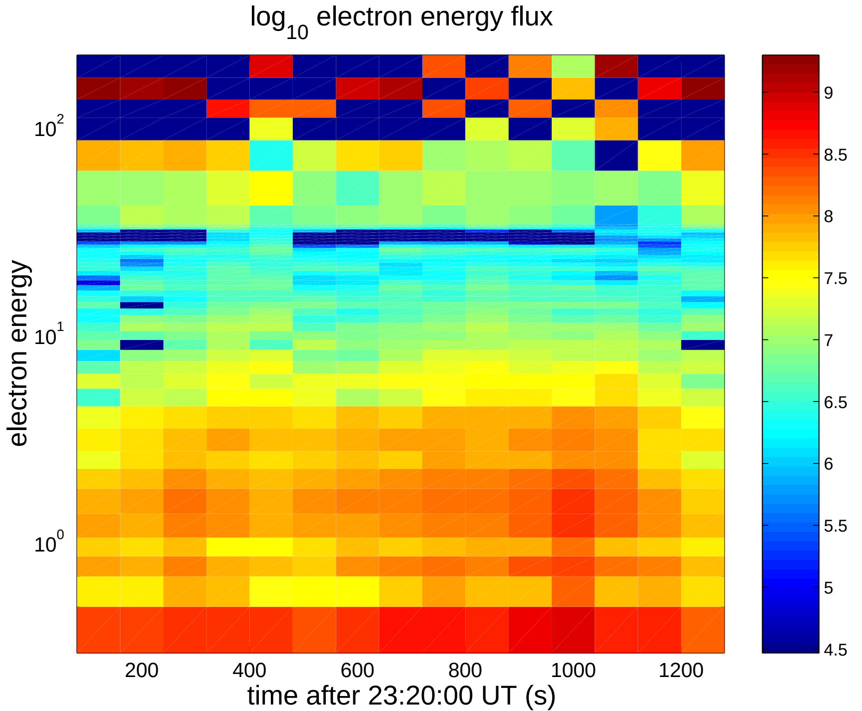
Auroral electron spectras,

from tomography,

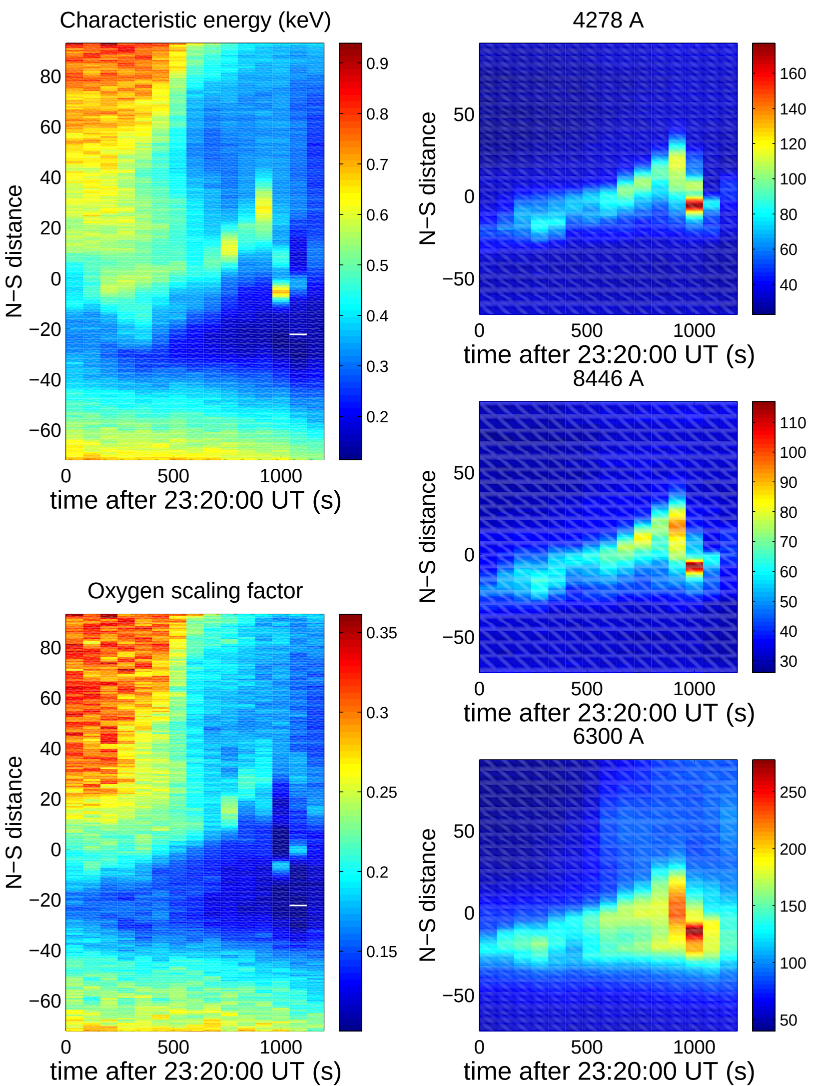


Auroral electron spectras,

from tomography,

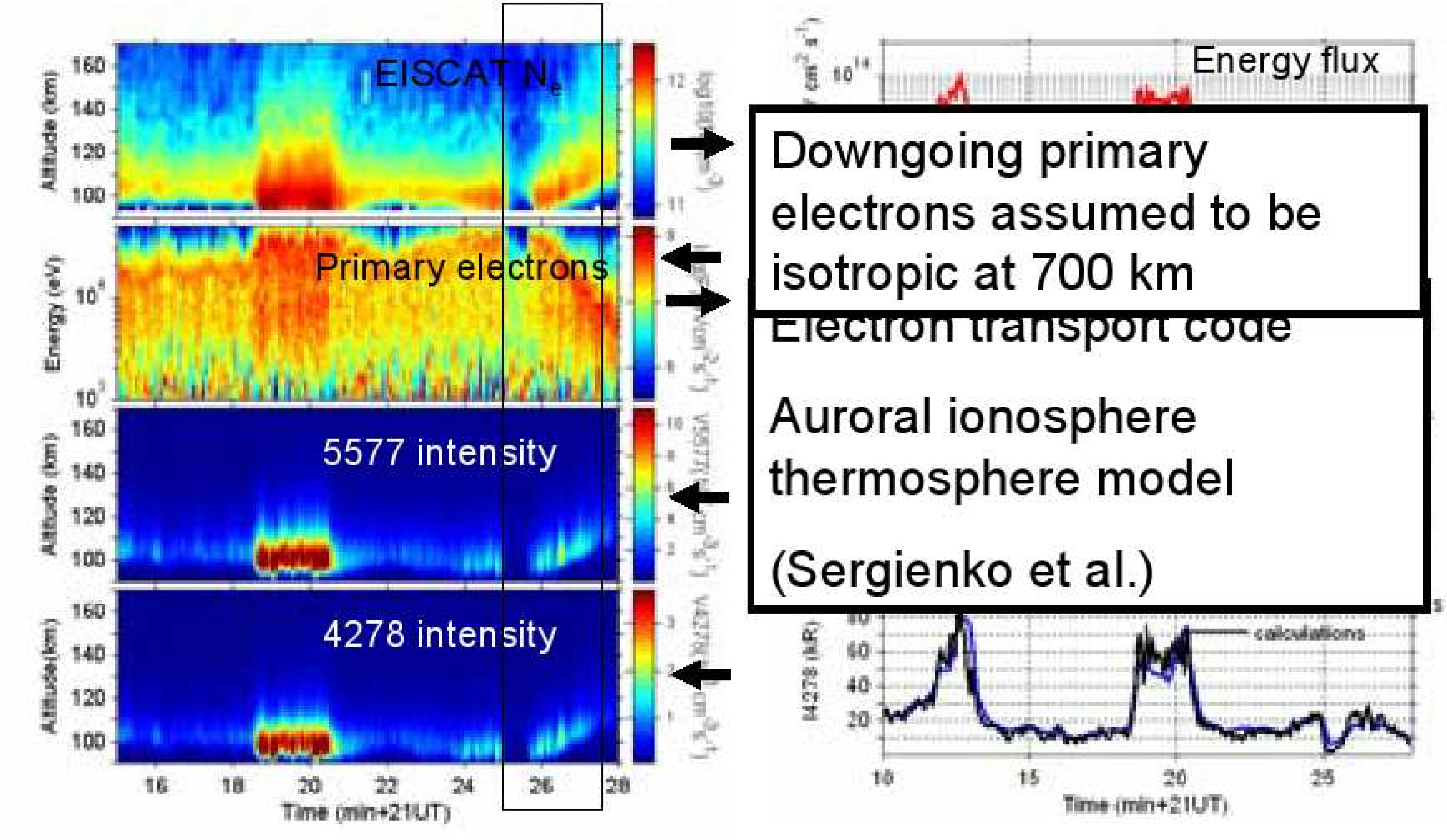


and from spectroscopic ratios (right panel).



After *Gustavsson et al.* [2001b], Phys. Chem. Earth 26.

Reconstruction of auroral electron spectra and emission intensities



Downgoing primary electrons assumed to be isotropic at 700 km

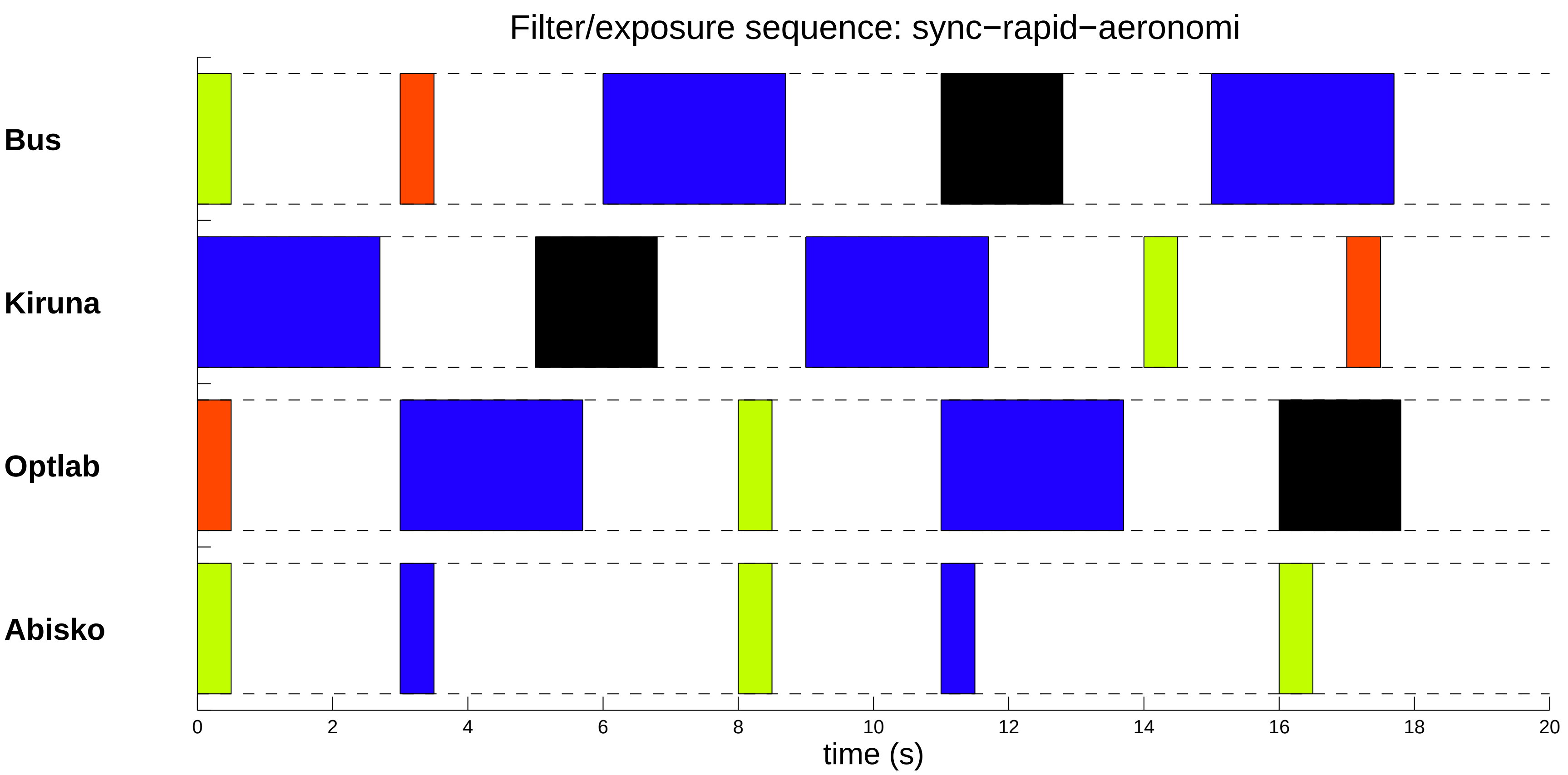
Electron transport code

Auroral ionosphere thermosphere model

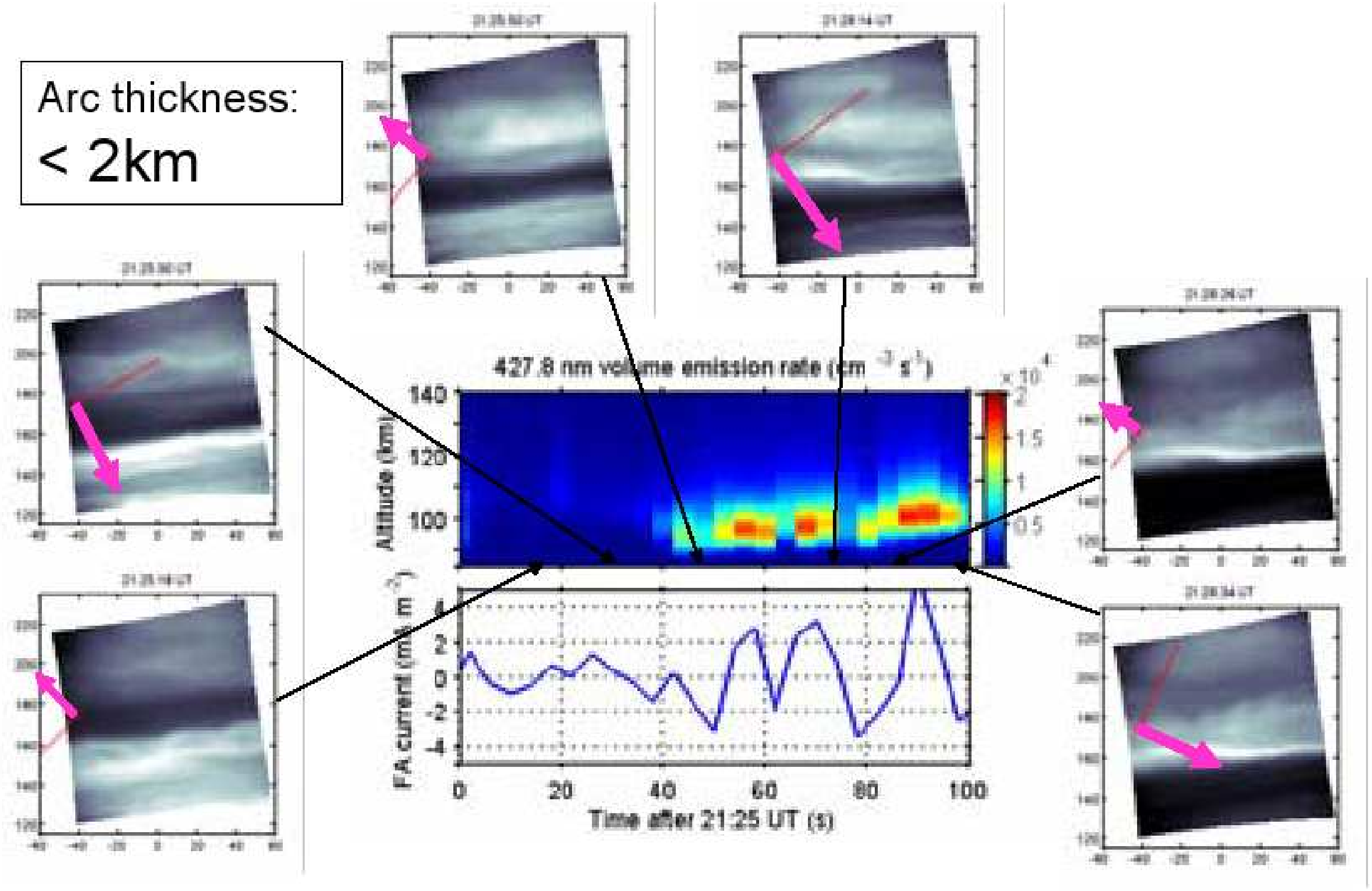
(Sergienko et al.)

Tima Sergienko et al.

filter/expose sequence



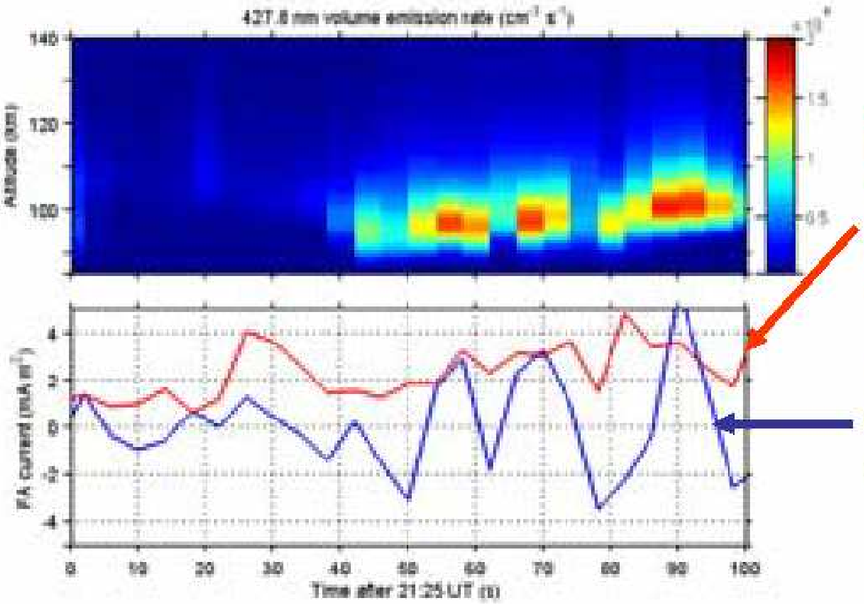
Field aligned currents from EISCAT and ALIS data
ALIS: Parallel arcs drift through EISCAT beam



Arc thickness:

< 2km

Field-aligned currents

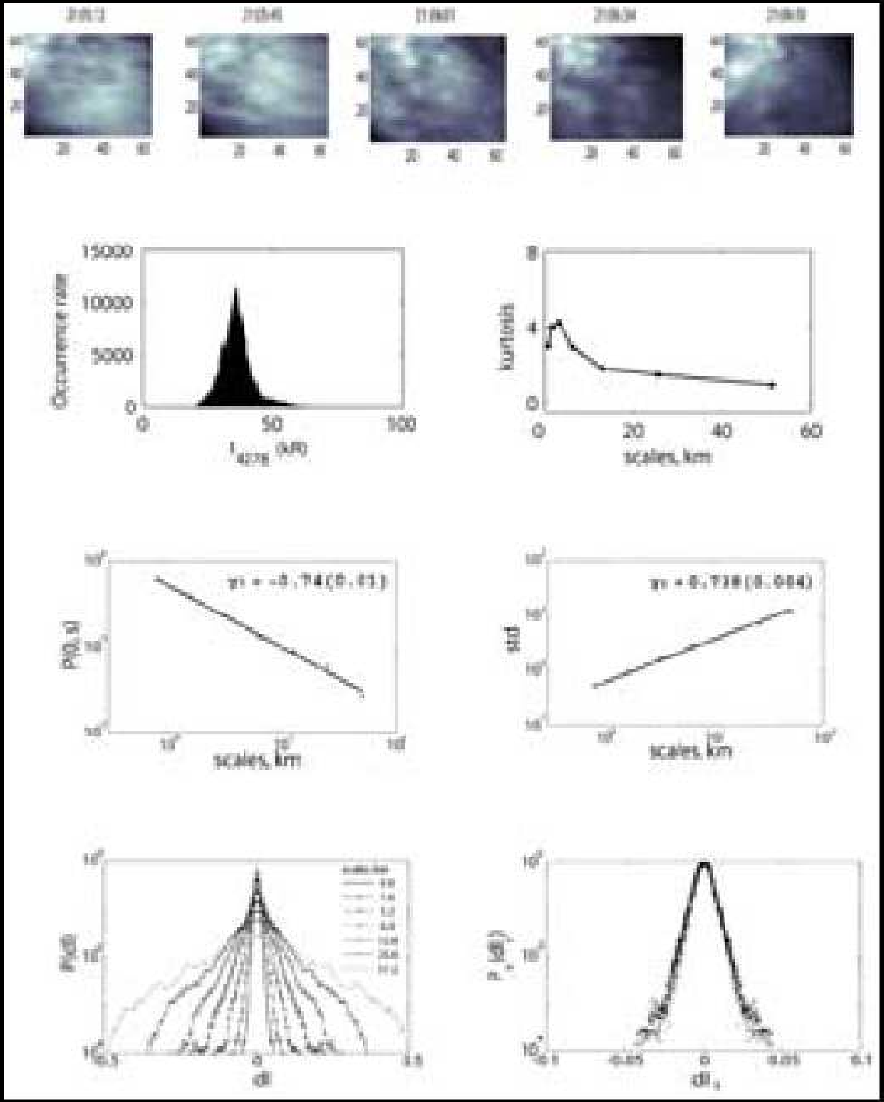


Field-aligned
current calculated
from electron
spectra x 500

Field-aligned current
deduced from
conductance and drift

$$j_{11} = -div_{\perp}(\hat{\Sigma} \cdot E)$$

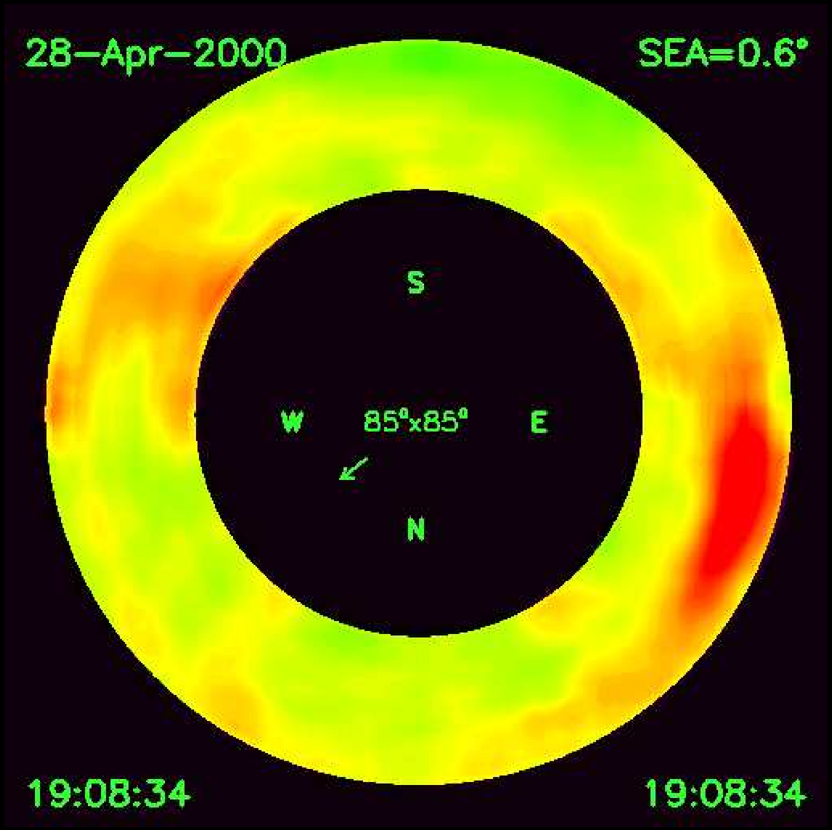
$$\boxed{>1\ \mathrm{mA/m^2}}$$



Scaling behavior of auroral luminosity fluctuations observed by ALIS

Irina Golovchanskaya et al., 2008

Daylight aurora

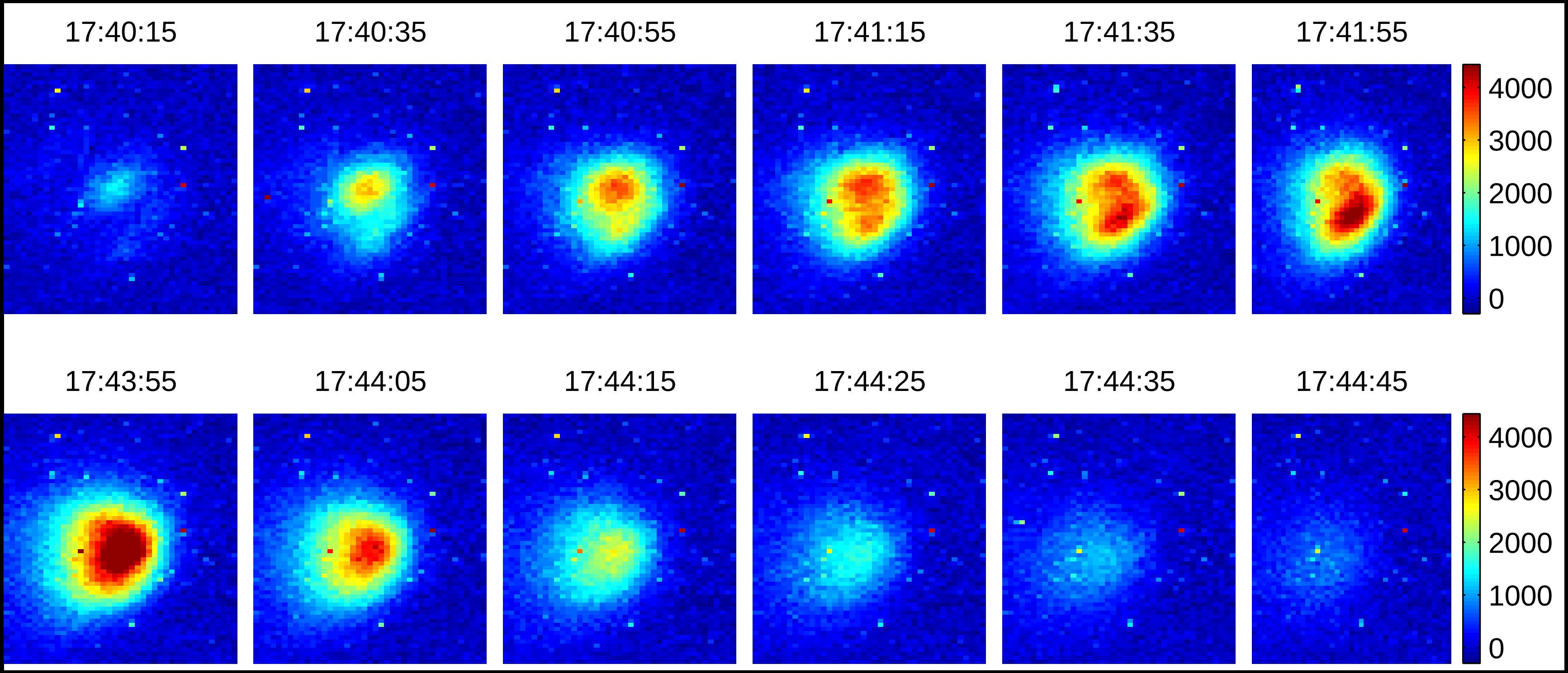


After *Rees et al.* [2000], GRL, 27.

Radio-induced optical emissions

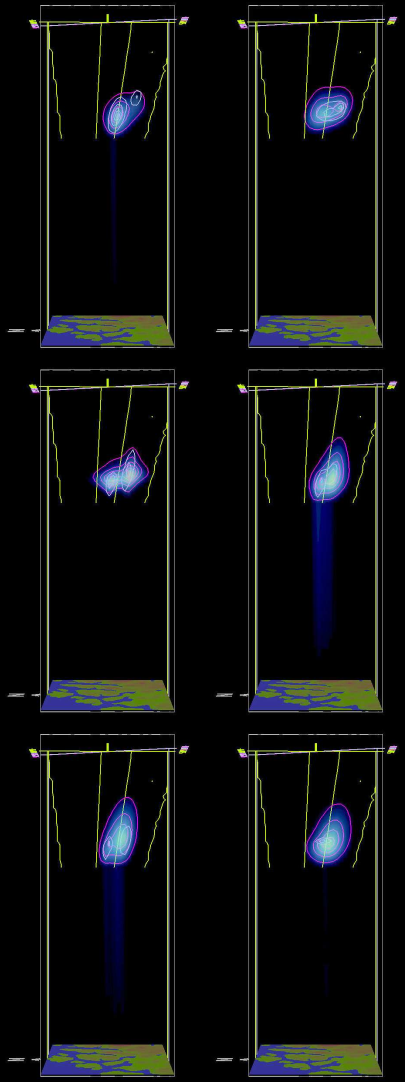
RIOE

ALIS made the first unambigous observation of high-latitude RIOE 1999-02-16



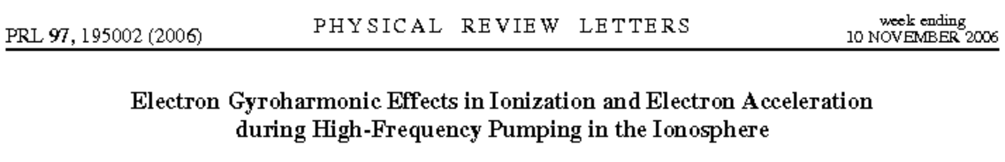
After [*Brändström et al.*, 1999], GRL, 26.

Tomography of RIOE



ALIS made the first tomographic estimate of volume distribution of RIOE.

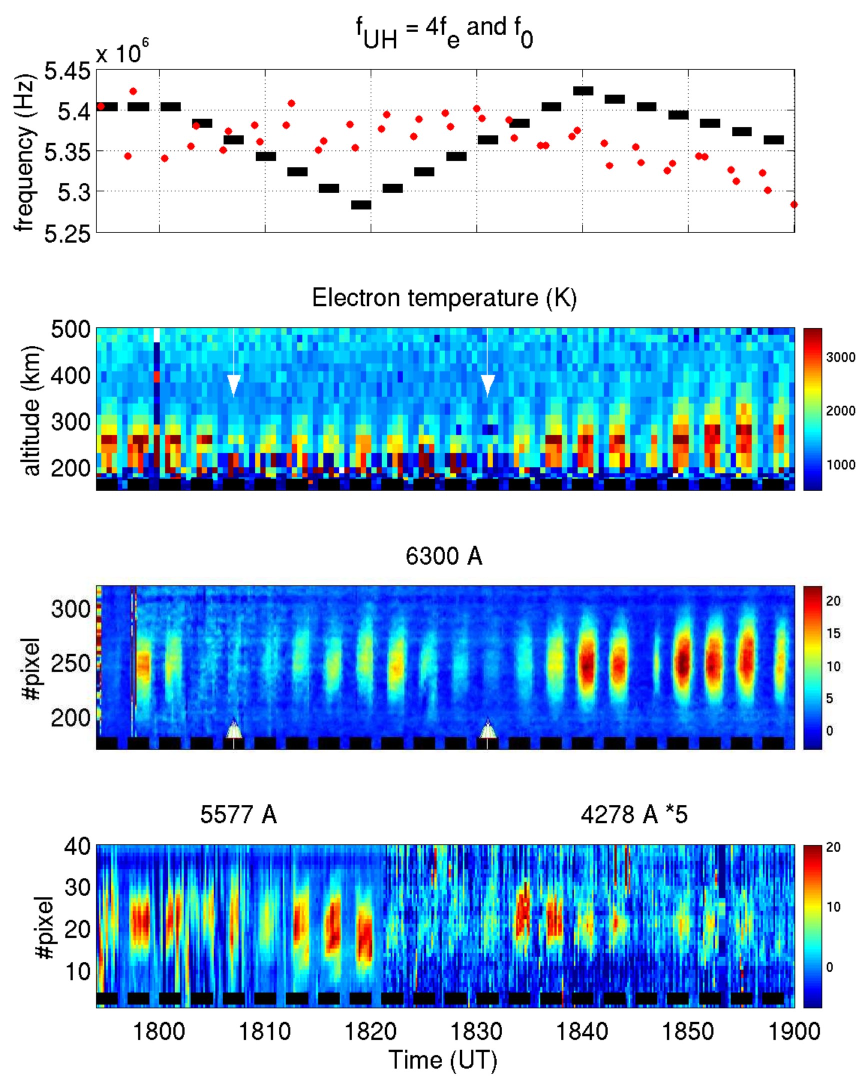
After *Gustavsson et al.* [2001a], JGR 106, 29

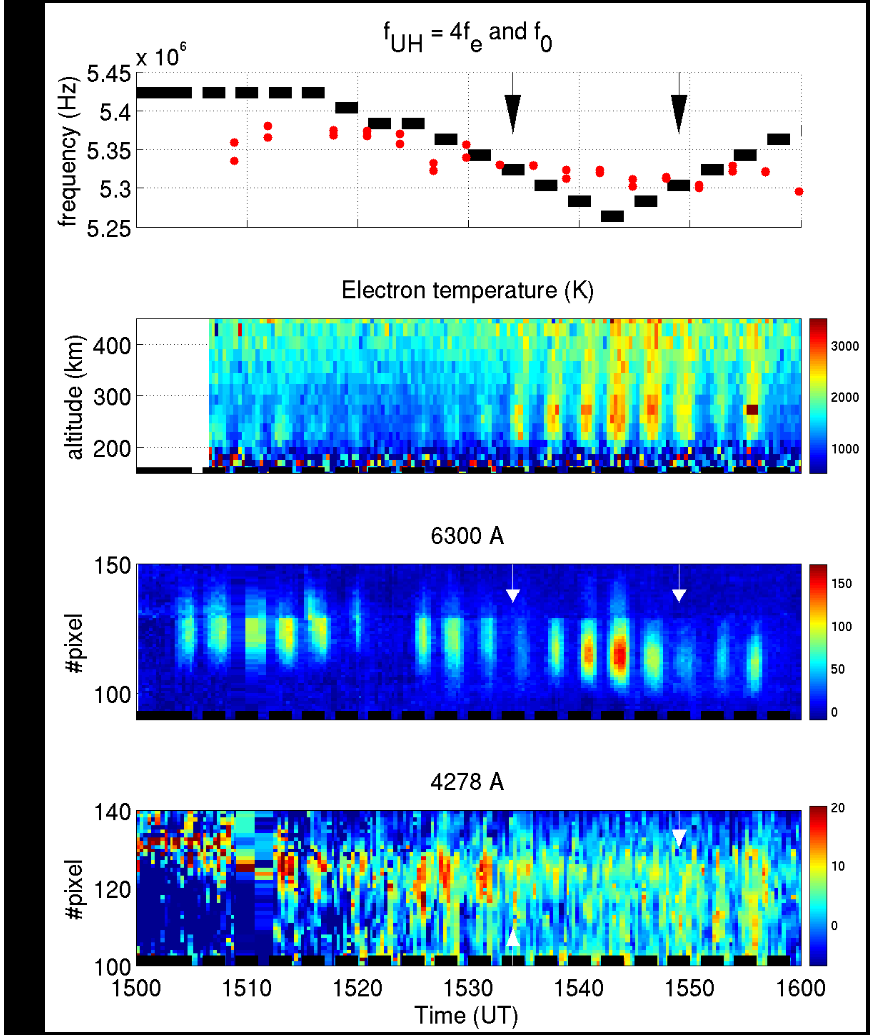


PRL 97, 195002 (2006) PHYSICAL REVIEW LETTERS week ending 10 NOVEMBER 2006

Electron Gyroharmonic Effects in Ionization and Electron Acceleration during High-Frequency Pumping in the Ionosphere

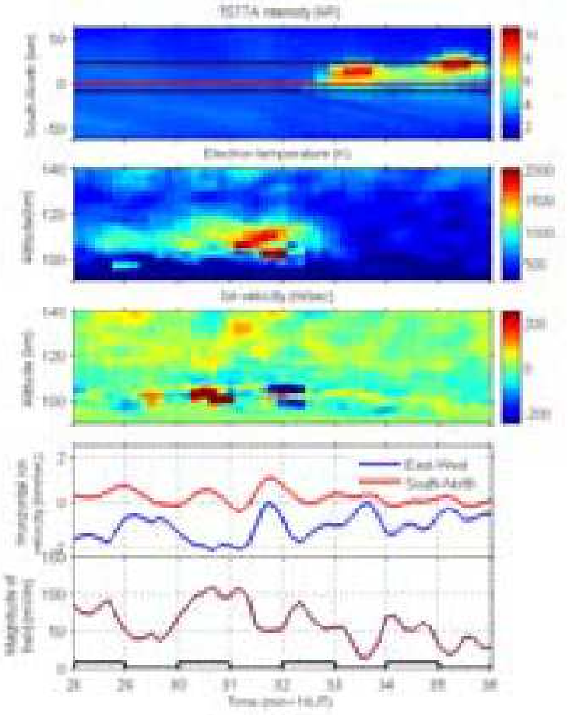
B. Gustavsson,[1,*] T. B. Leyser,[2] M. Kosch,[3] M. T. Rietveld,[4,†] Å. Steen,[5] B. U. E. Brändström,[6] and T. Aso[7]

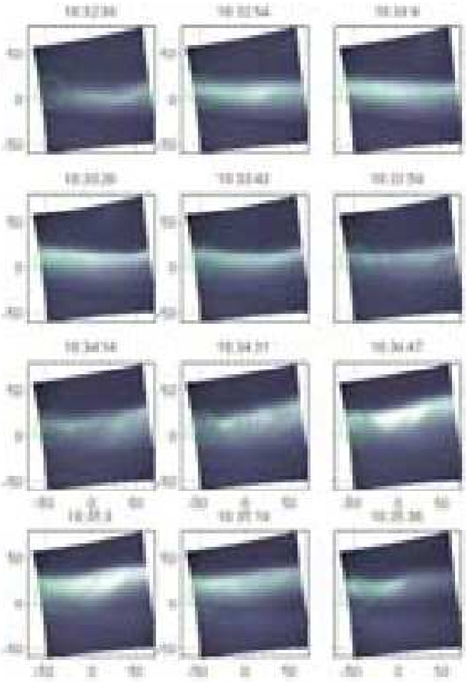




Auroral arc modulation caused by powerful HF ionosphere heating

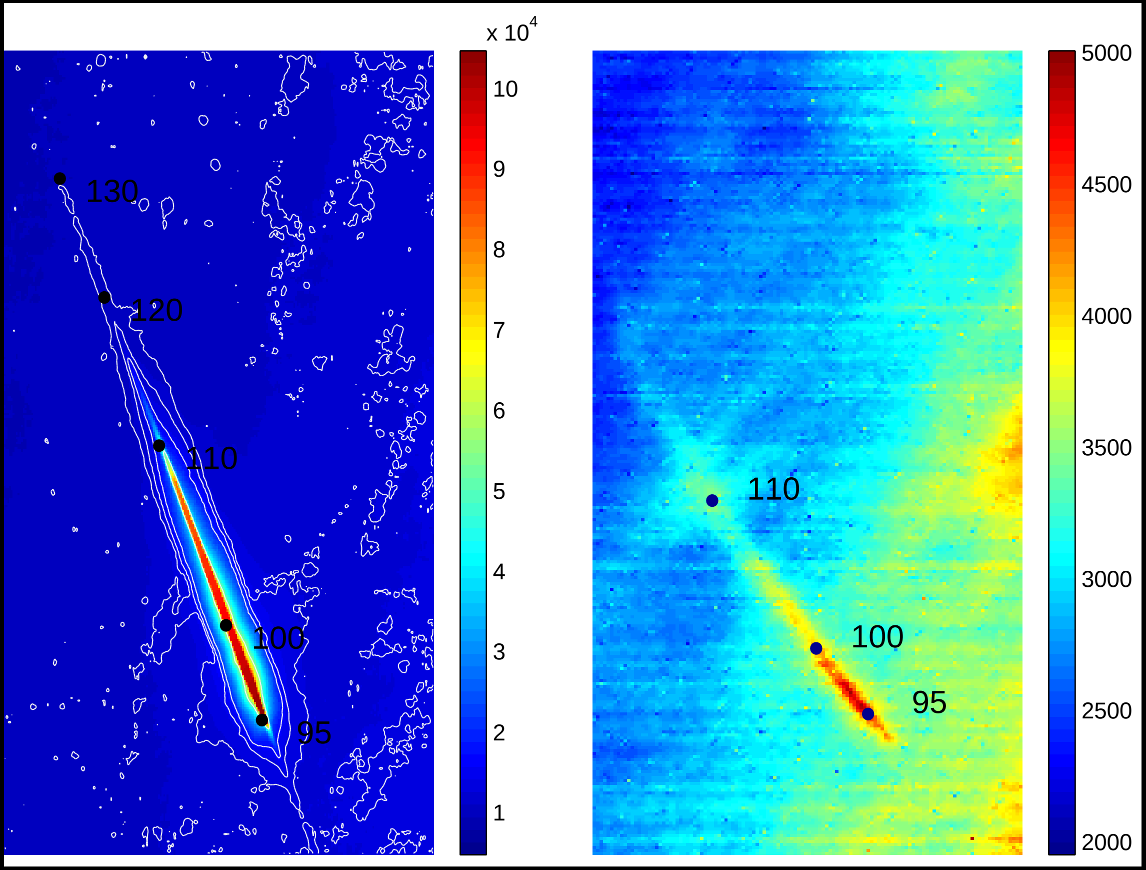
Tima Sergeinko et al.





Meteor research

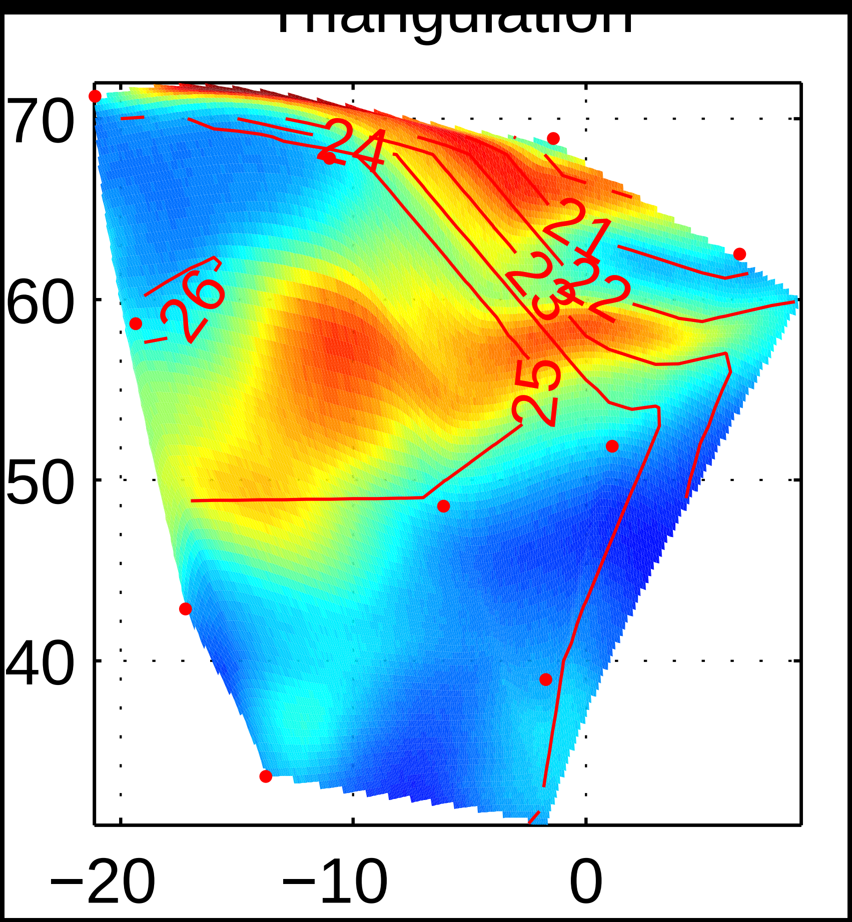
A strange meteor trail



4227 Å (left) 5893 Å (right)

After *Pellinen-Wannberg et al.* [2004, GRL 31], GRL 31.

Polar-Stratospheric clouds



After *Enell* [2002], IRF Sci. Rep. 278

Future plans and challenges

Small structure

The aurora is extremly rich in small structure

> “With respect to understanding the dynamic coupling between the magnetosphere and the auroral ionosphere the observational bias toward bright aurora is physically unjustified” [Semeter 2001]

We do not understand:

- Creation of narrow arcs

We do not understand:

- Creation of narrow arcs
- Diffuse aurora

We do not understand:

- Creation of narrow arcs
- Diffuse aurora
- Pulsating aurora

We do not understand:

- Creation of narrow arcs
- Diffuse aurora
- Pulsating aurora
- The role of the ionosphere in the magnetosphere-ionosphere coupling

We do not understand:

- Creation of narrow arcs
- Diffuse aurora
- Pulsating aurora
- The role of the ionosphere in the magnetosphere-ionosphere coupling
- How are different scales related to each other?

We do not understand:

- Creation of narrow arcs
- Diffuse aurora
- Pulsating aurora
- The role of the ionosphere in the magnetosphere-ionosphere coupling
- How are different scales related to each other?

Thus we need instruments measuring different scales with high temporal and spatial resolution, e.g. Polar/VIS, ASC, ALIS, ASK

ALIS 2010–2014

- Electrodynamics of auroral structures: get most out of EISCAT-UHF
- ALIS/EISCAT/REIMEI
- Improve temporal resolution: EMCCD
- Review which sites to use
- Ionospheric sounding rockets?
- Collaboration for development of methods and models
- Calibration!!!
- Improve access to data

In particular

we will work to answer the following specific questions:

1. What is the temporal and spatial scale distribution of small (less than a few km) auroral structures?.
2. What are the temporal and spatial variations of the primary particle distributions causing small auroral structures?
3. What is the detailed 3D electrodynamics of small auroral structures?
4. How does ionospheric feedback influence auroral structure?

and now. . .

My brain hurts!

Mr. T. F. Gumby:—Doctor! Doctor! DOCTOR! DOCTOR! Doctor!

— Are you the brain specialist? — My brain hurts!

`http://www.mwscomp.com/mpfc/gumbrain.ht`

It’s

The end!

THE END!

The end?

Kiruna ASC 2007-02-05 17.39.00 UTC 10s exp.

References

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