Errors in Airglow & Auroral Emission Measurements

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Acknowledgments

- Jeffrey Baumgardner Boston University
- Timothy Cook ’’
- Supriya Chakrabarti ’’

Outline

- Introduction
- Errors related to airglow/auroal brightness measurements:
    - Systematic (Determinate) errors
    - Limitations
    - Random (Indeterminate) errors
- SNR for different scenarios
- Summary

Scope of the tutorial

- Know the limitations and errors in airglow/auroral brightness measurements.
- With this information, take proper account of the sources in the data analysis.
- Guide one to estimate the SNR to expect for a given system.

What is airglow/aurora ?

Airglow/Aurora is the luminosity of an atmosphere.

Airglow: Initial excitation source is solar photons.
Aurora: Initial excitation source is energetic particles.

$$e'^{-} \quad H'^{+} / h\nu / \text{collisions} + X / XY / XY^{+} \longrightarrow X / XY^{*} / XY^{*+} + e'^{-} / H'^{+}$$

$$X^{*} / XY^{*} / XY^{*+} \longrightarrow X / XY / XY^{+} + \underset{\text{(FUV-IR) (AIRGLOW)}}{h\nu}$$

We will use "Emissions" to refer to both Airglow & Aurora

Why measure Airglow/Aurora?

Airglow/Auroral measurements are effective and fairly inexpensive method of remote sensing the behavior of the upper atmosphere.

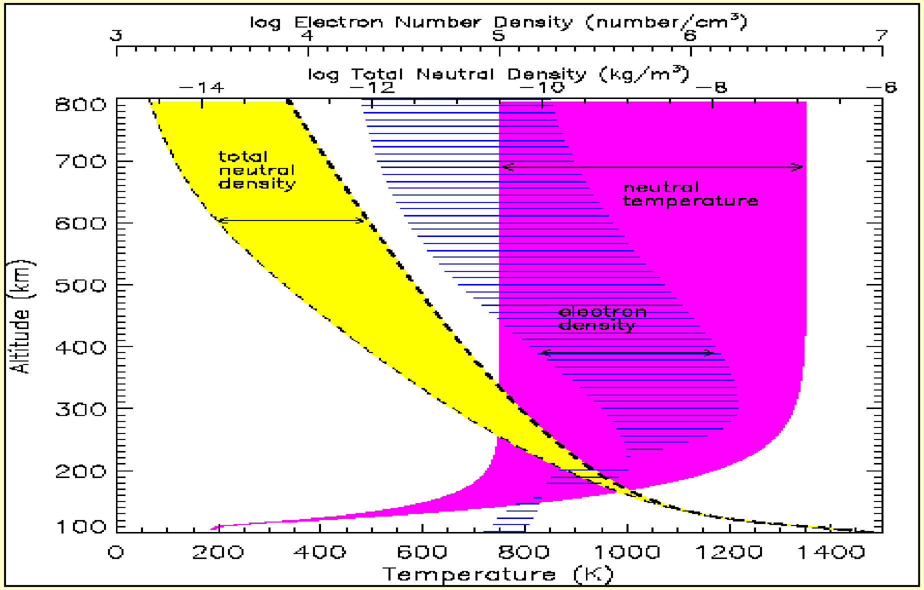
Physical Parameter(s) that can be derived	Requirements
Concentrations & Compositions:	Reaction rates, tomography.
Neutral temperatures and winds:	• High spectral-resolution measurements (Doppler & Rotational). • Twilight emissions.
Altitude coupling, (vertical propagation of waves):	Emission rates at multiple wavelengths.
Latitude & Longitude coupling:	Large field-of-view; measurements from multiple sites.
Plasma drifts, TEC:	Redline & 7774 Å emissions.
Energy inputs into earth:	Electron & proton induced aurora.

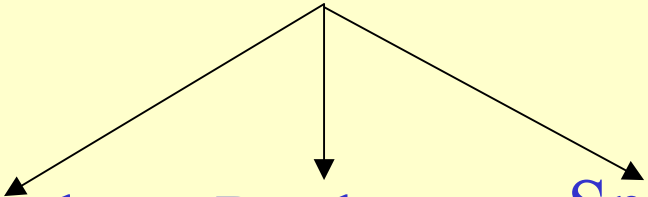
Different emissions originate at different altitudes

Emission altitudes are a function of the concentration of reactants, life times of the excited species and collision frequencies.

Some Commonly measured emissions:

OI	**630.0nm**	**(250km)**
	777.4nm	**(F-peak)**
	557.7nm	**(100km)**
N_2^+	**391.4nm**	**(150km)**
	427.8nm	**(150km)**
	470.9nm	**(150km)**
H_β	**486.1nm**	**(100 - 200km)**
H_α	**656.3nm**	**(100 - 200km)**
Na	**589.3nm**	**(92km)**
OH	**731.6nm**	**(85km)**





Observational Means

Ground

Rocket

Space

We will only discuss ground-based observations of visible emissions

How bright are nighttime atmospheric emissions?

Stars, Zodiacal light, Diffuse galactic light, Airglow

(Direct + Scattered)

↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓

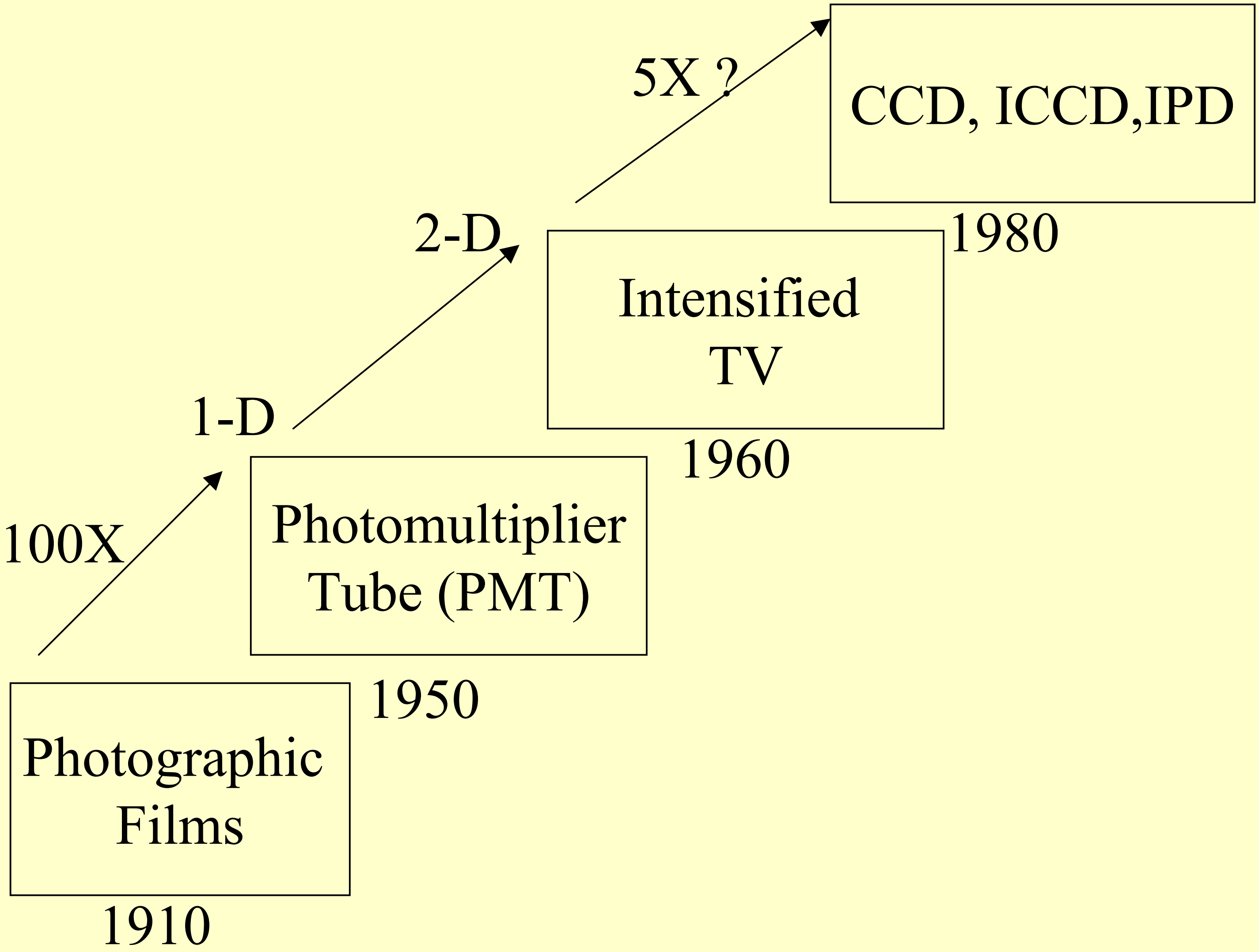
Airglow = (Observed light – calculated due to astrophysical sources)
(Derived)

Airglow as fraction of total (%)

Band	**U**	**B**	**V**	**R**
λ Range (nm)	**(331-395)**	**(395-495)**	**(495-590)**	**(590-700)**
Reference λ	**365**	**400**	**550**	**645**
	55%	**38 %**	**53 %**	**56 %**

Priedhorsky, 1996 (Appl. Opt)

Historical development of Detectors for emission measurements:



Photographic Films

1910

100X

1-D

Photomultiplier Tube (PMT)

1950

2-D

Intensified TV

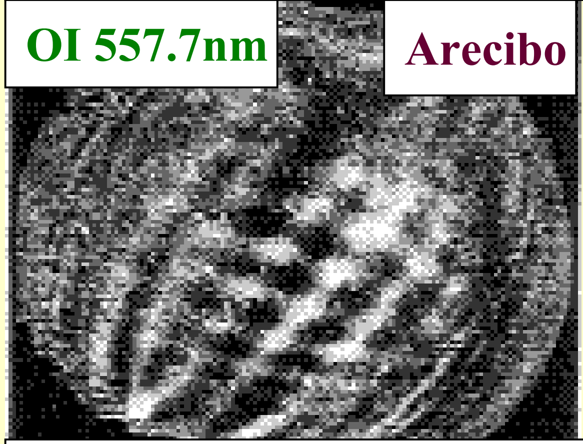
1960

5X ?

CCD, ICCD,IPD

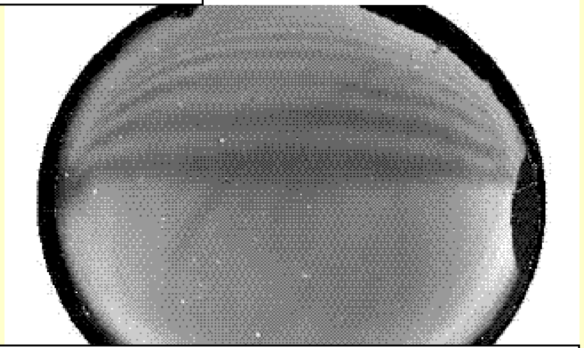
1980

Large scale aspects of many atmospheric phenomena have been discovered by all-sky optical measurements


OI 557.7nm

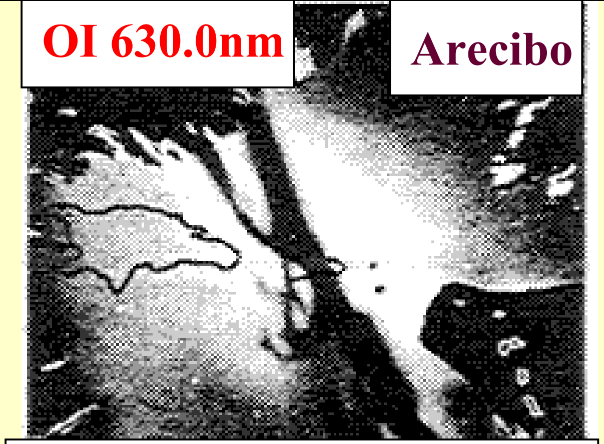
Arecibo

Taylor and Garcia, 1995


OI 557.7nm

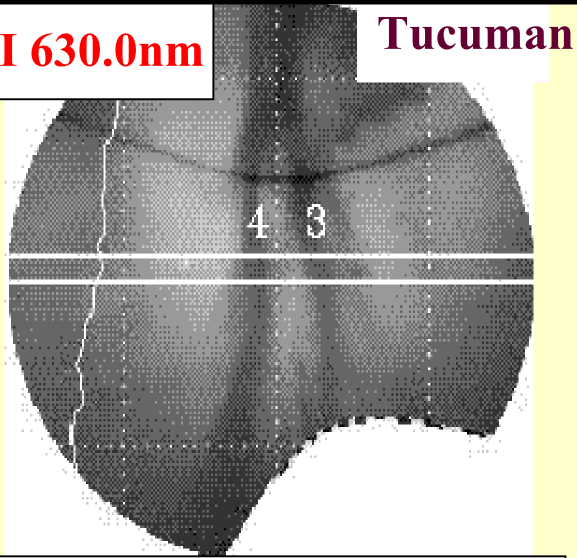
McDonald Obs.

Smith et al., 2003


OI 630.0nm

Arecibo

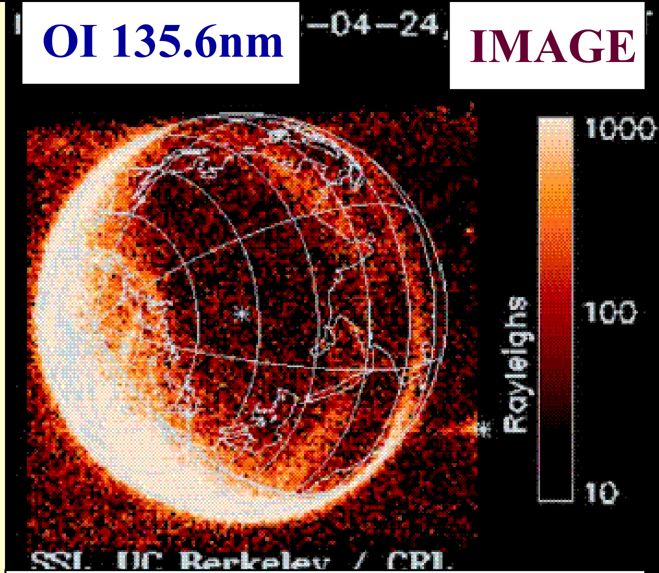
Kelley et al., 2000



OI 630.0nm

Tucuman

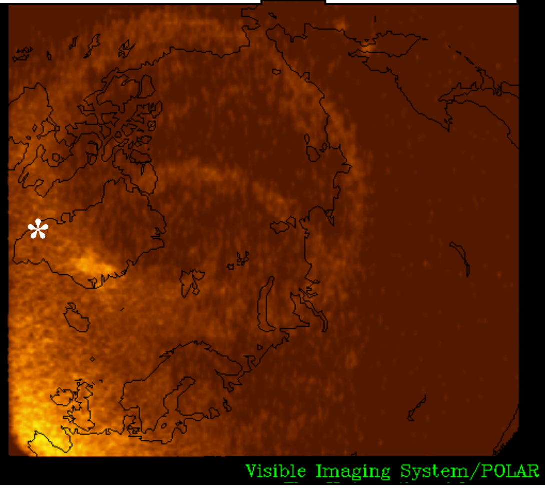
Martinis et al., 2003



OI 135.6nm

IMAGE

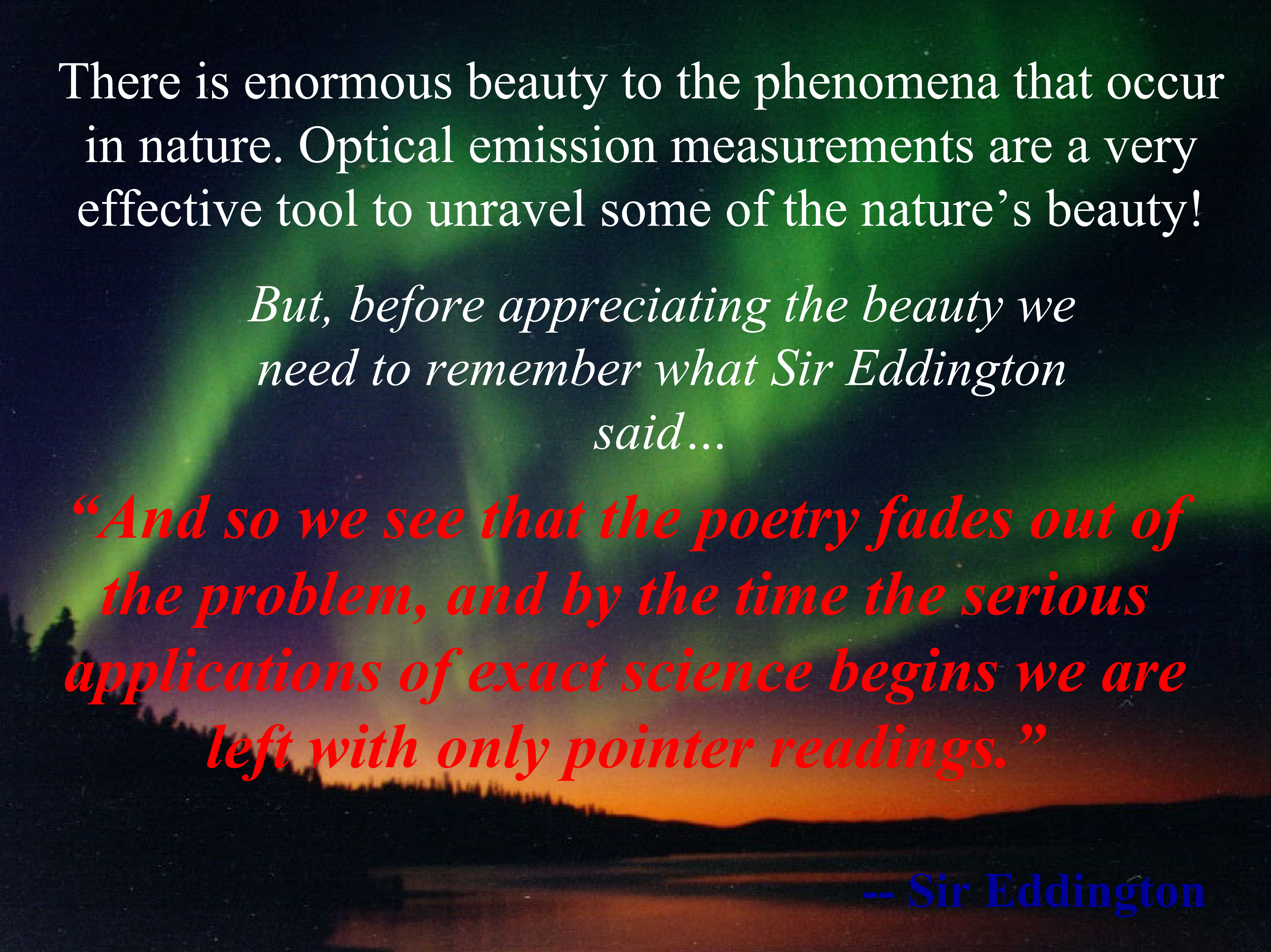
Sagawa et al., 2003



OI 135.6nm

POLAR

POLAR VIS Earth Camera.
Courtesy: F. Sigwarth & L. Frank



There is enormous beauty to the phenomena that occur in nature. Optical emission measurements are a very effective tool to unravel some of the nature’s beauty!

But, before appreciating the beauty we need to remember what Sir Eddington said…

“And so we see that the poetry fades out of the problem, and by the time the serious applications of exact science begins we are left with only pointer readings.”

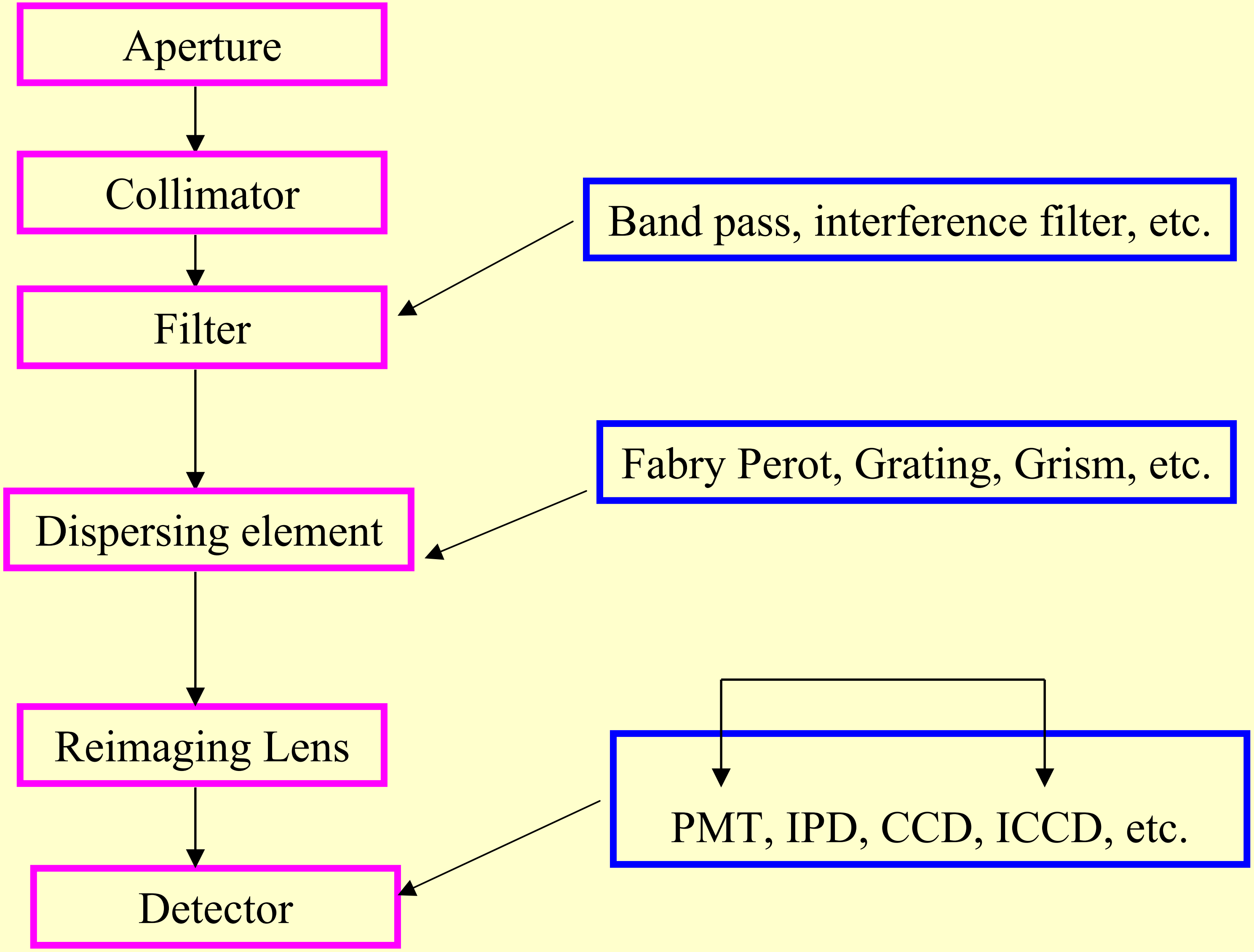
-- Sir Eddington

Different types of errors

Systematic errors: (Determinate)	Often called accuracy; (measured value – the “truth”).
Random errors: (Indeterminate)	Often called precision.
Dynamic errors: (Miscellaneous)	Errors related to dynamic properties of the instrumentation; ex., setting time, time constants, etc.
Illegitimate errors: (Miscellaneous)	Blunders, different units, computational glitches (rounding off, insufficient algorithms, double precision, etc.)

- **Uncertainty** = Systematic + Random + Miscellaneous errors.
- Uncertainty gives a measure of overall confidence of a measurement (σ).

Schematic of a typical optical system



Aperture

Collimator

Filter

Dispersing element

Reimaging Lens

Detector

Band pass, interference filter, etc.

Fabry Perot, Grating, Grism, etc.

PMT, IPD, CCD, ICCD, etc.

Not all systems may need all these components

Origin of Systematic/Determinate errors (same size and sign) for emission measurements

Note: In the following, the relevant issues are in red color and their ‘solutions’ are shown in blue.

Systematic

Detector Quantum efficiency

(i) Variation of QE with time.

(ii) Moisture condensation on the chip while cooling:

  (a) in places of high humidity, or

  (b) due to loss in vacuum.

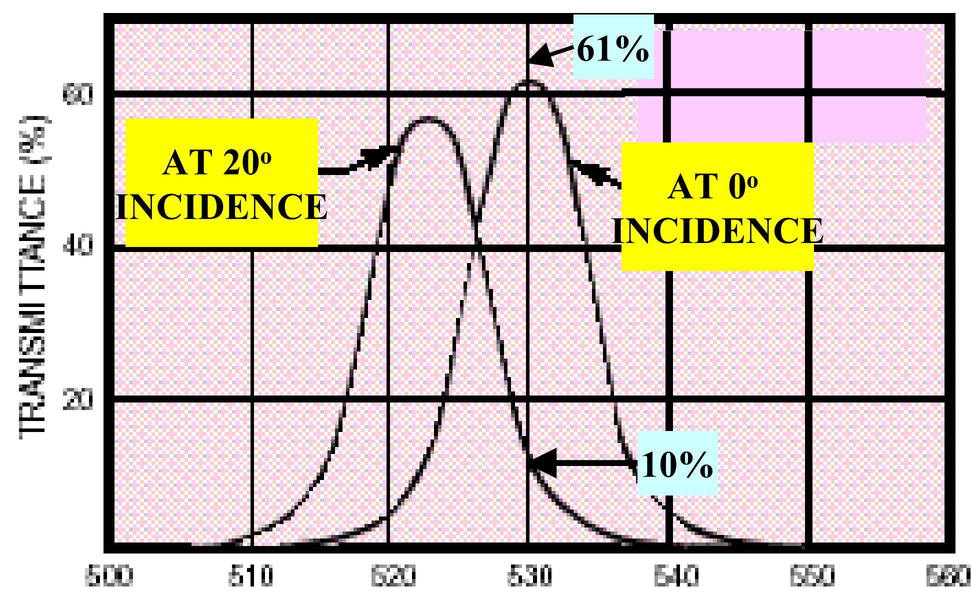
Periodic calibrations with known source (ground standards or stars).

Filter Transmission

Systematic

(i) For small bandwidth– reduction in transmission from low angles.

(ii) For large bandwidth– contribution from other wavelengths not avoidable.



(a) Be careful with all-sky measurements with narrow bandwidth filters.

Filter Transmission (Contd.)

Systematic

(iii) Temperature tuning– discrepancy between actual and displayed temperature. (Typical values: 0.16 – 0.27 Å $^{o}C^{-1}$)

(iv) Tilting of filter for background.

(v) Variation of filter characteristics with time.

(vi) Spatial variation in the transmission.

(b) Periodic calibration.

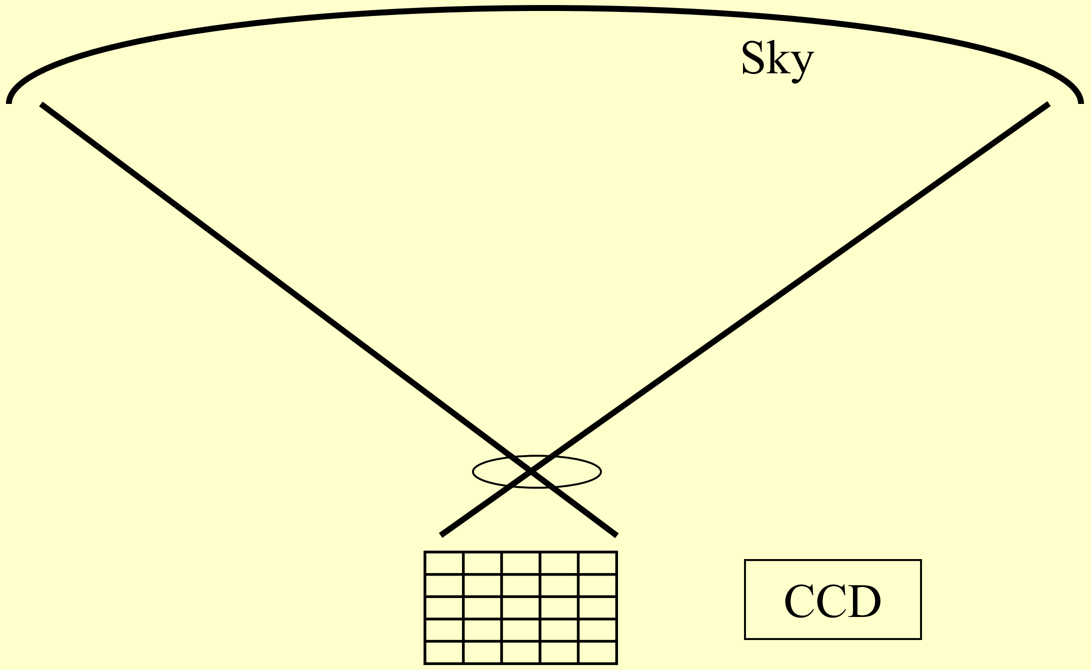
(c) Flat-fielding with monochromator.

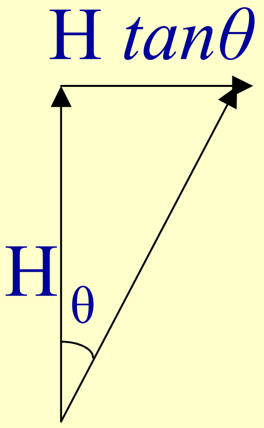
Angular/Geometric Calibration

Systematic

The relation between the view angles/sky position and pixels on the detector.

- Observations of stars when possible.
- Laboratory calibration.



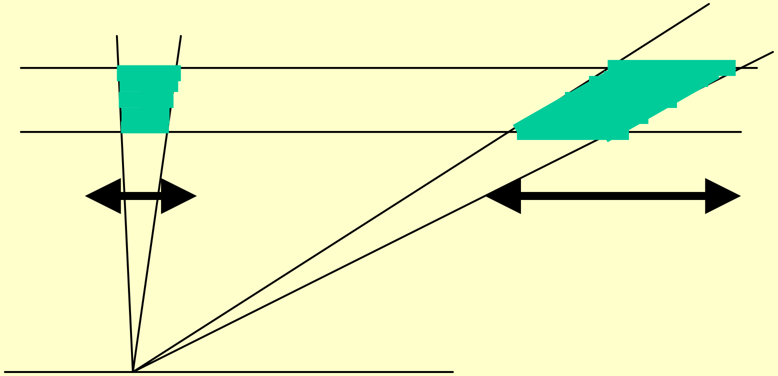


van Rhijn effect:

Systematic

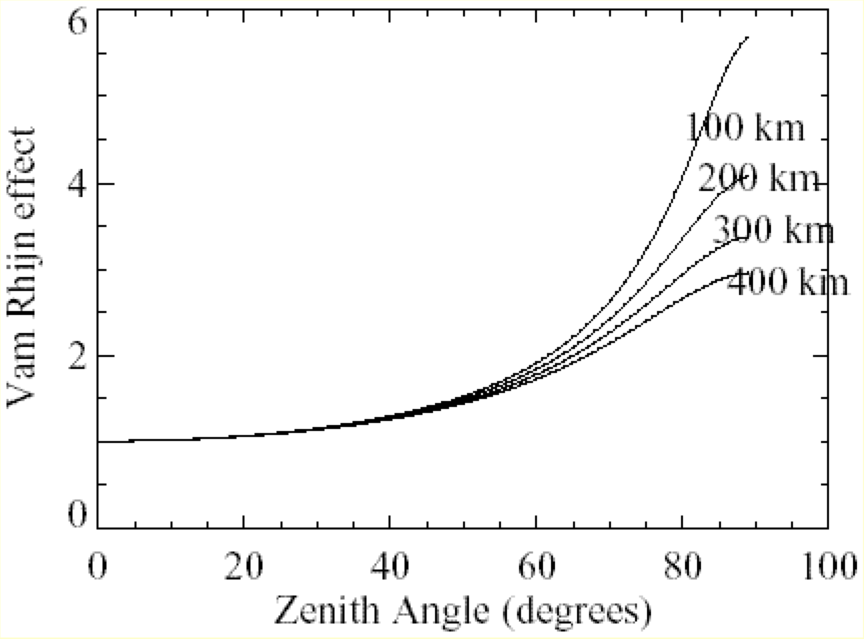
Column int. emissions vary with zenith angle (uniform slab).

Can be corrected with the assumption of uniform emission layer



$$\frac{I_{(z)}}{I_{(zenith)}} = \frac{1}{\sqrt{\left[1-\left(\frac{R}{R+h}\right)^{2}\sin^{2} z\right]}}$$

Where, z is the zenith angle, R is Radius of earth, h is the height of the emission and I(z) is the Intensity at a zenith angle z.



Roach and Gordon, 1973.

Flat field correction:

Systematic

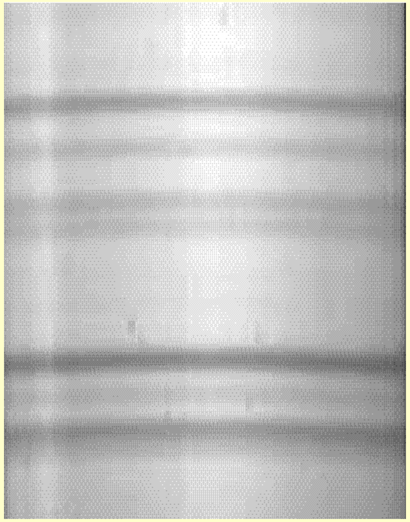
(i) Vignetting: The decrease in illumination away from the optical axis in an optical system.

(ii) Structures or dust within the instrument, “hot” pixels on the detector, etc.

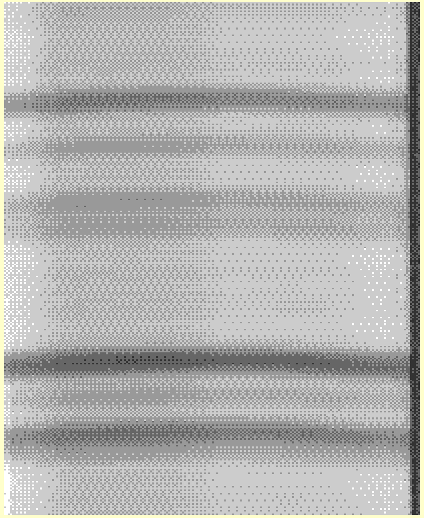
$$I_{corrected}(x,y) = \frac{I(x,y) - I_{dark}(x,y)}{I_{flat}(x,y) - I_{dark}(x,y)} K$$

Correcting the image with a structure-less white light image.

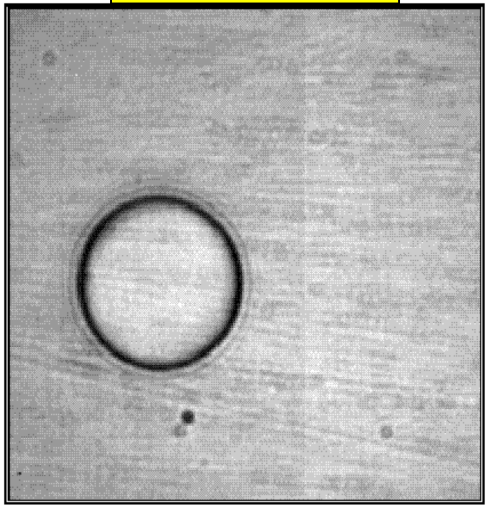
Before



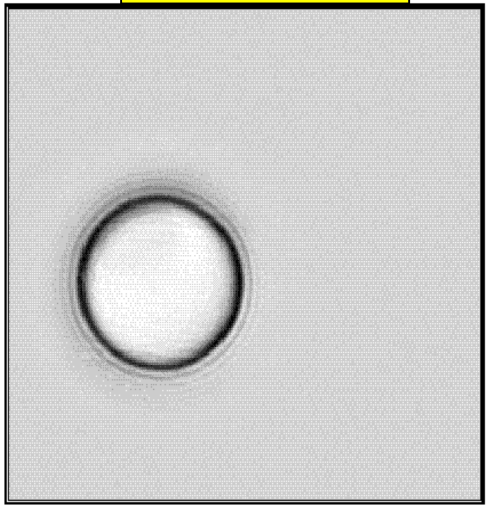
After



Before



After

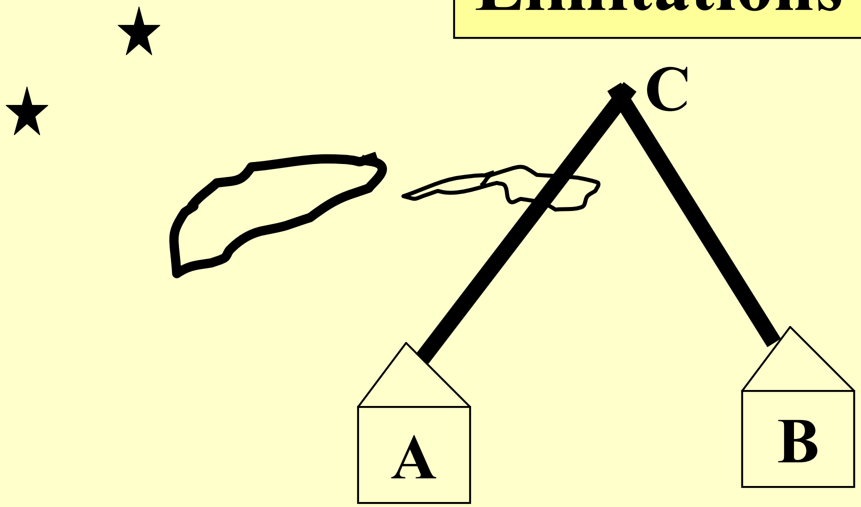


Imaging techniques need to correct every image by a flat-field

Limitations of optical emission measurements: Issues on which we do not have any control

Limitations

Sky Transmission:



(i) Thin sub-visual clouds.

(ii) Haze, fog, mist, dust.

(iii) Varies for different angles.

(iv) Ground lights magnify the effect.

(a) Measurements from high altitudes.

(b) Measurements from dry/desert locations.

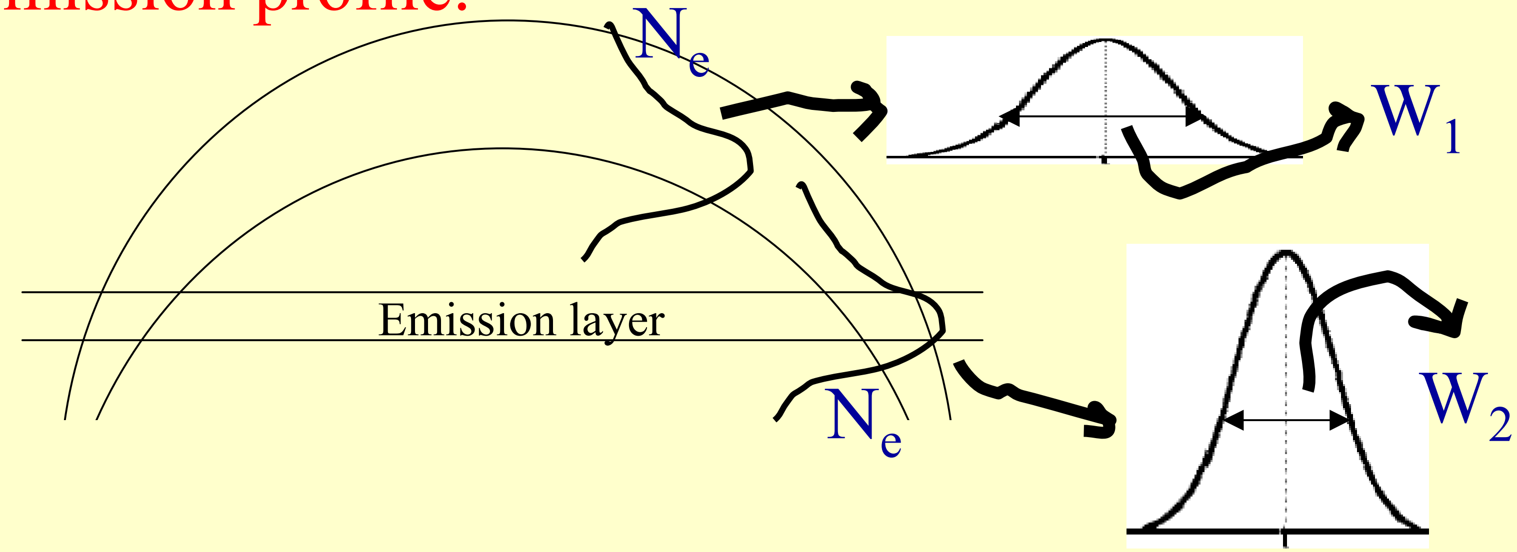
(c) Observing stars of known intensities.

Limitations

Emission height variation:

(i) The F-layer movement (down or up) will produce more or less emissions.

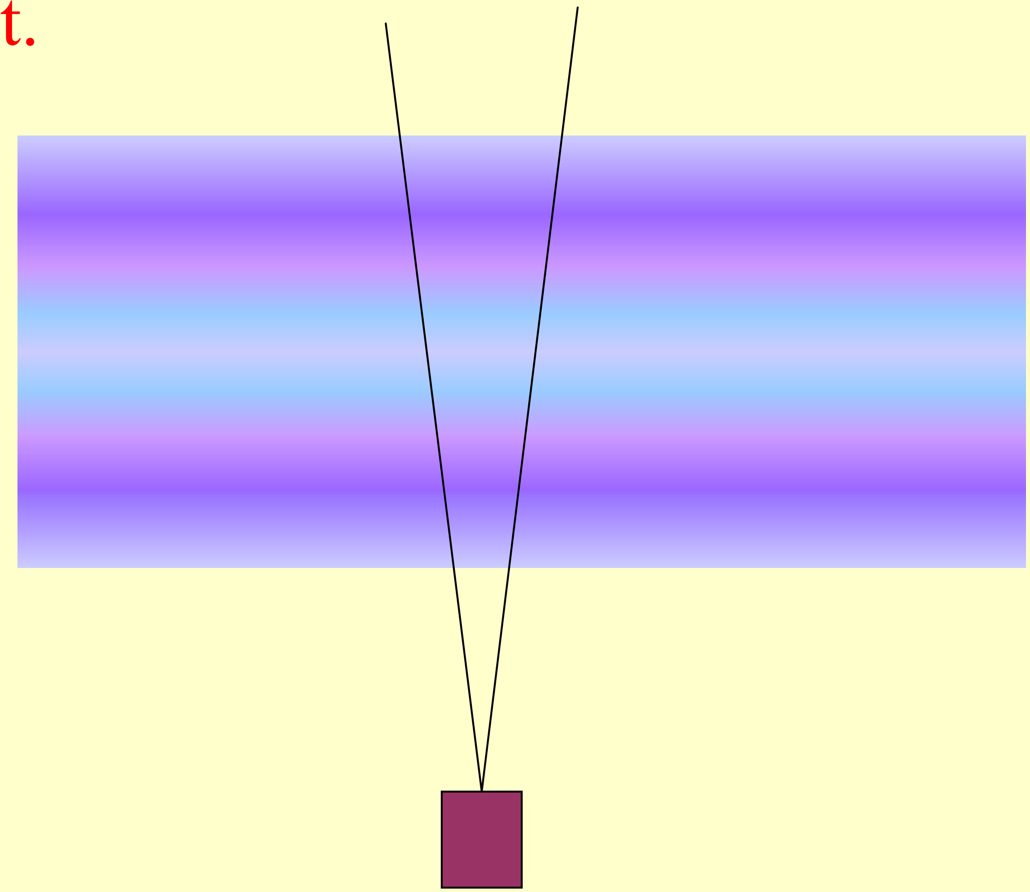
(ii) This will affect the doppler width (= T_n) of the observed emission profile.



(a) Data from other instruments, such as a digisondes will effectively complement the emission measurements to derive accurate physical parameters.

Structures in Emission height?

The obtained emissions are column integrated. So the information on vertical structures, if any, is integrated out.



Origin of Random/Indeterminate errors (different size and sign) for emission measurements

Random

Photon noise:

(i) Dependent on signal strength.
(ii) Not additive.

(a) Large signal or large time integration.
(b) Detectors of high sensitivity.

Thermal noise or Dark current:

Random

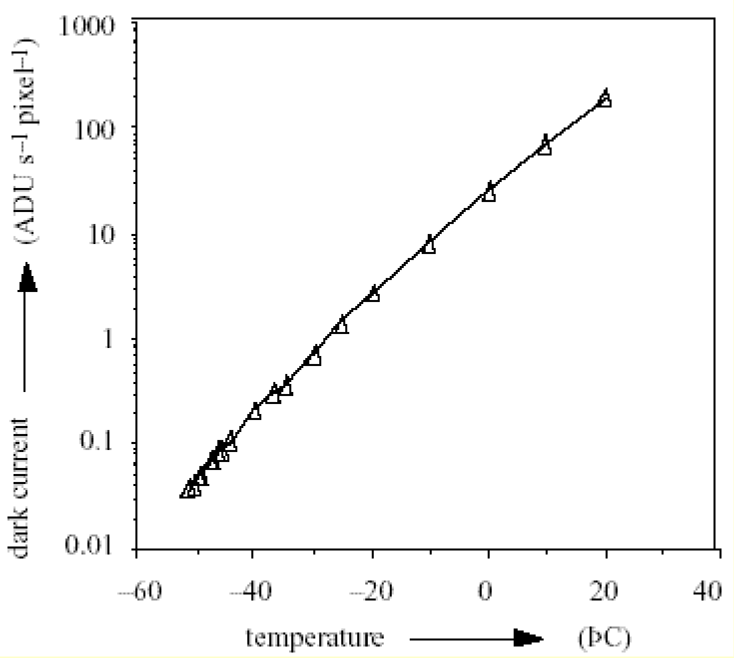
(i) Cannot be distinguished from photoelectrons due to signal.

(ii) Production rate of thermal electrons exponentially increases with temperature.

(iii) Thermal electrons reduce the dynamic range of a detector.

(a) Reduces by a factor of 2 for every 6 C reduction in temperature for CCDs.

(b) Take several dark images and subtract with the image containing data.



Random

Read Noise:

(i) Readout noise is additive.
(ii) Independent of signal.
(iii) Dependent on the readout rates.
(iv) It has a Gaussian deviation and is therefore expressed as its standard deviation (rms value).

Use small number of co-adds during data acquisition.

Quantization Noise:

Rounding off caused by the Analog-to-digital converter in converting the amplitude of electronic signal into a binary representation.

Insignificant and usually ignored.

Indeterminate Vs Determinate errors

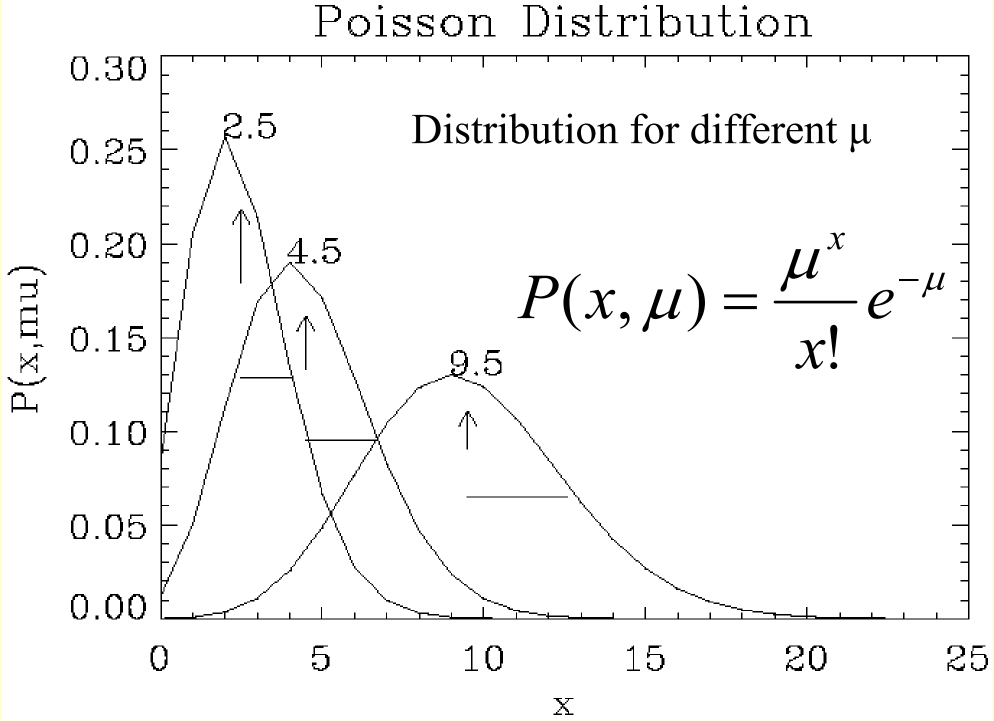
Determinate errors can be more serious than indeterminate errors. Because:

- There is no method of discovering and identifying them just by looking at the data.

- One can not reduce its adverse effects by repeating the experiment as it has the same sign and magnitude.

Photon statistics is governed by Poisson Distribution

Poisson statistics describes the result of experiments where one counts events that occur at random, but at a definite average rate.



Mean <x> = μ ;

Standard deviation, $\sigma = \sqrt{\mu}$

The final count is = $\mu \pm \sqrt{\mu}$

Fractional uncertainty is = $\frac{\sqrt{\mu}}{\mu} = \frac{1}{\sqrt{\mu}}$

Signal to Noise Ratio (SNR)

Assuming that systematic error is taken care of, the SNR is

$$\boxed{SNR=\frac{S}{\sqrt{\underline{(S+B)}+\underline{D}+\underline{R}}}}$$

Here the contributions to noise in addition to signal are the Background *B*,

dark noise or thermal noise of the detector, *D* and

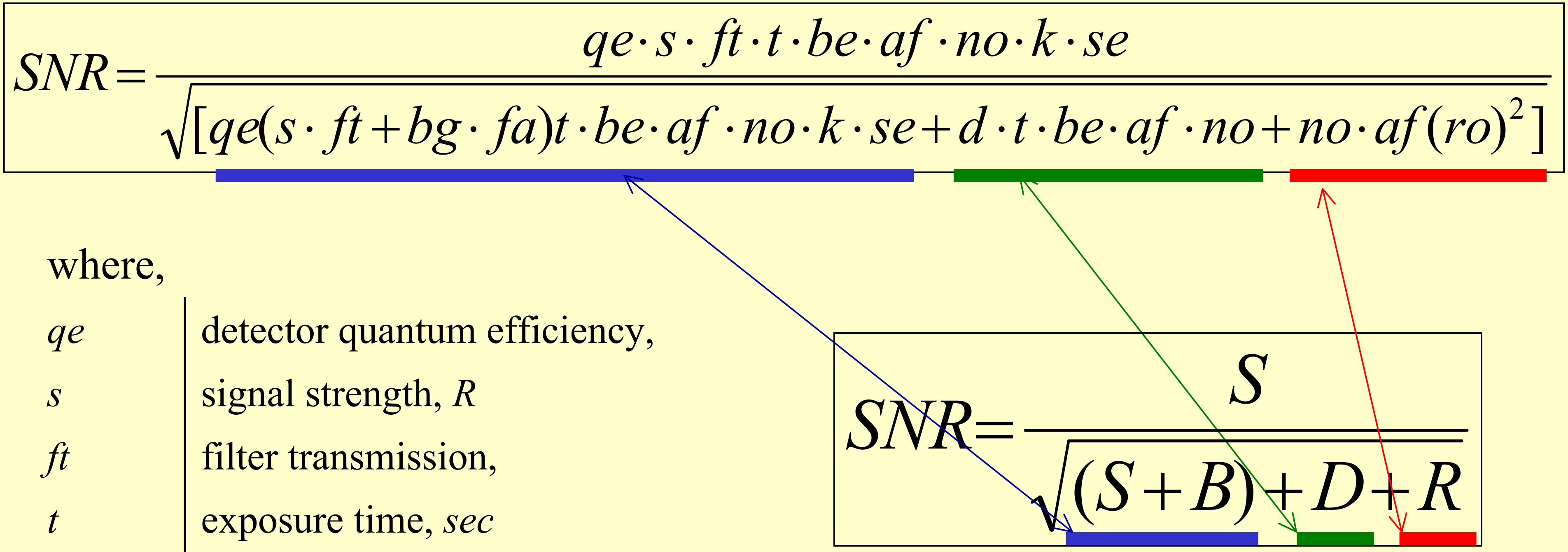
the read noise of the detector, *R*.

Relation between Uncertainty and SNR

Measurement uncertainty = 1/SNR

SNR = 10 ➔ a 10% error in a single measurement and

SNR = 20 ➔ a 5% error in a single measurement and so on..



$$SNR=\frac{qe\cdot s\cdot ft\cdot t\cdot be\cdot af\cdot no\cdot k\cdot se}{\sqrt{[qe(s\cdot ft+bg\cdot fa)t\cdot be\cdot af\cdot no\cdot k\cdot se+d\cdot t\cdot be\cdot af\cdot no+no\cdot af(ro)^2]}}$$

$$SNR=\frac{S}{\sqrt{(S+B)+D+R}}$$

where,

qe	detector quantum efficiency,
s	signal strength, *R*
ft	filter transmission,
t	exposure time, *sec*
bg	background continuum, $RÅ^{-1}$
fa	filter area (or bandwidth where background is considered), *Å*
d	Dark noise, $e^{-}\ pix^{-1}\ s^{-1}$
ro	read out noise, e^{-} *(RMS)*
be	number of pixels binned *before* readout,
af	number of pixels binned *after* readout,
no	number of co-adds,
k	$photons\ s^{-1}\ R^{-1}$ incident on a pixel for a given f/#.
se	system efficiency.

Adapted from:

Roesler, 1987.

Baumgardner et al., 1993.

Atmospheric emissions can be:

(i) Photon statistics limited or

(ii) Read noise limited.

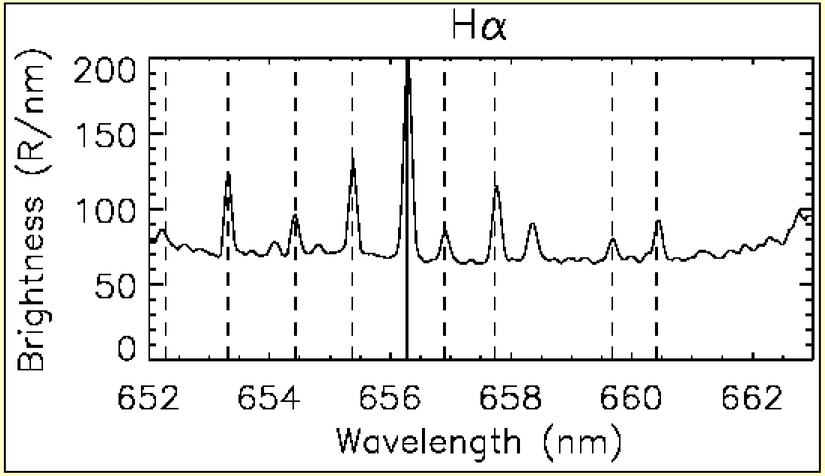
Let us consider different scenarios:

1. Small signal on small background (ex. Geocorona or proton aurora)
2. Large signal on small background (ex. Airglow/ aurora during night time)
3. Large signal on large background (ex. Airglow/ auroral emissions during Daytime or twilight time).

For investigating the SNR for different observational scenarios, following values have been used in the SNR relation:

qe	0.8 for CCD and 0.2 for ICCD
s	20-3000 R
ft	0.75,
t	1-20 s
bg	3 $R\text{Å}^{-1}$ – 5 $MR\text{Å}^{-1}$
fa	8 Å for nighttime and 0.18 Å for daytime emissions
d	0.1 $e^{-}\,pix^{-1}\,s^{-1}$
ro	6.e^{-} (RMS) for CCD
be	1.0
af	10.
no	5-50
se	1.0
k	For f/3= 4 x 10^{-2}; f/11 = 2.9 x 10^{-3} $photons\ s^{-1}\,R^{-1}\,pixel^{-1}$ (for 24μ pixel)

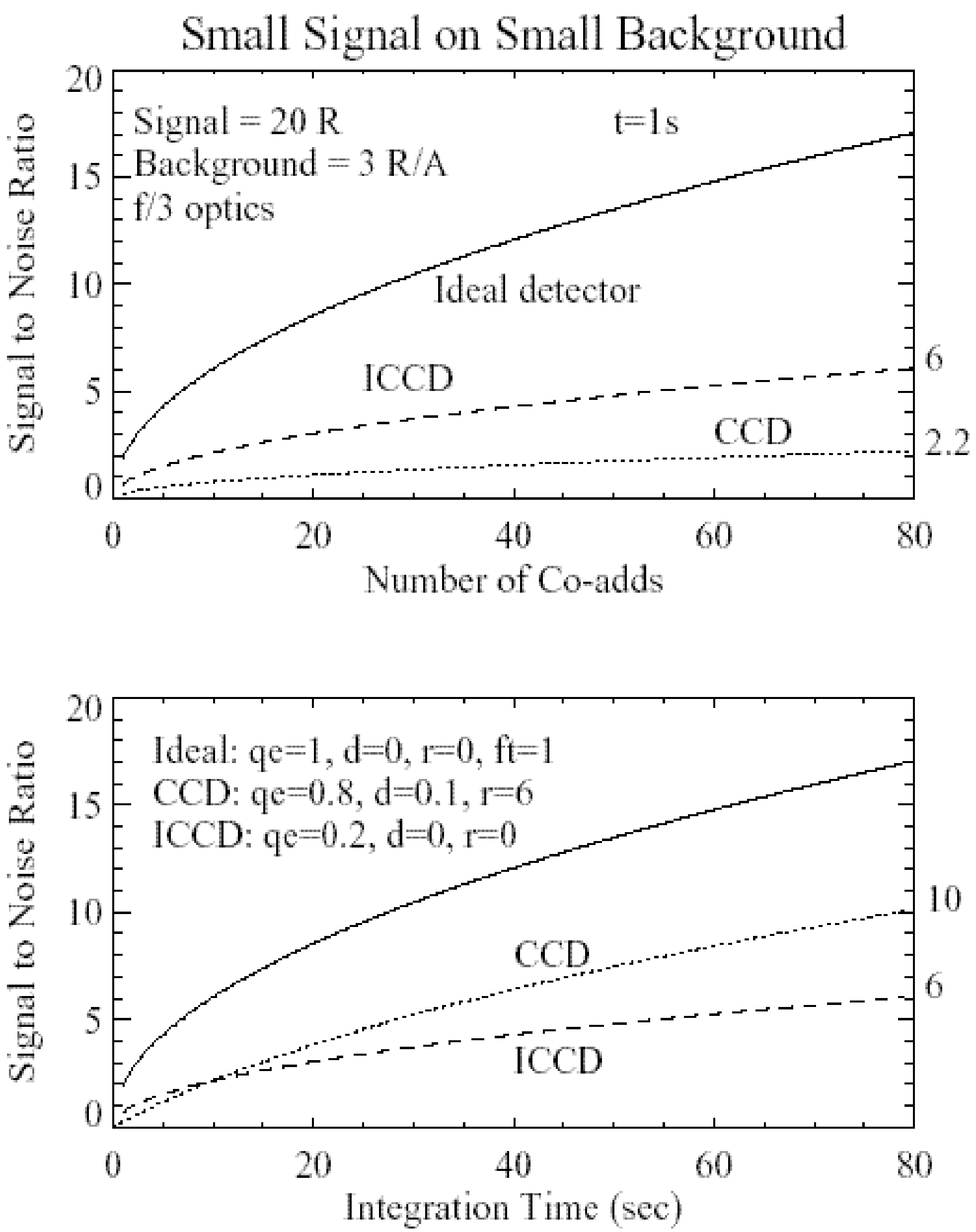
1. Small signal on small background (ex. Geocorona or proton aurora) s= 4-20R; bg=3R/Å



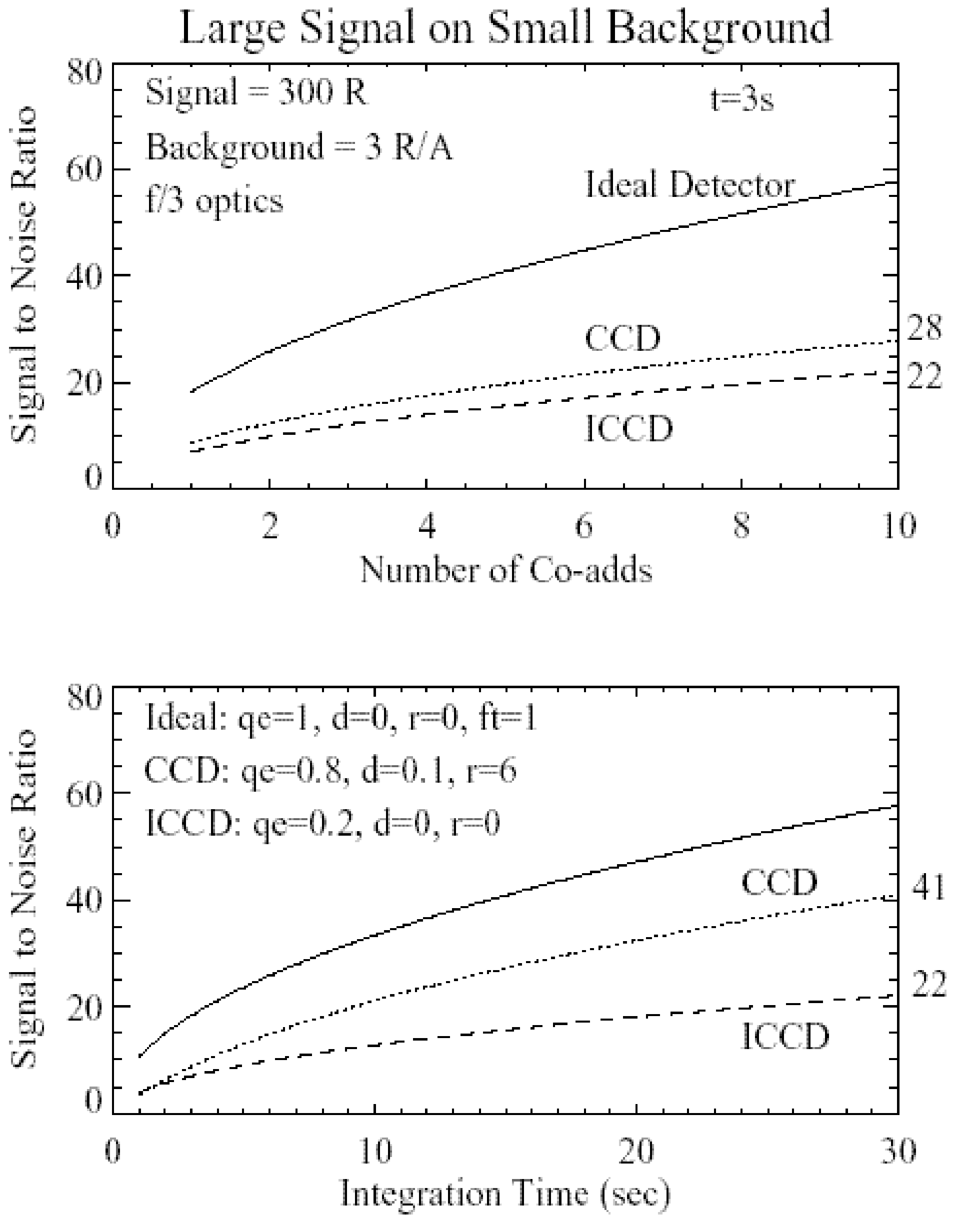
Galand et al., 2003

- Read out noise & dark signal affect the SNR.
- ICCD a better option than bare CCD for dynamically varying phenomena.

$$SNR=\frac{S}{\sqrt{(S+B)+D+R}}$$



2. Large signal on small background (ex. Nighttime emissions) s= 300R; bg=3R/Å



Both read out noise & dark signal affect the SNR.

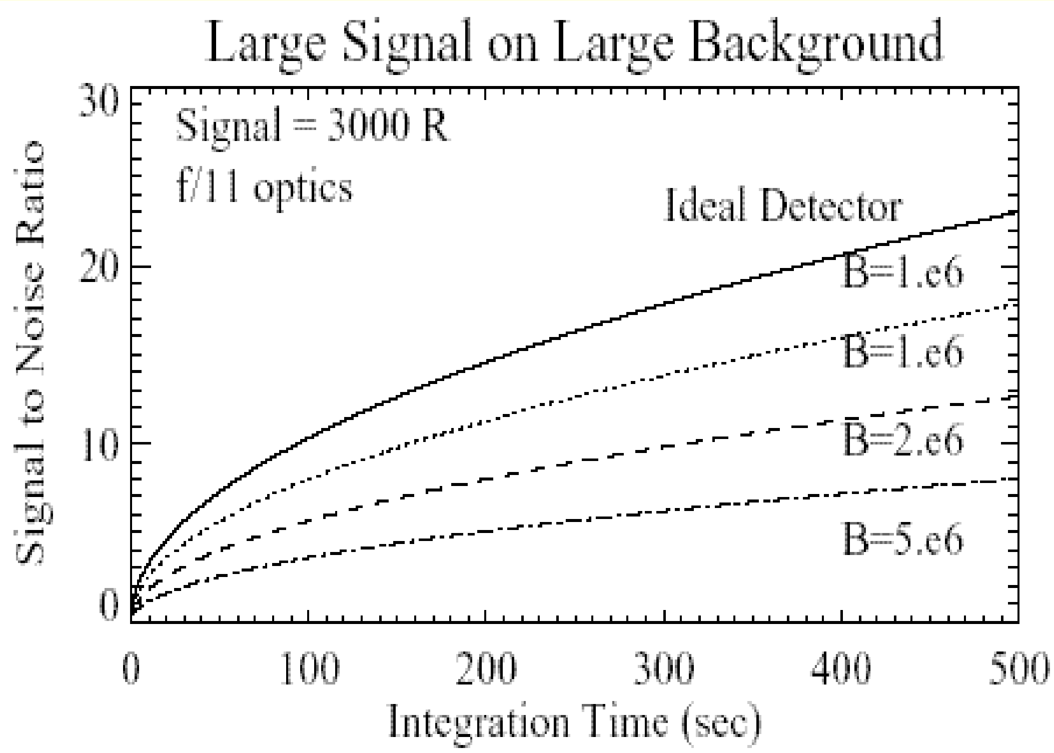
- Bare CCD to be used with large integrations.
- ICCD still useful for observing dynamically varying phenomena.

$$SNR = \frac{S}{\sqrt{(S+B)+D+R}}$$

3. Large signal on large background (ex. Daytime or twilighttime emissions) s= 3 kR; bg=1-5 MR/Å

$$SNR = \frac{S}{\sqrt{(S+B) + \cancel{D} + \cancel{R}}}$$

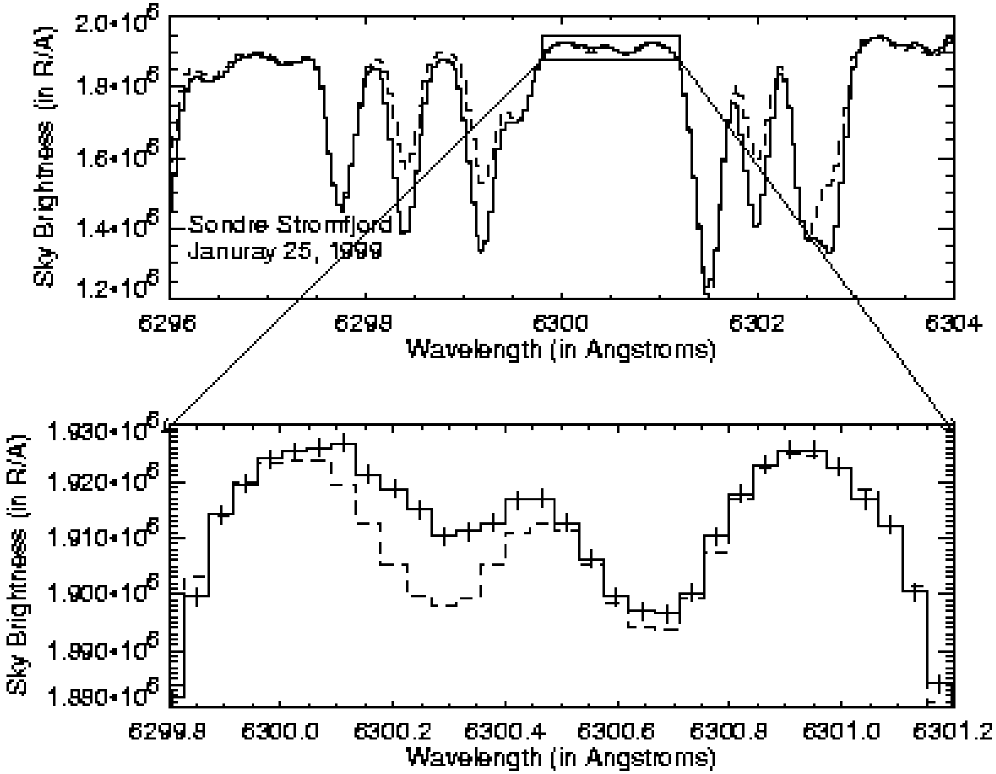
- SNR is limited by photon statistics.
- Read out noise & Dark noise DONOT affect the SNR.

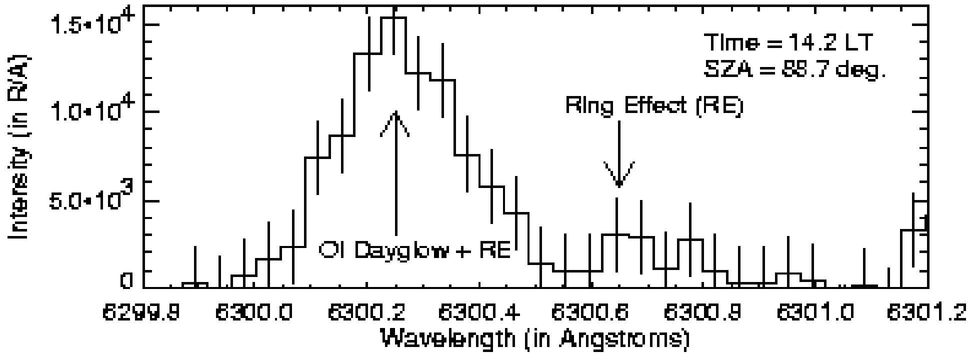


Ring effect: Filling-in of Solar Fraunhofer lines due to scattering by earths atmospheric gases: Needs to be accounted for.

Application of SNR Relation

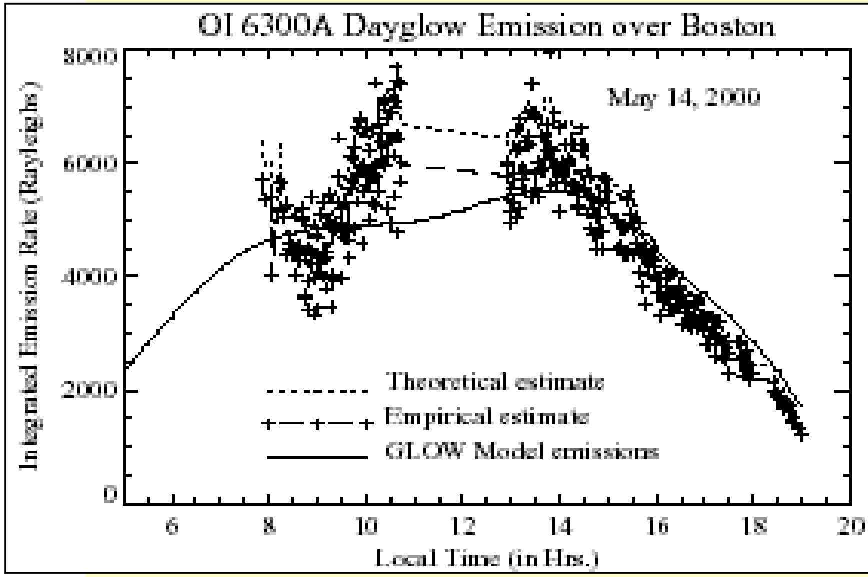
Example: HIRISE data

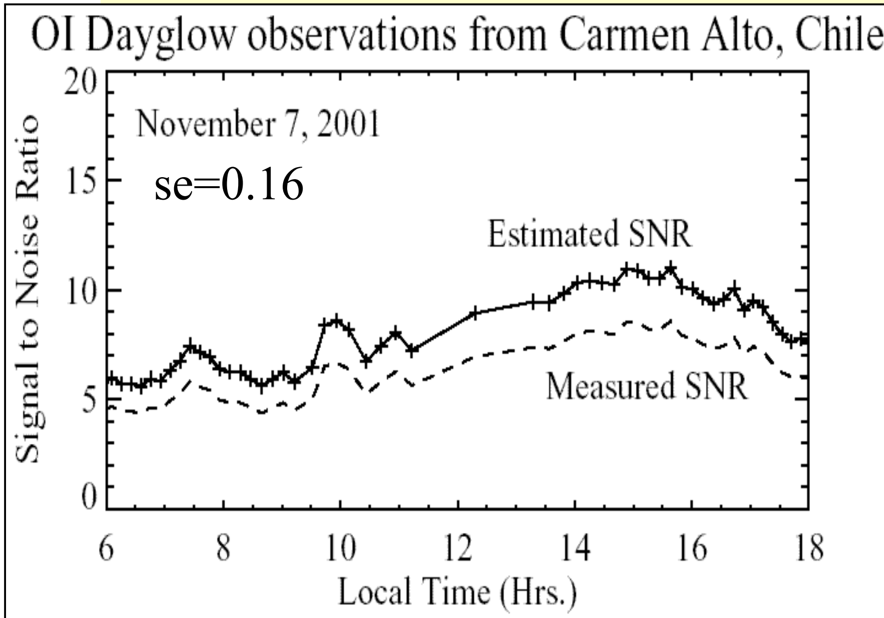




Pallamraju et al., 2001; JGR

Ring effect:
Pallamraju et al., 2000; GRL





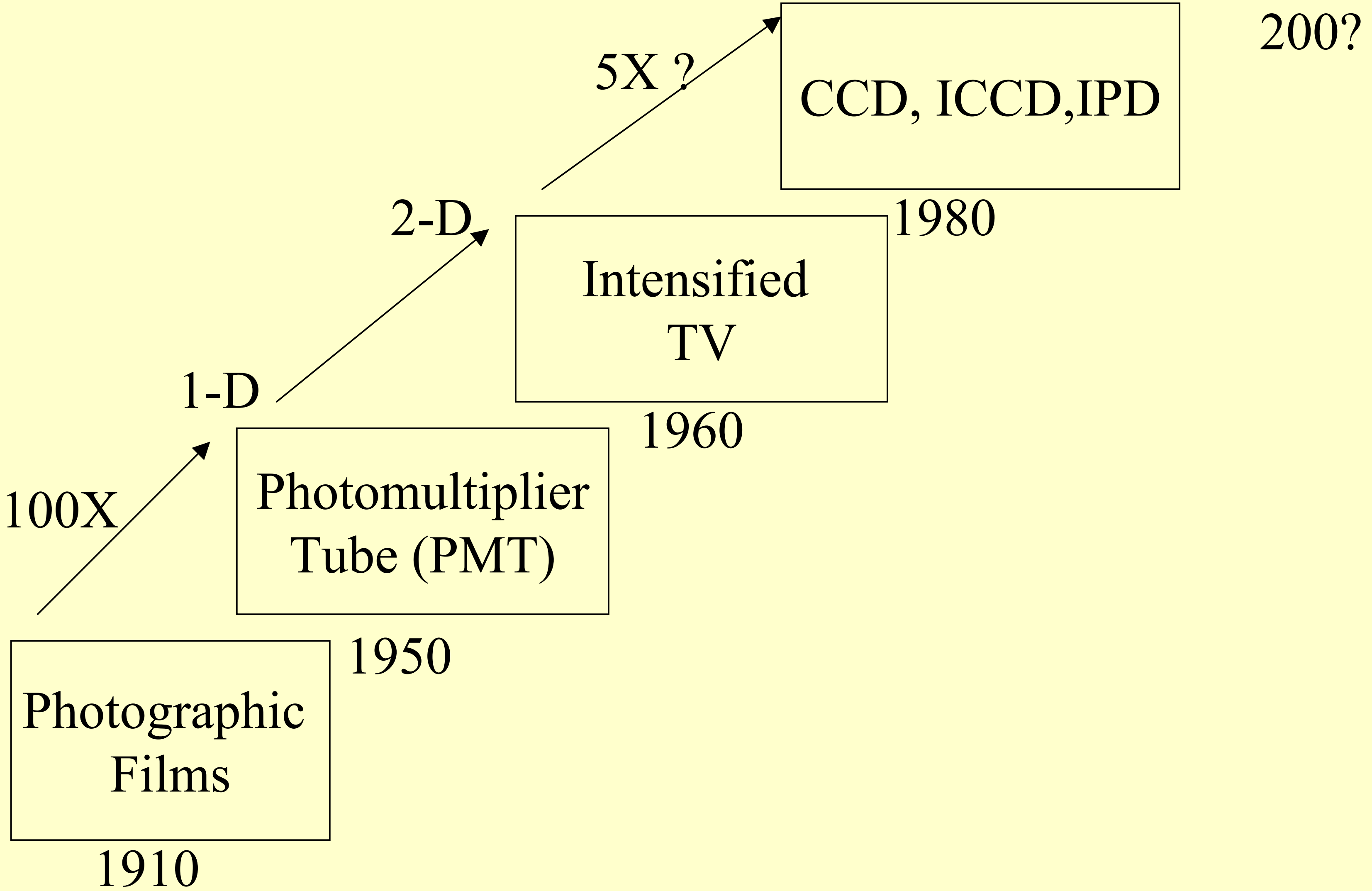
Future Requirements

- CCDs with:

Zero read noise!

Small pixel sizes

- Better filters



200?

CCD, ICCD,IPD

1980

5X ?

Intensified
TV

1960

2-D

Photomultiplier
Tube (PMT)

1950

1-D

100X

Photographic
Films

1910

Summary

- Airglow & Auroral measurements provide **unique perspective** of the atmospheric behavior.
- **Atmospheric transparency** is the major unknown for the nighttime emissions.
- **Statistical fluctuation** of photon noise is the major factor for daytime measurements.
- **Periodic calibrations** help correct systematic errors.
- Random errors can be reduced by:
  - large **time integrations**, **binning** more pixels and more **co-adds,** and
  - more **sensitive detectors**.