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Continuum observations

Total Intensity and Polarisation

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What are continuum observations meant for?

- To measure the bulk of the radio emission
  - energy density content
  - spectral behaviour
  - understanding emission processes
  - understanding object physics

- Synchrotron emission
- Free-free emission
- Thermal emission: starbursts galaxies (high freq: 20+ GHz)

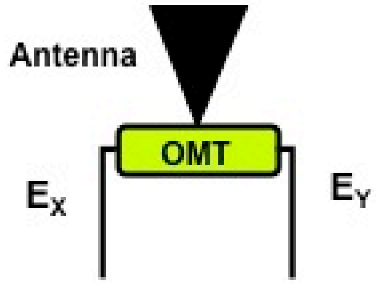
- high sensitivity (broadband)
- faintest radio sources

Radiometer offset

- The total power signal is the auto-correlation of each polarisations.

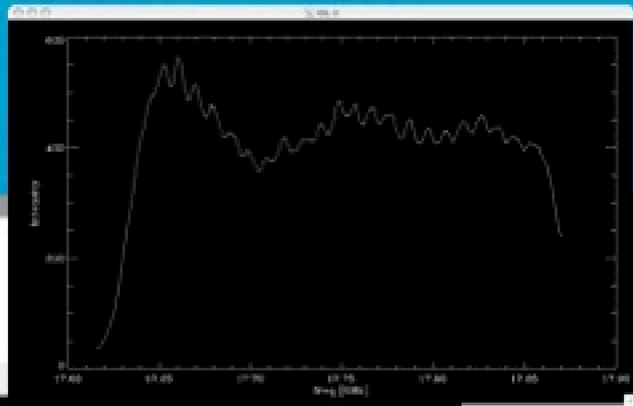
$$I = XX^* + YY^*$$

$$I = LL^* + RR^*$$

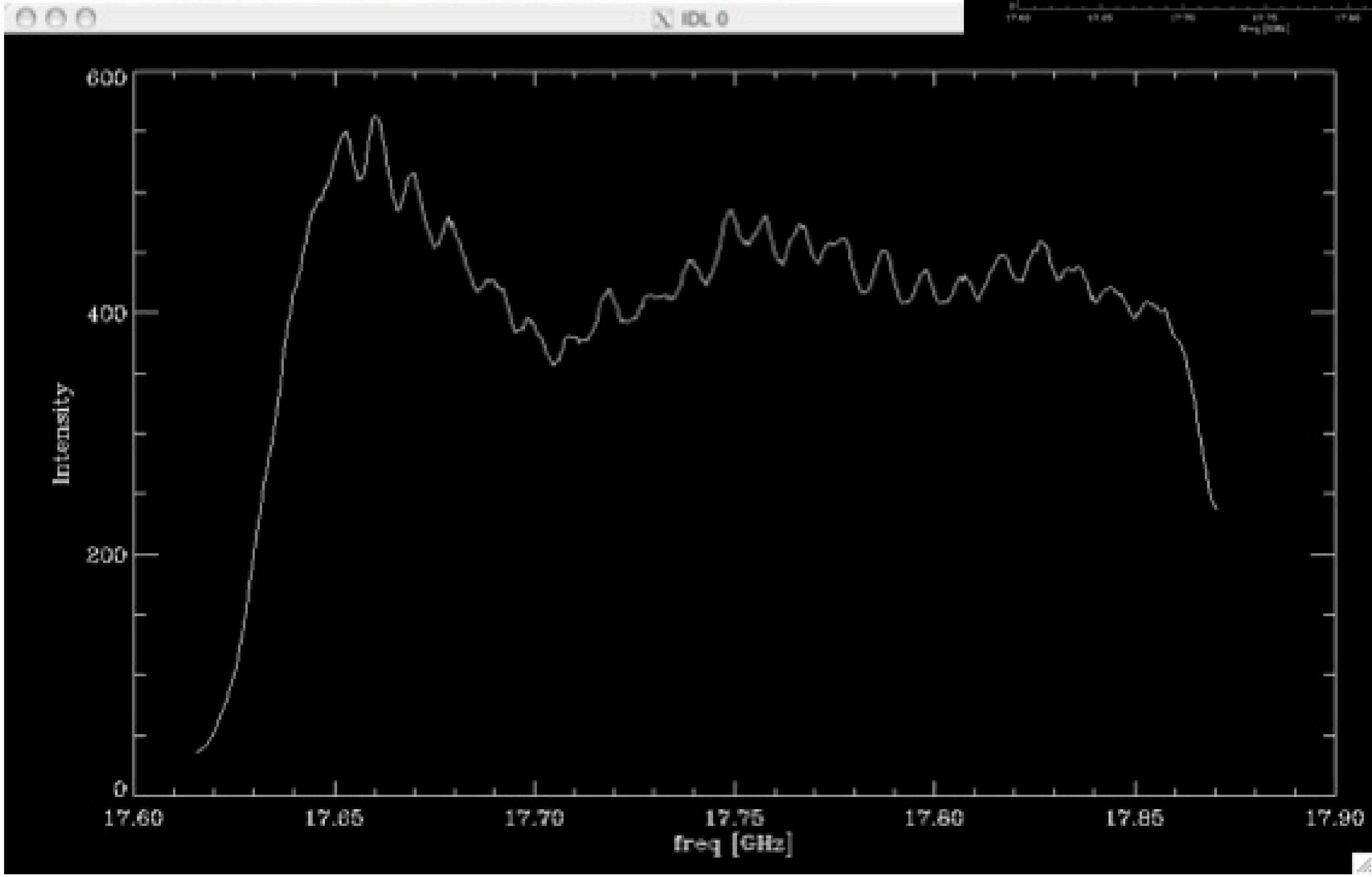


- Autocorrelation: also the noise is detected.

Radiometer offset



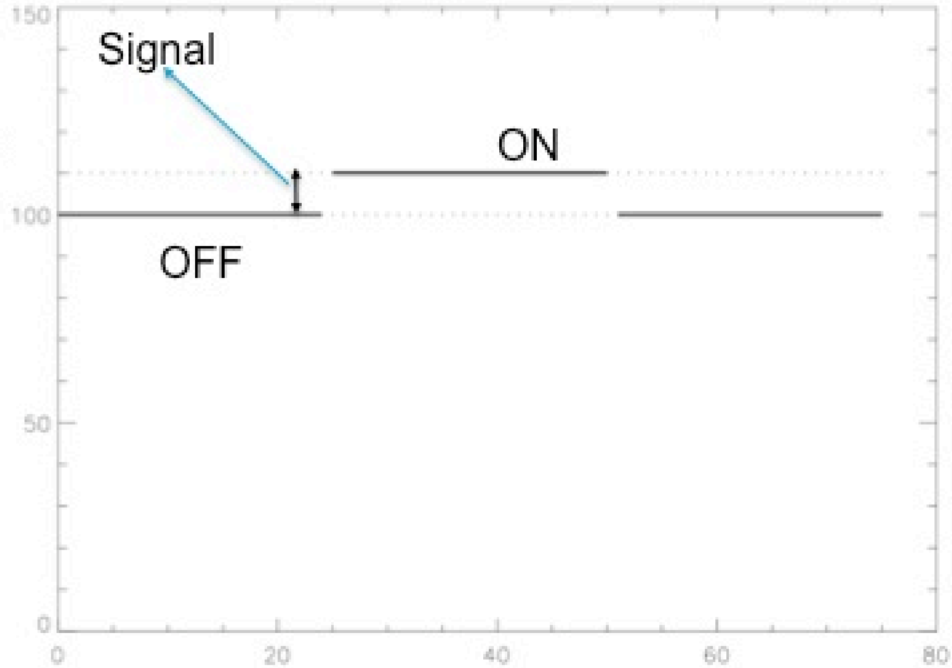
- The total power signal is non-zero.



Signal-offset separation

- Position switching
- It consists of at least two observations, one on-source, one off-source. The radiometer offset is common, and the subtraction gives the source signal:
  - off-source => $S_1 = S_{off}$
  - on-source => $S_2 = S_{src} + S_{off}$

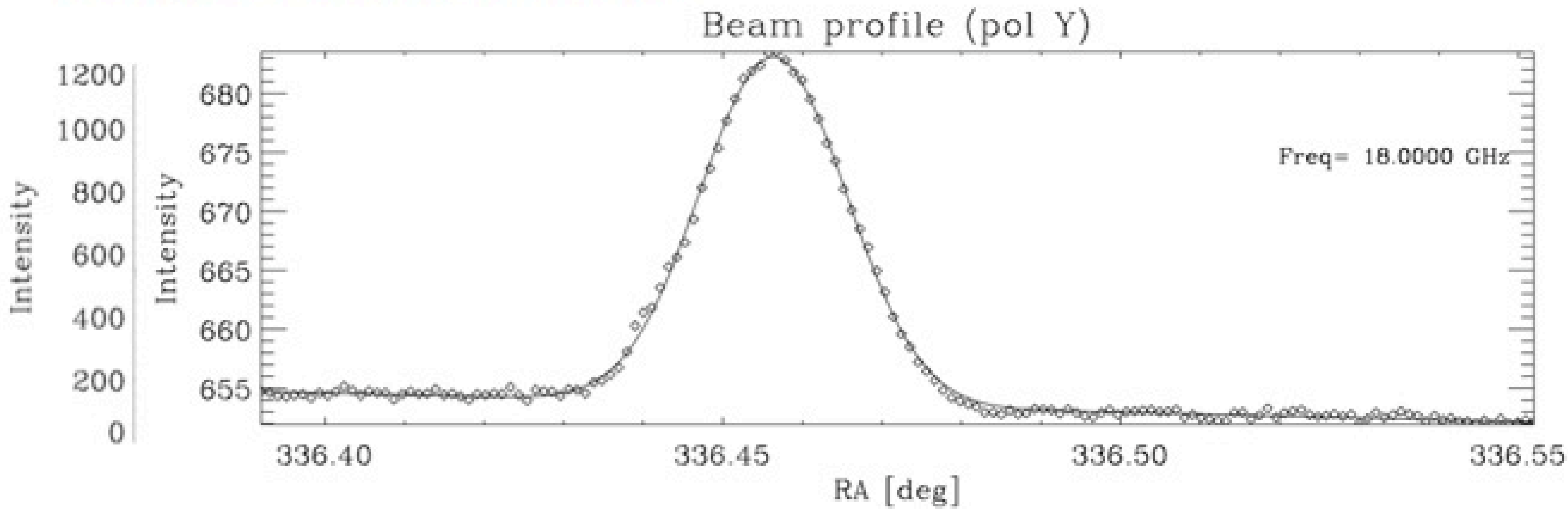
    - $S_{src} = S_2 - S_1$



- Atmospheric emission can depend on Elevation (EL)
  - preferred off position: AZ

Signal-offset separation

- On-The-Fly scanning (OTF)
- scan through the source
- fitting with beam shape (Gaussian) + polynomial baseline (linear) allows to separate source from offset/background emission.
- linear => variations with EL



Sensitivity Equation

- Receiver Sensitivity Equation:

$$\sigma = k \frac{T_{sys}}{\sqrt{BW * \tau}}$$

  - BW = bandwidth
  - τ = integration time
  - k ~ 1 (depends on the receiver architecture type. k=1 for TI)

- T_{sys} => quality of the receiver (LNAs, cryo, reflector, feed IL)

- BW => the broader, the better => continuum observations

Integration Time

$$\sigma = k \frac{T_{sys}}{\sqrt{BW * \tau}}$$

- τ => long integration time, better sensitivity

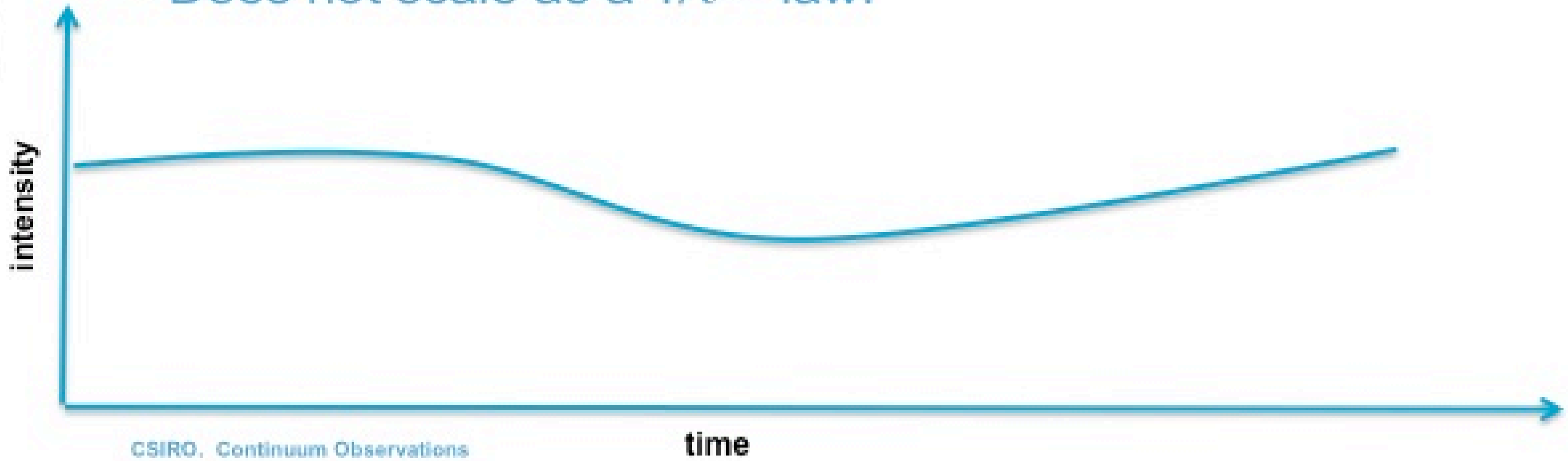
- Is it true?
- Is long integration time always good?

Real Sensitivity Equation

- Amplifiers (LNA) are active components => Gain fluctuations

$$\sigma = k * T_{sys}\sqrt{\frac{1}{BW * \tau} + \left(\frac{T_{off}}{T_{sys}}\frac{\Delta G}{G}\right)^2}$$

- Additional noise $\Delta G/G$:
  - 1/f noise (after its spectral properties).
  - Toff = Tsys (for total intensity)
- Does not scale as a $1/\tau^{1/2}$ law.



Gain Fluctuations

- Total Intensity observations have offsets, signal which is generated either internally or collected by the telescope:
  - internal noise (i.e. Tsys, either LNA noise or feed system)
  - atmosphere
  - ground emission
  - background emission (e.g., CMB => 3K)
- it runs from ~20K (e.g. L-band MB-20) to ~200K (e.g. 90GHz)

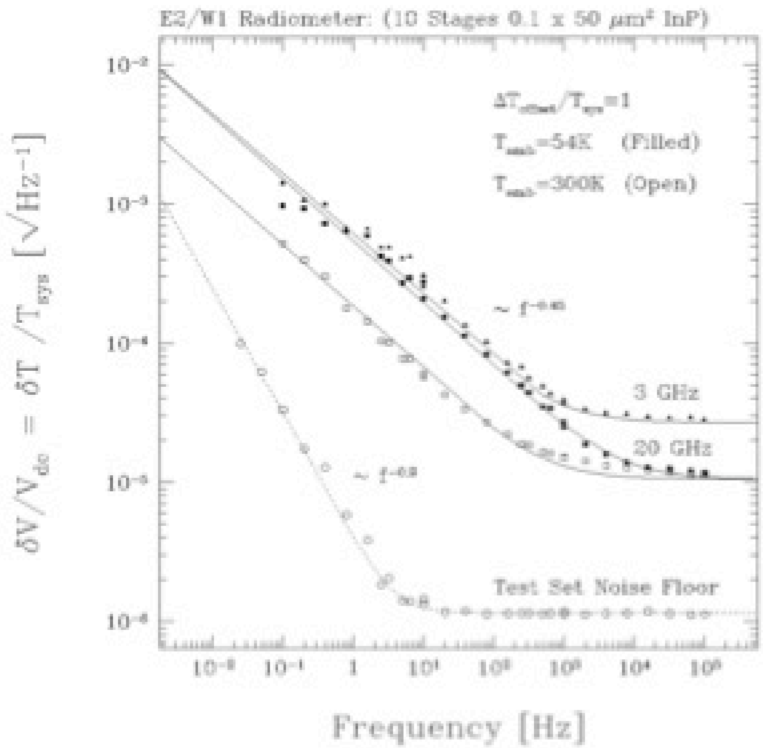
- Gain fluctuations of active components (e.g. LNAs) make this background to vary: even small fluctuations of a 20+ K background can jeopardise detection of ~mK signals.
- it is particularly important for Continuum obs (high sensitivity required)

1/f noise

- noise spectrum (receiver detected output)
  - Normal (ideal) white noise has flat spectrum: $P(f) = \sigma_0^2$
  - σ_0^2 = sensitivity for integration time of 1 sec
  - Gain fluctuations add a steep inverted component $P(f) \propto 1/f$

- Total spectrum:

$$P(f) = \sigma_0^2 \left(1 + \frac{f_{knee}}{f} \right)$$



1/f noise

- Total spectrum:

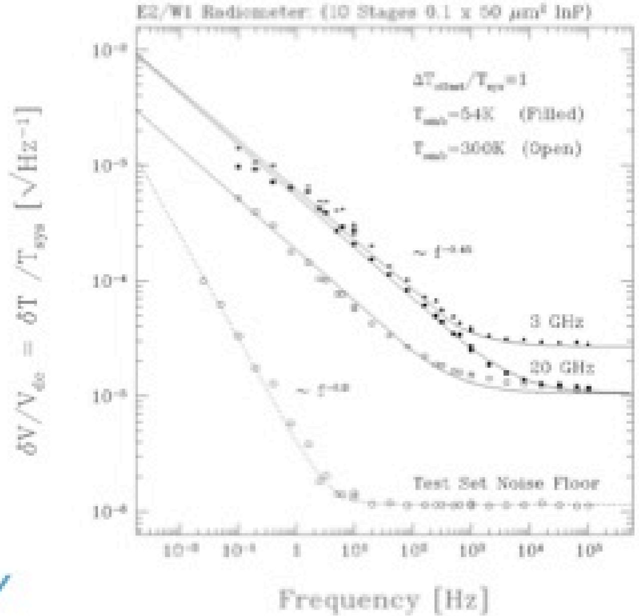
$$P(f) = \sigma_0^2\left(1 + \frac{f_{knee}}{f}\right)$$

  - key parameter => f_{knee} => 1/f equals white noise
  - $\tau_{knee} = 1/f_{knee}$ => transition time between the two ranges

- sensitivity:

$$\sigma^2(\tau = 1/f) \approx f * P(f)$$

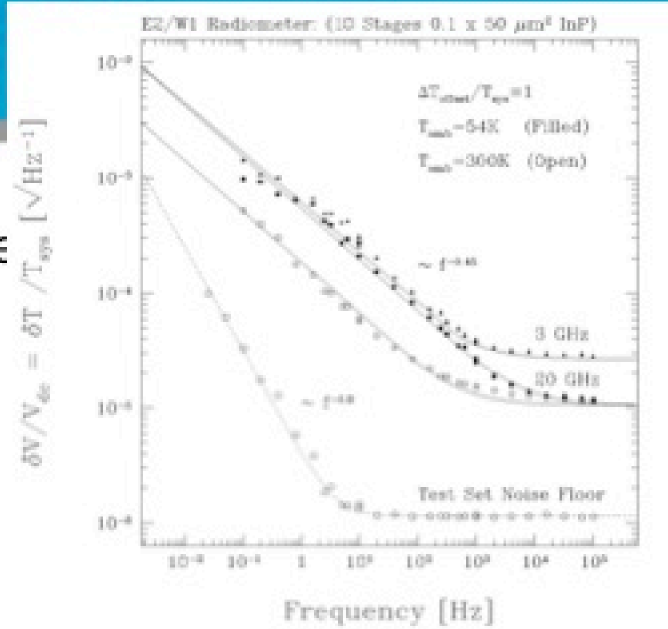
  - white noise: $\sigma_{wn}^2 \approx \sigma_0^2 * f \approx \sigma_0^2 / \tau$
  - 1/f noise: $\sigma_{1/f}^2 \propto f / f = const$



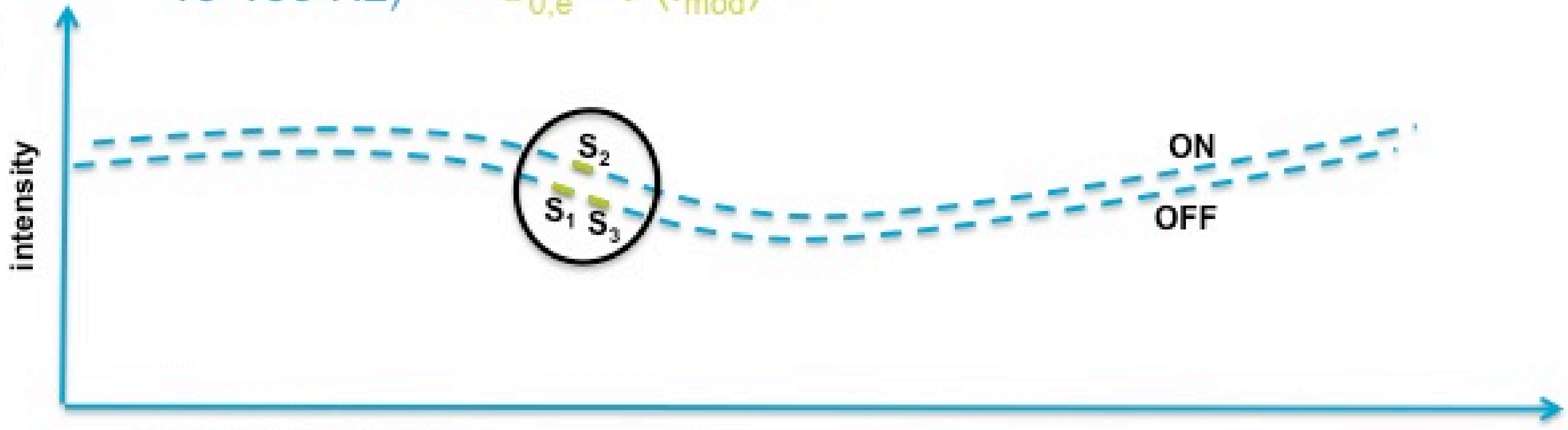
- for $\tau < 1/f_{knee}$ => NO GAIN IN SENSITIVITY

Position Switching

- if position-switching period $\tau_{mod} < 1/f_{knee}$ =>
  - ON and OFF have same behaviour and the
  - Most effective a three way procedure
    - pre off-source => $S_1 = S_{off}$
    - on-source => $S_2 = S_{src} + S_{off}$
    - post off-source => $S_3 = S_{off}$
    - $S_{src} = S_2 - (S_1+S_3)/2$

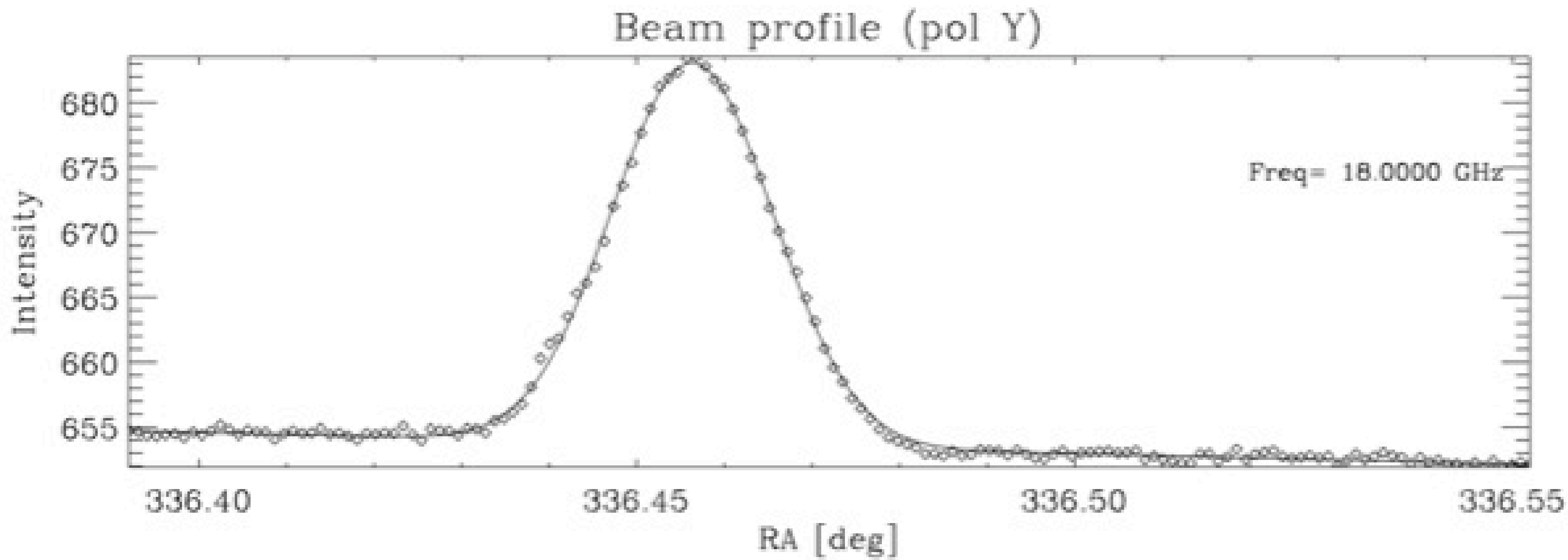


- Sensitivity worsen by a factor 2 (reasonable cost)
- typical scale 1-min: marginally effective for current systems (f_{knee} ~ 10-100 Hz) => $\sigma_{0,e} \sim P(f_{mod})^{1/2}$



source scanning

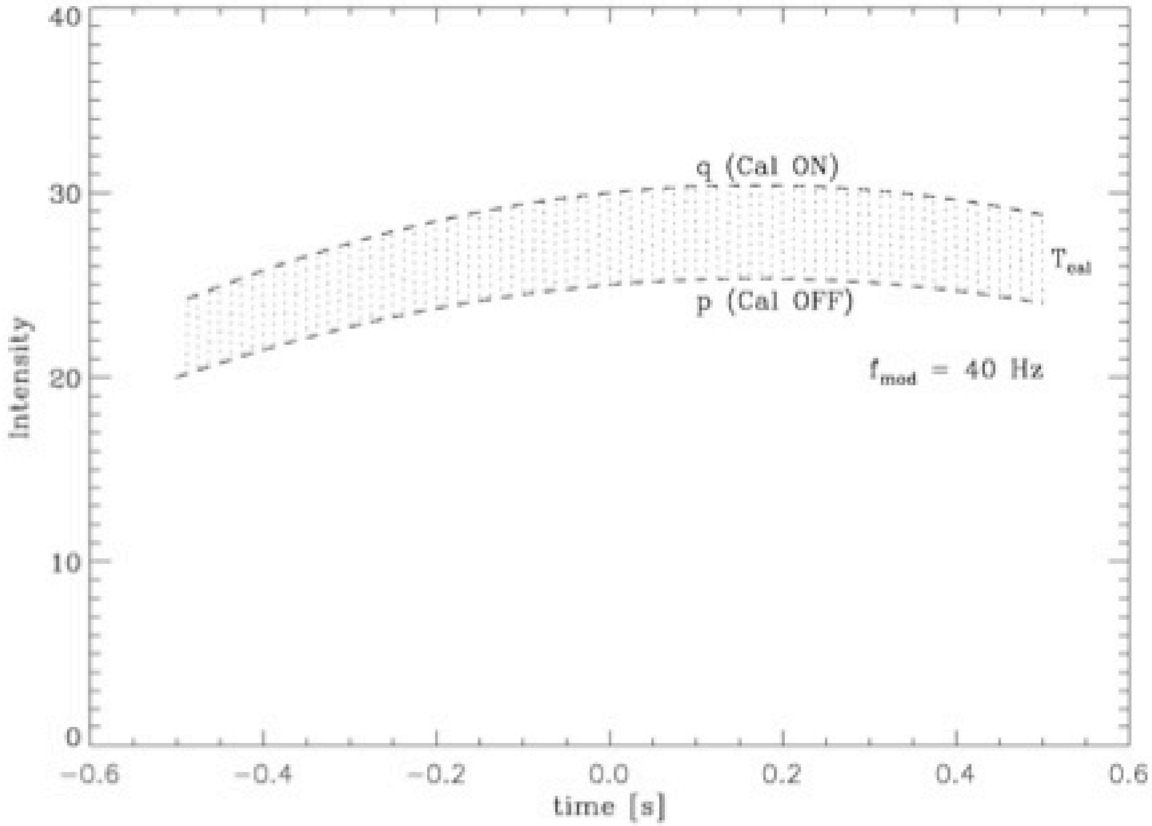
- baseline fitting allows accounting for the Gain fluctuations
- τ_{mod} similar to pos. switch. (slow method)
- same issue: $\sigma_{0,e} \sim P(f_{mod})^{1/2}$



Gain rectification by Calibration signal modulation (1)

- measuring the gain by modulating the signal: periodically firing a known calibrated signal with sufficient time resolution ($\tau_{mod} < \tau_{knee}$).
- rectifying the data
  - calibrated signal

$$S = \frac{T_{cal}}{q - p} p$$



Gain rectification by Calibration signal modulation (2)

- Requirements:
- high frequency cal modulation:
  - $\tau_{mod} < \tau_{knee}$ => typical: ~10-100 Hz
  - at feed level and firing signal modulated with a pin-diode switch
- increased noise $$\sigma_{cal} = 2\sigma \frac{\sqrt{1 + f + f^2/2}}{f}$$ $$f = \frac{T_{cal}}{T_{sys}}$$
- example
  - T_{sys} = 20K
  - T_{cal} = 1K
  - f << 1 => $\sigma_{cal} \approx \frac{2}{f}\sigma$ => $\sigma_{cal} \approx 40\sigma$
- high cal signal $$f = \frac{T_{cal}}{T_{sys}} \geq 1$$
  - f=1 => $\sigma_{cal} = \sqrt{10} \cdot \sigma$
  - f >> 1 => $\sigma_{cal} = \sqrt{2} \cdot \sigma$

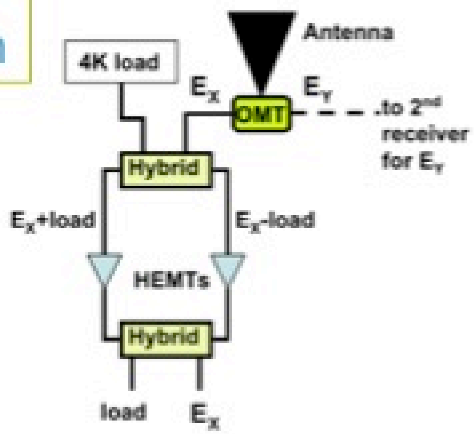
Pseudo-correlation

$$\sigma = k * T_{sys}\sqrt{\frac{1}{BW * \tau} + \left(\frac{T_{off}}{T_{sys}}\frac{\Delta G}{G}\right)^2}$$

- Receiver architectures to reduce offset:

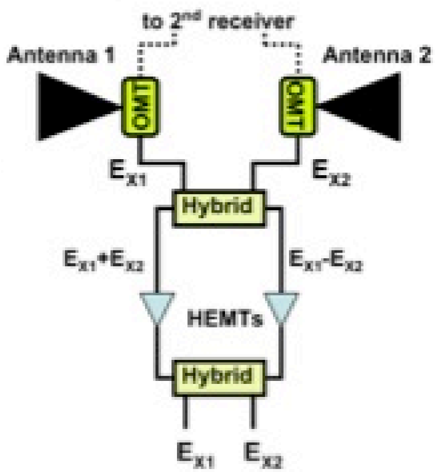
Pseudo-correlation

PLANK-LFI



$S = |E_X|^2 - |load|^2$

WMAP



$S = |E_X|^2 - |E_Y|^2$

Differential

Polarisation(1)

- Polarisation continuum observations are better suited
- Correlated outputs.

- Linear polarisation receiver

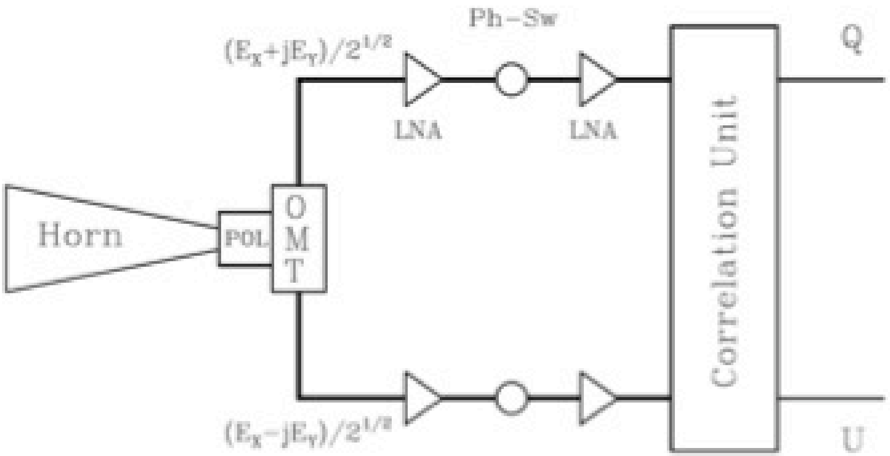
$$Q = |X|^2 - |Y|^2$$
$$U = \Re(XY^*)$$
$$V = \Im(XY^*)$$

- Q is a total power output => 1/f noise
- Not ideal for linear pol observations (Stokes Q & U)

Polarisation(2)

- Circular polarisation receiver:

$$Q = \Re\left(RL^*\right)$$
$$U = \Im\left(RL^*\right)$$
$$V = |R|^2 - |L|^2$$



Polarisation: cross-correlation

- How does cross-correlation reduce the 1/f noise?

$$Q = \Re\left(RL^*\right)$$
$$U = \Im\left(RL^*\right)$$
$$V = |R|^2 - |L|^2$$

- Noise generated by the two LNAs are uncorrelated
- Noise generated by the feed in the two polarisations is uncorrelated.
- Cross-correlation has virtually no-offset

$$\sigma = k * T_{sys}\sqrt{\frac{1}{BW * \tau} + \cancel{\left(\frac{T_{off}}{T_{sys}}\frac{\Delta G}{G}\right)^2}}$$

- Circular pol receiver: ideal for linear pol observations (Q & U)

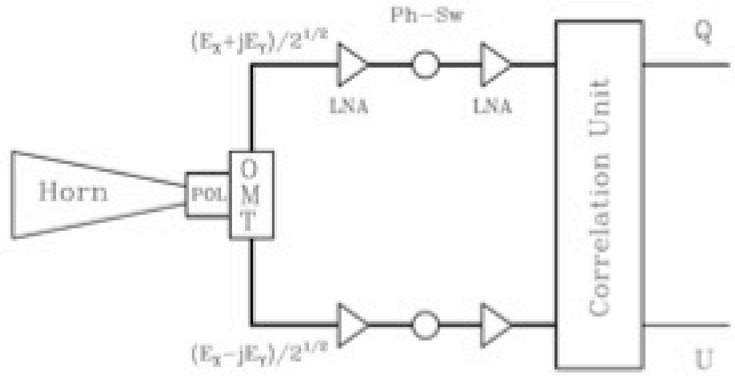
Polarisation: Stokes V

- Linear pol receiver: ideal for Stokes V observations

$$Q = |X|^2 - |Y|^2$$
$$U = \Re\left(XY^*\right)$$
$$V = \Im\left(XY^*\right)$$

Instrumental Polarisation

- Zero offset is the ideal case
- Leakages between the two polarisations make the noise partly correlated.
- The unpolarised sky and ground emission too
- Instrumental polarisation
- However T_{offset} << Tsys: Correlation receiver is much more stable than a total power one.



Instrumental Polarisation(2)

- How much more stable?

$$f_{knee} \propto \left(\frac{T_{off}}{T_{sys}}\right)^2$$

- instrumental pol P/I ~ 1% => $f_{knee,pol} \sim 10^{-4} f_{knee,TP}$
- instrumental pol P/I ~ 3% => $f_{knee,pol} \sim 10^{-3} f_{knee,TP}$

- => τ_{knee} ~ 100-1000s
- usually sufficient for radioastronomical applications

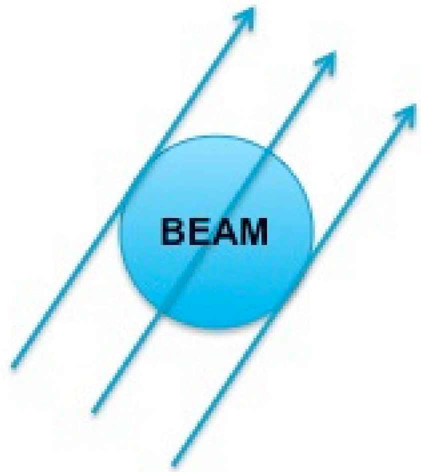
Mapping

- 1 receiver => 1-pixel
- a few receivers, if you are lucky (e.g. Parkes Multi Beam 20cm)

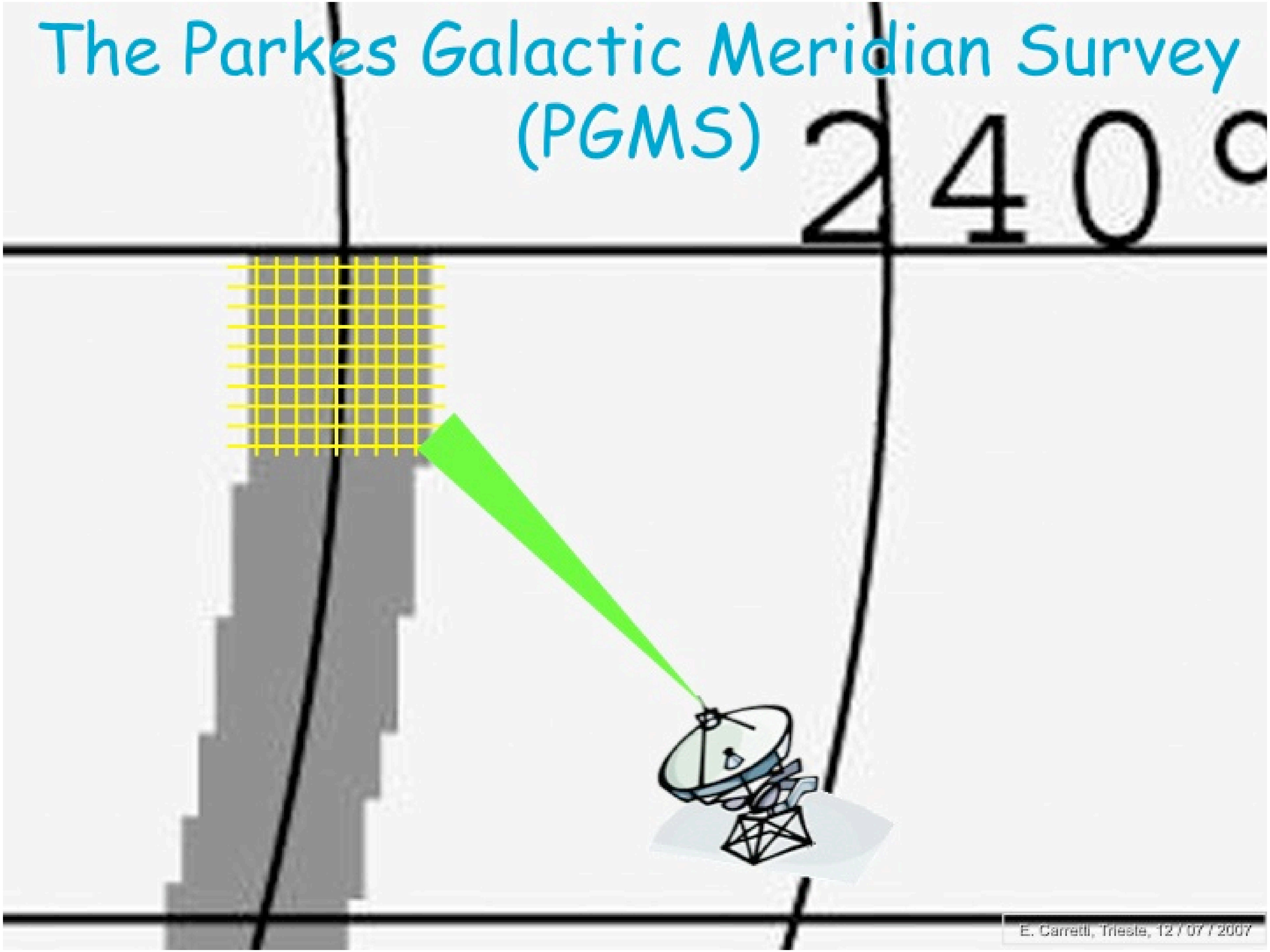
- imaging is not an option (e.g., optical or interferometry)

- mapping => scanning

- area is mapped with a grid of scans spaced to ensure full sampling
  - 2+ scans per FWHM
  - 3 scans per beam is best



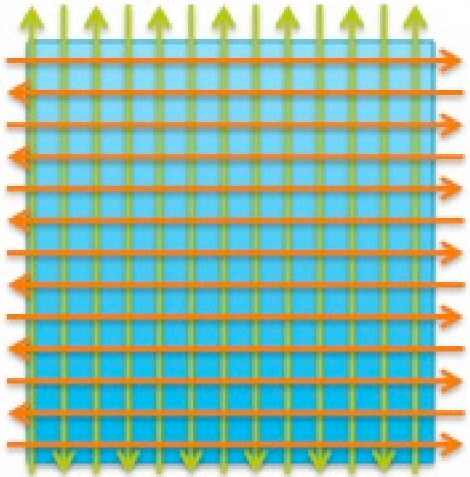
The Parkes Galactic Meridian Survey (PGMS)



E. Carretti, Trieste, 12 / 07 / 2007

Mapping

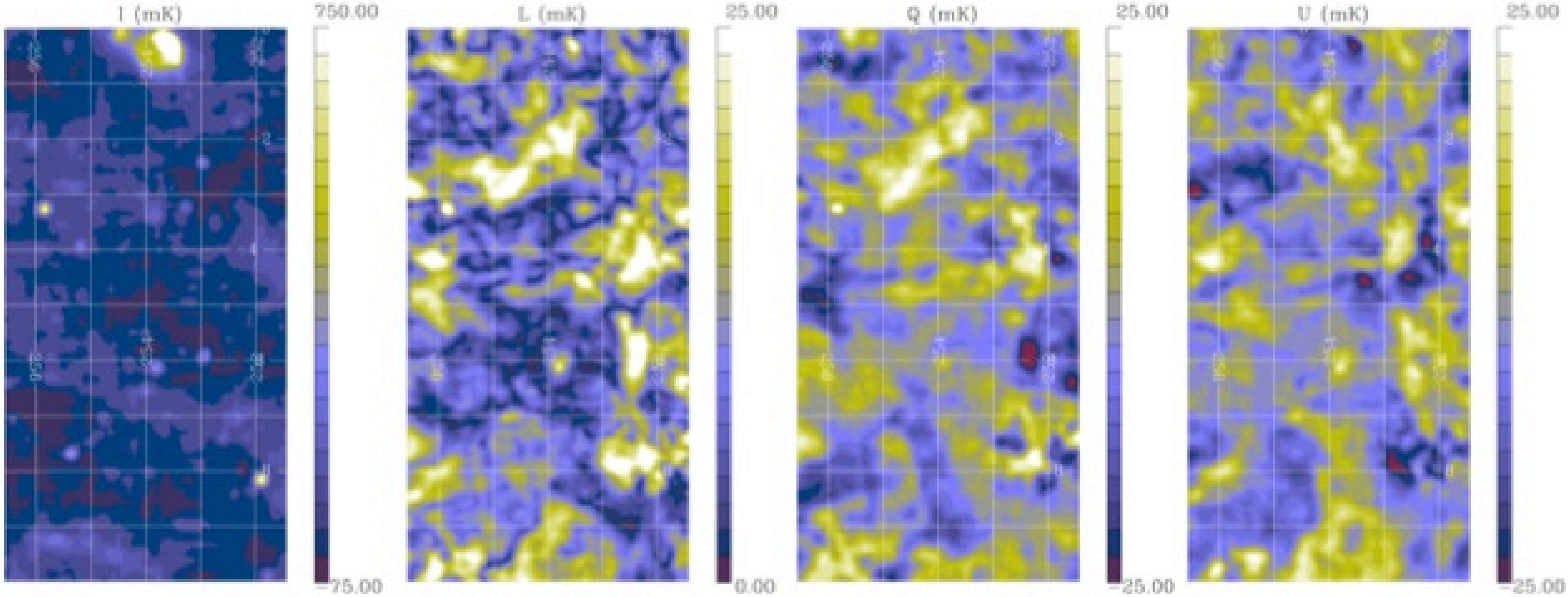
- offset: both for Total Intensity and Polarisation => baseline remove
- Scans conducted in a Sky coordinate system (Equatorial, Galactic)
- offset Variable with EL
- linear baseline remove
  - loss of signal along the orthogonal direction
- two full sets of scans along orthogonal directions (Basket-waving)



- scan sets combined off-line to recover full-scale information
  - Fourier Methods (e.g., Emerson & Graeve 1988)
  - Destriping algorithms (e.g., Delabrouille 1998, Sbarra 2003)
- Mean and gradient are lost (sufficient if area contains all the intended source)

Mapping: examples

- Maps of the PGMS (Parkes Galactic Meridian Survey)



Carretti et al 2009

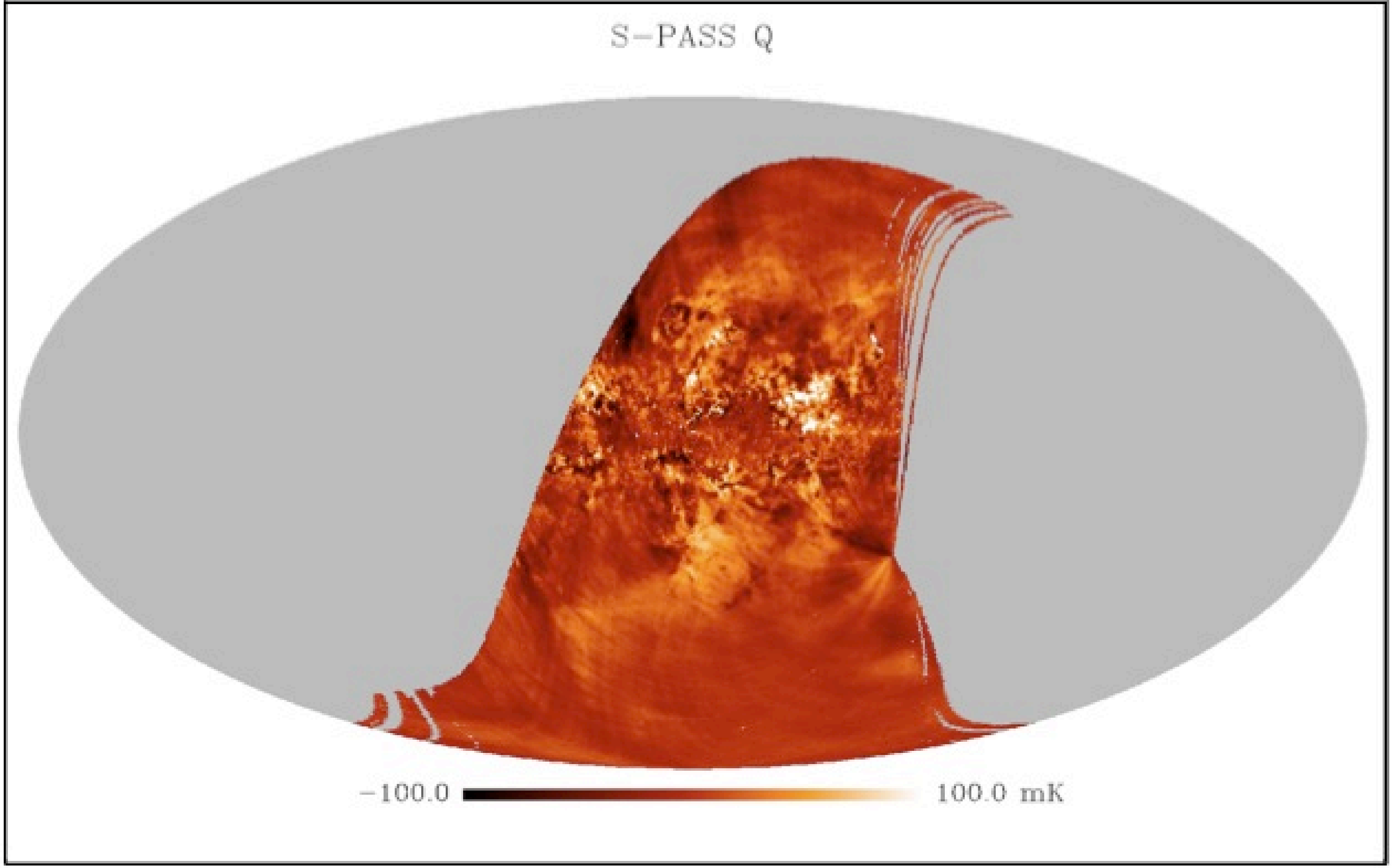
Mapping: All-sky class surveys

- All-sky class surveys:

- basket waving technique is an option
  - sky sub-divided in smaller areas then combined

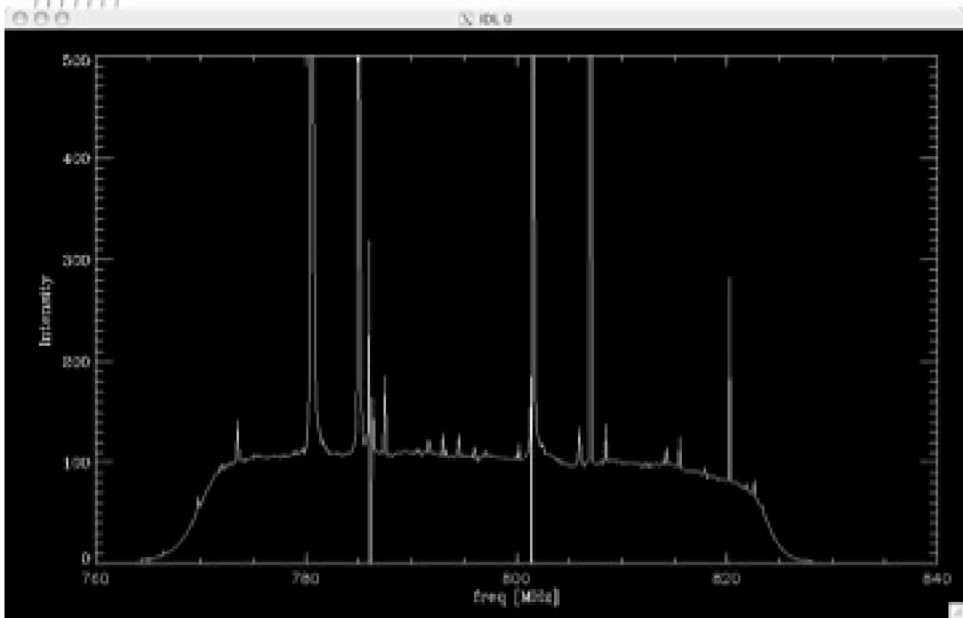
- Most efficient are some exotic/non-standard scanning strategies (Not offered by all telescopes. Parkes does)
  - AZ (EL) scans.
  - Long AZ scans to cover all Dec in one haul
  - uses the Sky rotation to observe all RA 24 hrs.   (Video)
  - each day/night a zig-zag track is observed in the sky
  - one zig-zag per night: accurate start timing is required

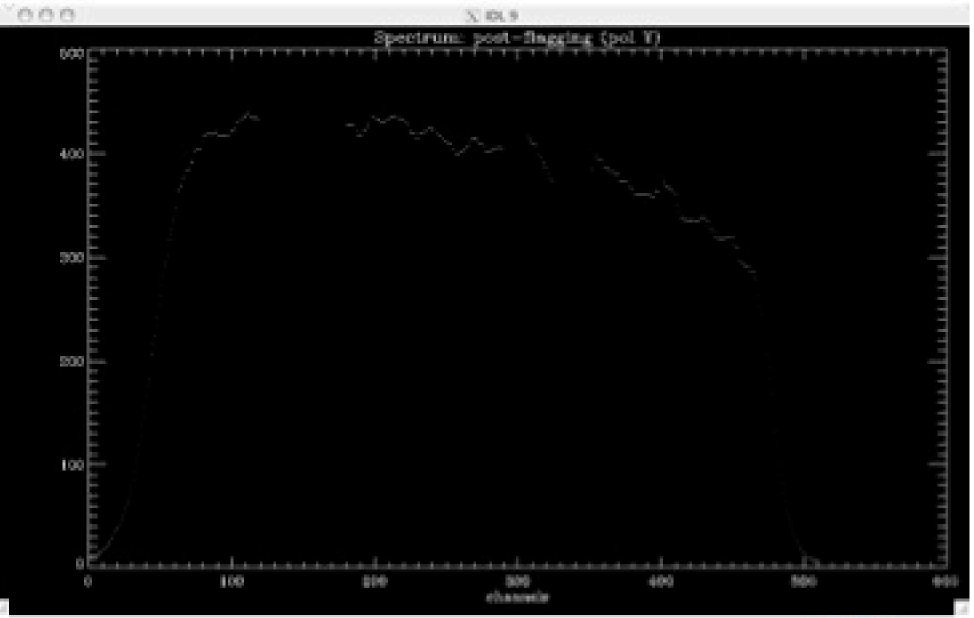
Mapping: All-sky class surveys



Spectral observations

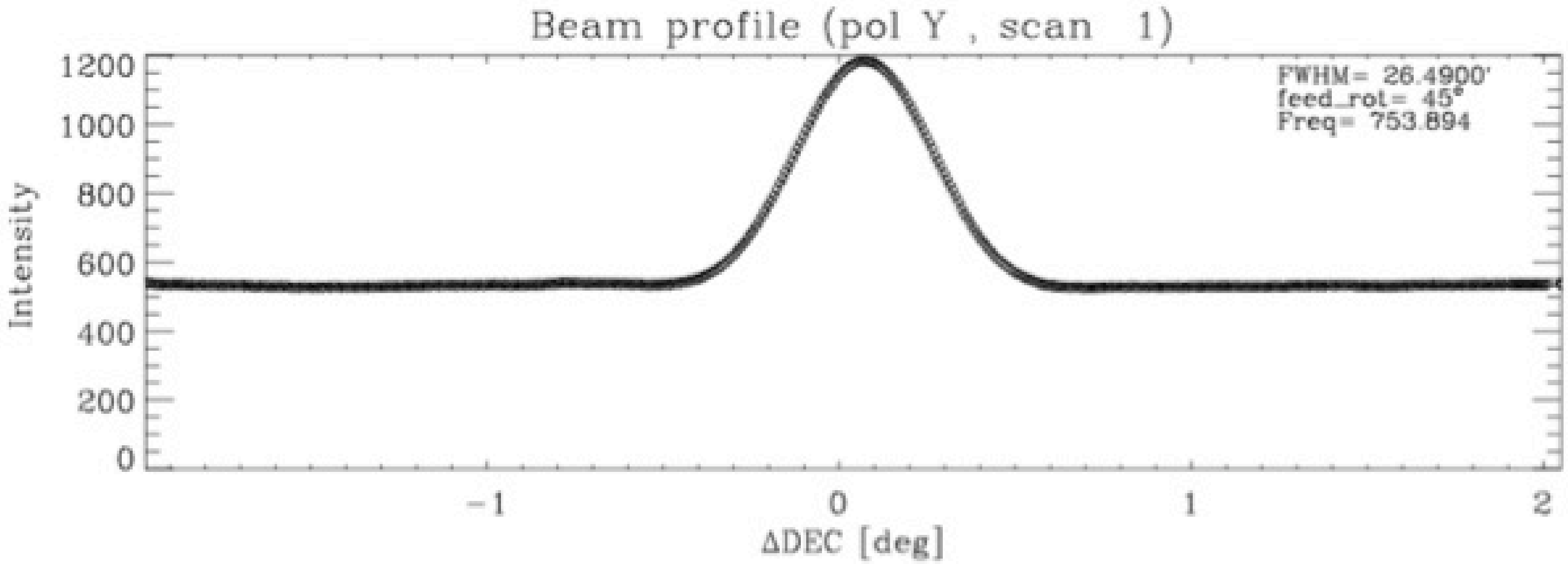
- Spectral observations with high frequency channel isolation (e.g. DFB3 => 65dB)
  - Strong RFI pollution => broad bands possible only flagging bad chan.
  - Spectral information + Rotation Measure (spectro-polarimetry)
- Now easily available with digital backends (Willem talk)





Basics on Calibration: Flux

- Scan over a strong flux calibrated source
- To measure the gain K = Jy/cnts



Basics on Calibration: Instrumental polarisation

- Scan over an unpolarised source
- To measure the fractional polarised response:

$$f_Q = Q_{inst} / I$$
$$f_U = U_{inst} / I$$
$$f_V = V_{inst} / I$$

- To correct the measured data

$$Q = Q_m - f_Q I$$
$$U = U_m - f_U I$$
$$V = V_m - f_V I$$

Basics on Calibration: polarisation angle

- Q and U measured as cross-product:

$$Q = \Re\left(RL^*\right)$$
$$U = \Im\left(RL^*\right)$$

- Any phase difference ϕ add an instrumental pol angle
  - $\Delta\alpha = \phi/2$
- Scan over a polarisation calibration of intrinsic polarisation angle α_0 to measure the phase error
  - $\phi = \tan^{-1}(Q_m/U_m) - 2\alpha_0$
- Similar considerations hold for Stokes V (linear polarisations)

Basics on Calibration: Mueller matrix

- Most complete calibration of polarisation leakages:

$$\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = M \begin{pmatrix} I_m \\ Q_m \\ U_m \\ I_{Vm} \end{pmatrix}$$

- In case of the calibration described earlier:

$$M = \begin{pmatrix} 1 & 0 & 0 & 0 \\ f_Q & \cos(\phi/2) & \sin(\phi/2) & 0 \\ f_U & -\sin(\phi/2) & \cos(\phi/2) & 0 \\ f_V & 0 & 0 & 1 \end{pmatrix}$$

Key points to plan a continuum obs

- Offset: to be estimated and removed
- Total intensity: 1/f noise kills sensitivity => signal modulation
- Polarisation: correlation kills 1/f noise => long integration times
- Polarisation: chose receiver type according to what you need:
  - Q & U => circular polarisation receiver
  - V => linear polarisation receiver
- Mapping => scanning (one or few receivers)
- Calibrations => flux and instrumental polarisation effects.

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