Source Noise

John Morgan

Interferometry Meeting
CSIRO Kensington Tuesday 2nd August 2022

Curtin University
International Centre for Radio Astronomy Research

Single Dish

$$\sigma_{on} = \frac{S+N}{\sqrt{B\tau}}; \sigma_{off} = \frac{N}{\sqrt{B\tau}} \quad (1)$$

- Point on source and measure some power
- Point off source and measure some power
- We can use flux density or temperature to describe these quantities (I'll use the former)
  - Source flux density S (e.g. ~ 1000 Jy for Virgo A)
  - SEFD N of a single element (e.g. $\sim 100\,000$ Jy for the MWA)

Power from VirA by the whole MWA $\approx$ system noise of a single tile

Key Point

Noise-like nature of source emission and system noise

Single Dish

$$\sigma_{on} = \frac{S + N}{\sqrt{B\tau}}; \sigma_{off} = \frac{N}{\sqrt{B\tau}} \quad (1)$$

- Point on source and measure some power
- Point off source and measure some power
- We can use flux density or temperature to describe these quantities (I'll use the former)
  - Source flux density S (e.g. $\sim$ 1000 Jy for Virgo A)
  - SEFD N of a single element (e.g. $\sim$ 100 000 Jy for the MWA)

Power from VirA by the whole MWA $\approx$ system noise of a single tile

Key Point

Noise-like nature of source emission and system noise

Single Dish

$$\sigma_{on} = \frac{S+N}{\sqrt{B\tau}}; \sigma_{off} = \frac{N}{\sqrt{B\tau}} \quad (1)$$

- Point on source and measure some power
- Point off source and measure some power
- We can use flux density or temperature to describe these quantities (I'll use the former)
  - Source flux density S (e.g. $\sim$ 1000 Jy for Virgo A)
  - SEFD N of a single element (e.g. $\sim$ 100 000 Jy for the MWA)

Power from VirA by the whole MWA $\approx$ system noise of a single tile

Key Point

Noise-like nature of source emission and system noise

Single Dish

$$\sigma_{on} = \frac{S+N}{\sqrt{B\tau}}; \sigma_{off} = \frac{N}{\sqrt{B\tau}} \quad (1)$$

- Point on source and measure some power
- Point off source and measure some power
- We can use flux density or temperature to describe these quantities (I'll use the former)
  - Source flux density S (e.g. ~ 1000 Jy for Virgo A)
  - SEFD N of a single element (e.g. $\sim 100\,000$ Jy for the MWA)

Power from VirA by the whole MWA $\approx$ system noise of a single tile

Key Point

Noise-like nature of source emission and system noise

Single-baseline Interferometer

$$\sigma = \frac{N}{\sqrt{2B\tau}} \quad (2)$$

- Assume $S \ll N$
- Noise is $\sqrt{2}$ lower
- (Collecting area is doubled, but we don't use the autocorrelations, so we're throwing some data away)

Key Point

Noise contributes equally to real and imaginary parts of the visibility

Single-baseline Interferometer

$$\sigma = \frac{N}{\sqrt{2B\tau}} \tag{2}$$

- Assume $S \ll N$
- Noise is $\sqrt{2}$ lower
- (Collecting area is doubled, but we don't use the autocorrelations, so we're throwing some data away)

Key Point

Noise contributes equally to real and imaginary parts of the visibility

large-N interferometer

$$\sigma = \frac{N}{\sqrt{2 n_b B \tau}} \tag{3}$$

- System noise (e.g. from amplifiers etc.) doesn't correlate between antennas
- Noise from different baselines add with random phase
- Diffuse emission (i.e. that which is totally resolved out by baselines) also doesn't correlate between antenas
- It behaves exactly like system noise and can be incorporated into N

large-N interferometer

$$\sigma = \frac{N}{\sqrt{2 n_b B \tau}} \tag{3}$$

- System noise (e.g. from amplifiers etc.) doesn't correlate between antennas
- Noise from different baselines add with random phase
- Diffuse emission (i.e. that which is totally resolved out by baselines) also doesn't correlate between antenas
- It behaves exactly like system noise and can be incorporated into N

Source Noise

However

- The noise from sources (that contribute to our visibilities) correlate across baselines
- We cannot beat down this noise down by combining baselines

This "Source noise" is a stochastic and ergodic; i.e. independent sample for each

- time, frequency, source

But it is

- Coherent across baselines

$$\sigma_{on} = \frac{S}{\sqrt{B\tau}}; S \gg N \tag{4}$$

(like single dish case)

Source Noise

However

- The noise from sources (that contribute to our visibilities) correlate across baselines
- We cannot beat down this noise down by combining baselines

This “Source noise” is a stochastic and ergodic; i.e. independent sample for each

- time, frequency, source

But it is

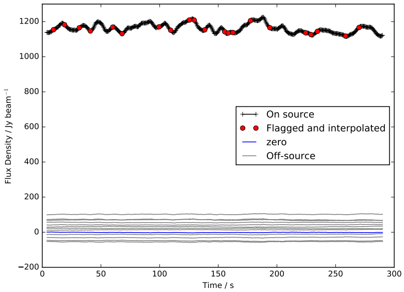
- Coherent across baselines

$$\sigma_{on} = \frac{S}{\sqrt{B\tau}}; S \gg N \tag{4}$$

(like single dish case)

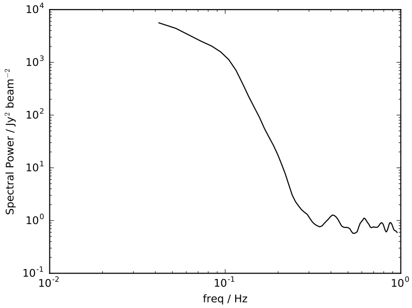
Plan

- Use IPS pipeline to explore what we see when we observe a bright source (Virgo A, 5-minute observation) away from the Sun (i.e. minimal IPS)
- Understand other sources of variability
  - Ionosphere
  - Noise
- Confirm detection of "source noise"



Ionosphere

- Beautiful ionospheric scintillation
- Scintillation index 2.7% ($r_{\mathrm{diff}} \sim 10\,\mathrm{km}$)
- $\sim$0.1 Hz (implied speed $\sim$100 m/s)
- Ionospheric Scintillation explored in Waszewski+ (2022)



Quantifying Source noise

$$\sigma_{\text{on}} = \frac{1}{\sqrt{B\tau}}\left(S + \frac{N}{\sqrt{2n_b}}\right) \tag{5}$$

Usually this effect is small; but recall

- Virgo A S ~1000 Jy
- SEFD of a single MWA tile N ~100 000 Jy

Virgo A source noise and system noise are of the same order of magnitude

In a snapshot of a bright unresolved source we have two types of noise:

- System noise we are familiar with
- Additional scaling of the PSF by source noise

Quantifying Source noise

$$\sigma_{\text{on}} = \frac{1}{\sqrt{B\tau}}\left(S + \frac{N}{\sqrt{2n_b}}\right) \qquad (5)$$

Usually this effect is small; but recall

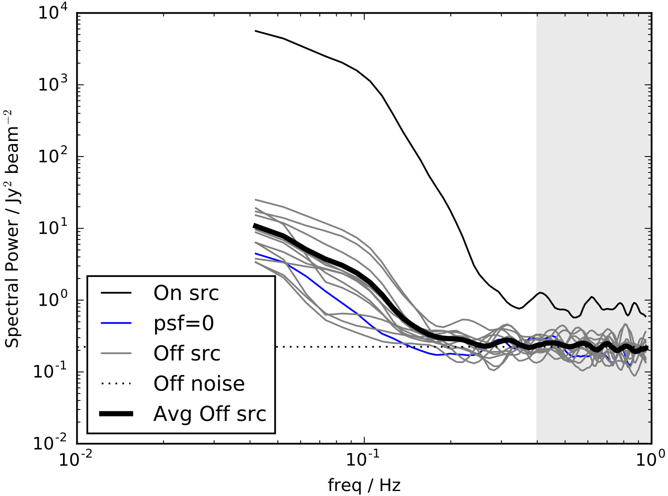
- Virgo A S ~1000 Jy
- SEFD of a single MWA tile N ~100 000 Jy

Virgo A source noise and system noise are of the same order of magnitude

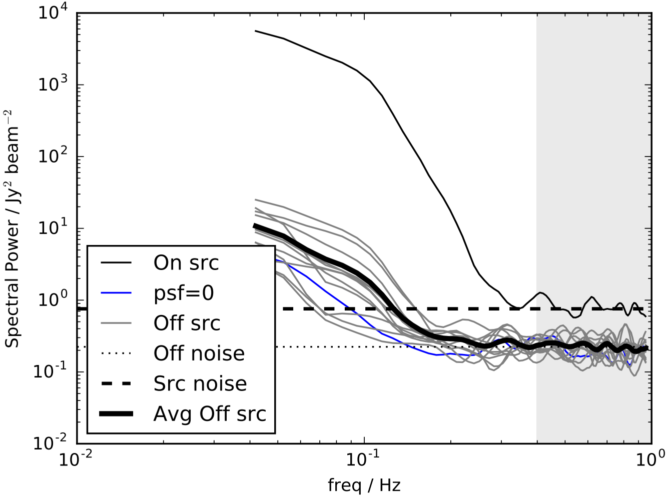
In a snapshot of a bright unresolved source we have two types of noise:

- System noise we are familiar with
- Additional scaling of the PSF by source noise

$$\sigma_{off} = \frac{N}{\sqrt{2n_b B\tau}};\sigma_{on} = \frac{1}{\sqrt{B\tau}}\left(S + \frac{N}{\sqrt{2n_b}}\right) \quad (6)$$

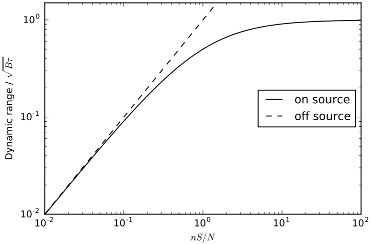


$$\sigma_{off} = \frac{N}{\sqrt{2n_b B\tau}}; \sigma_{on} = \frac{1}{\sqrt{B\tau}}\left(S + \frac{N}{\sqrt{2n_b}}\right) \tag{7}$$



Conclusions

- We have made a measurement of source noise
  - Unprecedented Accuracy
  - Arguably first detection in the "moderately bright source regime" ($N \gg S; S \sim N/n$)
- This phenomenon should be considered whenever a weak signal is being measured in the presence of a stronger signal
  - Could show up in time or frequency domain
  - Strong for the SKA: ~1 Jy
  - Implications of sidelobes etc. in paper.

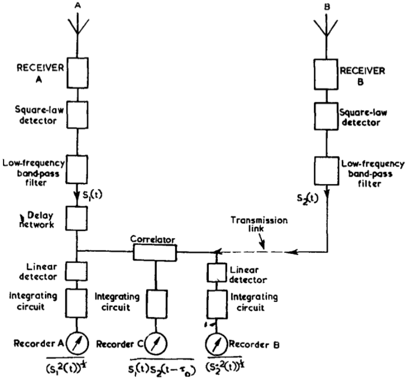


Instrument	N/n Jy
MWA	400
LOFAR	90
ASKAP	42.5
SKA-low	2.8
SKA-mid	1.7

Rewind 70 years

‘If the radiation from a source is picked up at two different places on Earth, is there anything else we can compare to find the mutual coherence?’
And into my mind came the image of a man looking at the ‘noise-like’ signal received from a radio source on a cathode ray tube. ‘Supposing’, I thought, ‘there was another man many miles away looking at an identical cathode ray tube. Would he see the same “noise-like signal?” — Robert Hanbury Brown – “Boffin”

An intensity interferometer

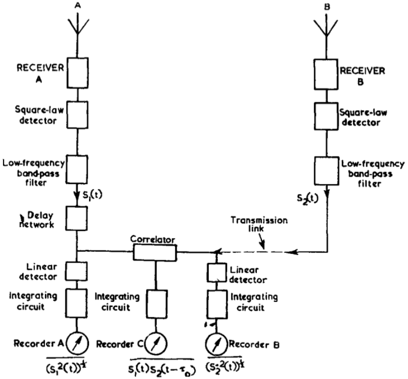


Block diagram of new type of interferometer.

Hanbury Brown&Twiss (1954)

- Record the power from two spaced antennas
- Filter with bandpass 0.1–1000 Hz
- Correlate
- Gives visibility amplitude squared of baseline
- In the event, most sources were resolved easily
- Intercontinental vision was eventually realised (Gubay+ 1969)

An intensity interferometer



Block diagram of new type of interferometer.

Hanbury Brown&Twiss (1954)

- Record the power from two spaced antennas
- Filter with bandpass 0.1–1000 Hz
- Correlate
- Gives visibility amplitude squared of baseline
- In the event, most sources were resolved easily
- Intercontinental vision was eventually realised (Gubay+ 1969)

Interpreting Source Noise

- For radio we can stick to classical physics, and the interpretation is fairly intuitive
- However Hanbury Brown & Twiss didn't stop there.
- They went on to conceive and build optical interferometers (most notably at Narrabri), which demands a quantum mechanical interpretation
- This is arguably one of the most significant contributions of Radio Astronomy to fundamental physics!

Aside: Michelson interferometry and Quantum Mechanics

- Hopefully we are all familiar with Young's slit and the Quantum Interpretation
  - The photon goes through both slits!
- We don't usually think about radio photons, but VLBI is one of the most dramatic examples of wave-particle duality
- This might seem to violate the uncertainty principle!
- We have the data recorded, so why can't we look at the voltages and see which slit the photon went through?

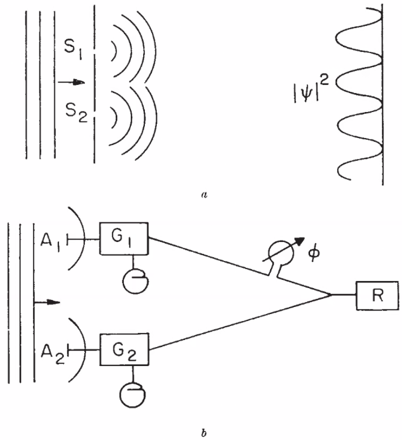


Fig. 1. *a*, Classical two-slit interference pattern. *b*, Radio analogue of two-slit interference with amplifiers and separate recorders.

Burke (1969)

Aside: Michelson interferometry and Quantum Mechanics

- Hopefully we are all familiar with Young's slit and the Quantum Interpretation
  - The photon goes through both slits!
- We don't usually think about radio photons, but VLBI is one of the most dramatic examples of wave-particle duality
- This might seem to violate the uncertainty principle!
- We have the data recorded, so why can't we look at the voltages and see which slit the photon went through?

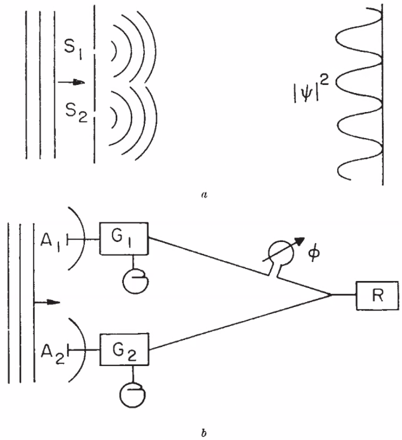


Fig. 1. *a*, Classical two-slit interference pattern. *b*, Radio analogue of two-slit interference with amplifiers and separate recorders.

Burke (1969)

Aside: Michelson interferometry and Quantum Mechanics

- Consider a VLBI observation with 1-bit sampling
- Maybe 1 bit in 10^3–10^4 might correlate (Sovers+ 1998) in addition to 50% that match by chance
- So which is the photon?
- OK, let's crank up the sensitivity and the bitrate
- This cannot be done arbitrarily
  - All amplifiers have excess noise $> \frac{h\nu}{k}$
- This is (one of the reasons) why infra-red interferometry is hard!

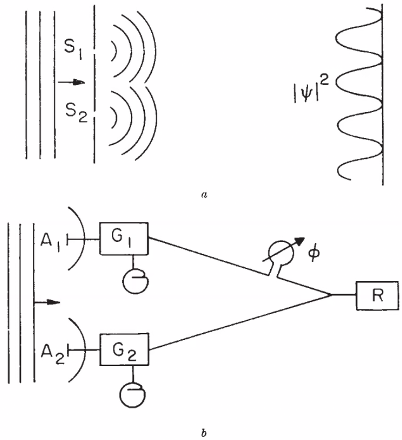


Fig. 1. a, Classical two-slit interference pattern. b, Radio analogue of two-slit interference with amplifiers and separate recorders.

Burke (1969)

Aside: Michelson interferometry and Quantum Mechanics

- Consider a VLBI observation with 1-bit sampling
- Maybe 1 bit in 10^3–10^4 might correlate (Sovers+ 1998) in addition to 50% that match by chance
- So which is the photon?
- OK, let's crank up the sensitivity and the bitrate
- This cannot be done arbitrarily
  - All amplifiers have excess noise $> \frac{h\nu}{k}$
- This is (one of the reasons) why infra-red interferometry is hard!

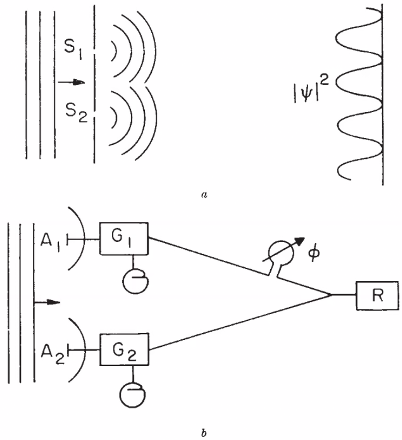


Fig. 1. a, Classical two-slit interference pattern. b, Radio analogue of two-slit interference with amplifiers and separate recorders.

Burke (1969)

Meanwhile in Particle Physics. . .

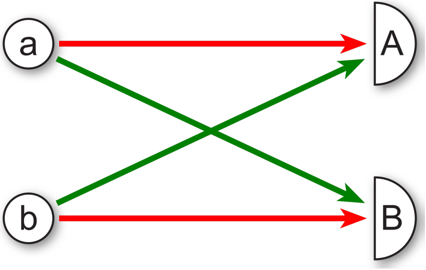
- Proton-antiproton annihilation
- Much more complicated than low-energy electron-positron annihilation as there is much more energy (and 6 quarks)
- non-fixed number of mesons (pions, mesons) produced via pair production, which then decay
- As early as the 1950s, there were unexpected correlations between detection of sources at different detectors

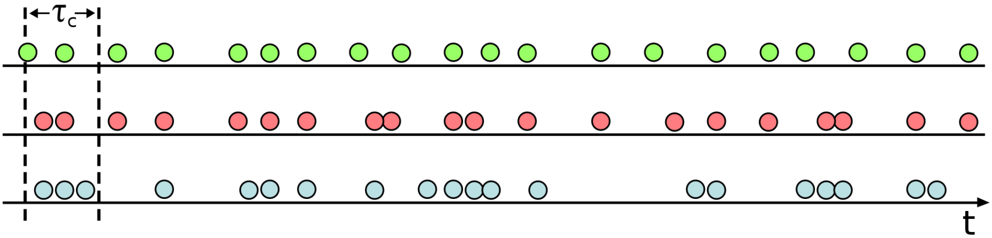
Meanwhile in Particle Physics. . .

- Proton-antiproton annihilation
- Much more complicated than low-energy electron-positron annihilation as there is much more energy (and 6 quarks)
- non-fixed number of mesons (pions, mesons) produced via pair production, which then decay
- As early as the 1950s, there were unexpected correlations between detection of sources at different detectors

Hanbury-Brown Twiss Effect

- Distinct from Young's slit
- Involves correlation in detection two particles
- Melrose (2008) argues for routine measurement of these coherence statistics





Conclusions

- We have made a clear detection of source noise in the weak regime
- Significant effect, precisely in line with predictions
- Effect of source noise for resolved source not entirely figured out
- Higher order coherence potentially an important observable

Melrose (2008)

The measures of coherence involve powers of the intensity (e.g., Mandel & Wolf 1995) averaged over a short observation time. The mean value of $\langle I^N \rangle$ for "coherent" radiation is $\langle I^N \rangle = \langle I \rangle^N$, and for "incoherent" (random phase) radiation is $\langle I^N \rangle = N!\langle I \rangle^N$. The quantities $\langle I^N \rangle / \langle I \rangle^N$ are measures of coherence. These measures must depend on the resolution time of the telescope and the coherence time of the radiation, and one expects interesting results only if the resolution time is shorter than the coherence time (which is not known *a priori*). There are additional measures of coherence from the auto- and cross-correlation functions between the Stokes parameters for polarized radiation. (In fact, the stated result for $\langle I^N \rangle$ is for completely polarized radiation, and there is a different value for partially polarized or unpolarized radiation.) At present there is no program for measuring these quantities, for example, by constructing a correlator that automatically determines these higher order correlation functions. There is also no systematic theory predicting what one would expect for various models of coherence.

A thought experiment

- Consider a pair of identical, very short baselines
- Measure source noise on visibilities
- Correlation of source noise between pairs of identical baselines should give visibility amplitude squared of baseline between baselines

Might be possible to test this with quiet Sun and MWA Hexes

- First full description of source noise for a resolved source.

A thought experiment

- Consider a pair of identical, very short baselines
- Measure source noise on visibilities
- Correlation of source noise between pairs of identical baselines should give visibility amplitude squared of baseline between baselines

Might be possible to test this with quiet Sun and MWA Hexes

- First full description of source noise for a resolved source.