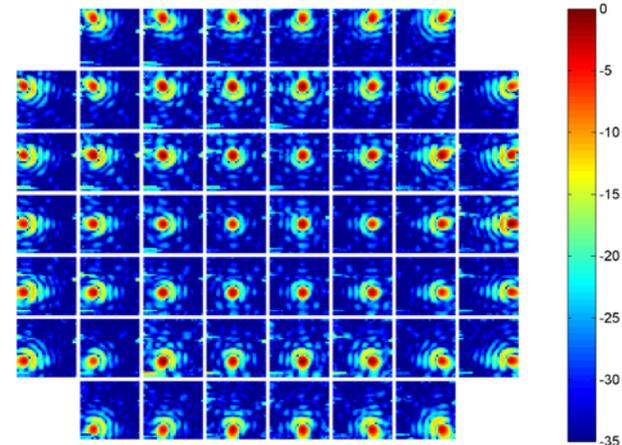


APERTIF Phased Array Feed development for the Westerbork Synthesis Radio Telescope

Wim van Cappellen, Laurens Bakker

BYU Phased Array Workshop

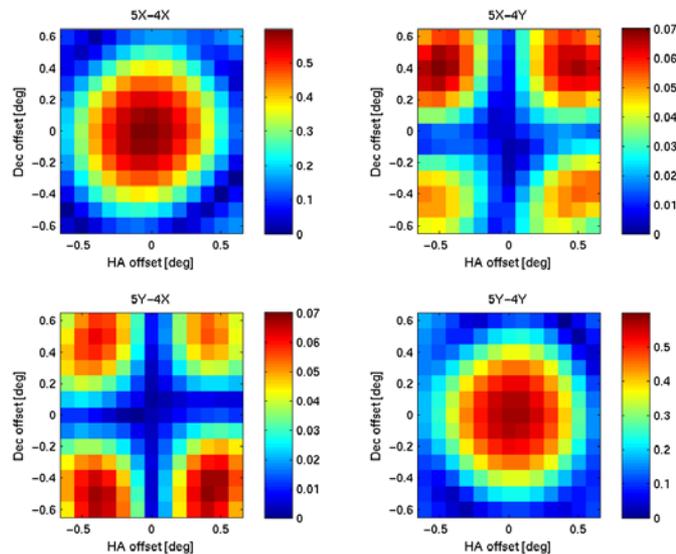
May 3 – 5, 2010



(Most of) The APERTIF Team, 2010



- Introduction APERTIF
- Overview of relevant activities and results
 - Except activities included in other ASTRON presentations
- Correlated noise in overlapping beams
- Summary



- Turn the WSRT into an effective survey telescope, to enable new fundamental astronomy
- Replace horn feeds with Phased Array Feeds to increase the field of view



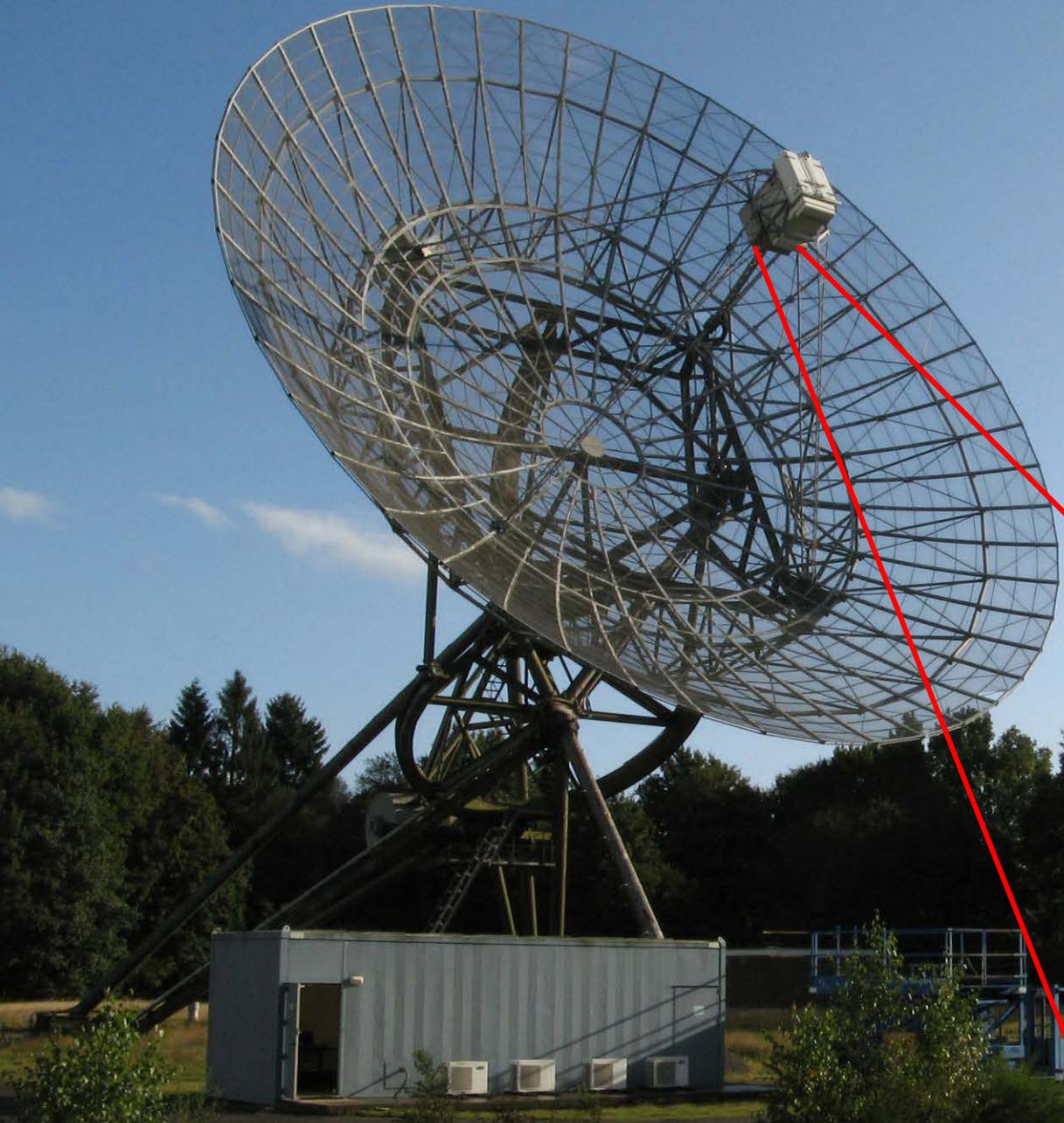
APERTIF Key Characteristics

- Frequency range 1000 – 1750 MHz
- Survey speed improvement
 - Including bandwidth 26x
 - Excluding bandwidth 14x
- Sensitivity (room temperature LNA) 0.7x MFFE
 (doubling of integration time)
 $\eta = 75\%$, $T_{\text{sys}} = 55 \text{ K}$

| | Dishes | FoV improvement | Bandwidth | Noise line | Noise cont | SSpeed line | SSpeed cont |
|----------------------------|--------|-----------------|-----------|------------|------------|-------------|-------------|
| Current WSRT system | 14 | 1 | 160 MHz | 1 | 1 | 1 | 1 |
| APERTIF baseline | 12 | 30 | 300 MHz | 1.47 | 1.07 | 14 | 26 |

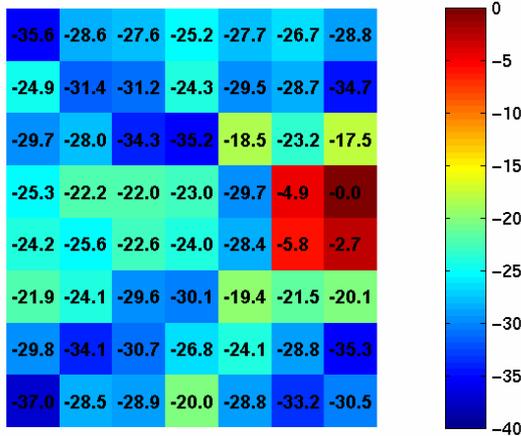
APERTIF prototype

- 144 element Vivaldi array on 25m WSRT dish
- Tunable from 1100 to 1800 MHz
- 48 MHz instantaneous bandwidth
- Real-time digital beamforming and cross-correlation

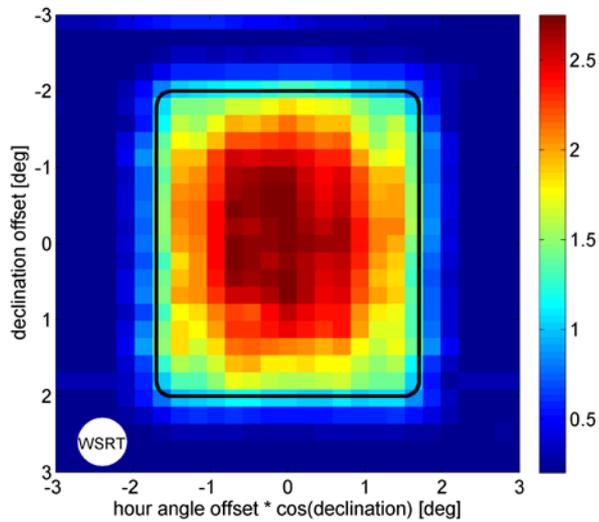
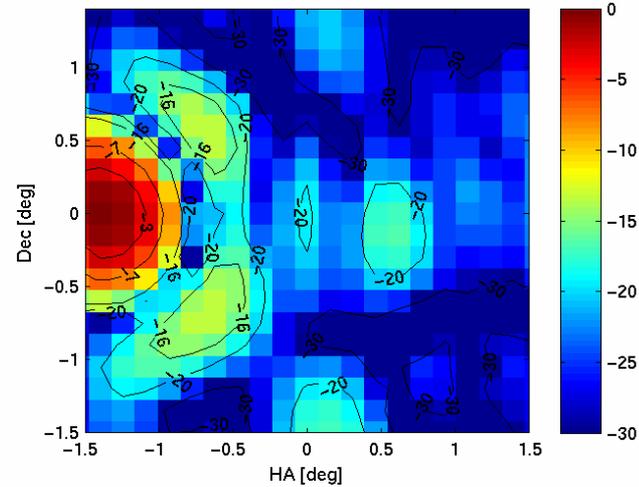


Weights

Amplitude of weighting coefficients for maximum SNR, 1421.2 MHz

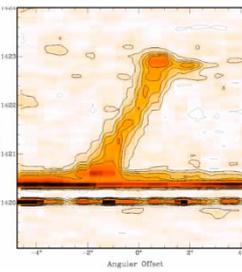
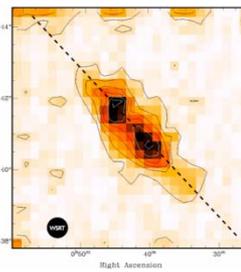
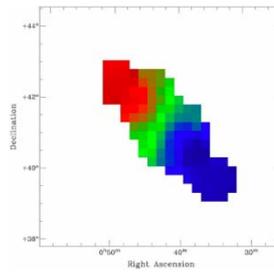
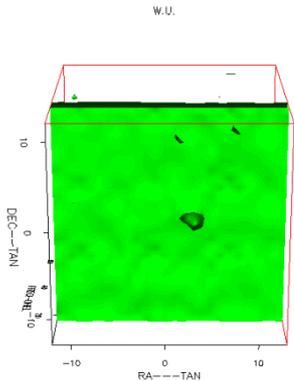
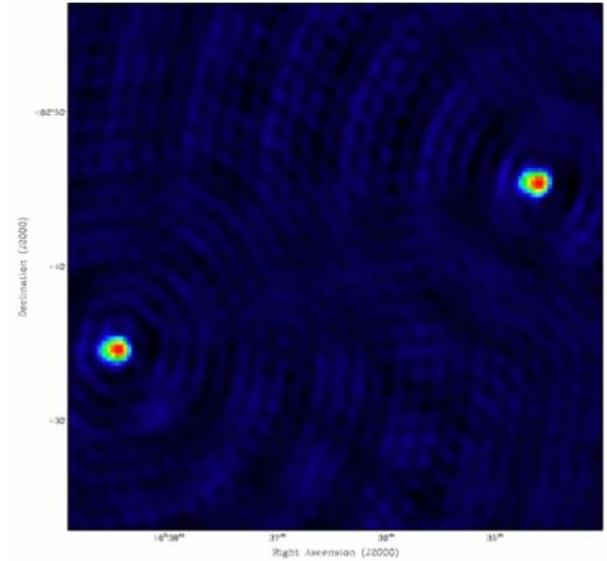
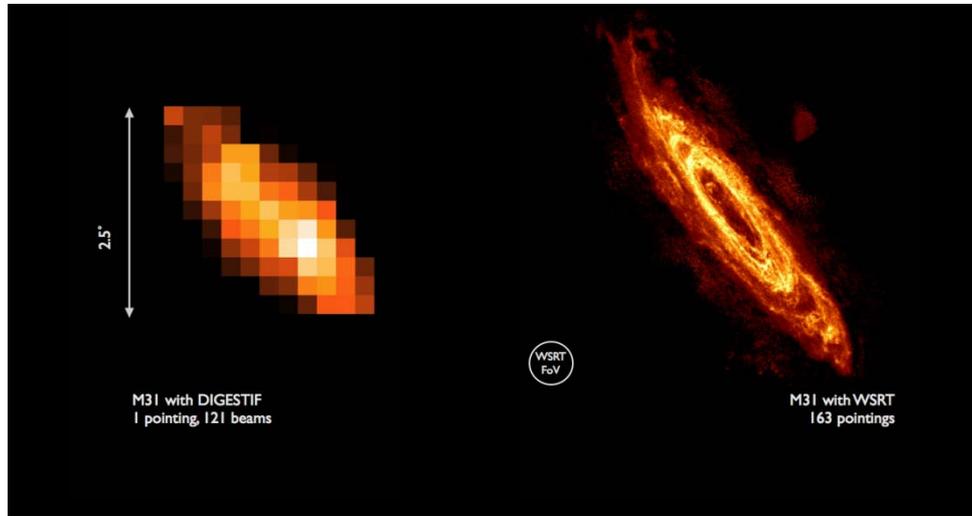


2D pattern



- Source: Cassiopeia A
- 1420 MHz
- Every pixel is from a compound beam in the desired direction
- Demonstrated 9 deg² field-of-view
- WSRT 0.3 deg²

- APERTIF Demonstrated single-dish and synthesis imaging with a Phased Array Feed

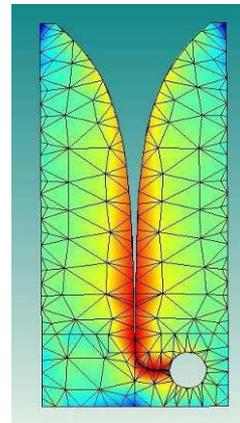
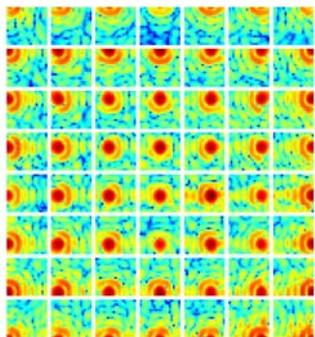


Recent Results

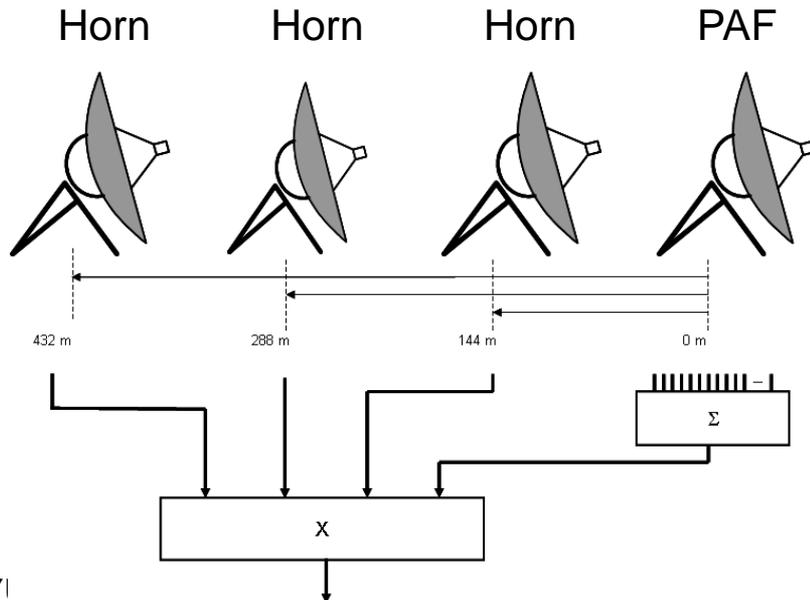
- Upgraded antenna array in WSRT dish
 - Measured $T_{\text{sys}}/\eta = 91 \text{ K}$, $T_{\text{sys}} \sim 68 \text{ K}$
 - Excellent agreement between simulated and measured sensitivity
 - On planned path to $T_{\text{sys}}=55 \text{ K}$ goal
- Front-end redesigned for low noise
 - Noise due to antenna losses: 4 K
 - LNA integrated on antenna
 - Using commercial ATF-54143 transistor

| | Current prototype | New prototype | Final APERTIF |
|--------------------|-------------------|---------------|---------------|
| Antenna losses | 9 | 6 | 6 |
| LNA + second stage | 82 | 40 | 28 |
| Noise coupling | 15 | 9 | 8 |
| Spillover | 15 | 10 | 10 |
| Sky noise | 3 | 3 | 3 |
| Total | 124 | 68 | 55 |

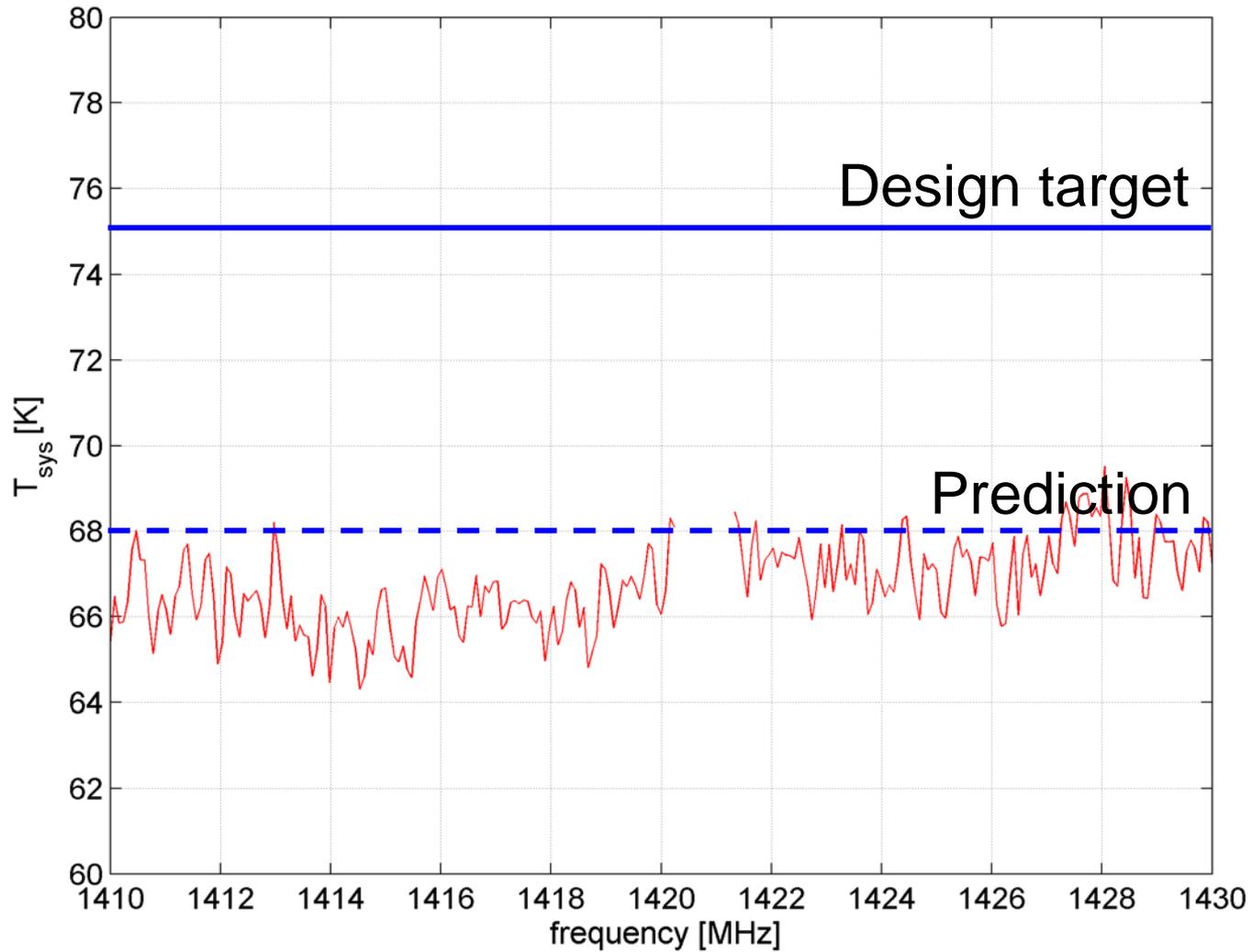
124 → 68 → 55 K



- 4-Dish interferometer: 3 x horn feed, 1 x PAF
- Point dishes to strong point source (3C147)
- Using EVLA Memo 127 (Perley):
 - Solve $(A_e/T_{sys})_{\text{Horn}}$ from Horn – Horn cross-correlation
 - Solve $(A_e/T_{sys})_{\text{PAF}}$ from Horn – PAF cross-correlation and $(A_e/T_{sys})_{\text{Horn}}$
- This procedure is more accurate than a single-dish hot/cold measurement
 - ‘Cold’ measurement is avoided
 - Flux density of 3C147 is more accurately known than Cas A



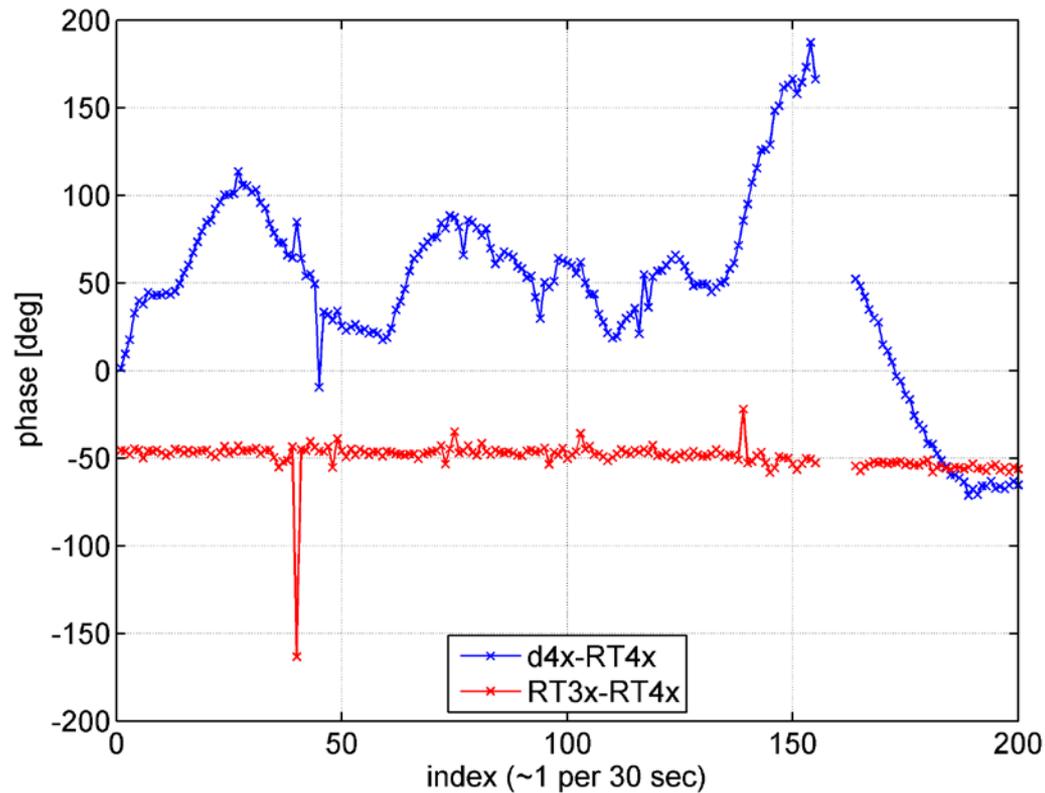
$$\frac{\rho_{i,j}}{\sqrt{\rho_{i,i} \cdot \rho_{j,j}}} = \frac{S}{\sqrt{\left(S + \frac{2kT_{\text{sys},i}}{A_{e,i}}\right) \left(S + \frac{2kT_{\text{sys},j}}{A_{e,j}}\right)}}$$



- $T_{\text{env}} = 7^\circ\text{C}$, assuming antenna efficiency of 75%

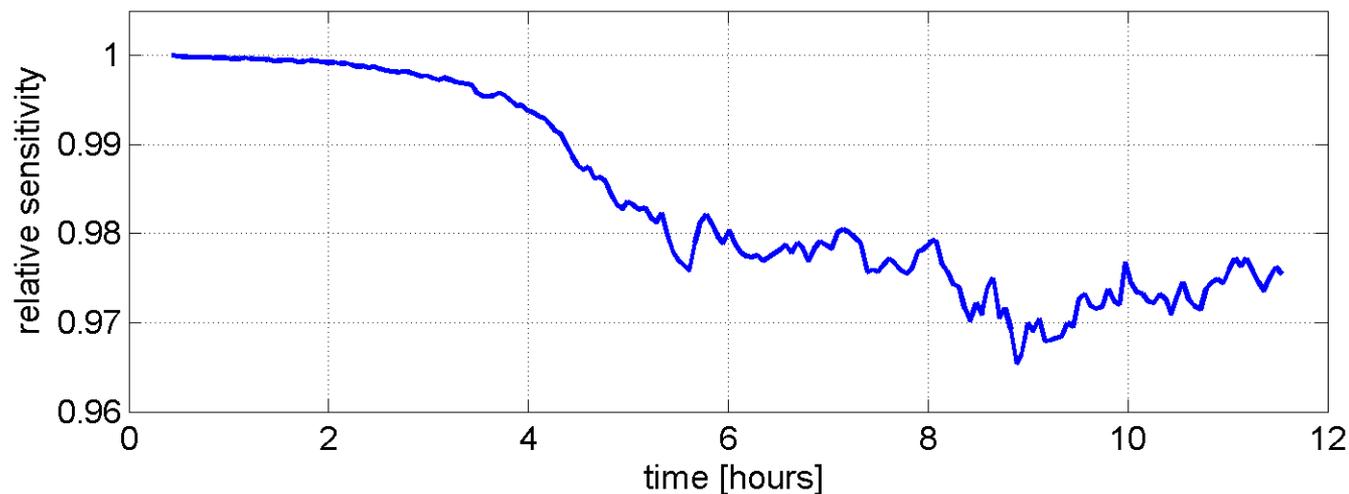
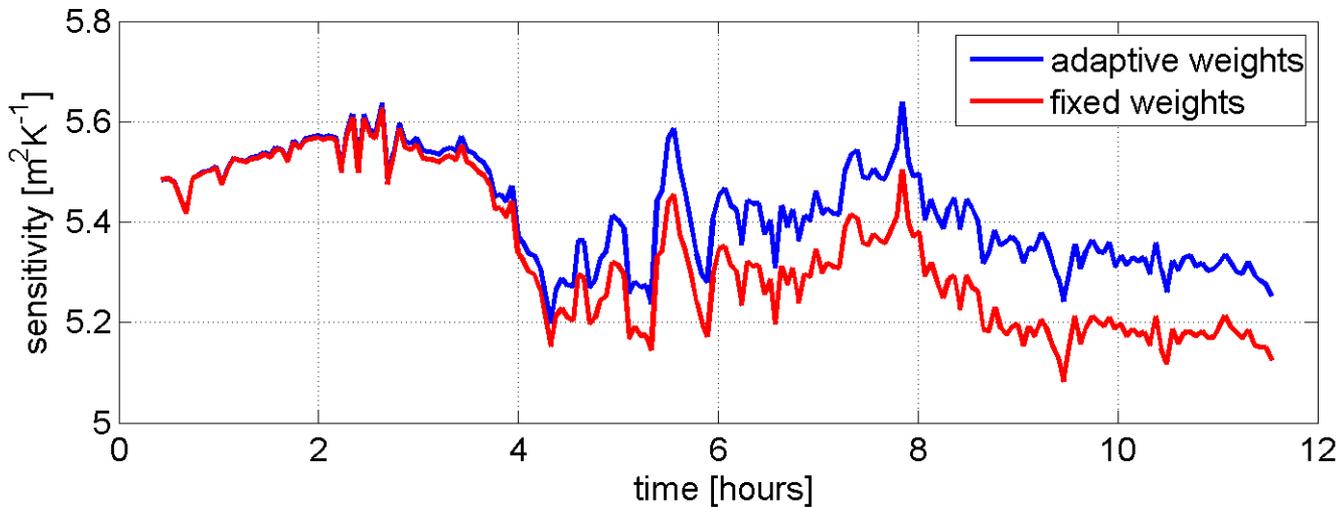
LO stability

- LO generation using COTS synthesizers in an air-conditioned cabin
- Measured visibility phase vs time after fringe stopping
- Huge phase gradients due to temperature dependence (airco on/off)
- Temporarily solved by using MFFE synthesizers



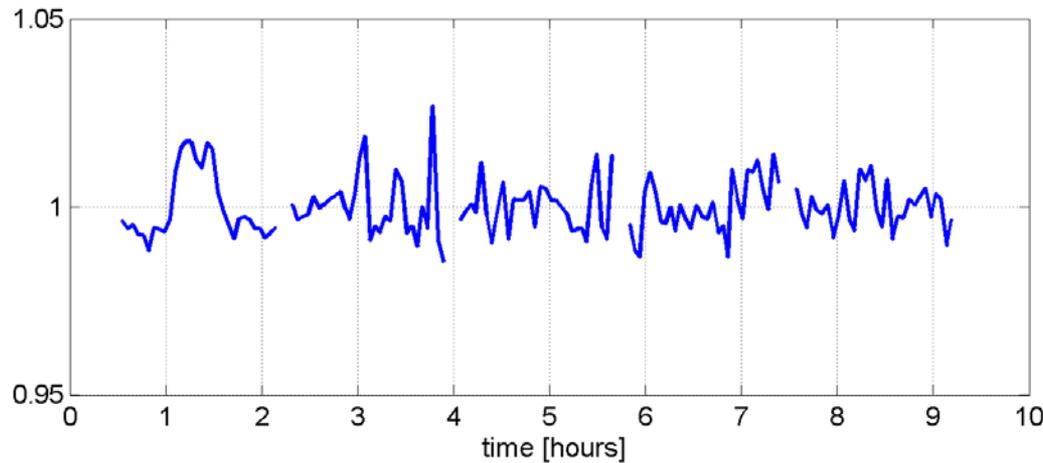
Sensitivity over time

- Adaptive weights or not??
- Measurement using MaxSNR weights

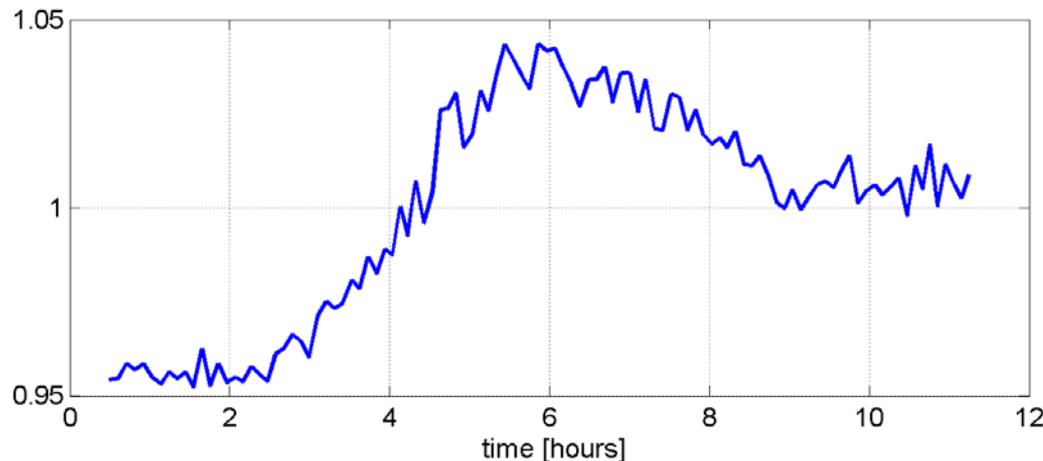


Beam stability

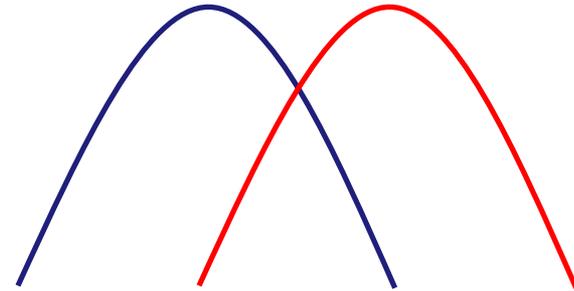
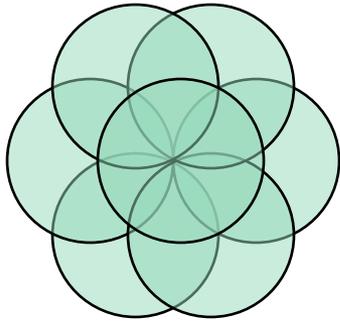
- Beam stability requirement: gain variation at half power < $\pm 1\%$
- Measured gain variation at half-power (fixed weights)



Day with stable temperature (best case)



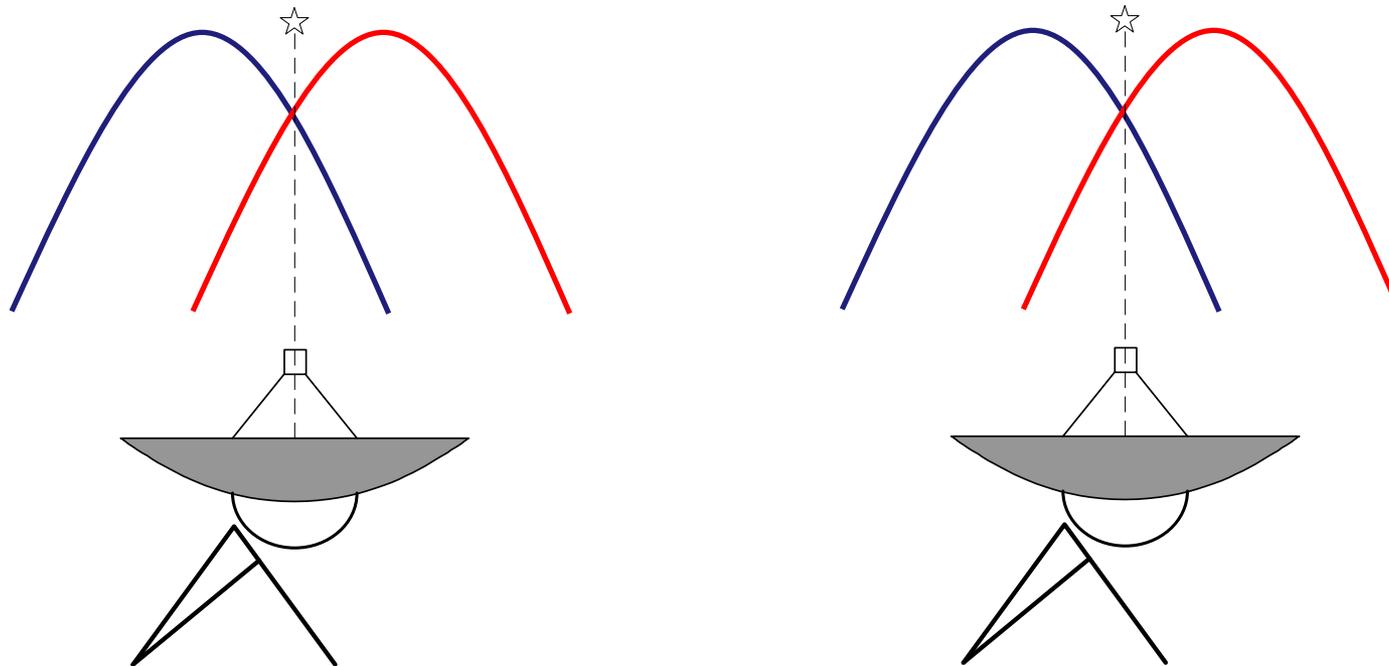
Day with large temperature variations (worst case)



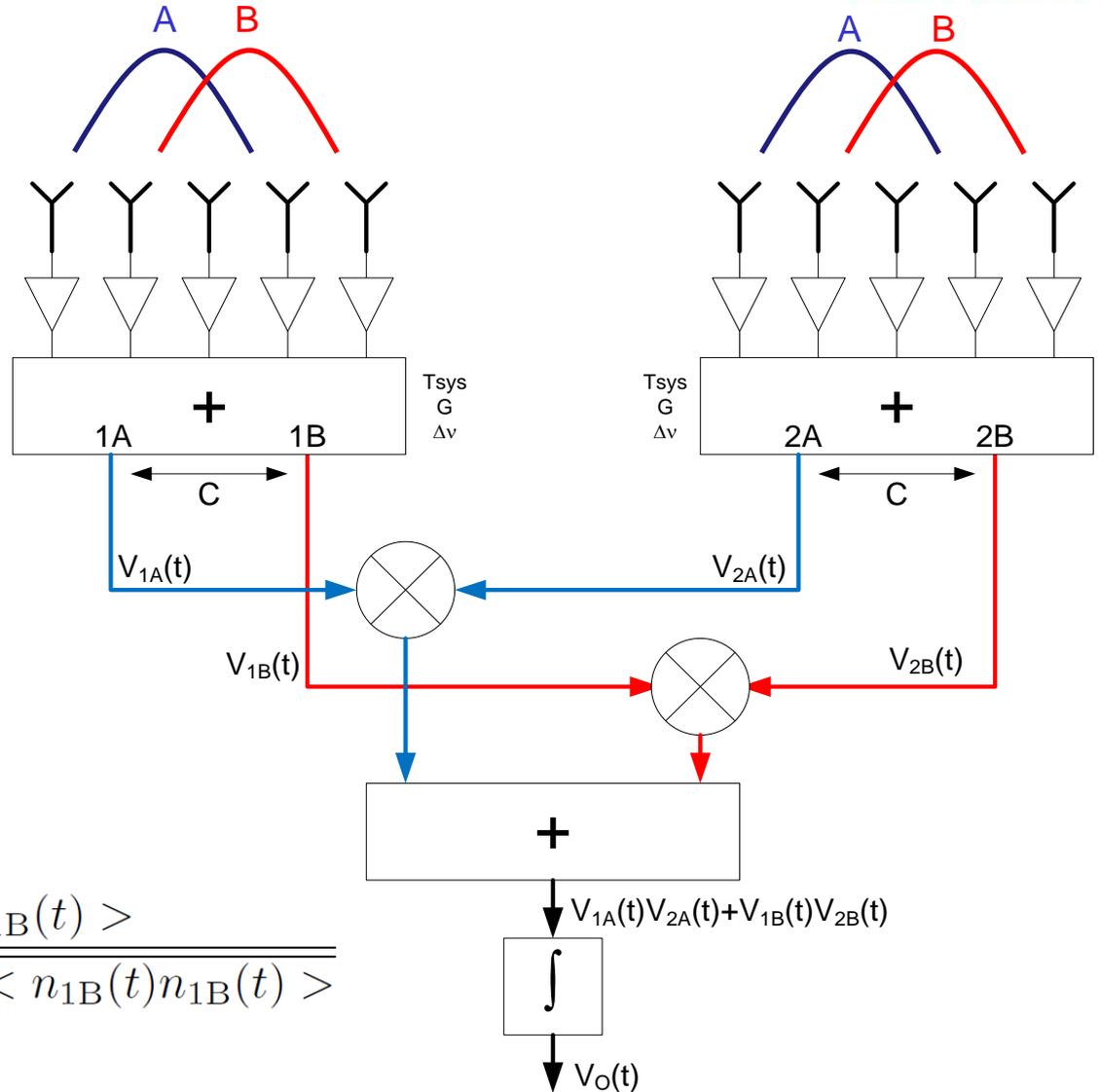
- Conventionally
 - Pointings are combined in the image plane
 - Images have significant overlap to flatten noise over the image
 - Images are measured consecutively hence their noise is independent
- Phased Array Feed
 - Many beams are measured instantaneously
 - Each beam uses the same PAF elements (with different weights)
 - Noise in each of the pointings is NOT independent
- What impact does this have on the noise in the combined image?

Approach

- Consider two PAF dishes, forming two compound beams each
- Each dish tracks an unpolarized point source, flux density S
- Noise between the two beams of each dish is partly correlated (C)
- Delay settings for all beams of each dish are identical
- Calculate SNR of visibility



PAF Model



$$v_{1A}(t) = s_{1A}(t) + n_{1A}(t)$$

$$v_{1B}(t) = s_{1B}(t) + n_{1B}(t)$$

$$v_{2A}(t) = s_{2A}(t) + n_{2A}(t)$$

$$v_{2B}(t) = s_{2B}(t) + n_{2B}(t)$$

$$C_{n_{1A}, n_{1B}} = \frac{\langle n_{1A}(t)n_{1B}(t) \rangle}{\sqrt{\langle n_{1A}(t)n_{1A}(t) \rangle \langle n_{1B}(t)n_{1B}(t) \rangle}}$$

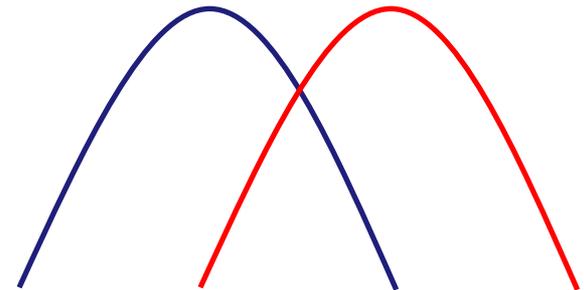
$$\phi_m(\tau) = \langle [v_{1A}(t)v_{2A}(t) + v_{1B}(t)v_{2B}(t)] [v_{1A}(t + \tau)v_{2A}(t + \tau) + v_{1B}(t + \tau)v_{2B}(t + \tau)] \rangle$$

- Assuming $S \ll 2k_B T_{\text{sys}}/A_e$
- Ratio of signal and noise voltages at correlator output for a single point source at beam crossover after 2 single beam pointings:

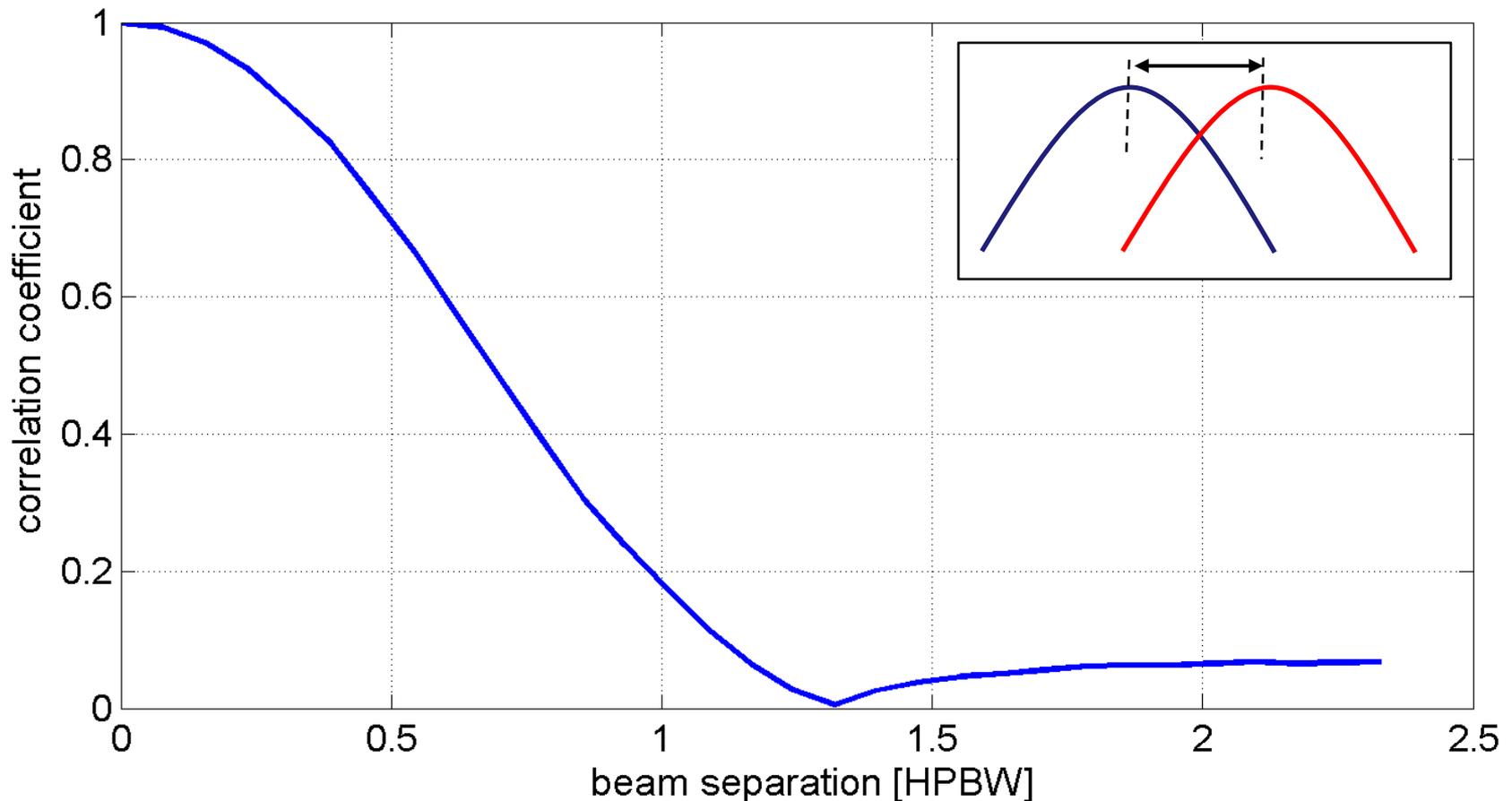
$$R_{\text{sn}} = \frac{A_e S}{T_{\text{sys}} k_B} \sqrt{\Delta \nu \tau}$$

- Ratio of signal and noise voltages at correlator output for a single point source at beam crossover after 1 PAF pointing:

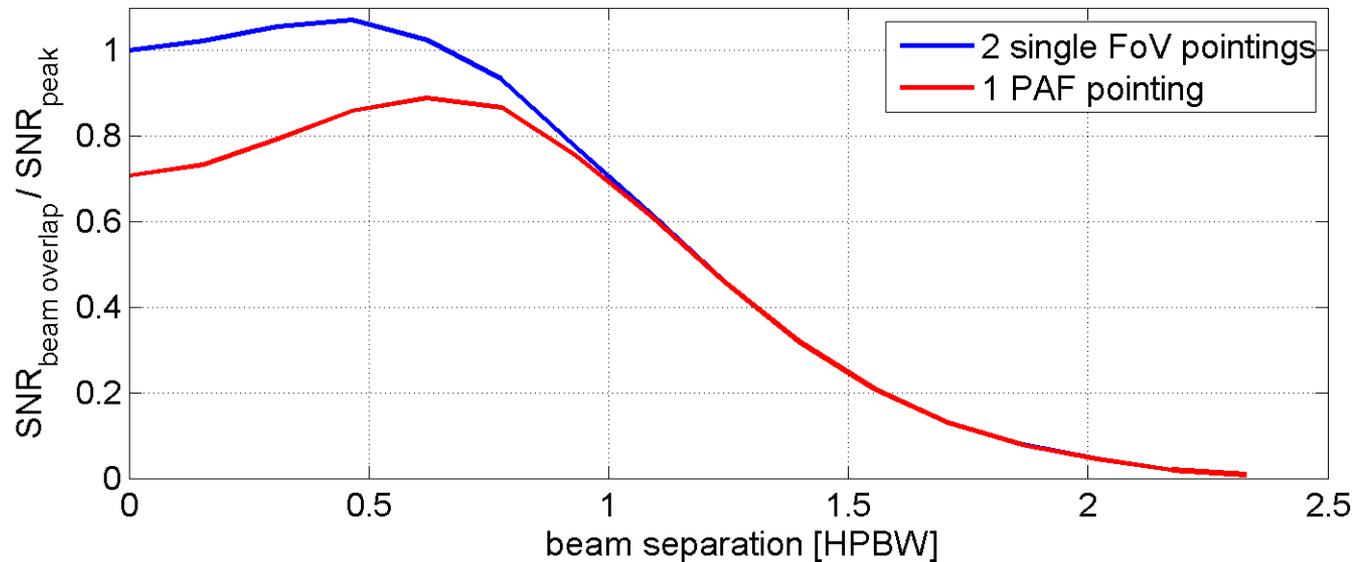
$$R_{\text{sn}} = \frac{A_e S}{T_{\text{sys}} k_B} \sqrt{\frac{\Delta \nu \tau}{C^2 + 1}}$$



- Measured correlation coefficient versus beam spacing between two compound PAF beams on an empty sky
- MaxSNR weights, $f/D=0.35$, 1420 MHz



- Reduction in SNR at beam cross-over point vs beam separation



Summary

- Significant progress has been made in demonstrating the feasibility of Phased Array Feeds for radio astronomy:
 - Demonstrated single dish and synthesis imaging with a Phased Array Feed system
 - Measured performance (sensitivity, field of view) agrees with expectations
- LO implementation needs attention
- Measured temporal sensitivity and beam pattern variations
 - Now focus on calibration to correct for these variations
- Considered impact of correlated noise in overlapping beams

