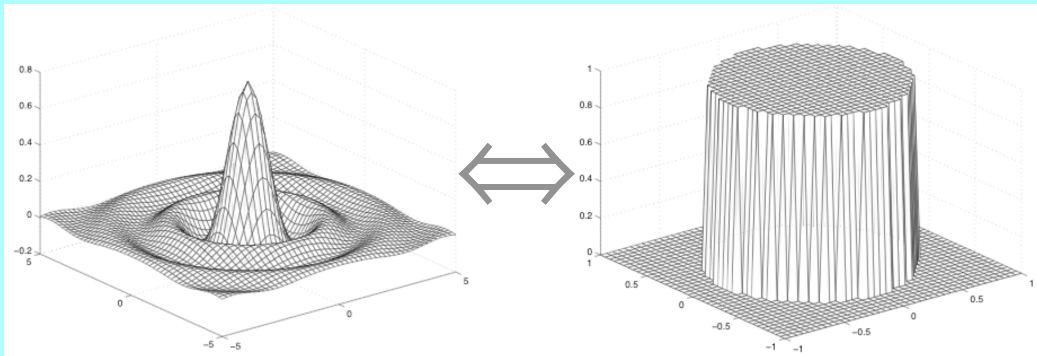
Controlling Field-of-View of Radio Arrays using Weighting Functions



MIT Haystack FOV Group:

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Fulfilling scientific promise of future high-sensitivity radio arrays (e.g., SKA) will require the ability to achieve simultaneously:

- high angular resolution (~0.1" @1.4 GHz)
- large fields-of-view (~1^{o})
- high dynamic range (~10^{6})

One way to meet these goals is with "large-N, small-D" arrays comprising vast numbers of suitably-distributed, small-diameter antennas, correlated on all baselines:

- small dish ⇒ large intrinsic FOV
- excellent *u-v* plane coverage ⇒ low sidelobes, high-quality PSF

But there are significant challenges....

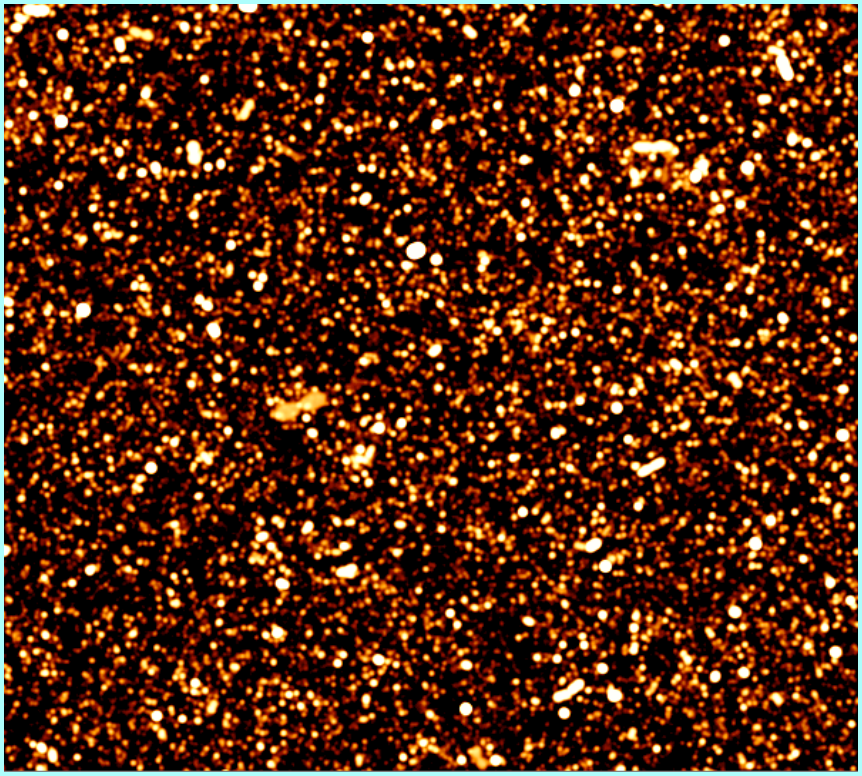
Difficulties:

At cm wavelengths, the radio sky is crowded with sources!

Sidelobes from out-of-beam sources will limit dynamic range within intended FOV

Computational load ~D^{-6} (Perley&Clark 2003, Cornwell 2004)

Removal of unwanted sources and their sidelobes via current techniques (i.e., post correlation) is untenable — expected data rates up to ~ PB/s! (Lonsdale 2003)



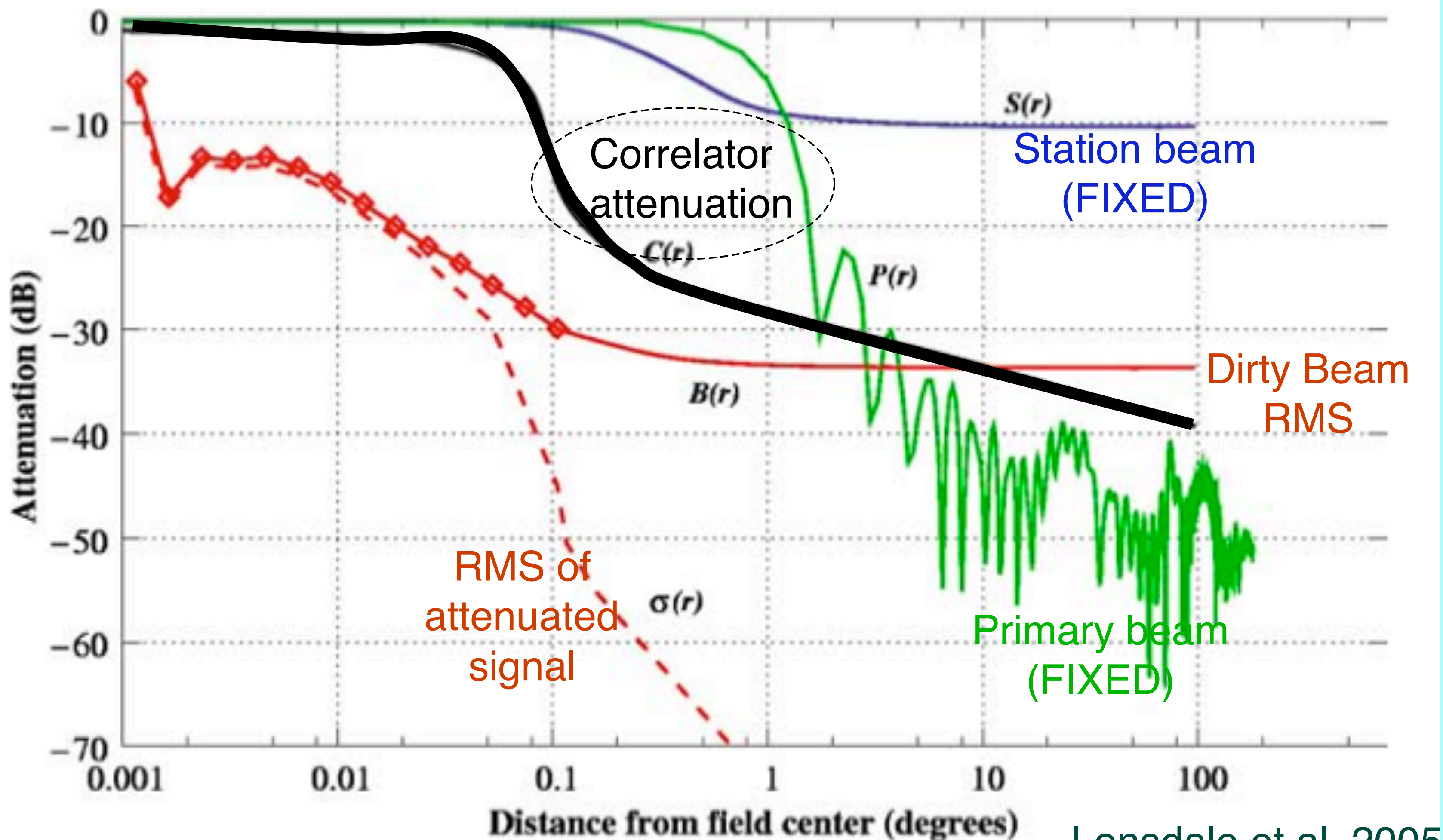
Simulated $1^o \times 1^o$ patch of sky at 1.4 GHz; 18'' resolution; $F_d \geq$ 10 nJy

from SKADS Simulated Sky (S^3), Oxford University

Solution: Correlator FOV Shaping

Employ intelligent weighting in frequency/time to limit FOV.

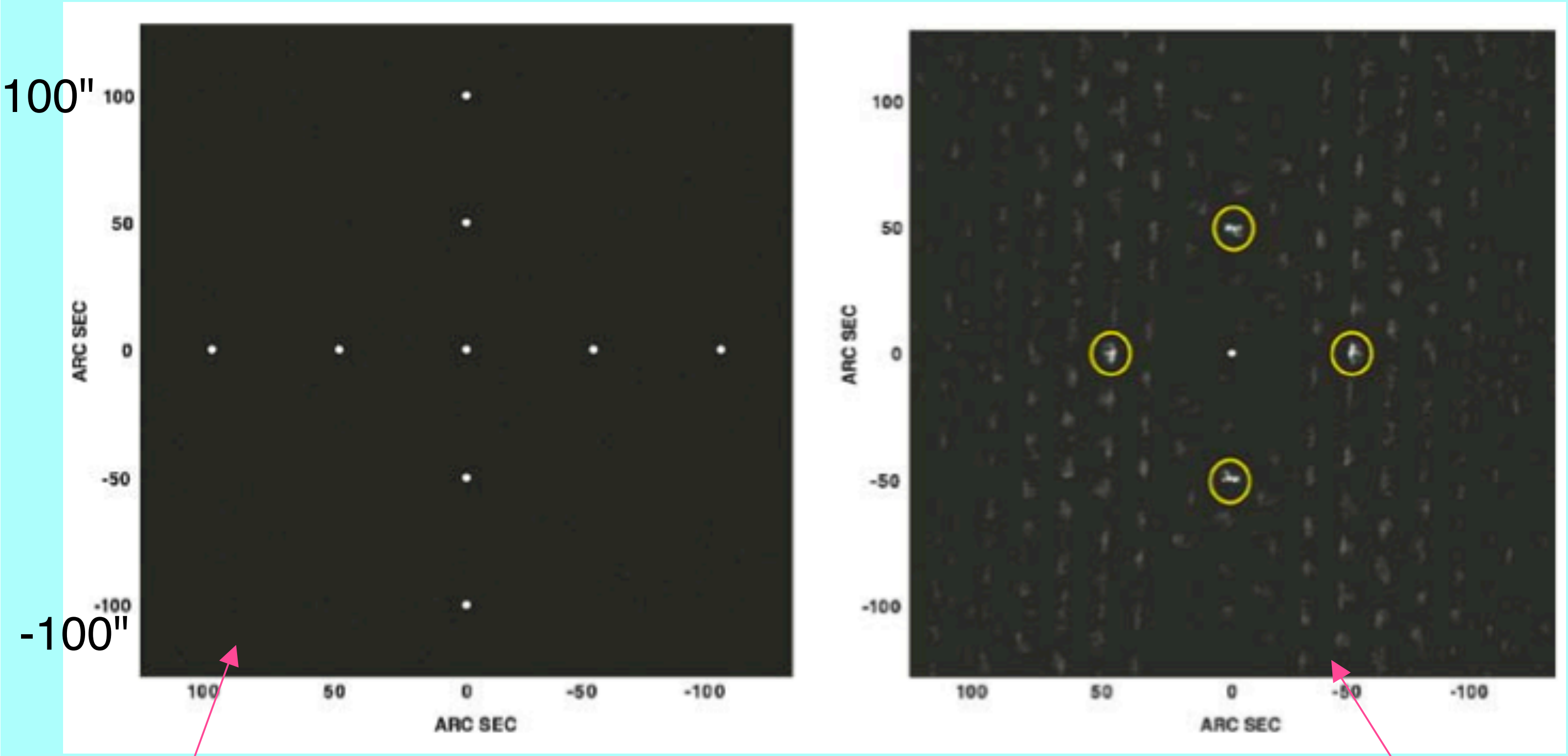
"Layers of Attenuation" for an Imaging Array



Lonsdale et al. 2005

Shaping of correlator FOV can effect an increase attenuation, *C(r)*

Time/bandwidth smearing affects *C(r) :*



from Lonsdale, Doeleman & Oberoi (2005)

CLEANed grid of points, no averaging

CLEANed, with time & frequency-averaging
Note: distorted images & unsubtracted sidelobes

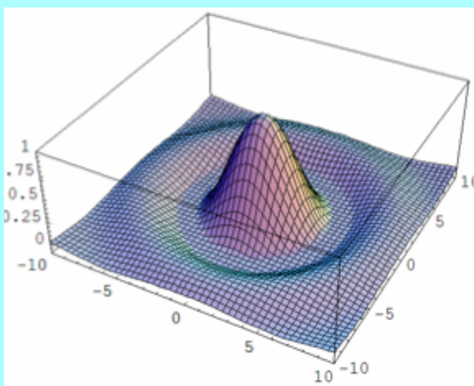
Transformation from *(f, t)* to *(u, v)* is *variable* between baselines ⇒ effective FOV varies between baselines⇒ poor image characteristics

Correlator FOV Shaping: A Better Approach

<u>Concept</u>:

- Make use of Fourier relationship between measurement (*u*-*v*) plane and the sky plane

- Multiply the sky by a weighting (window) function ⇔ convolve the *u*-*v* plane by Fourier transform of the window function, effectively tailoring the FOV



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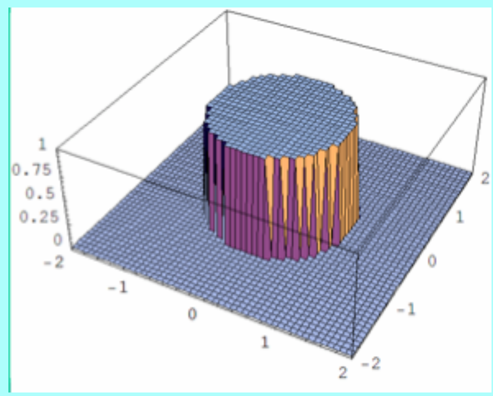
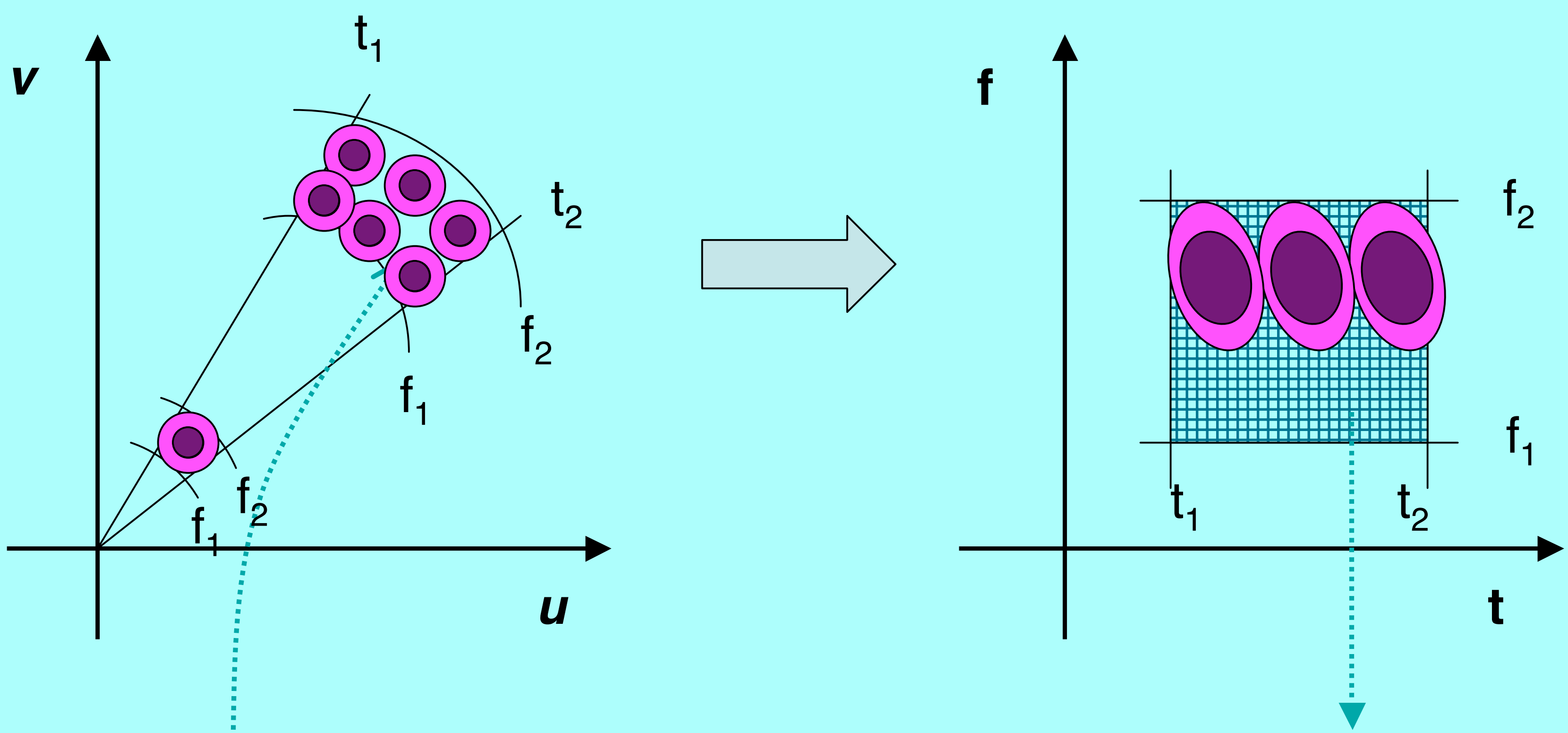


Jinc/top hat function

- Applying *single* weighting function in *(u, v)* plane will impose same FOV on all baselines

u-v plane **Correlator**



FOV convolution function
(same for all baselines)

Weighted sum yields
output visibility

For single baseline: time interval = $t_2 - t_1$
bandwidth = $f_2 - f_1$

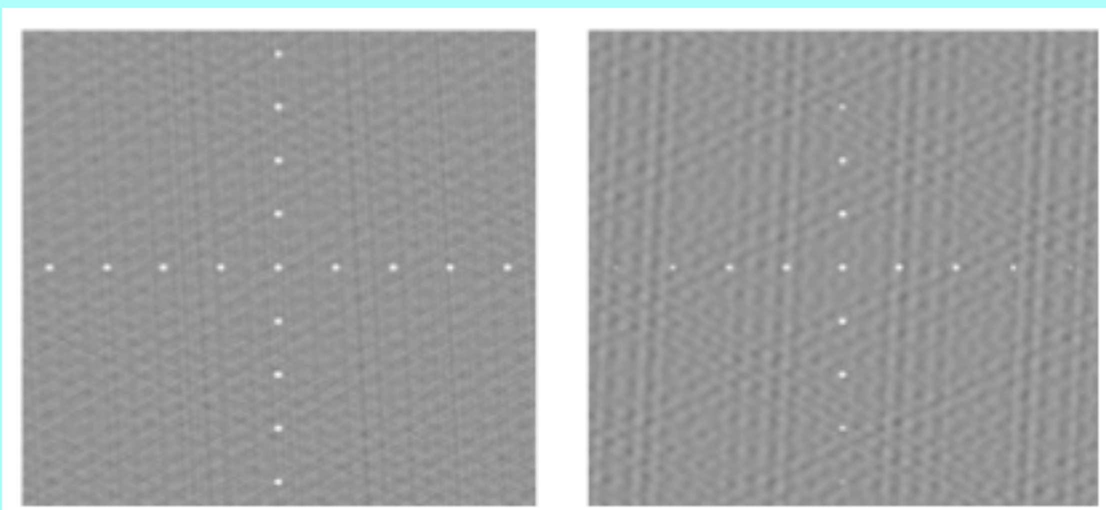
Constant size *u-v* patches
map to different-sized *f-t* sums
depending on baseline

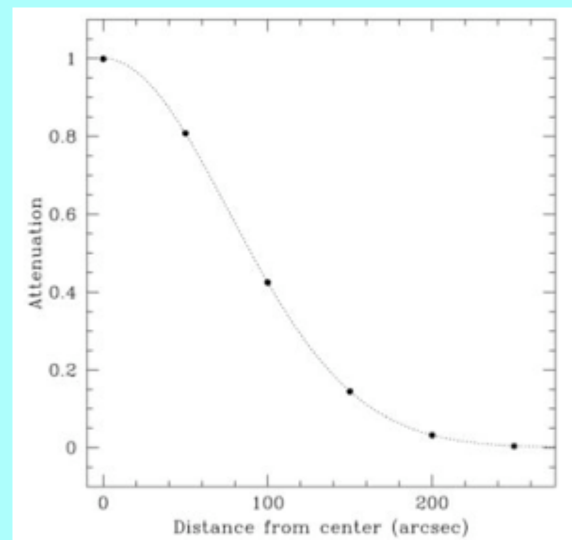
MIT Array Performance Simulator (MAPS): FOV Simulations

- General purpose radio array simulator developed at MIT Haystack/SAO (Doeleman, Lonsdale, Cappallo, Bhat, Oberoi, Attridge, Wayth)

- Correct handling of aperture plane effects (e.g., direction-dependent ionospheric distortions; receptor patterns; phased beam arrays)

- Incorporates model of correlator data averaging operation to properly treat effects of time and bandwidth smearing; ability to achieve virtually any time or frequency resolution





Source attenuation resulting from application of Gaussian FOV weighting

from Lonsdale, Doeleman & Oberoi (2005)

Limitations/Issues

• Short baselines need long (f, t) extent; calibration must be stable over Δt and Δt

$\Rightarrow$Sets limit on shortest baseline

• To support FOV weighting, granularity in freq. and time is proportional to baseline length.

$\Rightarrow$Sets limit on longest baseline

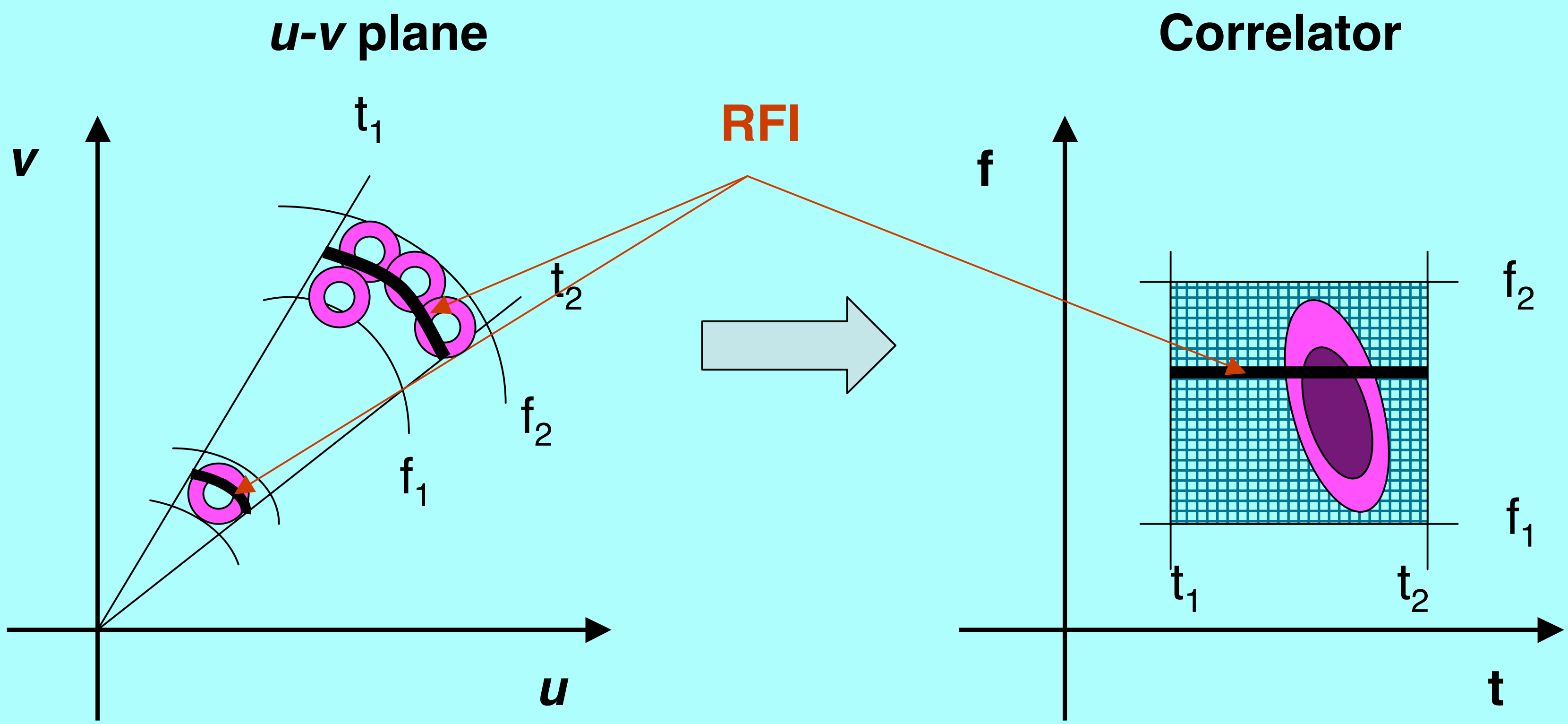
• Alternatively… data rate depends on baseline length:

  • Rate ~ $(b\_long/b\_short)^2$
  • Due to lowering of data rate on short baselines.

• To achieve desired reduction in data rate, ultimately will want to apply *before* data exit correlator - harness high speed computation.

• Effects of RFI excision require further investigation

The Problem of RFI:



Each excised time/frequency interval on a given baseline will cause a particular gap in the *u-v* patch for that baseline
⇒convolution function in *u-v* plane no longer uniform among baselines
⇒different FOV shape for each visibility

MAPS simulations will be used to characterize RFI effects.

(e)MERLIN: A Test Bed for FOV Shaping Algorithms

- Range of baseline lengths ideal for FOV algorithm testing
- Number of baselines small and manageable
- Data correlation can be performed with Haystack correlator

Tests ongoing with data from 4- & 6-element arrays; ν_0=1650 MHz, $\Delta\nu$=16.0 MHz/512 (V. Fish & D. Foight):

1. Field 1: Two 3C sources separated by ~29´
2. Field 2: M31

Results so far:

- Both "Jinc" and "Gaussian" weighting functions appear to provide predicted suppression; superior sidelobe rejection compared with time/bandwidth smearing

- Technique remains effective even in cases of heavy flagging (up to ~50%) "Jinc" more sensitive to heavy flagging than "Gaussian" (D. Foight 2007)

Prospects for the EVLA?

With new WIDAR correlator:

- 100 ms dumps w/ 1 Gb/s ethernet; factor of 10+ improvement possible
- Δt & $\Delta \nu$ control on individual baselines allowed by hardware, but not current software; current Binary Data Format would also need to be updated (M. Rupen)

$\Rightarrow$ future tests for subset of A-configuration antennas?

Possible motivations: way to mitigate effects of wide-field imaging errors?
testbed for algorithm development

Potential problems:
- may not work on the shortest baselines
- RFI excision in real time would likely be necessary
- $$ + time

Issues Currently Being Investigated

- What is the most effective weighting function to use? Gaussian? Jinc? Other?

- How will presence of realistic skies affect performance of algorithm?

- How will use of FOV shaping algorithms affect implementation of various calibration schemes?

- How will various types of RFI affect algorithm performance?

- Computational demands?

- Implementation of FOV shaping in post-correlation hardware?
- Impact on future array cost equations.

Ongoing testing with real (MERLIN) and simulated (MAPS) data at Haystack should provide many new insights