

# Tapering, DDE, and PSFs

<sup>1</sup> Department of Physics & Electronics, Rhodes University, PO Box 94, Grahamstown, 6140, South Africa

<sup>2</sup> SKA South Africa, 3rd Floor, The Park, Park Road, Pinelands, 7405, South Africa

<sup>3</sup> GEPI, Observatoire de Paris, CNRS, Université Paris Diderot, 5 place Jules Janssen, 92190 Meudon, France

Received / Accepted

**Abstract.**

## 1. Introduction

## 2. Motivation

## 3. Matrix formulation of the problem - 1D interferometer

Here I intend to use convolution matrices properties to *qualitatively* study how “pseudo-PSF” vary as a function of source location. Here I limit myself to a 1-dimensional interferometer (scalar only), so that Convolution matrices are Toeplitz-symetric (see below). In a more general case, (along my intuition - but should be thought more carefully), convolution matrices should be block-Toeplitz (each block is a Toeplitz), while symetricity should still be true.

### 3.1. Remarks on the convolution and linear algebra

In functional form the convolution theorem can be written as follows:

$$\mathcal{F}\{a.b\} = \mathcal{F}\{a\} * \mathcal{F}\{b\} \quad (1)$$

Noting the convolution product is linear, we can re-express the convolution product and associated theorem using linear transformations:

$$\mathbf{F} \mathbf{A} \mathbf{b} = \mathbf{C}_\mathbf{A} \mathbf{F} \mathbf{b} \quad (2)$$

where  $\mathbf{F}$  is the Fourier operator of size  $n_{uv} \times n_{lm}$  ( $\mathbf{F}$  is unitary  $\mathbf{F}^H \mathbf{F} = \mathbf{1}$ ),  $\mathbf{b}$  is a vector with size  $n_{lm}$ . The matrix  $\mathbf{A}$  models the scalar multiplication of each point in  $\mathbf{b}$ , and is therefore diagonal of size  $n_{lm} \times n_{lm}$ , and  $\mathbf{C}_\mathbf{A}$  is the convolution matrix of size  $n_{uv} \times n_{uv}$ . There is a bijective relation

$$\mathbf{A} \longleftrightarrow \mathbf{C}_\mathbf{A} \quad (3)$$

in the sense that a scalar multiplication defines a convolution function and conversely. The matrices  $\mathbf{A}$  and  $\mathbf{C}_\mathbf{A}$  always have the following properties:

- $\mathbf{A}$  is diagonal
- In the 1D case
  - $\mathbf{C}_\mathbf{A}$  is Toeplitz
  - In addition, for radiointerferometry, because the uv plane is symetric,  $\mathbf{C}_\mathbf{A}$  is symetric

The matrix  $\mathbf{C}_\mathbf{A}$  being Toeplitz, each row  $[\mathbf{C}_\mathbf{A}]_l$  with sky coordinate  $l$  can be built using a rolling operator  $\Delta_l$  that shifts the first row (the PSF at the field center for example) to location of row  $l$ :

$$[\mathbf{C}_\mathbf{A}]_l = \Delta_l \{[\mathbf{C}_\mathbf{A}]_0\} \text{ and} \quad (4)$$

$$[\mathbf{C}_\mathbf{A}]_0 = \mathbf{F}^H \text{diag}(\mathbf{A}) \quad (5)$$

The rolling operator is essentially just a reindexing, and has the following properties:

$$\Delta_l \{a\mathbf{x}\} = a\Delta_l \{\mathbf{x}\} \quad (6)$$

$$\Delta_l \left\{ \sum_i \mathbf{x}_i \right\} = \sum_i \Delta_l \{\mathbf{x}_i\} \quad (7)$$

### 3.2. PSF behaviour

If  $\mathbf{X}$  is the true sky, then the dirty image  $\mathbf{X}_{ij}^D$  of baseline  $(ij)$  can be written as:

$$\mathbf{x}_{ij}^D = \mathbf{F}^H \mathbf{S}_{c,ij} \mathbf{C}_\mathbf{T} \mathbf{S}_{\square,ij} \mathbf{F} \mathbf{A} \mathbf{x} \quad (8)$$

where  $\mathbf{A}_{ij}$  models the DDE effects and is an  $n_{pix} \times n_{pix}$  diagonal matrix (taking polarisation into account it is an  $4n_{pix} \times 4n_{pix}$  block diagonal matrix),  $\mathbf{T}$  is the tapering/averaging function,  $\mathbf{S}_\square$  samples the region over which

the tapering/averaging is made, and  $\mathbf{S}_{c,ij}$  selects the central point of the averaged/tapered visibility set. Using Eq. 4, we have:

$$\mathbf{x}_{ij}^D = \mathbf{C}_{S_{c,ij}} \mathbf{T} \mathbf{C}_{S_{\square,ij}} \mathbf{F}^H \mathbf{F} \mathbf{A}_{ij} \mathbf{x} \quad (9)$$

$$= \mathbf{C}_{S_{c,ij}} \mathbf{T} \mathbf{C}_{S_{\square,ij}} \mathbf{A}_{ij} \mathbf{x} \quad (10)$$

$$\sim \mathbf{C}_{S_{c,ij}} \mathbf{T} \mathbf{A}_{ij} \mathbf{x} \quad (11)$$

where Eq. 11 is true when the support of the function  $T$  is smaller than the sampling domain of  $\mathbf{S}_{\square}$ .

Averaged over all baselines, the dirty image becomes:

$$\mathbf{x}^D = \mathbf{C}_{STA} \mathbf{x} \quad (12)$$

$$\text{with } \mathbf{C}_{STA} = \sum_{ij} \mathbf{C}_{S_{c,ij}} \mathbf{T} \mathbf{A}_{ij} \quad (13)$$

### 3.3. Deriving the Pseudo-PSF

#### 3.3.1. PSF and Pseudo-PSF

We can already see that  $\mathbf{C}_{S_{c,ij}} \mathbf{T} \mathbf{A}_{ij}$  in Eq. 11 is NOT Toeplitz anymore because each column is multiplied by a different value (DDE multiplied by the tapering function). The dirty sky is therefore not anymore the convolution of the true sky by the psf ie the PSF varies across the field of view.

#### 3.3.2. Slow way

Calculate the psf estimating  $\mathcal{C}$  from direct calculation. Eventually at discrete locations on a grid.

#### 3.3.3. Quickly deriving the Pseudo-PSF

This is tricky part. The problem amount to finding any column  $l$  of  $\mathcal{C}$  on demand. For notation convenience, we merge  $\mathbf{T}$  and  $\mathbf{A}_{ij}$  together in  $\mathbf{A}_{ij}$ . Operator  $[\mathbf{M}]_l$  extracts column  $l$  from matrix  $\mathbf{M}$ , and using Eq. 6, 7 and 12:

$$[\mathcal{C}]_l = \left[ \sum_{ij} \mathbf{C}_{S_{c,ij}} \mathbf{A}_{ij} \right]_l \quad (14)$$

$$= \sum_{ij} a_{ij}^l [\mathbf{C}_{S_{c,ij}}]_l \quad (15)$$

$$\text{with } a_{ij}^l = \mathbf{A}_{ij}(l) \quad (16)$$

$$= \sum_{ij} \Delta_l \{ a_{ij}^l [\mathbf{C}_{S_{c,ij}}]_0 \} \quad (17)$$

$$= \sum_{ij} \Delta_l \{ \mathbf{F}^H a_{ij}^l \text{diag}(\mathbf{S}_{c,ij}) \} \quad (18)$$

If we now assume that at any given location  $l$ , the scalar  $a_{ij}^l$  can be described by a smooth function of the uv coordinates ( $(ij)$ -indices), then we can write:

$$[\mathcal{C}]_l = \sum_{ij} \Delta_l \{ \mathbf{F}^H \mathbf{A}^l \text{diag}(\mathbf{S}_{c,ij}) \} \quad (19)$$

$$= \sum_{ij} \Delta_l \{ \mathbf{C}_{A^l} \mathbf{F}^H \text{diag}(\mathbf{S}_{c,ij}) \} \quad (20)$$

$$= \sum_{ij} \Delta_l \{ \mathbf{C}_{A^l} [\mathbf{C}_{S_{c,ij}}]_0 \} \quad (21)$$

$$= \Delta_l \left\{ \mathbf{C}_{A^l} \sum_{ij} [\mathbf{C}_{S_{c,ij}}]_0 \right\} \quad (22)$$

$$= \Delta_l \{ \mathbf{C}_{A^l} [\mathbf{C}_{S_c}]_0 \} \quad (23)$$

$$(24)$$

The approximate observed Pseudo-PSF is the convolution of the PSF at the phase center ( $[\mathbf{C}_{S_c}]_0$ ) and the fourier transform of the uv-dependent tapering function at given  $lm$  ( $\mathbf{C}_{A^l}$ ).

In other words, to compute the PSF at a given location ( $lm$ ):

- Find  $\mathbf{A}$ :
  - Compute weight  $w_{ij}$  for each baseline ( $ij$ )
  - Fit the uv-dependent weight by (for example), a Gaussian function  $w_{ij} \sim w(u, v) = \mathcal{G}(u, v)$
- Compute the  $PSF_{lm}$  at ( $lm$ ) from the PSF at the phase center  $PSF_0$  as  $PSF_{lm} = \mathcal{F}^{-1}(w) * PSF_0$

For example if the long baselines are more tapered, they are "attenuated". The effective PSF on the edge of the field will get larger by the convolution... Something like that...

## 4. Numerical Experiments

We demonstrate the computational complexity of the quick, the slow derived PSF as a function of sky coordinates and perform a direct numerical results.

### 4.1. Slow derivation

### 4.2. Quick derivation

We will now show how to derived a pseudo PSF which is based and resolved on the nominal PSF but labelled by a set of band-limited integration. In order to further optimize the slow derivation of the PSF described above to particularly reduce the computational cost, we will need to understand the concept and theory of signal correlation in aperture synthesis. It is worth noting in Radio Astronomy community that the cross-correlator output of two elements interferometer in response to a source with spectral brightness distribution  $I_\nu(\mathbf{s})$  as a function of the pointing direction  $\mathbf{s}$  is the visibility function defined in Eq.25 and obtained by integrating over the solid angle  $d\Omega$  (Thompson et al. 2008; Taylor et al. 1999)

$$V(\mathbf{b}) = \int_{\Omega} I_\nu(\mathbf{s}) e^{-2\pi i \mathbf{b} \cdot \mathbf{s}} d\Omega, \quad (25)$$

where  $\mathbf{b} = \mathbf{b}(t, \nu) = (u_{t\nu}, v_{t\nu}, w_{t\nu})$  is the so called "base-line vector" in wavelength and with modulus the distance between the two elements interferometer. The measurement in Eq.25 is over the entire surface of the celestial sphere, practically the measurement is generally taken over a finite surface area of the celestial sphere due to the finite nature of the tracking source and other effects. Furthermore, the results is averaged over finite time/frequency bins. Suppose  $\Delta t$  centered at  $t_0$  and  $\Delta \nu$  centered at  $\nu_0$  the time and frequency averaged intervals respectively. Assuming that  $\Delta t$  and  $\Delta \nu$  are small enough so that  $I_\nu(\mathbf{s})$  remains constant while the complex phase,  $-2\pi i \mathbf{b} \mathbf{s}$  varies linearly. Eq.25 becomes:

$$V(\mathbf{b}_0) = \frac{1}{\Delta t \Delta \nu} \iint_{\Delta t \Delta \nu} W_{t_0, \nu_0}(t, \nu) \left[ \int_{\Omega} I_\nu(\mathbf{s}) e^{-2\pi i \mathbf{b} \mathbf{s}} d\Omega \right] dt d\nu \quad (26)$$

$$= \iint_{uv} W_{\mathbf{b}_0}(\mathbf{b}) \left[ \int_{\Omega} I_\nu(\mathbf{s}) e^{-2\pi i \mathbf{b} \mathbf{s}} d\Omega \right] dudv, \quad (27)$$

where the following shorthand notation has been used.

$$\begin{aligned} \mathbf{b}_0 &= \mathbf{b}(t_0, \nu_0) \\ &= (u_{t_0\nu_0}, v_{t_0\nu_0}, w_{t_0\nu_0}), \\ W_{\mathbf{b}_0}(\mathbf{b}) &= \frac{W_{t_0, \nu_0}(t, \nu)}{\Delta t \Delta \nu}. \end{aligned}$$

Here,  $\mathbf{b}_0$  is the baseline vector at centre of a sampling interval and the sampling kernel  $W_{\mathbf{b}_0}(\mathbf{b})$  is defined as:

$$W_{\mathbf{b}_0}(\mathbf{b}) = \Pi(\mathbf{b} - \mathbf{b}_0) w(\mathbf{b} - \mathbf{b}_0), \quad (28)$$

where,  $\Pi(\mathbf{b} - \mathbf{b}_0)$  is a windowing function and  $w(\mathbf{b} - \mathbf{b}_0)$  a weighting kernel.

As previously mentioned, we are interested on PSF's response. Therefore, Eq.27 is restricted to the complex visibility measured by the two elements interferometer for a point source located towards the direction  $\mathbf{s}$  with unitary brightness. That said,  $I_\nu(\mathbf{s}) = \delta(\mathbf{b}_0)$  with  $\delta$  the Dirac delta. It then follows that Eq.27 can be written as

$$V(\mathbf{b}_0) = \iint_{uv} W_{\mathbf{b}_0}(\mathbf{b}) * \delta(\mathbf{b}_0) e^{-2\pi i (u_{t\nu} l + v_{t\nu} m + w_{t\nu} (n-1))} dudv, \quad (29)$$

The operator  $*$  indicates convolution. Note that Eq.29 is obtained after a delay correction of  $\mathbf{b} \mathbf{s}_0$  is applied to the signals from the antennas array to steer towards the direction  $\mathbf{s}_0$  and  $\mathbf{b}(\mathbf{s} - \mathbf{s}_0) = u_{t\nu} l + v_{t\nu} m + w_{t\nu} (n-1)$  describes the time difference between the two incoming signals. The three directions cosine  $l, m$  and  $n-1$  are components of  $\mathbf{s} - \mathbf{s}_0$  given in radian with  $n = \sqrt{1 - l^2 - m^2}$ . For an extensive Discussion, see (Thompson et al. 2008; Taylor et al. 1999)

Eq.29 is two dimensional Fourier transform, making used of the convolution theorem which the literature

states that the Fourier transform of the product of two functions result to a convolution and vice-versa, the following expansion is valid

$$V(\mathbf{b}_0) = \mathcal{F}\{W_{\mathbf{b}_0}(\mathbf{b})\} \mathcal{F}\{\delta(\mathbf{b}_0)\} \quad (30)$$

$$= \left[ \mathcal{F}\{\Pi(\mathbf{b} - \mathbf{b}_0)\} * \mathcal{F}\{w(\mathbf{b} - \mathbf{b}_0)\} \right] \mathcal{F}\{\delta(\mathbf{b}_0)\} \quad (31)$$

$$= C_{lm}(\mathbf{b}_0) \left[ \mathcal{F}\{\Pi(\mathbf{b})\} * \mathcal{F}\{w(\mathbf{b})\} \right] \mathcal{F}\{\delta(\mathbf{b}_0)\} \quad (32)$$

The symbol  $\mathcal{F}$  denotes the Fourier transform and  $C_{lm}(\mathbf{b}_0)$  is obtained after we had apply the shifted Fourier transform properties. In other words,  $C_{lm}(\mathbf{b}_0)$  is defined as

$$C_{lm}(\mathbf{b}_0) = e^{-2\pi i (u_{t_0\nu_0} l + v_{t_0\nu_0} m + w_{t_0\nu_0} (n-1))}$$

If it is assumed that  $\Pi(\mathbf{b})$  is the top-hat windowing function, then it can be demonstrated that its Fourier transform is (see Appendix A)

$$\mathcal{F}\{\Pi(\mathbf{b})\} = \text{sinc} \frac{-2\pi t \Delta \nu}{2} \text{sinc} \frac{-2\pi \nu \Delta t}{2}$$

It is demonstrated in (Smirnov 2011) that for natural weighting, Eq.32 is approximated in term of the phase changing in time  $\Delta \Psi$  and frequency  $\Delta \Phi$  for the case of smearing as:

$$V(\mathbf{b}_0) \simeq C_{lm}(\mathbf{b}_0) \left[ \text{sinc} \frac{\Delta \Psi}{2} \text{sinc} \frac{\Delta \Phi}{2} * \mathcal{F}\{w(\mathbf{b}_0)\} \right] \mathcal{F}\{\delta(\mathbf{b}_0)\}$$

where  $\Delta \Psi$  and  $\Delta \Phi$  are explicitly defined as

$$\begin{aligned} \Delta \Psi &= 2\pi \left[ (u_{t_s \nu_0} - u_{t_e \nu_0}) l + (v_{t_s \nu_0} - v_{t_e \nu_0}) m \right. \\ &\quad \left. + (w_{t_s \nu_0} - w_{t_e \nu_0}) (n-1) \right], \\ \Delta \Phi &= 2\pi \left[ (u_{t_0 \nu_s} - u_{t_0 \nu_e}) l + (v_{t_0 \nu_s} - v_{t_0 \nu_e}) m \right. \\ &\quad \left. + (w_{t_0 \nu_s} - w_{t_0 \nu_e}) (n-1) \right], \end{aligned}$$

and  $t_s, t_e, \nu_s$  and  $\nu_e$  are the sampling intervals starting time, ending time, starting frequency and ending frequency respectively.

We then generalized the approximation of smearing where  $\Pi(\mathbf{b})$  is a random windowing function as follows:

$$V(\mathbf{b}_0) \simeq C_{lm}(\mathbf{b}_0) \left[ \mathcal{F}\{\Pi(\mathbf{b}_0)\} * \mathcal{F}\{w(\mathbf{b}_0)\} \right] \mathcal{F}\{\delta(\mathbf{b}_0)\}$$

#### 4.3. Imaging

Assuming that all the baselines are pointing at the same phase tracking centre, during conventional interferomet-

ric imaging, the baseline visibilities are mapped on a uv-plane, and the result is inverse Fourier transformed:

$$PSF(\mathbf{s}) \simeq \mathcal{F}^{-1} \left\{ \sum_{j=1}^{n_{bl}n_v} V_{pq}(\mathbf{b}_j) \right\} \quad (33)$$

$$\simeq \mathcal{F}^{-1} \left\{ \sum_{j=1}^{n_{bl}n_v} C_{lm}(\mathbf{b}_j) \left[ \mathcal{F} \{ \Pi(\mathbf{b}_j) \} \right. \right. \quad (34)$$

$$\left. * \mathcal{F} \{ w(\mathbf{b}_j) \} \right] \mathcal{F} \{ \delta(\mathbf{b}_j) \} \left. \right\} \quad (35)$$

$$\simeq \mathcal{C}(\mathbf{s}) * PSF(\mathbf{s}_0), \quad (36)$$

where  $PSF(\mathbf{s}_0)$  is the PSF at the phase tracking center and  $\mathcal{C}(\mathbf{s})$  is the image plane smearing response for a source located toward the direction  $\mathbf{s}$  ( $\mathbf{s} \neq \mathbf{s}_0$ ) given as

$$\mathcal{C}(\mathbf{s}) = \sum_{j=1}^{n_{bl}n_v} \mathcal{F}^{-1} \left\{ C_{lm}(\mathbf{b}_0) \right\} * \left[ \Pi(\mathbf{b}_0) w(\mathbf{b}_0) \right]. \quad (37)$$

Note that,  $n_v \times n_{bl}$  is the array total number of visibilities with  $n_v$  and  $n_{bl}$  the number of visibilities per baseline after approximation and the number of baselines respectively.

The smeared unnormalized PSF of a source,  $PSF(\mathbf{s})$  located toward the direction  $\mathbf{s}$  was derived and shown that it is proportional to the PSF,  $PSF(\mathbf{s}_0)$  of a source at the phase centre.

#### 4.3.1. Computational cost

### 5. Simulation and comparison

### 6. Discussion and conclusion

*Acknowledgements.* No thanks

### References

- Smirnov O. M., 2011, *Astronomy & Astrophysics*, 527, A106
- Taylor G. B., Carilli C. L., Perley R. A., 1999, in *Synthesis Imaging in Radio Astronomy II* Vol. 180, Synthesis imaging in radio astronomy ii
- Thompson A. R., Moran J. M., Swenson Jr G. W., 2008, *Interferometry and synthesis in radio astronomy*. John Wiley & Sons

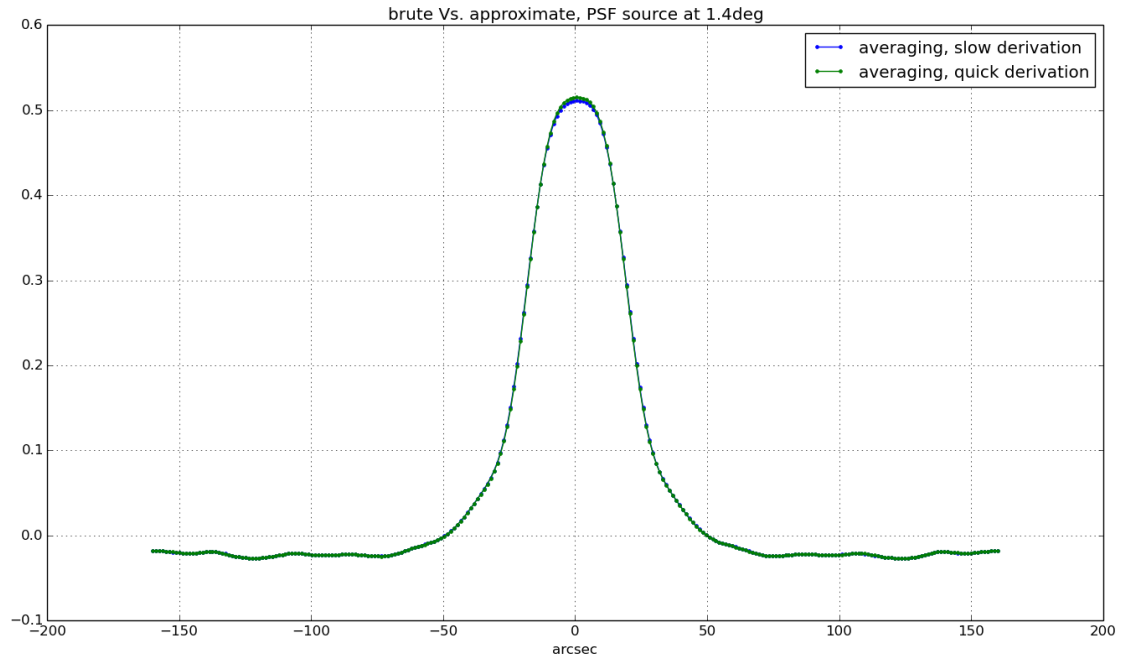
### Appendix A: The Fourier Transform of a top-hat windowing function

$$\Pi(\mathbf{b}) = \begin{cases} 1 & \text{for } t \times \nu \in [t_s, t_e] \times [\nu_s, \nu_e], \\ 0 & \text{for } t \times \nu \notin [t_s, t_e] \times [\nu_s, \nu_e] \end{cases} \quad (\text{A.1})$$

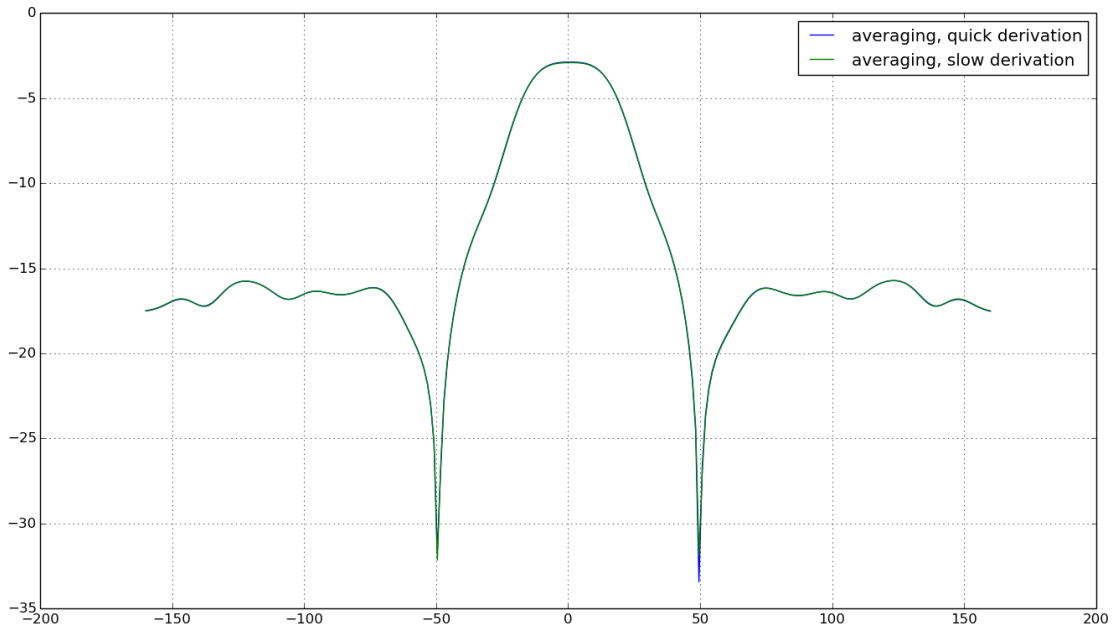
The Fourier transform, of Eq.A.1 is given by

$$\mathcal{F} \{ \Pi(\mathbf{b}) \} = \text{sinc} \frac{-2\pi t \Delta \nu}{2} \text{sinc} \frac{-2\pi \nu \Delta t}{2}$$

Let suppose that



**Fig. 1.** Brute Vs approximate PSF for a source at 1.4deg



**Fig. 2.** Brute Vs approximate PSF for a source at 1.4deg compare in log space

