

# Tapering, DDE, and PSFs

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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 symmetric,  $\mathbf{C}_\mathbf{A}$  is symmetric

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

In order to further optimize the slow derivation of the PSF described above to particularly reduce its computational cost, we will need to understand the concept and theory of signal correlation in aperture synthesis. It is worth noting that in the Radio Astronomy community 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 result 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 sampling 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:

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

However, performing the integration over a surface of size,  $\Delta t \times \Delta \nu$  yields a nonzero value only in this surface area, which is reconized as integrating of a windowing function  $\Pi_{t_0, \nu_0}(t, \nu)$  of size  $\Delta t \times \Delta \nu$ . Let  $\mathbf{b}_0 = \mathbf{b}(t_0, \nu_0) = (u_{t_0 \nu_0}, v_{t_0 \nu_0}, w_{t_0 \nu_0})$  be the baseline vector at the centre of the sampling intervals and  $W_{t_0, \nu_0}(t, \nu)$  a weighting kernel. The sampling kernel,  $W_{\mathbf{b}_0}(\mathbf{b})$  for a given  $(u, v)$  track associated with the weighting kernel is defined by

$$W_{\mathbf{b}_0}(\mathbf{b}) = \frac{\Pi_{t_0, \nu_0}(t, \nu)}{\Delta t \Delta \nu} W_{t_0, \nu_0}(t, \nu) \quad (27)$$

$$= \Pi(\mathbf{b} - \mathbf{b}_0) W(\mathbf{b} - \mathbf{b}_0). \quad (28)$$

If it is assumed that,  $\frac{dt d\nu}{dudv} \sim 1$  then Eq.26 can be written in terms of  $\mathbf{b}_0$  and can thus be expressed as an integration over  $uv$ -bins. We can write

$$V(\mathbf{b}_0) = \iint_{uv} W_{\mathbf{b}_0}(\mathbf{b}) \left[ \int_{\Omega} I_\nu(\mathbf{s}) e^{-2\pi i \mathbf{b} \mathbf{s}} d\Omega \right] dudv. \quad (29)$$

As previously mentioned, we are interested in PSF response. Therefore, Eq.29 is restricted to the complex visibility measured by the two-element interferometer for a point source located towards the direction  $\mathbf{s}$  with unit brightness. That said,  $I_\nu(\mathbf{s}) = \delta(\mathbf{b}_0)$  with  $\delta$  the Dirac delta. It then follows that Eq.29 can be written as

$$V(\mathbf{b}_0) = \iint_{uv} W_{\mathbf{b}_0}(\mathbf{b}) e^{-2\pi i (u_{t\nu} l + v_{t\nu} m + w_{t\nu} (n-1))} dudv. \quad (30)$$

Note that Eq.30 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 direction cosines  $l, m$  and  $n$  are components of  $\mathbf{s} - \mathbf{s}_0$  in radians with  $n = \sqrt{1 - l^2 - m^2}$ . For an extensive discussion, see (Thompson et al. 2008; Taylor et al. 1999; Leshem & van der Veen 2000). Let  $G_{lm}(w_{t\nu}) = e^{-2\pi i [w_{t\nu} (n-1)]}$ . Then Eq.30 becomes a two dimensional Fourier transform and making use of the convolution theorem which states that the Fourier transform

of the product of two functions result in a convolution and vice-versa<sup>1</sup>, we have

$$V_{w_{t\nu}}(\mathbf{b}_0) = G_{lm}(w_{t\nu}) * \iint_{uv} W_{\mathbf{b}_0}(\mathbf{b}) e^{-2\pi i (u_{t\nu} l + v_{t\nu} m)} dudv. \quad (31)$$

Also,  $W_{\mathbf{b}_0}(\mathbf{b})$  is defined as a product of two functions (refer to Eq. 28), making use of the shifted Fourier transform properties and the convolution theorem, the following expansion is valid

$$V_{w_{t\nu}}(\mathbf{b}_0) = G_{lm}(w_{t\nu}) * \left[ C_{lm}(\mathbf{b}_0) \tilde{\Pi}(\mathbf{b}) \right] * \left[ C_{lm}(\mathbf{b}_0) \tilde{W}(\mathbf{b}) \right] \quad (32)$$

The symbols  $*$  and  $\sim$  denote the convolution operator and the Fourier transform respectively. The phase gradient,  $C_{lm}(\mathbf{b}_0)$  is defined as

$$C_{lm}(\mathbf{b}_0) = e^{-2\pi i (u_{t_0 \nu_0} l + v_{t_0 \nu_0} m)} \quad (33)$$

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)

$$\tilde{\Pi}(\mathbf{b}) = \text{sinc}\left(\frac{-2\pi t \Delta \nu}{2}\right) \text{sinc}\left(\frac{-2\pi \nu \Delta t}{2}\right) \quad (34)$$

It is demonstrated in (Smirnov 2011) that for natural weighting, Eq.31 can be approximated in term of the phase change in time,  $\Delta \Psi$  and in frequency  $\Delta \Phi$  for the case of smearing as:

$$V_{w_{t_0 \nu_0}}(\mathbf{b}_0) \simeq G_{lm}(w_{t_0 \nu_0}) \left[ \left( C_{lm}(\mathbf{b}_0) \text{sinc} \frac{\Delta \Psi}{2} \text{sinc} \frac{\Delta \Phi}{2} \right) * \left( C_{lm}(\mathbf{b}_0) \tilde{W}(\mathbf{b}_0) \right) \right] \quad (35)$$

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

$$\Delta \Psi = 2\pi \left[ (u_{t_s \nu_0} - u_{t_e \nu_0}) l + (v_{t_s \nu_0} - v_{t_e \nu_0}) m + (w_{t_s \nu_0} - w_{t_e \nu_0}) (n-1) \right], \quad (36)$$

$$\Delta \Phi = 2\pi \left[ (u_{t_0 \nu_s} - u_{t_0 \nu_e}) l + (v_{t_0 \nu_s} - v_{t_0 \nu_e}) m + (w_{t_0 \nu_s} - w_{t_0 \nu_e}) (n-1) \right], \quad (37)$$

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

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

$$V_{w_{t_0 \nu_0}}(\mathbf{b}_0) \simeq G_{lm}(w_{t_0 \nu_0}) \left[ \left( C_{lm}(\mathbf{b}_0) \tilde{\Pi}(\mathbf{b}_0) \right) * \left( C_{lm}(\mathbf{b}_0) \tilde{W}(\mathbf{b}_0) \right) \right] \quad (38)$$

<sup>1</sup> <http://mathworld.wolfram.com/ConvolutionTheorem.html>  
[http://en.wikipedia.org/wiki/Convolution\\_theorem](http://en.wikipedia.org/wiki/Convolution_theorem)

### 4.3. Imaging

In the above section, an approximate visibility,  $V_{w_{t_0\nu_0}}(\mathbf{b}_0)$  is predicted for each baseline corresponding to its averaged uv track. Now, let us suppose that  $V_{w_{t\nu}}(\mathbf{b})$  are the predicted visibilities for a baseline  $pq$  corresponding to a full synthesis. During conventional interferometric imaging, the baseline visibilities are mapped on a uv-plane and the result is inverse Fourier transformed

$$I_D = \mathcal{F}^{-1} \left\{ \sum_{pq} S_{pq}^{lm} \mathcal{F} \{ I_{pq}^{lm} \} \right\}, \quad (39)$$

where  $S_{pq}^{lm}$  is the sampling function of the baseline  $pq$ . The sampling function is only nonzero in the neighborhood of the approximate track described by  $\mathbf{b}$ , and account in our case for both the observed *source location*, the windowing kernel, the imaging weights and the interpolation coefficients of the gridding process. Thus, the sampling function for the baseline  $pq$  is

$$S_{pq}^{lm} = V_{w_{t\nu}}(\mathbf{b}). \quad (40)$$

Taking this into account, Eq39 is rewritten as

$$I_D = \sum_{pq} P_{pq}^{lm} * I_{pq}^{lm}, \quad (41)$$

where  $P_{pq}^{lm} = \mathcal{F}^{-1} \{ V_{w_{t\nu}}(\mathbf{b}) \}$  is the normalized PSF associated with the baseline  $pq$ . Note that in the case of each baseline seeing a common sky  $I^{lm}$ , the above becomes

$$I_D = \left( \sum_{pq} P_{pq}^{lm} \right) * I^{lm}. \quad (42)$$

Eq42 demonstrates the *shift-variant* nature of the PSF and that the dirty image  $I_D$  is a convolution of the true sky at each location by the array PSF at the location which is given by

$$P^{lm} = \left( \sum_{pq} P_{pq}^{lm} \right). \quad (43)$$

which is not the familiar result that the dirty image is the convolution of the true sky by the PSF of the array (Grobler et al. 2014).

This works well than equation 38 but I do not see what is faster in this equation. Please check and tell me

$$V_{w_{t_0\nu_0}}(\mathbf{b}_0) \simeq G_{lm}(w_{t_0\nu_0}) \left[ s_{\mathbf{b}_0} \cdot \left( \left( C_{lm}(\mathbf{b}_0) \tilde{\Pi}(\mathbf{b}) \right) * \left( C_{lm}(\mathbf{b}_0) \tilde{W}(\mathbf{b}) \right) \right) \right] \quad (44)$$

where  $s_{\mathbf{b}_0}$  is a functional operator that select the centre of the sampling interval.

#### 4.3.1. Computational cost

## 5. Simulation and comparison

## 6. Discussion and conclusion

*Acknowledgements.* No thanks

## References

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

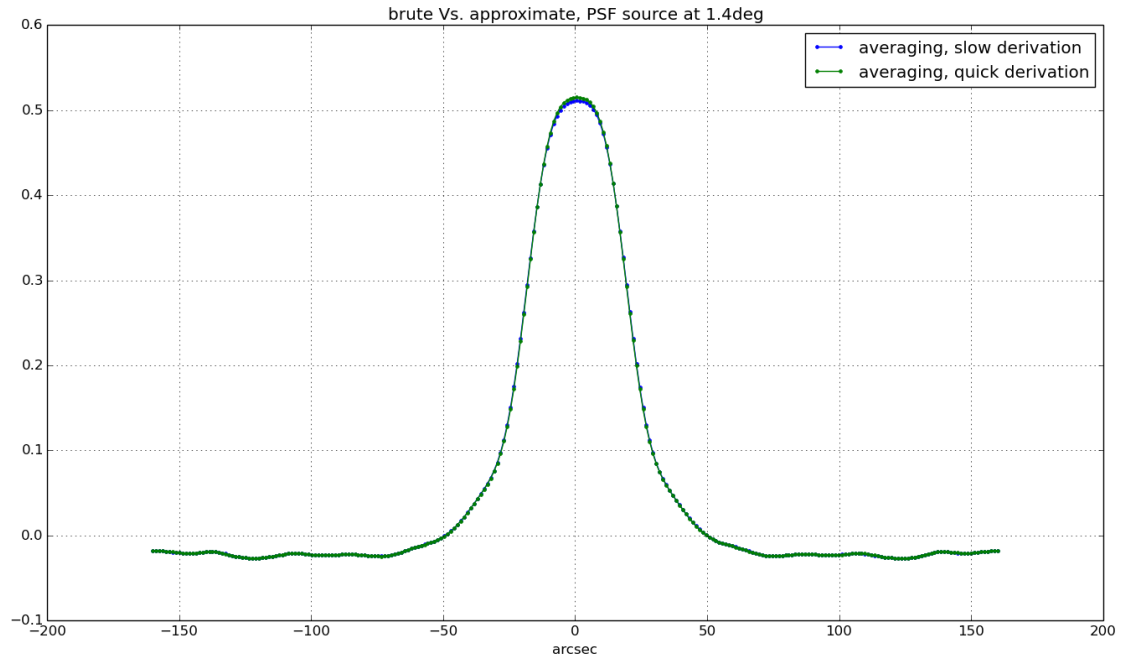
A two dimensional top-hat window is defined as

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

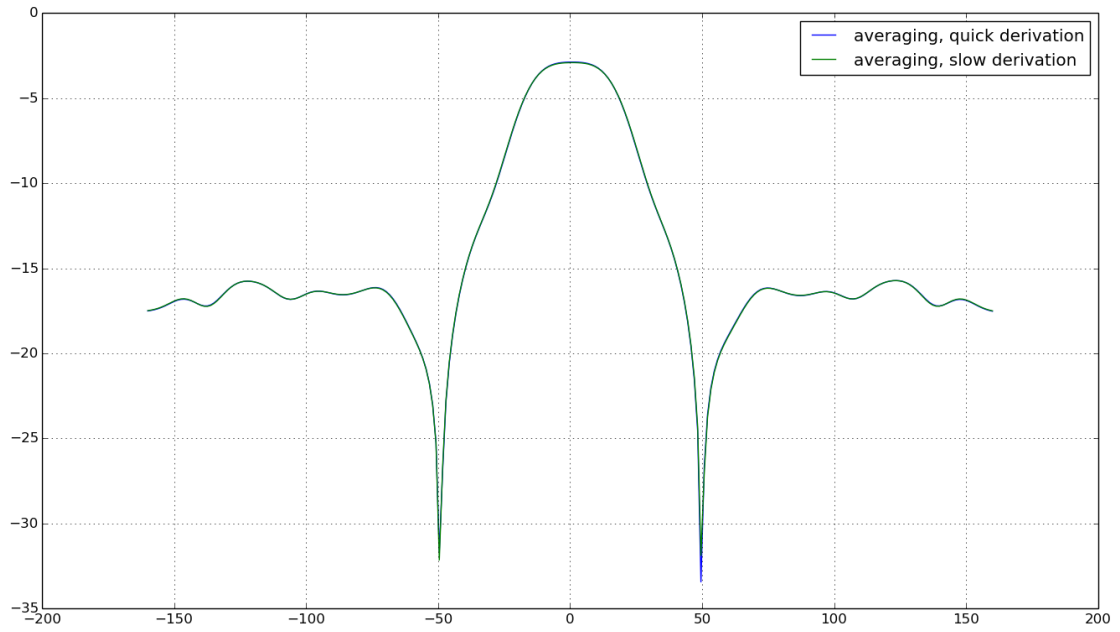
where  $[t_s, t_e] \times [\nu_s, \nu_e]$  is the passband region.

$$\tilde{\Pi}(\mathbf{b}) = \frac{1}{\Delta t \Delta \nu} \int_{t_s}^{t_e} \int_{\nu_s}^{\nu_e} e^{-2\pi i t \nu} dt d\nu$$

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

