Introduction	Background	Faraday synthesis	Proof of concept implementation	Summary

# Faraday Synthesis The synergy of aperture and rotation measure synthesis

#### M.R. Bell

with T. Enßlin - MPA

MKSP Workshop - Bologna - November 24, 2011

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Outline				



## 2 Background

- Brief review of aperture synthesis
- Brief review of RM Synthesis

## 3 Faraday synthesis

- Proof of concept implementation
  - fsimager software and mock data
  - Test results

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 Next generation radio astronomy
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• RM synthesis takes advantage of bandwidth, provides many benefits

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- RM synthesis takes advantage of bandwidth, provides many benefits
  - Increased sensitivity

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- RM synthesis takes advantage of bandwidth, provides many benefits
  - Increased sensitivity
  - More accurate measurement of Faraday depth

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- RM synthesis takes advantage of bandwidth, provides many benefits
  - Increased sensitivity
  - More accurate measurement of Faraday depth
  - Separate sources at different Faraday depths for independent study

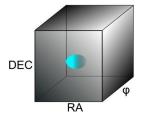
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- RM synthesis takes advantage of bandwidth, provides many benefits
  - Increased sensitivity
  - More accurate measurement of Faraday depth
  - Separate sources at different Faraday depths for independent study
  - Probe the mangetic fields between source and observer

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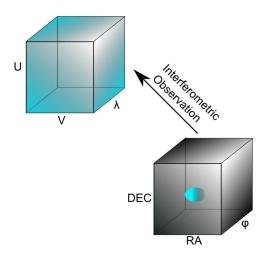
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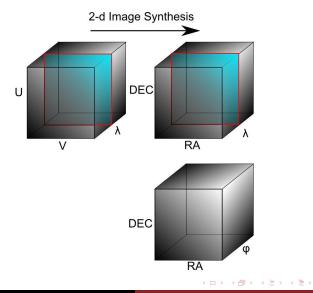
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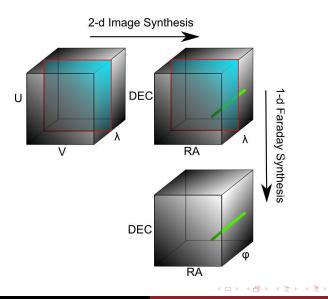
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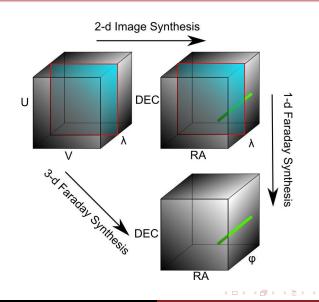
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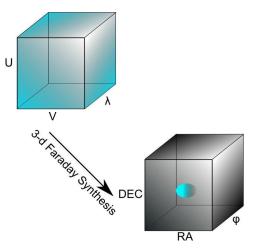
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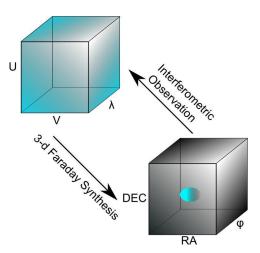
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Interfero	metry			

## Van Cittert–Zernike theorem

$$V(u,v,v) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} dl \, dm \, \mathscr{I}(l,m,v) e^{-2\pi i (ul+vm)} = \mathscr{F}_{2D}[\mathscr{I}]$$



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#### Van Cittert-Zernike theorem

$$V(u,v,v) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} dl \, dm \, \mathscr{I}(l,m,v) e^{-2\pi i (ul+vm)} = \mathscr{F}_{2D}[\mathscr{I}]$$

The sky is also attenuated by the antenna reception pattern
A(l,m,v)

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#### Van Cittert-Zernike theorem

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- The sky is also attenuated by the antenna reception pattern
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- The *uv*-plane is only partially sampled
  - S(u, v, v)

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#### Van Cittert-Zernike theorem

$$V(u,v,v) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} dl \, dm \, \mathscr{I}(l,m,v) e^{-2\pi i (ul+vm)} = \mathscr{F}_{2D}[\mathscr{I}]$$

- The sky is also attenuated by the antenna reception pattern
  A(l,m,v)
- The *uv*-plane is only partially sampled
  - S(u,v,v)

$$\widehat{V}(u,v,v) = S\mathscr{F}_{2D}[A(l,m,v)\mathscr{I}(l,m,v)]$$

Imaging	the sky			
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$$\begin{aligned} \mathscr{I}_D(l,m,v) &= \mathscr{F}_{2D}^{-1} \left[ \widehat{V}(u,v,v) \right] \\ &= B(l,m,v) * [A(l,m,v) \mathscr{I}(l,m,v)] \end{aligned}$$

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Imaging	the sky			

$$\begin{aligned} \mathscr{I}_D(l,m,\mathbf{v}) &= \mathscr{F}_{2D}^{-1} \left[ \widehat{V}(u,v,v) \right] \\ &= B(l,m,v) * [A(l,m,v) \mathscr{I}(l,m,v)] \end{aligned}$$

- Sky brightness convolved with  $B = \mathscr{F}_{2D}^{-1}[S]$
- B is nasty, so deconvolution is required (e.g. CLEAN)



• The Faraday effect rotates a plane polarized wave according to

• 
$$\chi = \chi_0 + \phi \lambda^2$$

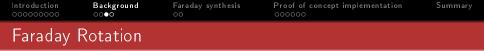


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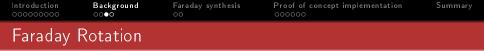
- The Faraday effect rotates a plane polarized wave according to
  - $\chi = \chi_0 + \phi \lambda^2$
- $\phi$ , Faraday depth
  - $\phi(z) \propto \int_0^z dz' n_e(z') B_z(z')$

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- The Faraday effect rotates a plane polarized wave according to
  - $\chi = \chi_0 + \phi \lambda^2$
- φ, Faraday depth
  - $\phi(z) \propto \int_0^z dz' n_e(z') B_z(z')$
- $P(l,m,\lambda^2) = \int_{-\infty}^{\infty} d\phi F(l,m,\phi) e^{2i\phi\lambda^2} = \mathscr{F}_{1D}[F(l,m,\phi)]$

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- The Faraday effect rotates a plane polarized wave according to
  - $\chi = \chi_0 + \phi \lambda^2$
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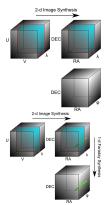
#### see Brentjens & de Bruyn, 2005

$$F_D(l,m,\phi) = \mathscr{F}_{1D}^{-1} \left[ S(l,m,\lambda^2) P(l,m,\lambda^2) \right]$$
  
=  $F(l,m,\phi) * B(l,m,\phi)$ 

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RM Synt	hesis			

- $\bullet~2D$  imaging of Stokes Q and U at each  $\lambda^2$ 
  - 2D deconvolution with limited sensitivity !!
  - UV coverage varies with frequency !!
- Stack images, perform RM synthesis along each LOS
  - UV tapering and a uniform restoring beam used to make up for varying UV coverage
  - Deconvolve again (e.g. RMCLEAN *Heald* et al., 2009)



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Putting it	t all toget	her		

• Aperture synthesis, Stokes Q

• 
$$\widehat{V}_Q = S\mathscr{F}_{2D}[AQ]$$

• RM synthesis

• 
$$Q = \mathscr{F}_{1D}[F_Q]$$
, NOTE:  $F_Q \in \mathbb{C}$ 

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$$Q = \mathscr{F}_{1D}[F_Q]$$
, NOTE:  $F_Q \in \mathbb{C}$ 

$$\widehat{\mathcal{V}_Q} = S\mathscr{F}_{2D} [A\mathscr{F}_{1D}(F_Q)] = S\mathscr{F}_{3D} [a * F_Q]$$

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Putting it	: all toget	her		

• Aperture synthesis, Stokes Q

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$$\widehat{V_Q} = S\mathscr{F}_{2D}[AQ]$$

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$$Q = \mathscr{F}_{1D}[F_Q]$$
, NOTE:  $F_Q \in \mathbb{C}$ 

$$\widehat{V_Q} = S\mathscr{F}_{2D}[A\mathscr{F}_{1D}(F_Q)] 
= S\mathscr{F}_{3D}[a * F_Q]$$

•  $A(l,m,\lambda^2) = \mathscr{F}_{1D}[a(l,m,\phi)]$ 

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3D Imag	ing			

$$(a * F_Q)_D = \mathscr{F}_{3D}^{-1} \left[ \widehat{V_Q} \right]$$
  
=  $B * a * F_Q$ 

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3D Imag	ing			

$$(a * F_Q)_D = \mathscr{F}_{3D}^{-1} \left[ \widehat{V_Q} \right]$$
  
=  $B * a * F_Q$ 

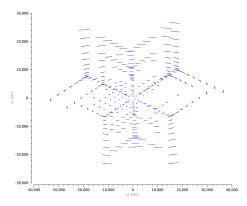
- The 3D dirty image is a convolution between
  - The Faraday spectrum, F
  - The 3D beam (PSF), B
  - The primary beam, transformed into Faraday space, i.e.  $a(I, m, \phi)$

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fsimage	er			

- fsimager Faraday synthesis imaging software
  - Written in Python, plus some Cython for speed
  - Gridding & imaging
  - Deconvolution via a 3D Clark CLEAN algorithm
- Only the basics for now...
  - No beam corrections, widefield imaging, etc.
  - Everything resides in memory, which severely limits the image size

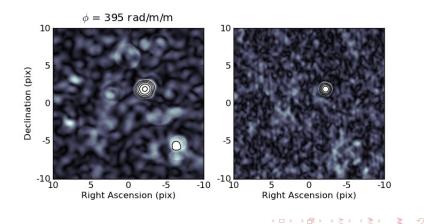
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Mock ob	servations			

- 30 point sources
  - Random locations
  - Random fluxes (0.06 - 64 Jy)
- "Observed" with the VLA from 1-4 GHz (x64 channels)
- Added Gaussian white noise,  $\sigma=$ 10 Jy



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Results				

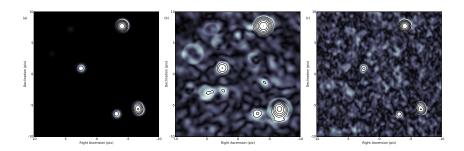
Side by side comparison



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Results				

$$\phi = 68 \text{ rad/m}^2$$



## Model - 2+1D - fsimager

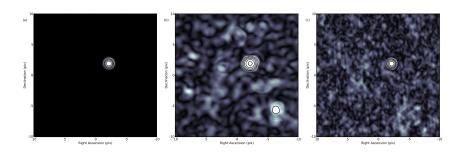
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Results				

$$\phi = 395 \text{ rad/m}^2$$



## Model - 2+1D - fsimager

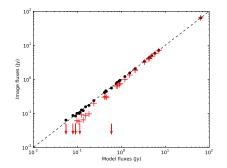
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Results				

- Noise levels about the same  $@\sim 5 mJy/Beam$
- Model sources at  $10\sigma$  and higher
- Recall: 30 sources in the model
- fsimager:
  - 32 sources detected above 50 mJy/Beam
  - No sources missing
- 2+1D
  - 147 sources detected above 50 mJy/Beam
  - 5 real sources not detected





crosses = Aperture + RM synthesis

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Summary	/			

- Faraday synthesis improves on aperture + RM synthesis
  - Improveded fidelity
  - Higher resolution
  - Less computationally expensive (in principle)
- Provides a solid framework for building new image reconstruction algorithms
- A production implementations is needed!