# The LOFAR MKSP RM-Synthesis Pipeline

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**(DIAS)**

*on behalf of*

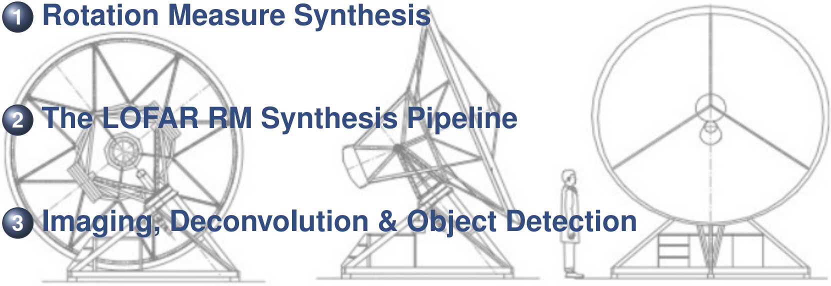
**Mike Bell**
**(MPIA Garching)**

*& the LOFAR MKSP*

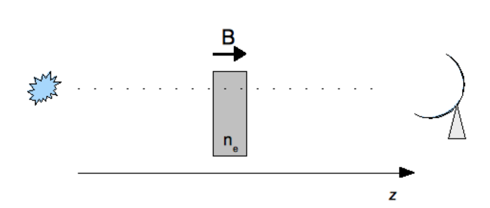
CALIM 2011, University of Manchester

# Outline

1. Rotation Measure Synthesis
2. The LOFAR RM Synthesis Pipeline
3. Imaging, Deconvolution & Object Detection

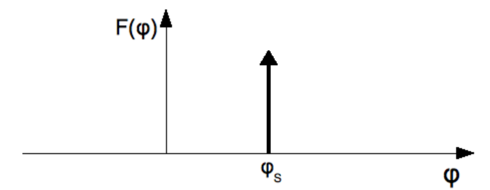


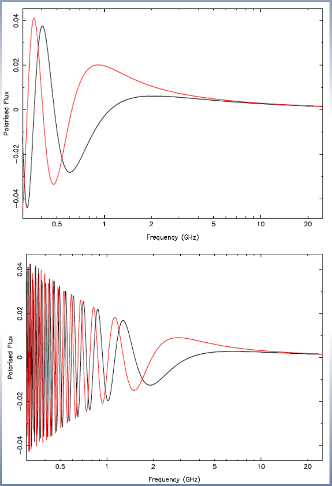
# Faraday Rotation




$$\phi = 0.81 \int_{\text{pc}} \frac{n_e}{\text{cm}^{-3}} \frac{B_{||}}{\mu\text{G}} \, \text{d}z \ \text{rad m}^{-2}$$

For an external screen: $\phi = RM$



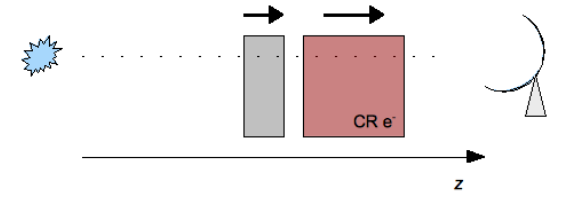
# Faraday Depth

In general:

$$\phi \neq RM, \quad RM = \frac{\mathrm{d}\chi(\lambda^2)}{\mathrm{d}\lambda^2} \quad \text{where} \quad \chi = \frac{1}{2}\tan^{-1}\frac{U}{Q}.$$

For the single source:

$$\chi(\lambda^2) = \chi_0 + \phi\lambda^2, \text{ therefore } \frac{\mathrm{d}\chi(\lambda^2)}{\mathrm{d}\lambda^2} = \phi = RM.$$




Multiple Faraday structures:

$$P(\lambda^2) = \int F(\phi) \mathrm{e}^{2i\phi\lambda^2} \mathrm{d}\phi \text{ (Burn 1966)}$$

That single source again:

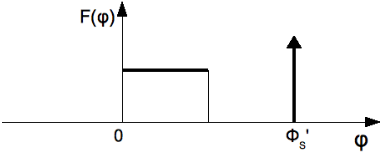
$$F(\phi) = \delta(\phi - \phi_0) \rightarrow P(\lambda^2) = \mathrm{e}^{2i\phi_0\lambda^2} = \cos(2\phi_0\lambda^2) + i\sin(2\phi_0\lambda^2) = Q + iU$$

# RM Synthesis

The Faraday dispersion function is a Fourier relationship:

$$P(\lambda^2) = \int F(\phi) e^{2i\phi\lambda^2} \mathrm{d}\phi \quad \text{(Burn 1966)}$$

$$F(\phi) = \int P(\lambda^2) e^{-2i\phi\lambda^2} \mathrm{d}\phi$$




Similarly to the relationship between the *uv* and image planes in aperture synthesis it is not fully sampled:

$$P(\tilde{\lambda}^2) = W(\lambda^2) P(\lambda^2)$$

We get a response function similar to that of a PSF:

$$RMSF(\phi) = \frac{\int_{-\infty}^{\infty} W(\lambda^2) e^{-2i\phi\lambda^2} \mathrm{d}\lambda^2}{\int_{-\infty}^{\infty} W(\lambda^2) \mathrm{d}\lambda^2}$$

Brentjens & de Bruyn 2005

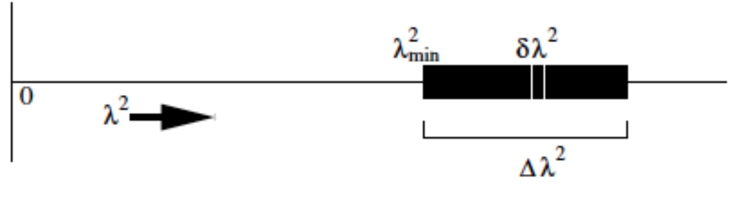
# RM Synthesis

Resolution is a function of coverage in $\lambda^2$:

$$\delta\phi \approx \frac{2\sqrt{3}}{\Delta\lambda^2}$$

Sensitivity to maximum scale in $\phi$ is a function of resolution in $\lambda^2$:

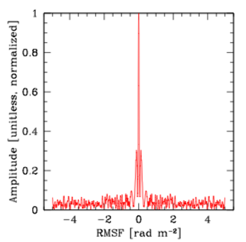
$$||\phi_{\max}|| \approx \frac{\sqrt{3}}{\delta\lambda^2}$$

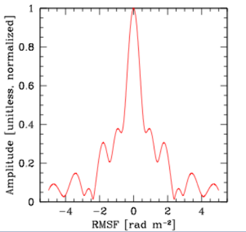


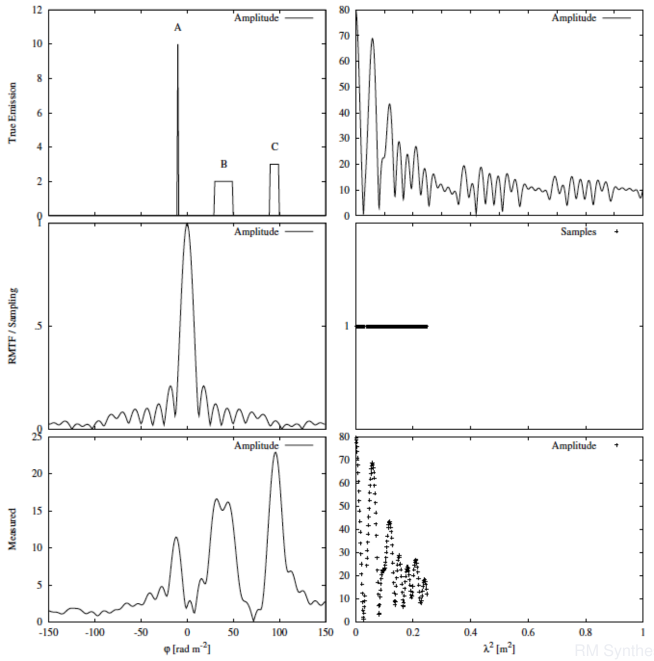
# RM Synthesis

- RMSF from 30-50 MHz + 60-80 MHz:
  $\delta\phi = 0.05\,\mathrm{rad\,m^{-2}}$,
  $\phi_{\max} = 19\,\mathrm{rad\,m^{-2}}$
- RMSF from 120-150 MHz + 180-210 MHz:
  $\delta\phi = 1.0\,\mathrm{rad\,m^{-2}}$,
  $\phi_{\max} = 1200\,\mathrm{rad\,m^{-2}}$

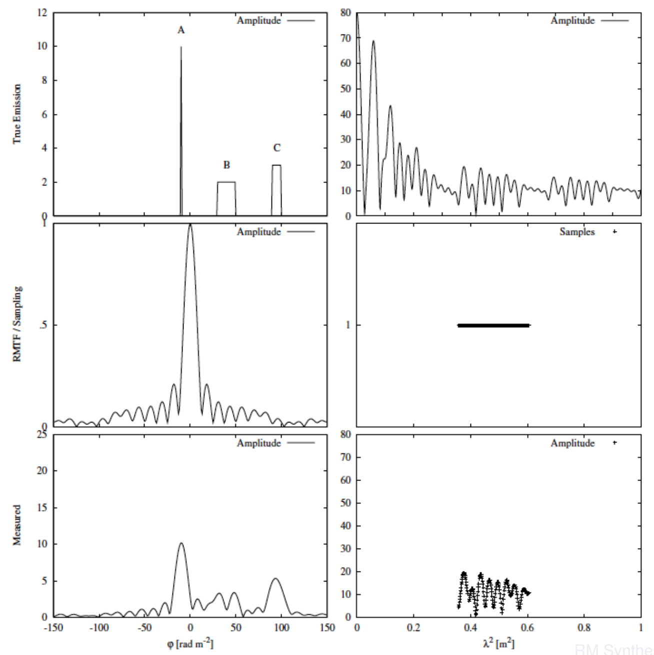
**Heald 2009**

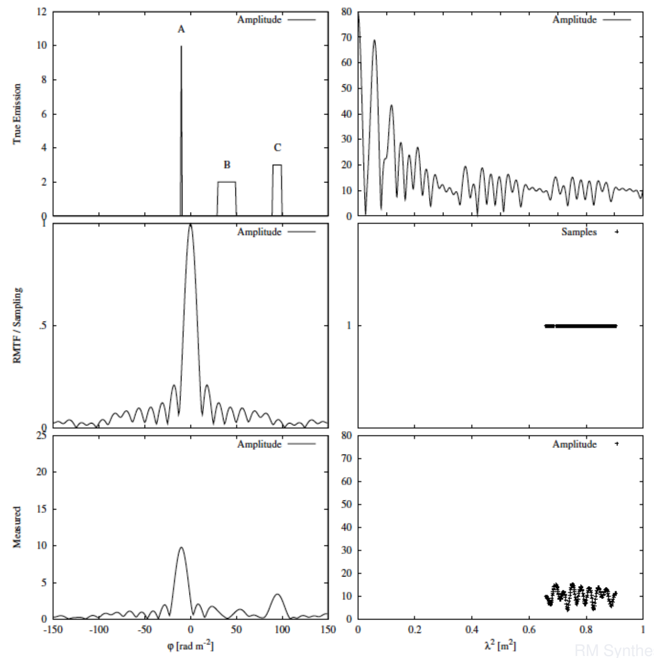




Amplitude
A
B
C
True Emission
Amplitude
Amplitude
RMTF / Sampling
Samples
Amplitude
Measured
Amplitude
φ [rad m^-2]
λ^2 [m^2]


Amplitude
A
B
C
True Emission
Samples
RMTF / Sampling
Measured
φ [rad m$^{-2}$]
λ$^2$ [m$^2$]

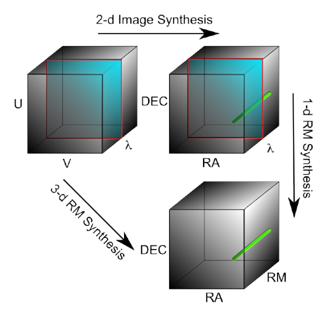


True Emission
RMTF / Sampling
Measured
Amplitude
Samples
A
B
C
φ [rad m$^{-2}$]
λ$^2$ [m$^2$]

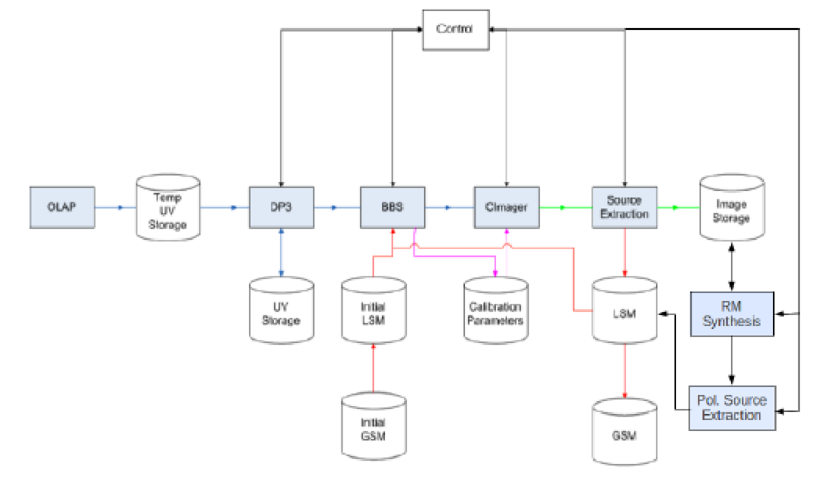


# RM Synthesis Pipeline

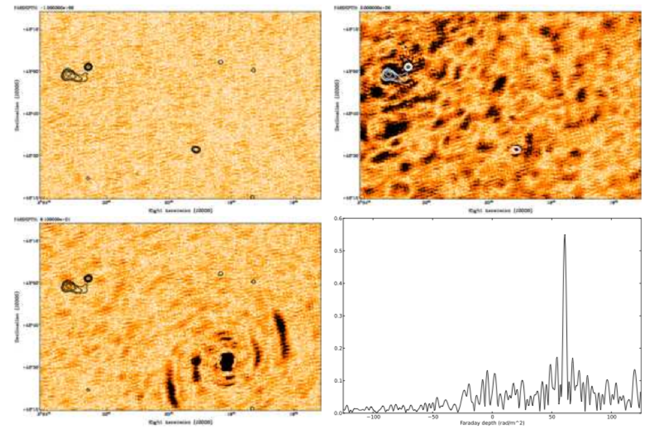
- FFT based synthesis
- RM-Clean and Wiener Filter deconvolution implemented
- Wavelet deconvolution under development
- Supports multiple image formats



# RM Synthesis Pipeline

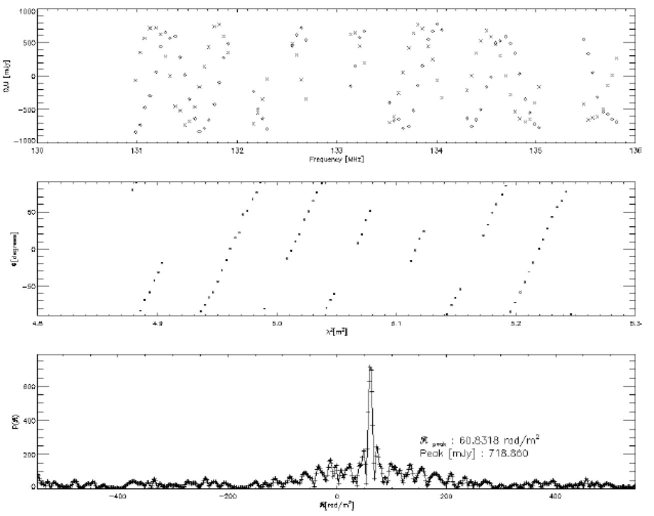


# Early Results

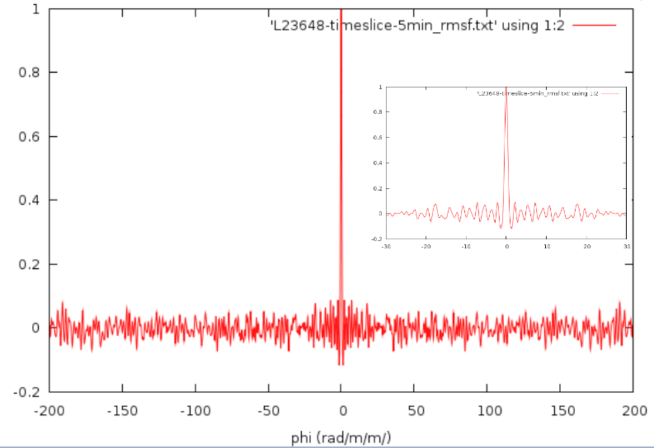



Heald et al. 2011

# Early Results



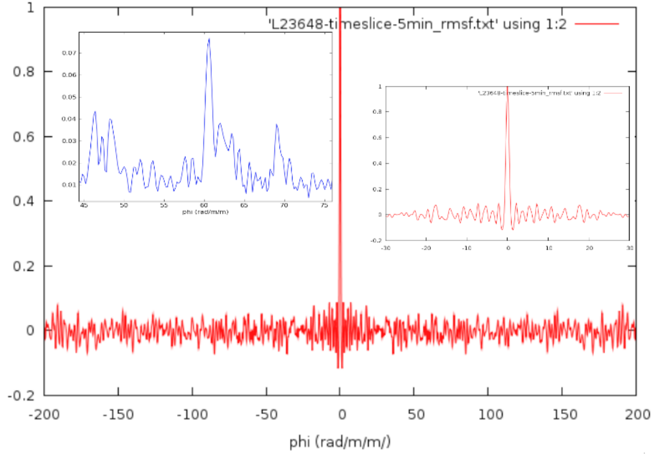
# Early Results




Andreas Horneffer



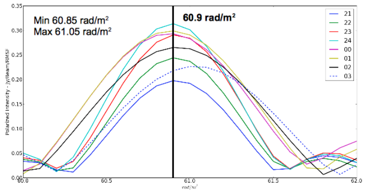
# Early Results



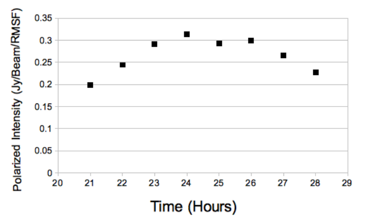

Andreas Horneffer

# Early Results

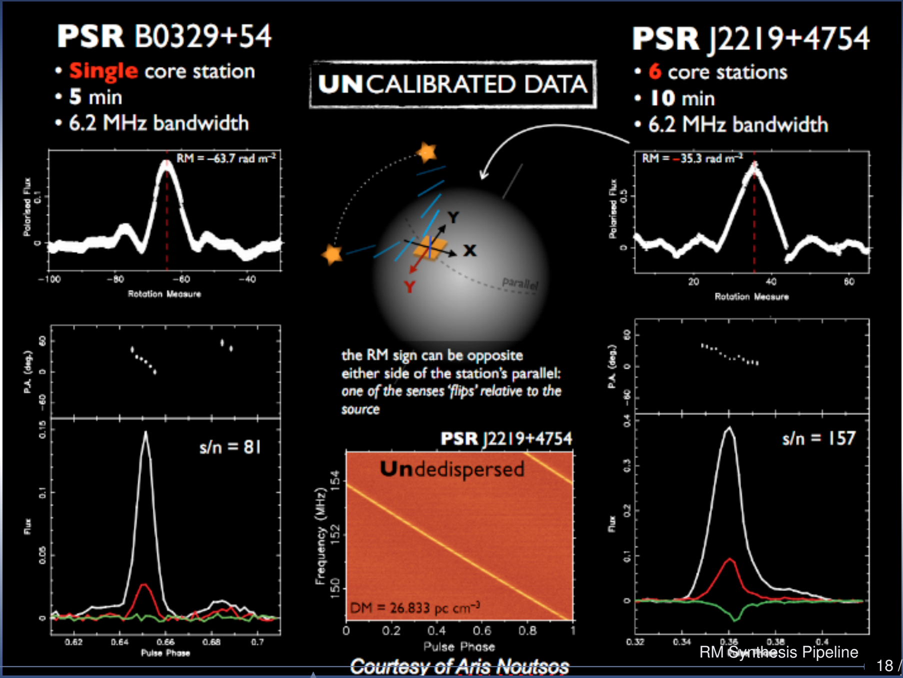
- Observation split into $8 \times 1$ hour blocks

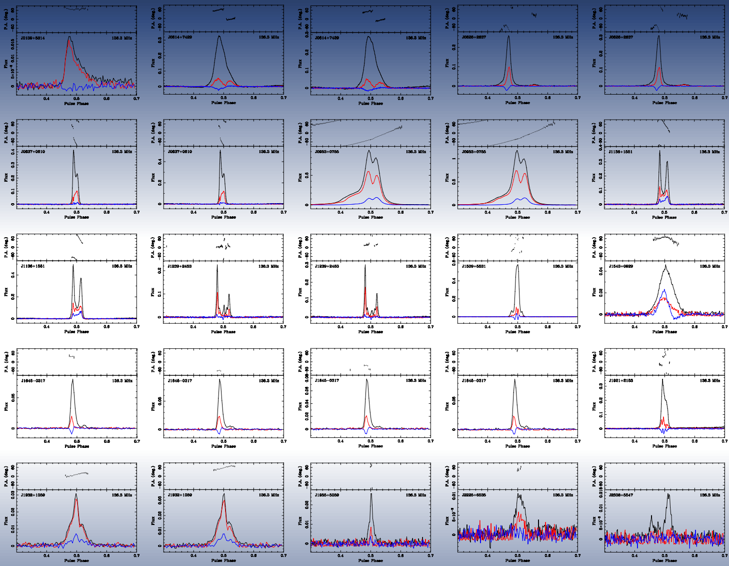


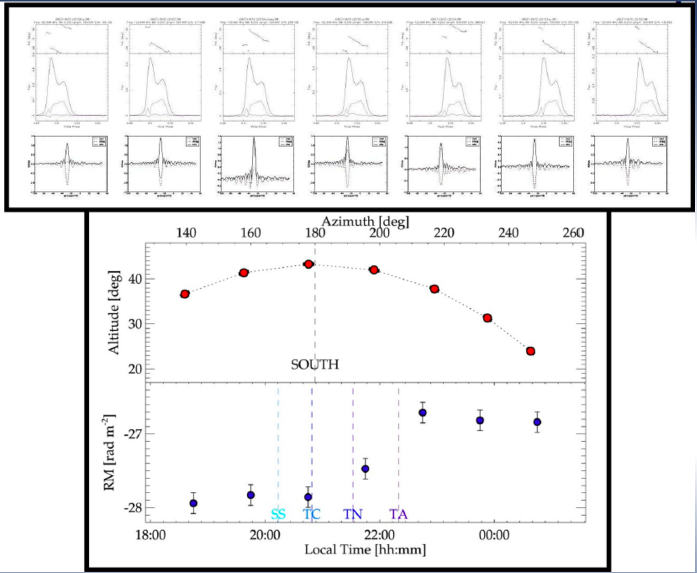

Pulsar Polarized Intensity




Andreas Horneffer


PSR B0329+54
• Single core station
• 5 min
• 6.2 MHz bandwidth
UNCALIBRATED DATA
PSR J2219+4754
• 6 core stations
• 10 min
• 6.2 MHz bandwidth
RM = –63.7 rad m$^{-2}$
Polarised Flux
Rotation Measure
RM = –35.3 rad m$^{-2}$
Y
X
Y
parallel
P.A. (deg.)
the RM sign can be opposite either side of the station's parallel: one of the senses 'flips' relative to the source
s/n = 81
Flux
Pulse Phase
PSR J2219+4754
Undedispersed
Frequency (MHz)
DM = 26.833 pc cm$^{-3}$
Pulse Phase
s/n = 157
Courtesy of Aris Noutsos



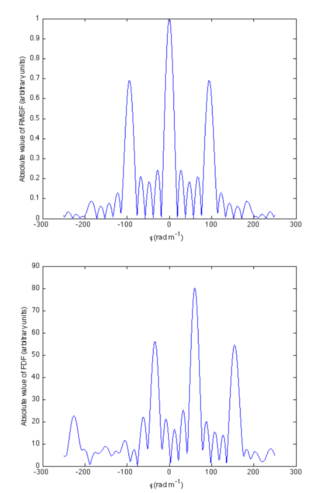

Azimuth [deg]
140
160
180
200
220
240
260
Altitude [deg]
40
30
20
SOUTH
RM [rad m-2]
-27
-28
SS
TC
TN
TA
18:00
20:00
22:00
00:00
Local Time [hh:mm]

# RM Clean

RM Clean (Heald 2009)

Works in the same way as standard CLEAN

Iterative subtraction of a $\delta$-fnc scaled by a loop gain factor.



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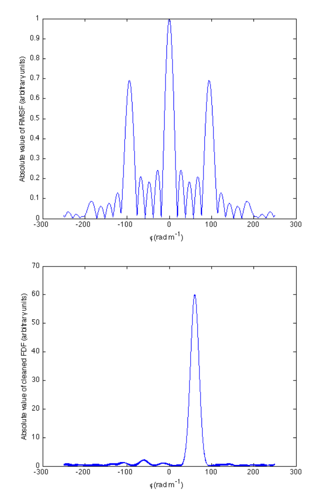
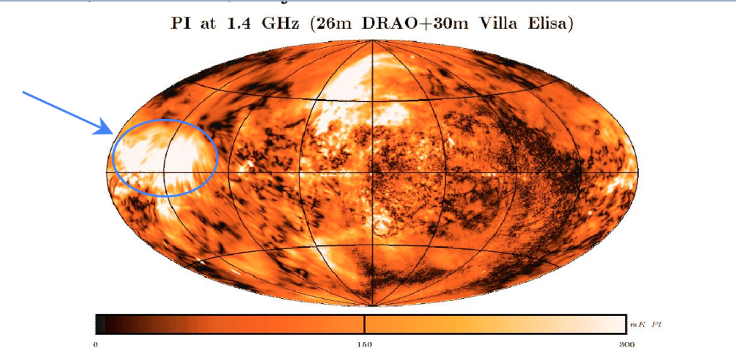
Iterative subtraction of a $\delta$-fnc scaled by a loop gain factor.

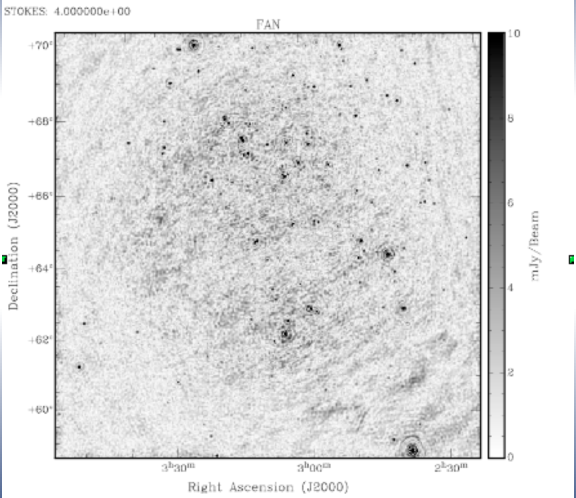


# Fan region

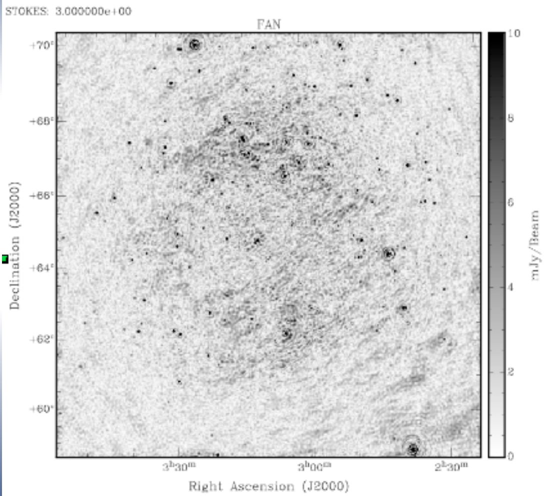



Marijke Haverkorn

# Fan region

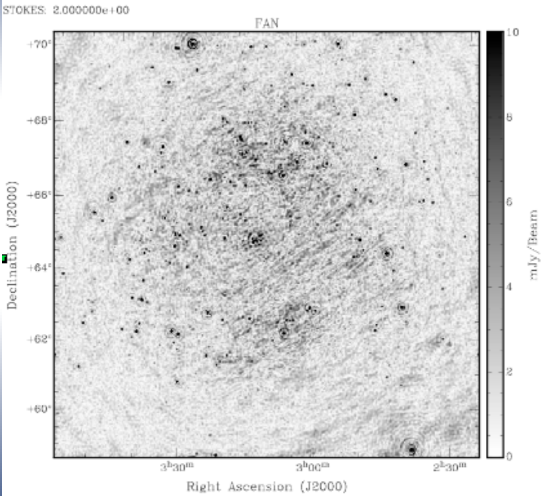

STOKES: 4.000000e+00
FAN
+70°
+68°
+66°
+64°
+62°
+60°
Declination (J2000)
3h30m
3h00m
2h30m
Right Ascension (J2000)
10
8
6
4
2
0
mJy/Beam

# Fan region

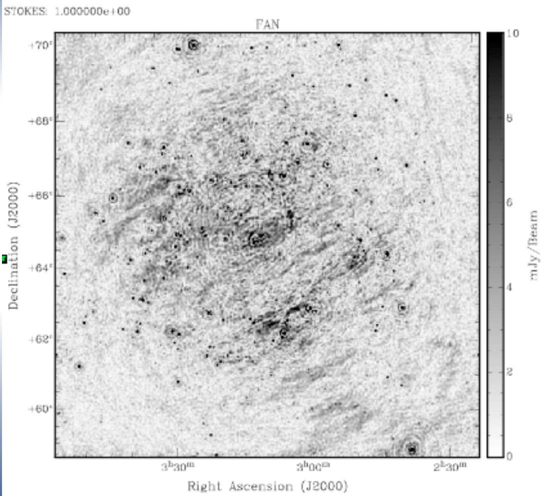


STOKES: 3.000000e+00
FAN
+70°
+68°
+66°
+64°
+62°
+60°
Declination (J2000)
3h30m
3h00m
2h30m
Right Ascension (J2000)
10
8
6
4
2
0
mJy/Beam

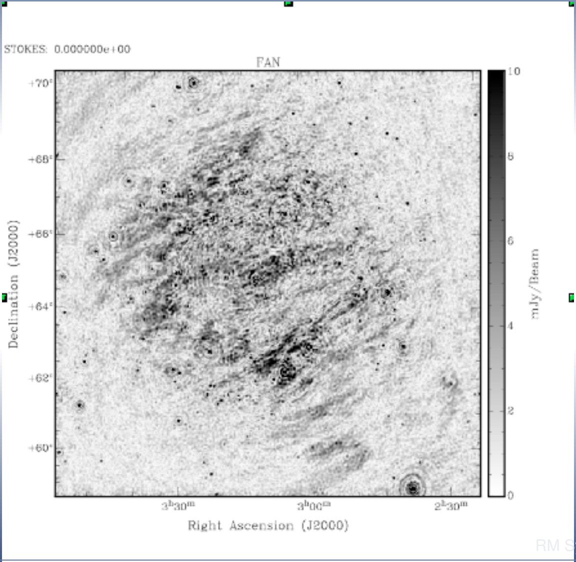
# Fan region


STOKES: 2.000000e+00
FAN
+70°
+68°
+66°
+64°
+62°
+60°
Declination (J2000)
3h30m
3h00m
2h30m
Right Ascension (J2000)
10
8
6
4
2
0
mJy/Beam

# Fan region


STOKES: 1.000000e+00
FAN
+70°
+68°
+66°
+64°
+62°
+60°
Declination (J2000)
3h30m
3h00m
2h30m
Right Ascension (J2000)
10
8
6
4
2
0
mJy/Beam

# Fan region



STOKES: 0.000000e+00
FAN
+70°
+68°
+66°
+64°
+62°
+60°
Declination (J2000)
3h30m
3h00m
2h30m
Right Ascension (J2000)
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6
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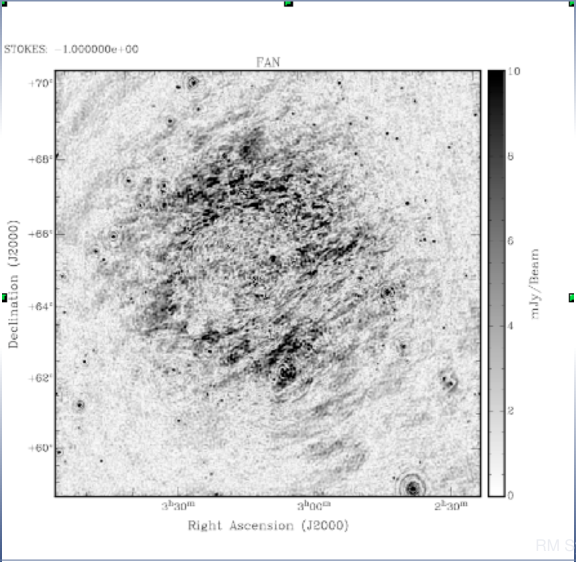
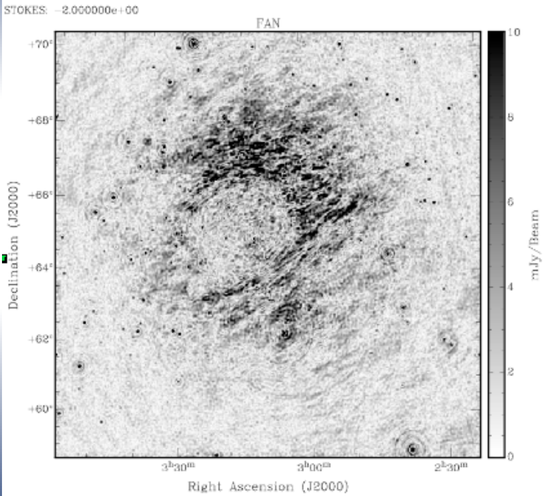
0
mJy/Beam

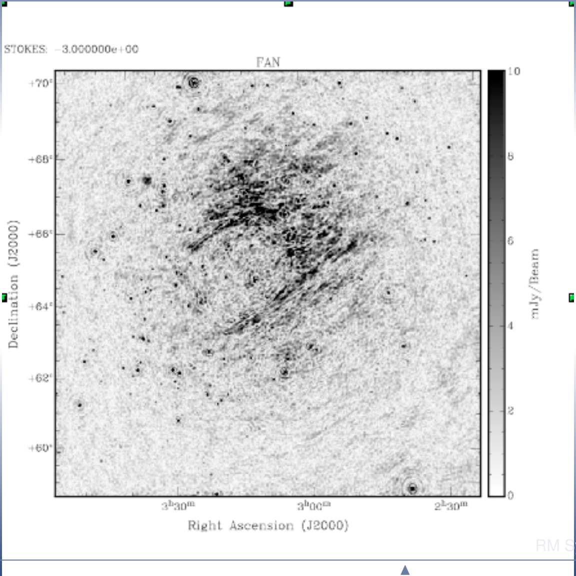
# Fan region


STOKES: 1.000000e+00
FAN
+70°
+68°
+66°
+64°
+62°
+60°
Declination (J2000)
3h30m
3h00m
2h30m
Right Ascension (J2000)
10
8
6
4
2
0
mJy/Beam

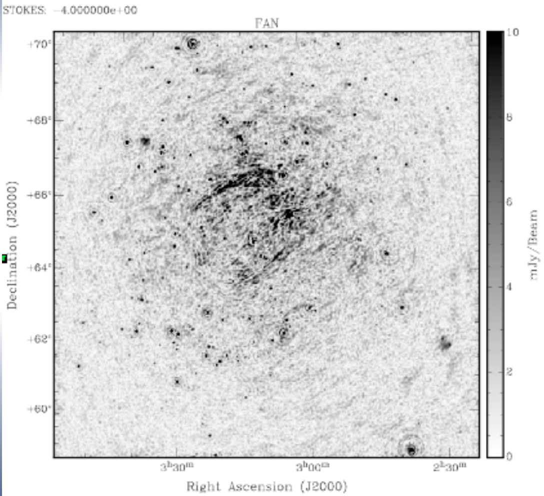
# Fan region


STOKES: -2.000000e+00
FAN
+70°
+68°
+66°
+64°
+62°
+60°
Declination (J2000)
3h30m
3h00m
2h30m
Right Ascension (J2000)
10
8
6
4
2
0
mJy/Beam

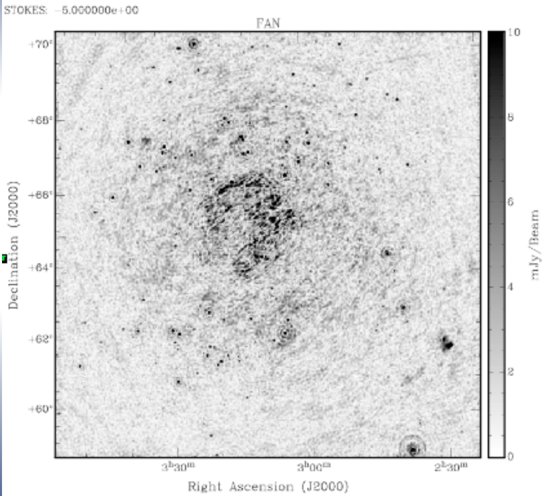
# Fan region


STOKES: -3.000000e+00
FAN
+70°
+68°
+66°
+64°
+62°
+60°
Declination (J2000)
3h30m
3h00m
2h30m
Right Ascension (J2000)
10
8
6
4
2
0
mJy/Beam

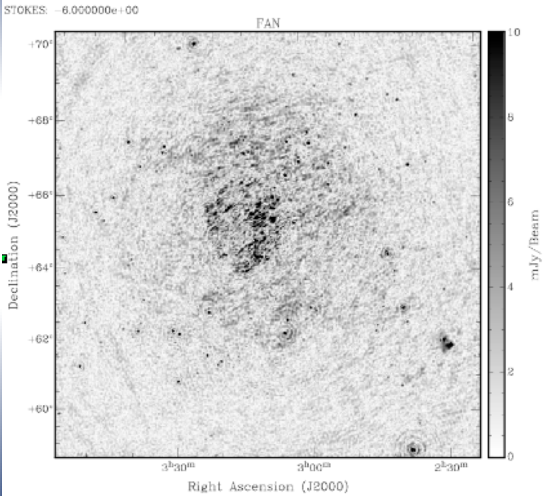
# Fan region


STOKES: -4.000000e+00
FAN
+70°
+68°
+66°
+64°
+62°
+60°
Declination (J2000)
3h30m
3h00m
2h30m
Right Ascension (J2000)
10
8
6
4
2
0
mJy/Beam

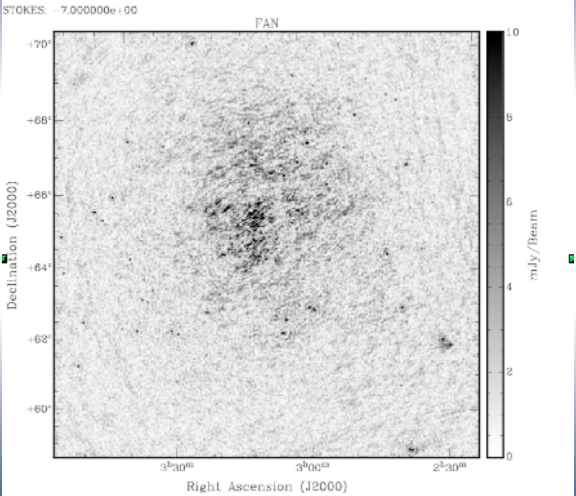
# Fan region


STOKES: -5.000000e+00
FAN
+70°
+68°
+66°
+64°
+62°
+60°
Declination (J2000)
3h30m
3h00m
2h30m
Right Ascension (J2000)
10
8
6
4
2
0
mJy/Beam

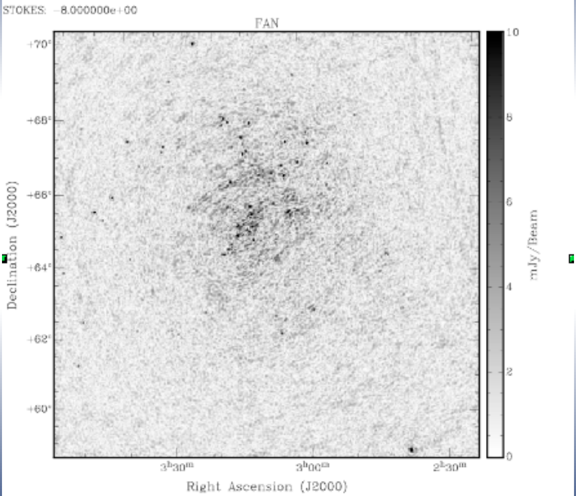
# Fan region


STOKES: -6.000000e+00
FAN
+70°
+68°
+66°
+64°
+62°
+60°
Declination (J2000)
3h30m
3h00m
2h30m
Right Ascension (J2000)
10
8
6
4
2
0
mJy/Beam

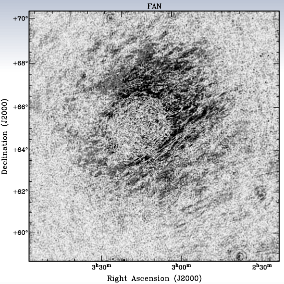
# Fan region


STOKES: -7.000000e+00
FAN
+70°
+68°
+66°
+64°
+62°
+60°
Declination (J2000)
3h30m
3h00m
2h30m
Right Ascension (J2000)
10
8
6
4
2
0
mJy/Beam

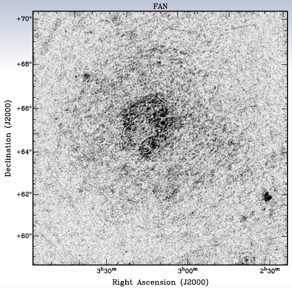
# Fan region


STOKES: -8.000000e+00
FAN
+70°
+68°
+66°
+64°
+62°
+60°
Declination (J2000)
$3^h30^m$
$3^h00^m$
$2^h30^m$
Right Ascension (J2000)
10
8
6
4
2
0
mJy/Beam

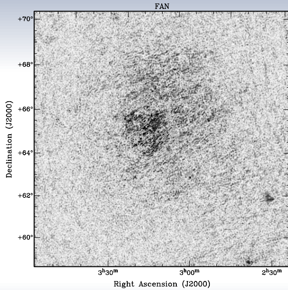
# Extended emission (Fan region)




RM=2 rad $m^{-2}$



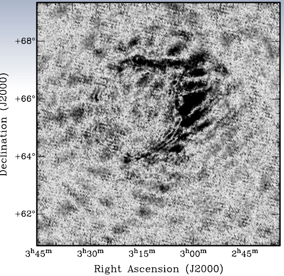

RM=5 rad $m^{-2}$



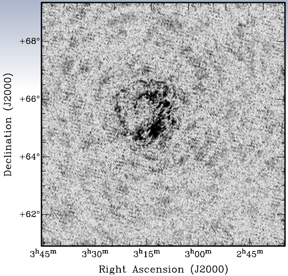

RM=7 rad $m^{-2}$

WSRT

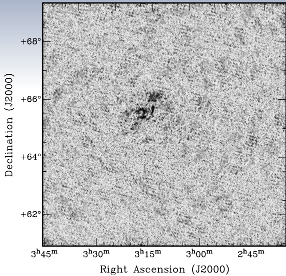
# Extended emission (Fan region)




RM=-2 rad $m^{-2}$




RM=-5 rad $m^{-2}$




RM=-7 rad $m^{-2}$

LOFAR: Marco Iacobelli & Marijke Haverkorn

# RM Synthesis

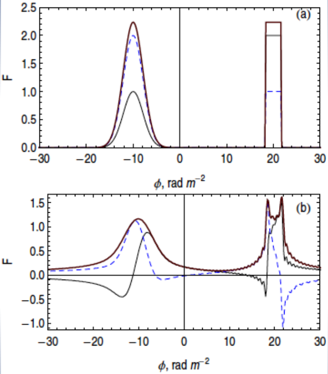
Faraday spectra are **complex**: the modulus defines the emission and the phase the PA

$$P(\lambda^2) = \int \epsilon(z) e^{2i\chi(z)} e^{2i\phi(z)\lambda^2} dz$$

$$F(\phi) = \epsilon(\phi) e^{2i\chi(\phi)} \left(\frac{d\phi}{dz}\right)^{-1}$$

Standard RM Synthesis does not recover the complex components as there is no information at $\lambda^2 < 0$

Requires a degree of inference about the underlying signal distribution

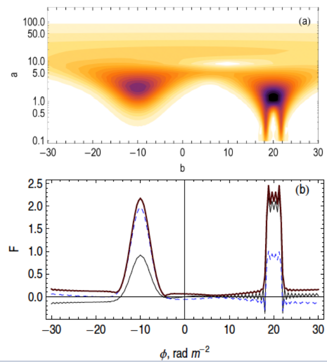



Frick et al. 2010

# RM Synthesis

Wavelet based RM Synthesis can recover real and imaginary parts of $F(\phi)$ more accurately

Requires a degree of inference about the underlying signal distribution → symmetry of dispersion function



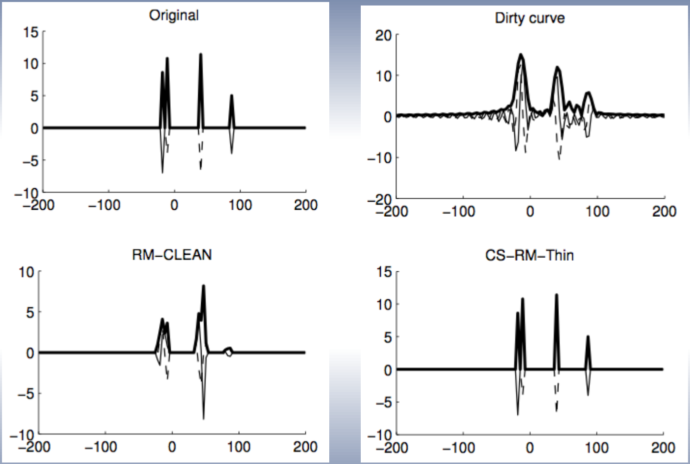

Frick et al. 2010

# Inference Based Reconstruction

max $L$ subject to $\Pi$

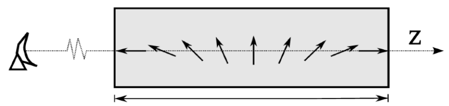
| Signal | Method |
| --- | --- |
| Sparse in pixel space (Dirac basis) | CLEAN |
| Sparse in some basis + RIP | Compressed Sensing |
| Gaussian Random Field | Wiener filtering |
| Non-Gaussian Random Field | Information Theory |

# CS for Faraday Thin Sources




Li et al. 2011

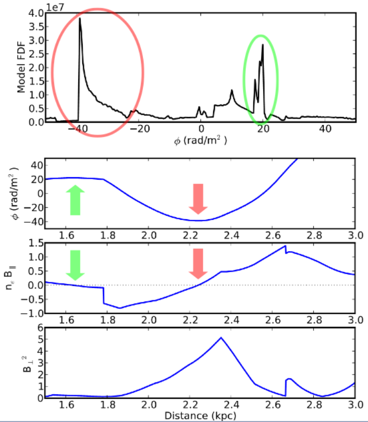
# Faraday Caustics




(Bell, Enßlin & Junklewitz 2011)

Caused by reversals of the B-field along the l.o.s.

Leads to Heaviside functions in the Faraday dispersion spectrum





# CS for Faraday Caustics

$\min ||\bar{x}||_{\mathrm{TV}}$ subject to $\tilde{\chi}^2 \leq \epsilon^2$

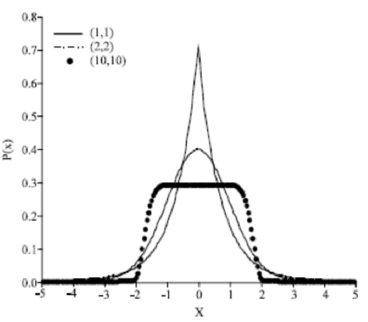
Generalized Gaussian Distribution:

$P(\nabla x|\rho) \propto \exp -|\frac{\nabla x}{\rho s}|^q$

Sparse if $q \leq 1$

$\min ||\bar{x}||^q_{\mathrm{TV}}$ subject to $\tilde{\chi}^2 \leq \epsilon^2$

(Wiaux, Puy & Vandergheynst 2010)



# LOFAR RM Pipeline Status

| Task | Status |
|---|---|
| Definition of input/output format(s) | Not started |
| DFT synthesis algorithm | Done |
| Gridding & FFT synthesis algorithm | Translate to C++ |
| RMCLEAN algorithm | Translate to C++ |
| Wiener Filter algorithm | Done |
| Support for automatic beam convolution | Translate to C++ |
| Document | On going |

# Conclusions

- Polarization imaging is already possible with LOFAR. . . although polarization calibration currently isn't
- There is an interim RM synthesis pipeline (python-based) in place
- The RM synthesis pipeline accepts both imaging and pulsar pipeline data
- Reconstruction of complex Faraday spectra requires some prior information on the signal
- Inference based reconstruction methods are under development for the pipeline