The Future of VLASS

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AUI
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Basic data products, currently available through the NRAO archive:

- Raw visibility data
- Calibration products
- Quick Look continuum images (note that Epoch1 lacks astrometric correction, other epochs are ok), Stokes I

Basic data products per epoch, forthcoming:

- Single epoch continuum images (including in-band spectral index information, production will start this fall)
- Coarse Resolution (128MHz) cubes in Stokes IQU (V will be a single plane; pipeline development almost finished)

Data products that span multiple epochs:

- Cumulative images and cubes combined in the image domain (rms-weighted averages, with average beams)
- Cumulative images (and cubes) based on joint imaging of all visibilities

Other:

- Fine cubes with 16MHz resolution (for selected regions and on demand)
- Tapered images for SE and cumulative

Catalogs will be primarily delivered by the CIRADA group
CIRADA will is also working on other enhanced data products and tools such as an image cutout server

VLASS data is entirely public and the community is invited to produce their own data products!

QuickLook images:

- Fairly basic imaging for faster turnaround
- Has automated quality checks
- Re-imaging with better parameters or flagging when initial qa fails
- Images are single plane, Stokes I, multiterm (including spectral index maps)
- Usage of ‘mosaic’ gridder plus astrometric correction

- Data products: primary beam corrected images (tt0), rms images

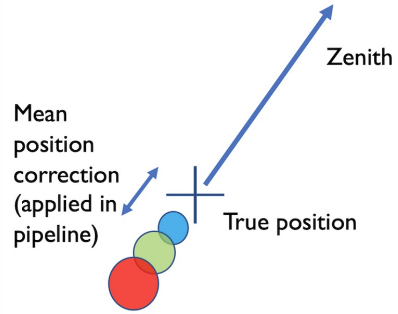
Fast turnaround requires shortcuts in data processing…

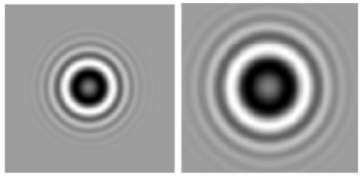
- The images still contain some deconvolution errors (sidelobes) around brighter sources
- Phase errors from transfer of complex gain calibrator
- No sophisticated clean regions
- Occasional clean divergences
- No direct w-term correction

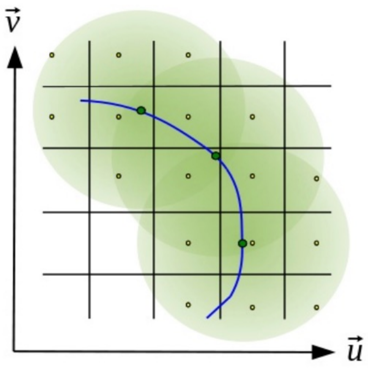
Task	
1. **hifv_importdata**: Register VLA measurement sets with the pipeline	
2. **hif_editimlist**: Editimlist	Image definition
3. **hif_transformimagedata**: Transformimagedata	
4. **hif_makeimages**: Make target per-spw continuum images	Image creation
5. **hifv_pbcor**: Pbcor	Primary beam correction
6. **hif_makermsimages**: Makermsimages	RMS image creation
7. **hif_makecutoutimages**: Makecutoutimages	

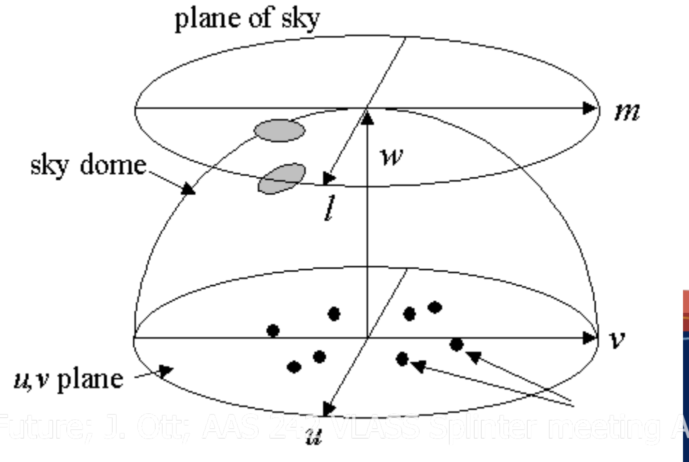
Astrometry

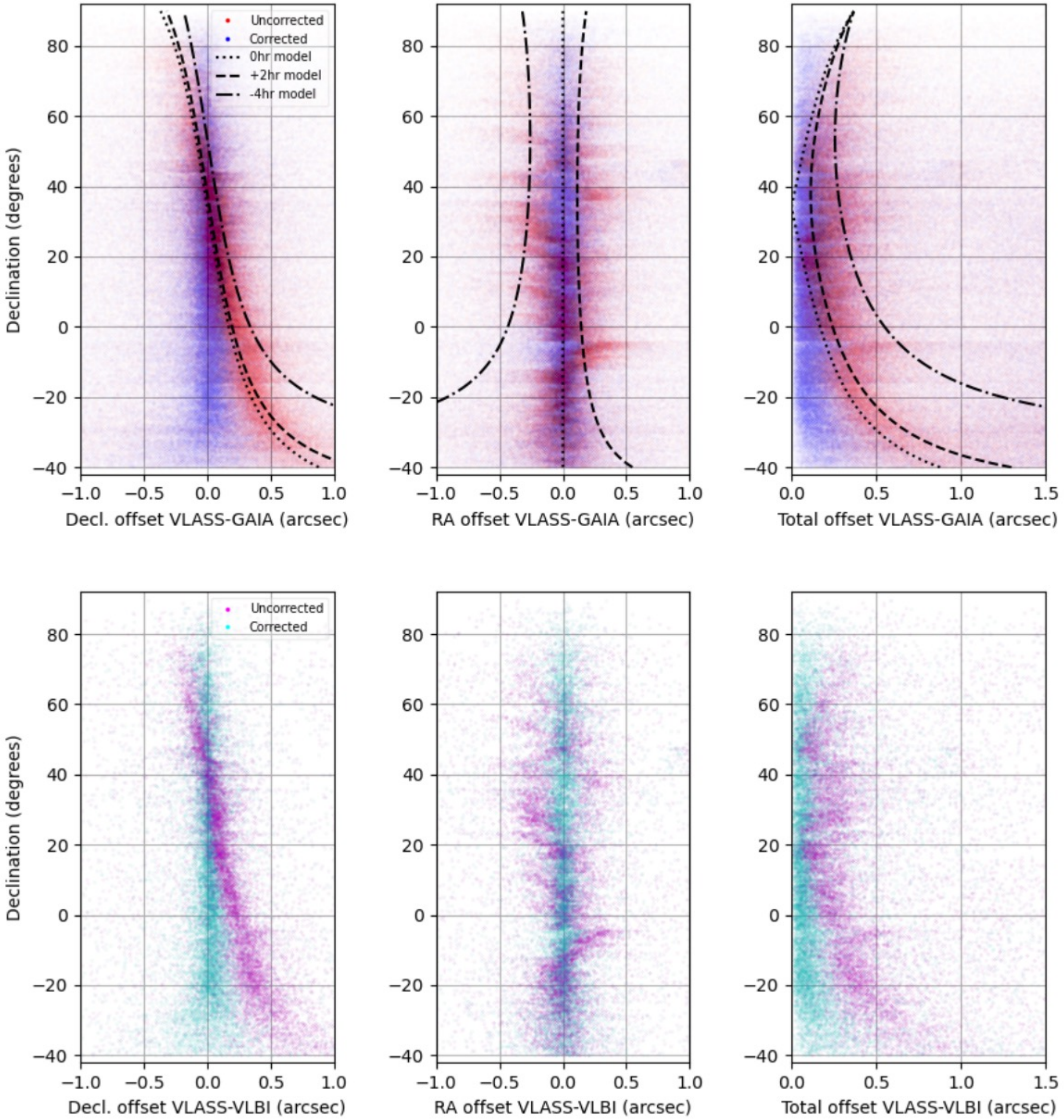
- Imaging uses the ‘mosaic’ gridder in CASA. It projects the visibility for all pointings on the uv-plane with a Gaussian kernel (adding phase gradients for the offsets). It is fast, but does not correct for 3D w-term needed for sky curvature. Depends on zenith angle (Hour angle and declination).
- The effect is dependent of frequency, so spectral indices are also affected.
- We use an analytical function to correct images as a whole (reference pixel), based on offsets relative to GAIA and VLBA (M. Lacy VLASS memo #14)
- AW-projection corrects for w-term effects directly, using a different gridding kernel, but it is *much* slower (also introduces a slight increase in noise)





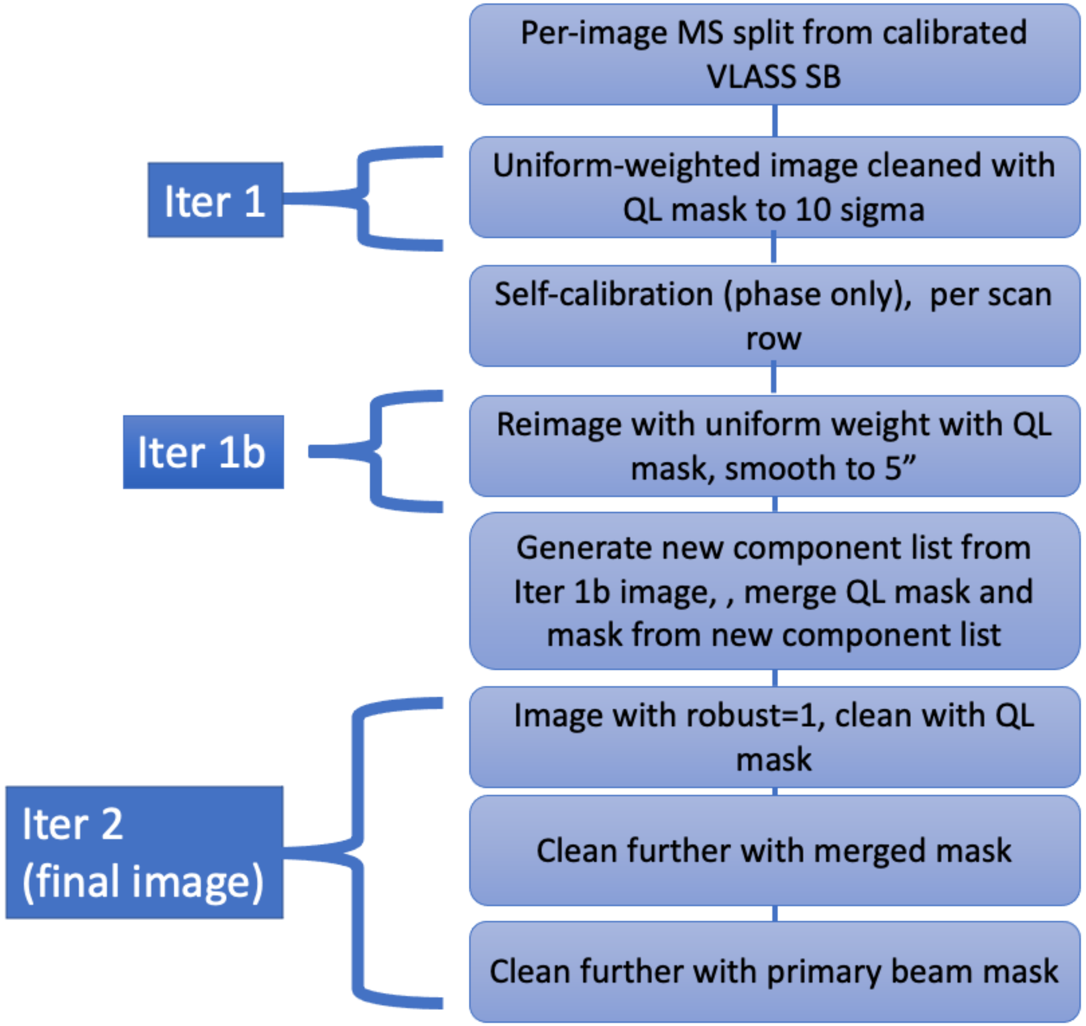






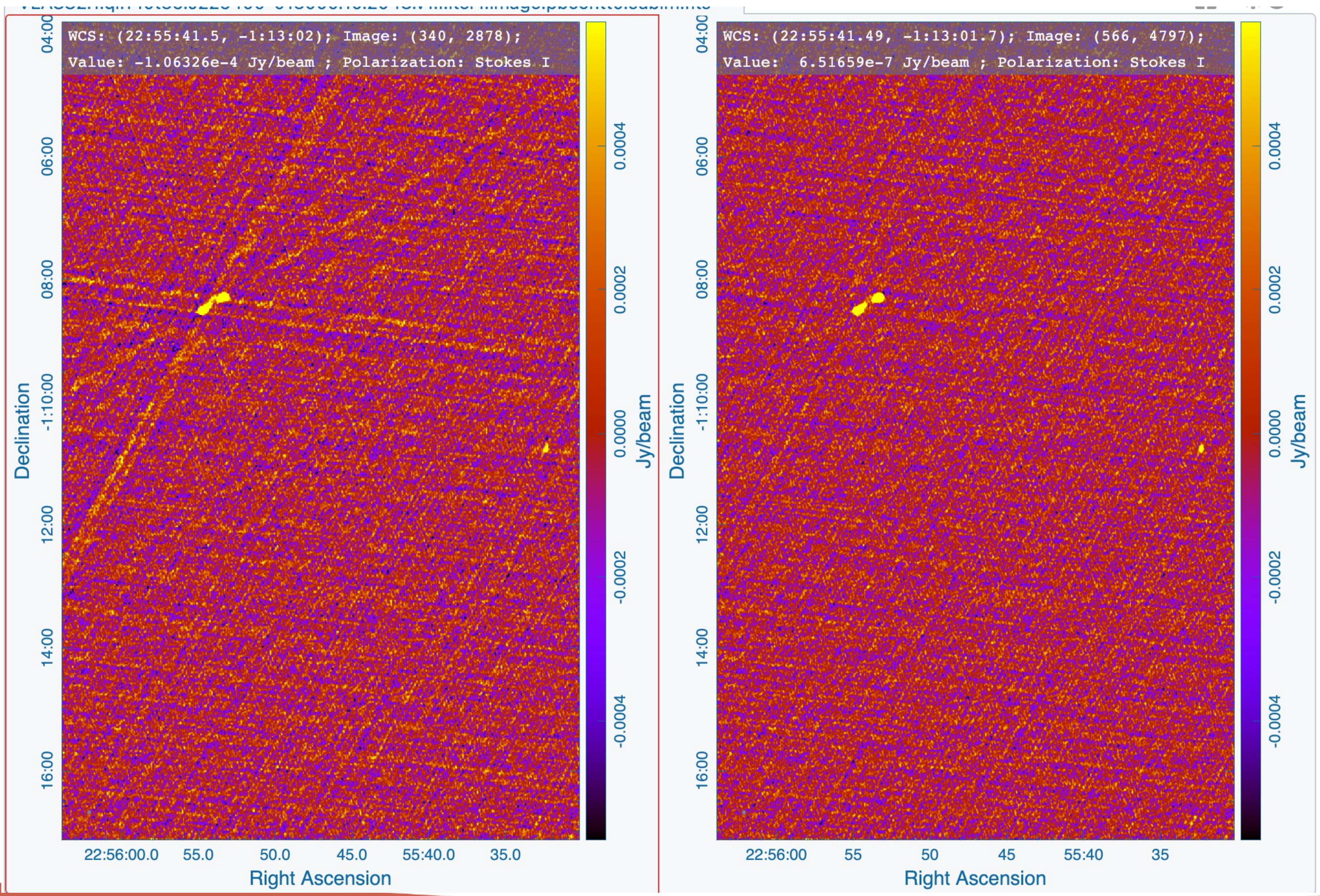
Single Epoch images:
(based on VLASS memo #15)

- Better image quality (fidelity, rms) after additional processing steps
  - Initial uniform weighting to avoid divergences (Dirty PSF is better defined)
  - Self-calibration
  - Initial mask from QL, secondary mask from the data themselves
- Data products are
  - Stokes I image (tt0, tt1, alpha), primary beam corrected
  - RMS images
  - Region files/catalog
- SE images also use the ‘mosaic’ gridder with an analytic astrometric correction for zenith angles <45deg; expect to use aw-projection for larger zenith angles (better positions and spectral indices)



1. **hifv_importdata**: Register VLA measurement sets with the pipeline
2. **hif_editimlist**: Editimlist
3. **hif_transformimagedata**: Transformimagedata
4. **hifv_vlassmasking**: Produce a VLASS Mask
5. **hif_makeimages**: Make target aggregate continuum images
6. **hifv_checkflag**: Checkflag summary
7. **hifv_statwt**: Reweight visibilities
8. **hifv_selfcal**: Selfcal tables
9. **hif_editimlist**: Editimlist
10. **hif_makeimages**: Make target aggregate continuum images
11. **hif_editimlist**: Editimlist
12. **hifv_vlassmasking**: Produce a VLASS Mask
13. **hif_makeimages**: Make target aggregate continuum images
14. **hifv_pbcor**: Pbcor
15. **hif_makermsimages**: Makermsimages
16. **hif_makecutoutimages**: Makecutoutimages
17. **hif_analyzealpha**: Analyzealpha

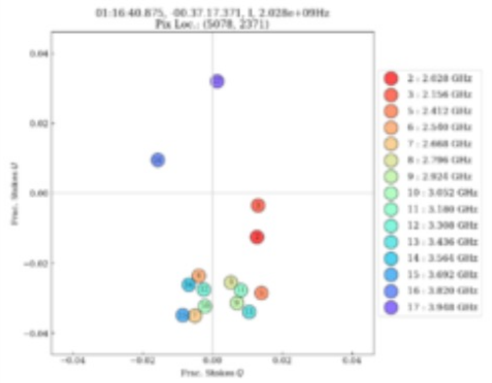
Comparison **QuickLook** vs. **Single Epoch**



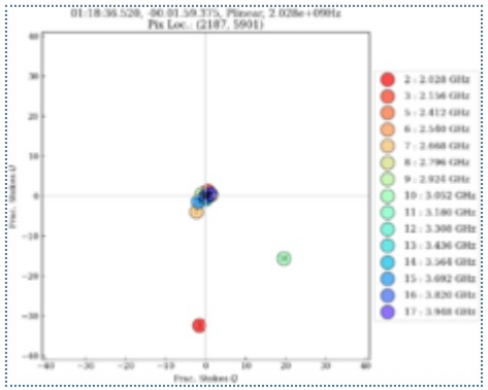
RMS is also improved by ~10%

Coarse Cubes (CC):

- VLASS data was intrinsically observed in 16 spectral windows, 128MHz bandwidth each. Every spectral window has 64 channels (2MHz resolution across the entire VLA 10cm S-band)
- some polarization analysis, like Faraday rotation, requires spectral information
- CCs are imaged to combine each spectral window into a separate image, the Single Epoch heuristics is used for each image plane
- Imaging in full Stokes IQUV
    - Given that detectable Stokes V emission is rare but would use significant archive space, the Stokes V planes will be collapsed into a single image



Peak of the Stokes-I map at 2.028 GHz



Peak of the linearly polarized intensity map at 2.028 GHz

Task

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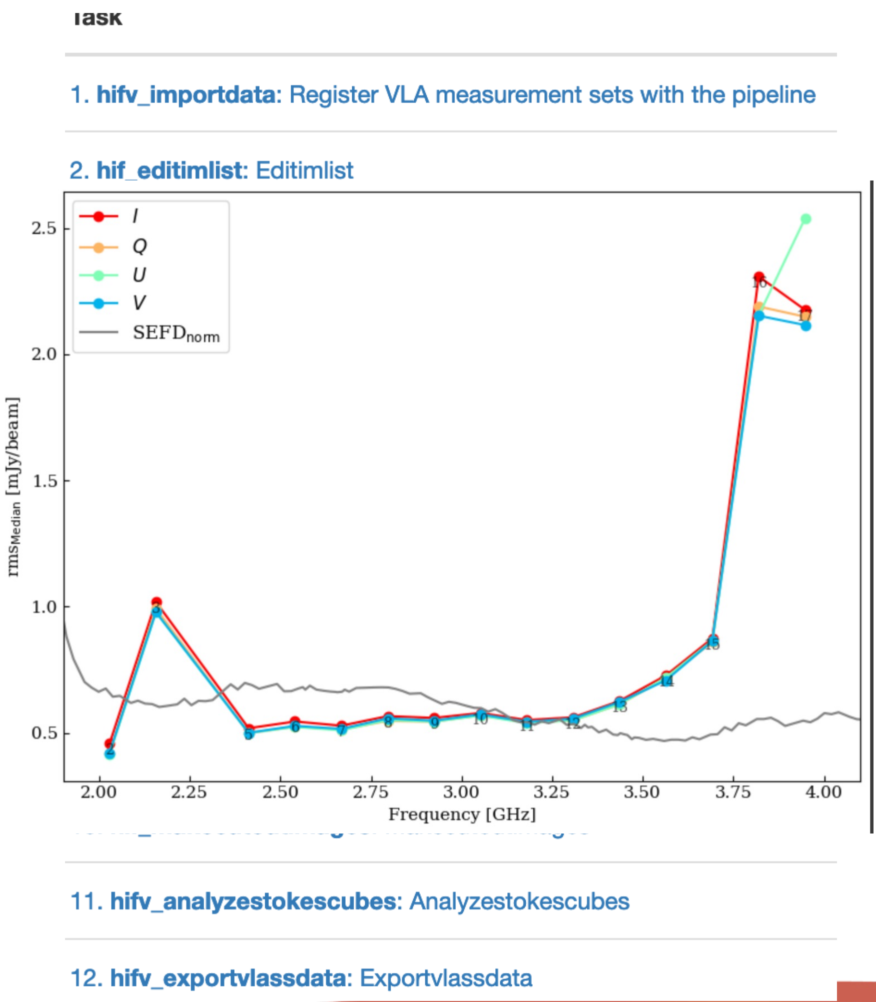
2. **hif_editimlist**: Editimlist
3. **hif_transformimagedata**: Transformimagedata
4. **hifv_restorepims**: Restorepims
5. **hifv_flagtargetsdata**: VLA Flagtargetsdata
6. **hif_editimlist**: Editimlist
7. **hif_makeimages**: Make target aggregate continuum images
8. **hifv_pbcor**: Pbcor
9. **hif_makermsimages**: Makermsimages
10. **hif_makecutoutimages**: Makecutoutimages
11. **hifv_analyzestokescubes**: Analyzestokescubes
12. **hifv_exportvlassdata**: Exportvlassdata

Coarse Cubes (CCs):

- VLASS data was intrinsically observed in 16 spectral windows, 128MHz bandwidth each. Every spectral window has 64 channels (2MHz resolution across the entire VLA 10cm S-band)
- some polarization analysis, like Faraday rotation, requires spectral information
- CCs are imaged to combine each spectral window into a separate image, the Single Epoch heuristics is used for image plane
- Imaging in full Stokes IQUV
    - Given that detectable Stokes V emission is rare but would use significant archive space, the Stokes V planes will be collapsed into a single image
- CCs allow a more classical spectral index determination directly as a fit across the planes, will provide an alternative to Taylor term algorithm used in SE (although with a somewhat degraded resolution)
- Some of the 16 planes have significant RFI. Depending on the severeness, they will either not be imaged at all or not used in any spectral analysis (such as spectral index calculation)



National Radio Astronomy Observatory

Computing:

The NRAO cluster is powerful and designed for High Throughput Processing. We also have clusters at partner institutes (New Mexico Tech, RADIAL project).

Current limitations:
We produce 35,500 fields to image per epoch.

- A QuickLook image takes about a day to process
- An Single Epoch image takes about 3-4 days, and even longer for complex fields
- A Coarse Cube takes about 10-12 days
- All of these image products are calculated with the less precise mosaic gridder, followed by an analytic astrometric correction on the fits files
- The w-term errors can be corrected with aw-projection algorithms. But those are notoriously slow

(SE image would stretch weeks, CC months)

Multicore processing speeds up the processing times, but will reduce the number of images being processed. For our purpose it is more efficient to run multiple datasets on single cores.

A possible speed-up will be a **new GPU based gridder** that is currently being developed and tested by the CASA group. First CASA tests in *tclean* show a ~14 times improvement in processing speed for the imaging using the aw-projection. Tests for VLASS are planned once the gridder has been validated in CASA.

Cumulative Imaging:

We will produce images and cubes that combine all VLASS epochs. Goals are to improve the signal-to-noise ratio and potentially the image fidelity.

A range of combination methods have been tested (upcoming VLASS memo by JO) and we plan on:

- Combination of epochs in the image domain, weighted by rms in each image
- Joint imaging of the calibrated visibilities from all epochs together

Image domain:

✅ Straightforward computation
✅ Fast
✅ Analytical astrometric correction for each epoch

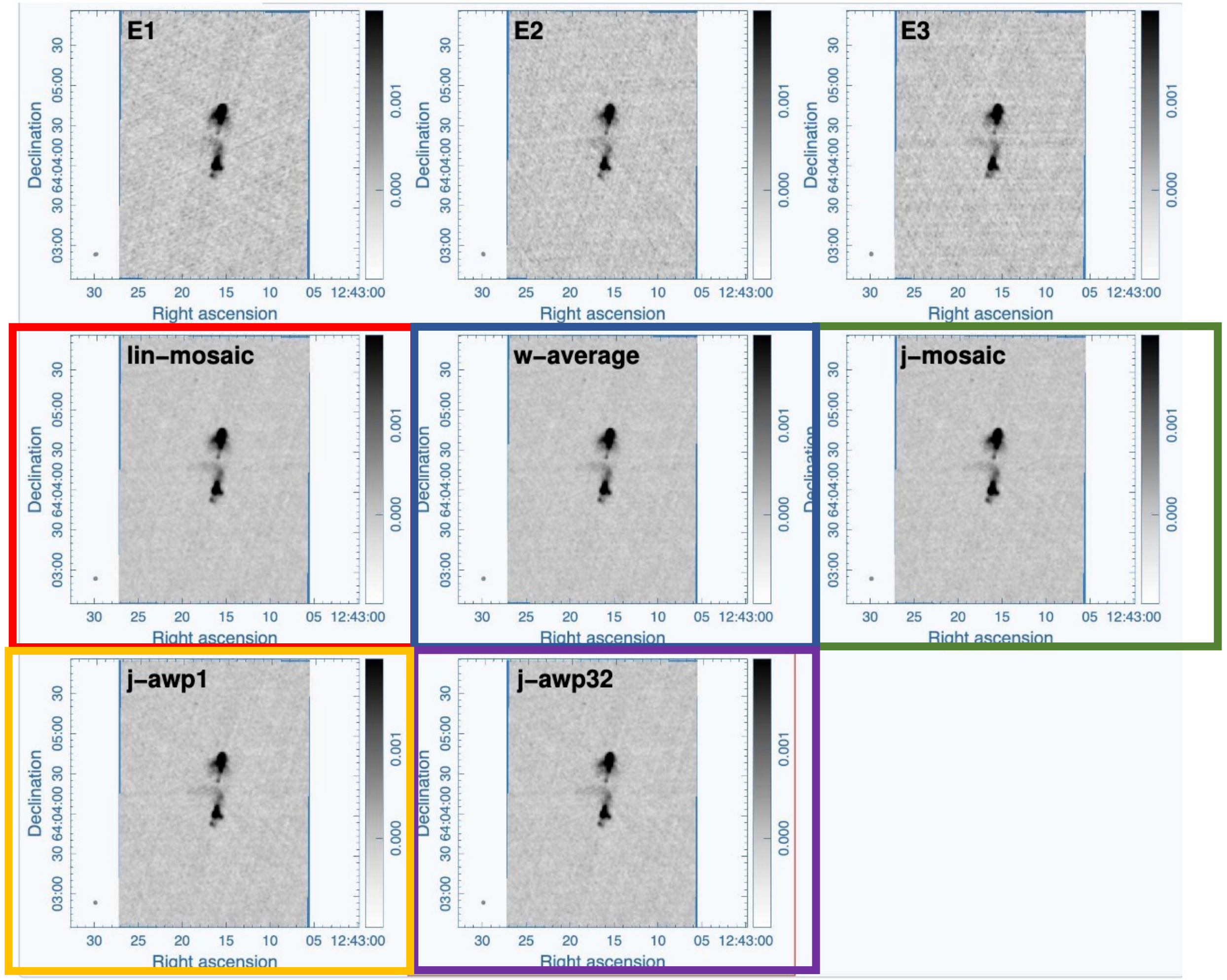
❌ PSF is the average of input PSFs, not a pure Gaussian anymore
❌ Deconvolution errors from individual epochs will be averaged into final product
❌ Not taking advantage of an improved uv-coverage

Joint Imaging :

✅ Combined uv-coverage produces a better PSF and improved image fidelity
✅ Proper calculation of the w-term corrections are possible
✅ Optimized imaging parameters for the combined images (including more options for weighting, PSF calculation)
✅ Cleaning boxes are possible for fainter sources

❌ Mosaic gridder+analytic correction is not possible due to different zenith angles of the input visibilities (although an average correction may be ok)
❌ w-projection very slow (GPU gridder will be essential), mosaic is also much slower than combination in image domain
❌ Deconvolution errors for variable sources

Cumulative Imaging - examples:



The three input images (SE)

Linear mosaic combination;

rms-weighted average;

joint imaging (mosaic gridder)

Joint imaging (aw-projection, single w-projection plane);

Joint imaging (aw-projection, 32 w-projection planes);

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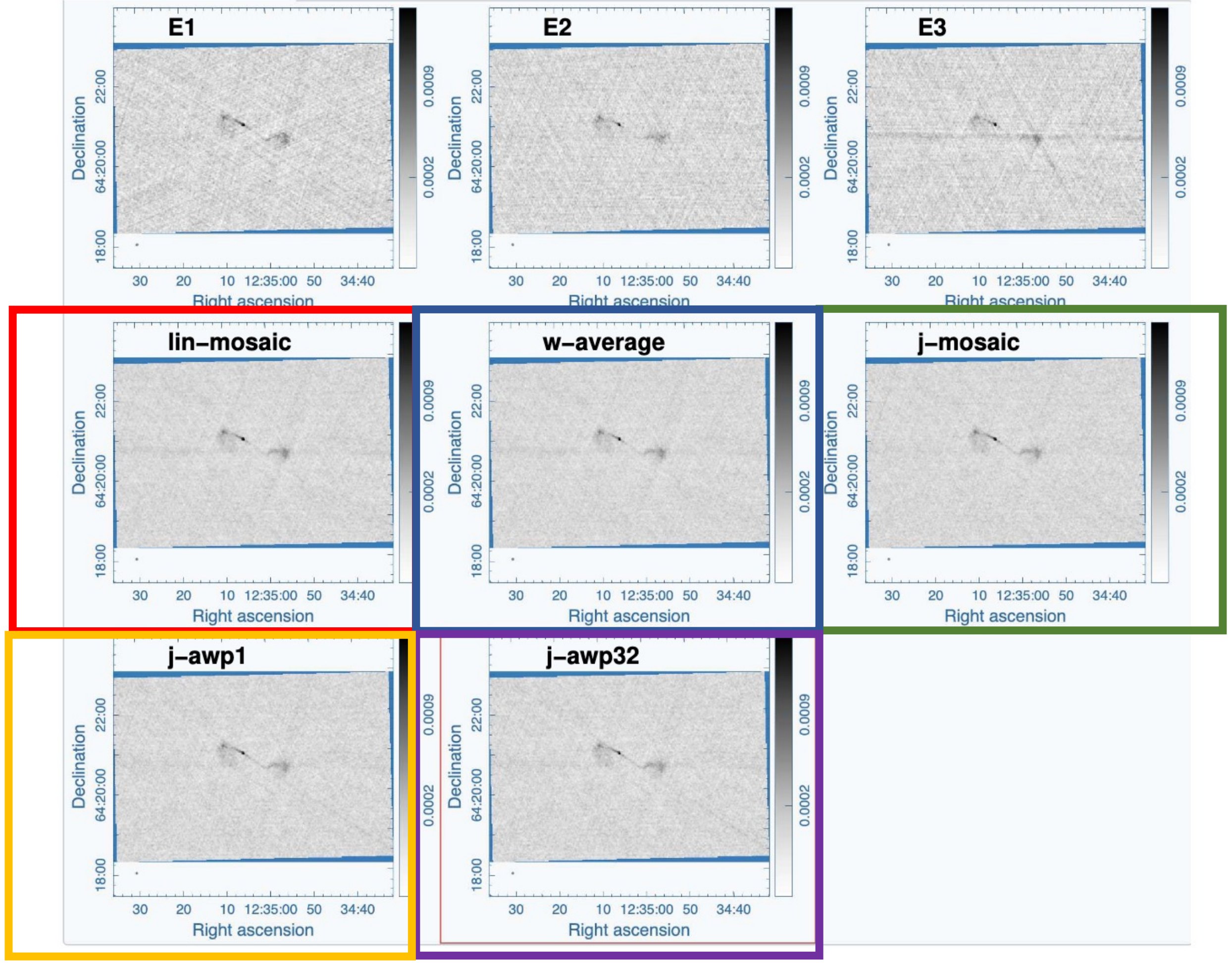

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Images	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	>2033
Quick Look	3.1	3.2									
SE Continuum (Epoch 2)			Ep 2 complete								
SE Cubes (Epoch 2)				Ep 2 complete							
SE Continuum (Epoch 3)						Ep 3 complete					
SE Cubes (Epoch 3)							Ep 3 complete				
SE Continuum (Epoch 1)								Ep 1 complete			
SE Cubes (Epoch 2)									Ep 1 complete		
Cumulative (Continuum+Coarse cubes)									Image combined		uv-combined
Cumulative (fine cubes)										Fine Cubes	

VLASS Epoch 4!

- The original timescale for VLASS was to produce a comprehensive, unique survey before ngVLA comes online
- At the time of planning, 3 epochs appeared to be appropriate before ngVLA construction disrupts VLA operations
- Updated ngVLA construction timelines would now potentially allow for a 4th VLASS epoch

- Scientific motivation: Time cadence extended from ~5 years to ~10 years, and overlap with Rubin and Roman operation
- For the anticipated timeline, the 4th epoch may be scheduled 1.5-3 years after epoch 3. This will allow us to also catch up with the data processing of the more elaborated products

- Prospectus sent to the NRAO director, full proposal is currently prepared by the VLASS SSG

- We need community input, so if you have science applications or comments, please get in touch with the SSG, or use the NRAO helpdesk to contact the VLASS team