VLBA Imaging of ICRF 3 Sources

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A (Very) Brief History of the ICRF

Celestial Reference Frame

- Useful for telescope pointing, celestial navigation, Earth Orientation
- Created by finding accurate position of celestial sources (using Very Long Baseline Interferometry)

Global solution includes data from the onset of VLBI in August 1979 through the present

VLBI observations at 13 and 3.6 cm simultaneously

- Accurate calibration of Earth's ionosphere
- Least-squares analysis over multiple channels in each band for precise group delay
- CALC/SOLVE software used for source position derivation (see Ma et al. 1986)

Current ICRF Solution contains 4536 sources

- 303 defining sources

ICRF Source Requirements

Choose to observe radio loud quasars

- Quasars are compact distant objects
  - Point-like on the sky = Precise position on sky with little confusion
  - Relative position on the sky should not change (far away)
- Radio Loud = Easy to see
  - If source has high intensity we can observe them quickly
  - Can then observe many sources in a short time
  - Allows us to quickly create a grid of the sources on the sky
- Ability to continuously monitor these sources
  - Can observe same source numerous times to reduce effects of error

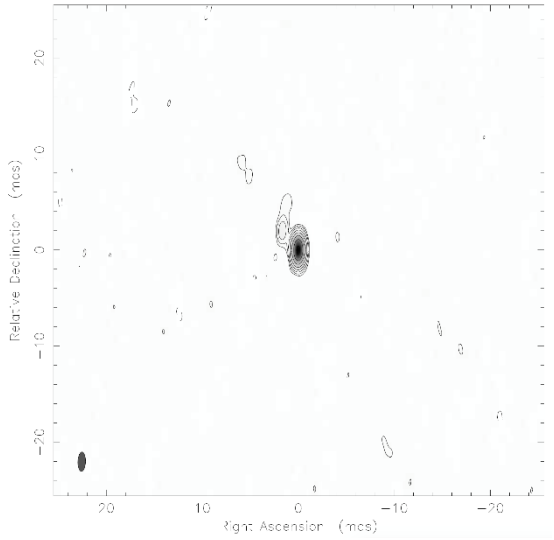
Astrometric positions derived from accurate measurement of group delay

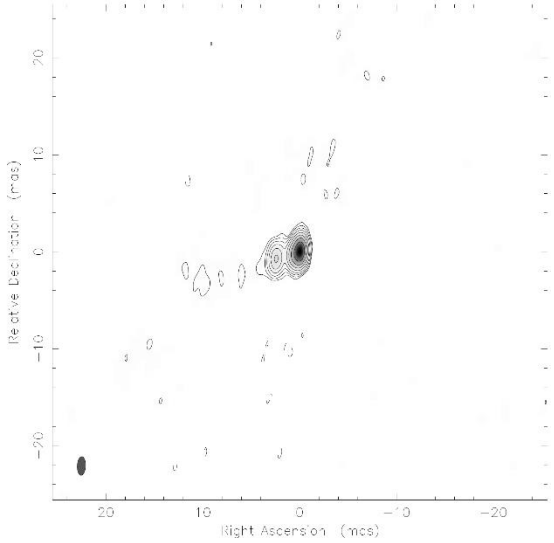
- Can observe in short bursts to get good measurement of delay
  - Short observations may not be optimal for imaging. So why am I talking about it?

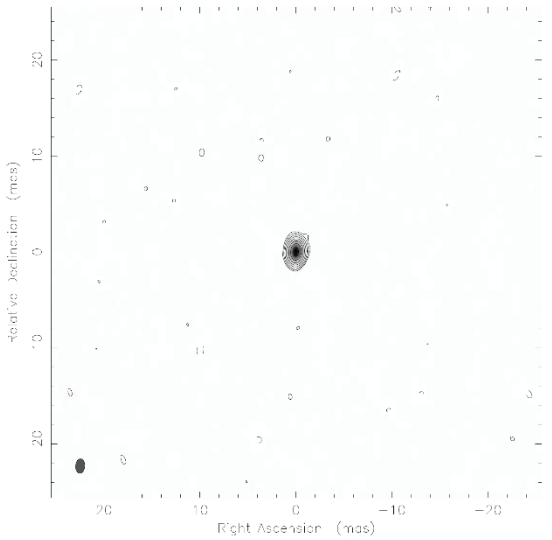
Why Make Images?

Since we have the data, we might as well use it

- Doesn't really cost extra
- Can tell us important information
  - Source compactness
    - Determine suitability as astrometric source
    - Determine suitability as a calibrator
  - Variability
    - Compare images over time
  - Other Utility?
    - Make data products publicly available to astronomical community







VLBA S/X Observations

USNO VLBA session to observe ICRF3 sources

- Most of the ~2200 VCS Sources included in ICRF have been observed only a handful of times
  - Can improve position accuracy of those sources with more observations
  - This should improve overall accuracy of ICRF
- Search for more high-quality sources
  - Add to defining sources?

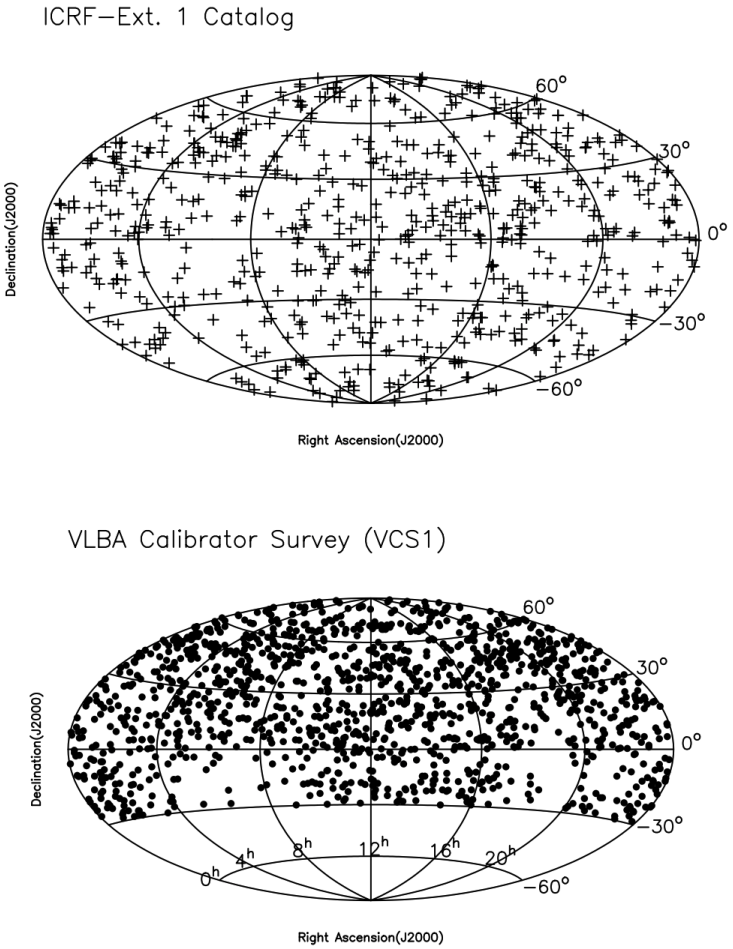


FIG. 1.—Equal-area projection of celestial distribution of ICRF-Ext. 1 (667 sources, *top*) and VCS1 catalogs (1332 sources, *bottom*).

Beasley+ 2002

Observing set-up/Calibration

Simultaneous S/X Band

- 2.3 (S)/8.7 (X) GHz
- 16 sub-bands
  - 4 at S-band, 12 at X-band
- 32 MHz bandwidth per sub-band
  - 64 channels/sub-band
- Right Circular Polarization

24 hour observations

- ~2 observations a month for 20 observations per year
- ~300 objects observed per observation per frequency
- Over 11,000 images

Calibration done in AIPS

- Follow standard procedure

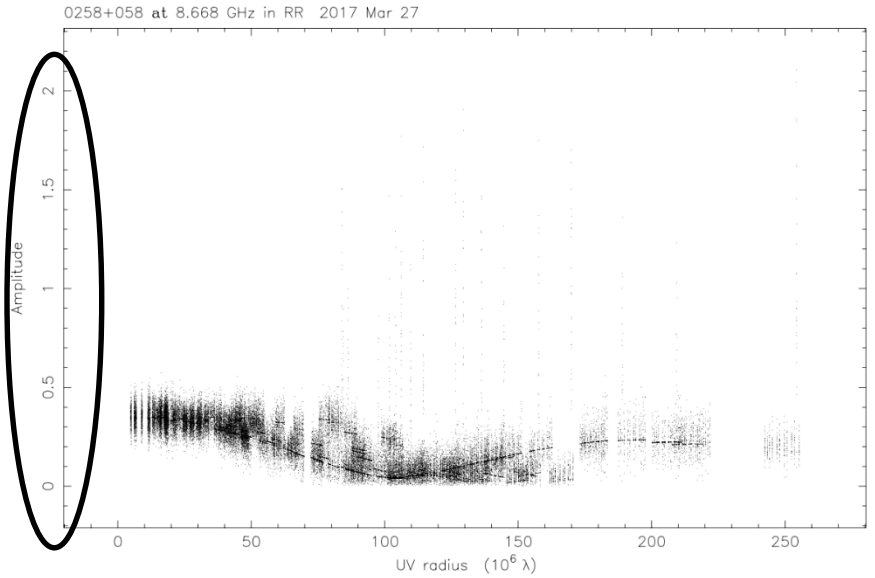
Imaging done in program called Difmap

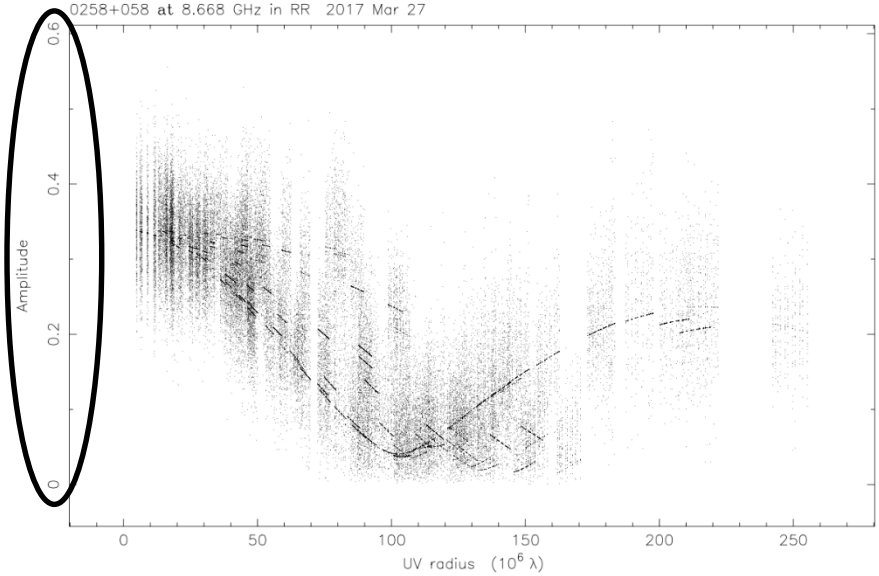
- Automated imaging

Imaging

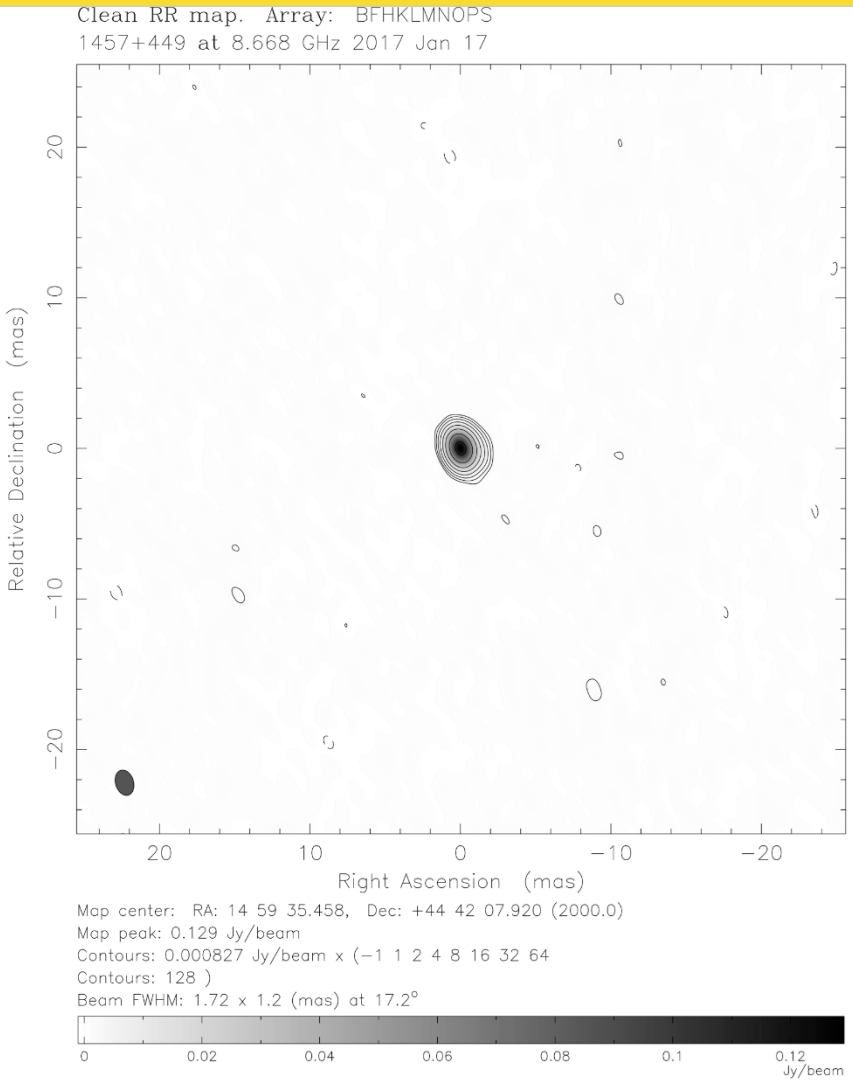
Difmap Scripts

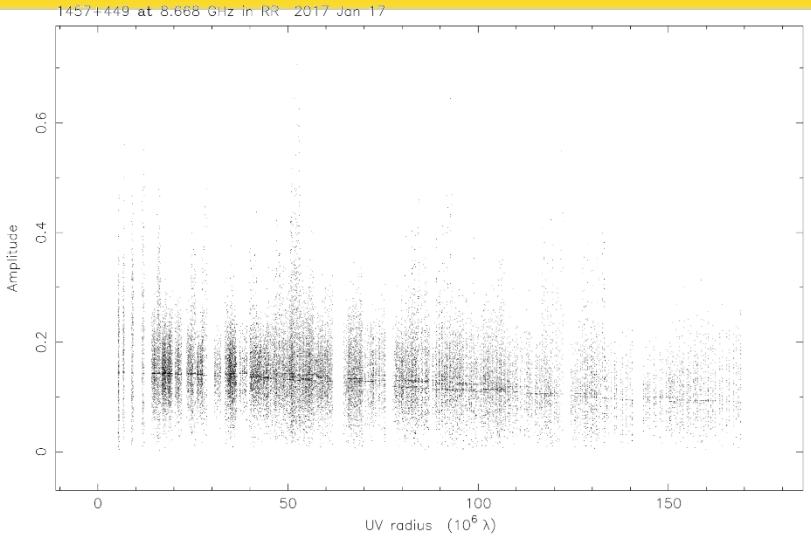
- Data split from aips, run through difmap using script
  - Script was used for previous RDV imaging, therefore outputs products similar to those available on RRFID
    - .fits, model, log, par, image, uv plot
- Data with bad points manually flagged in difmap
  - Large PDF file created showing image and amp/uv plot. Manually inspect to find number of successful sources and sources that need more editing
  - Manually inspecting images and flagging data takes a lot of time
  - Bottleneck! Find ways to automate

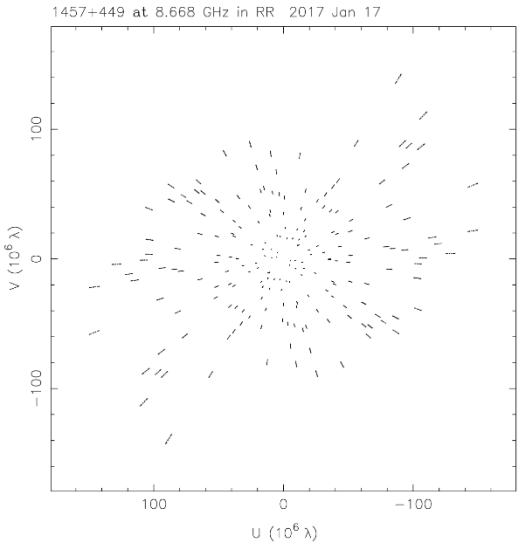




Images (X-band)







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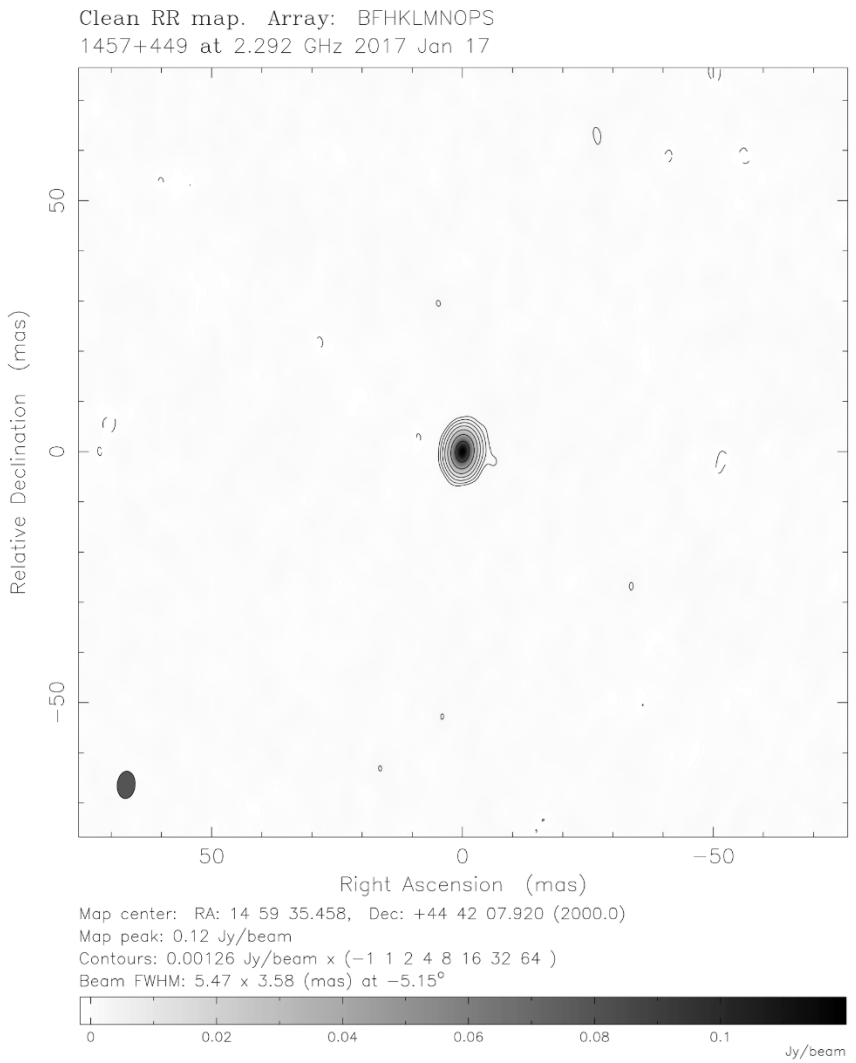

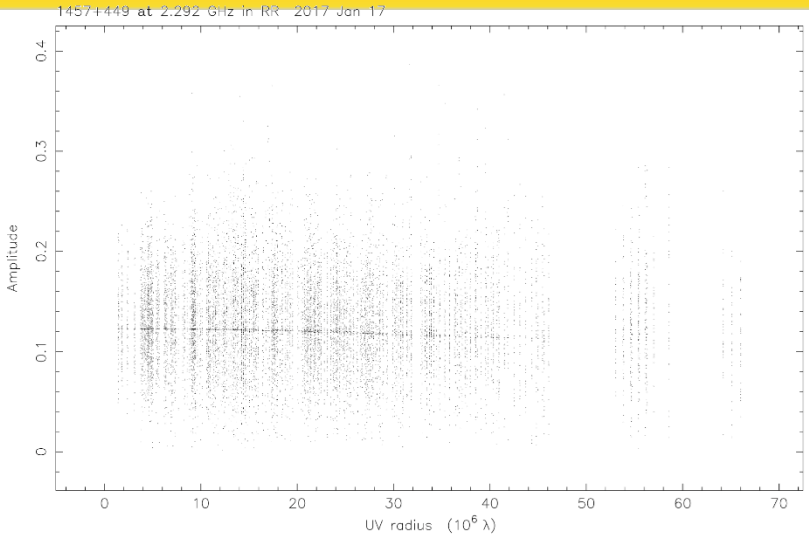

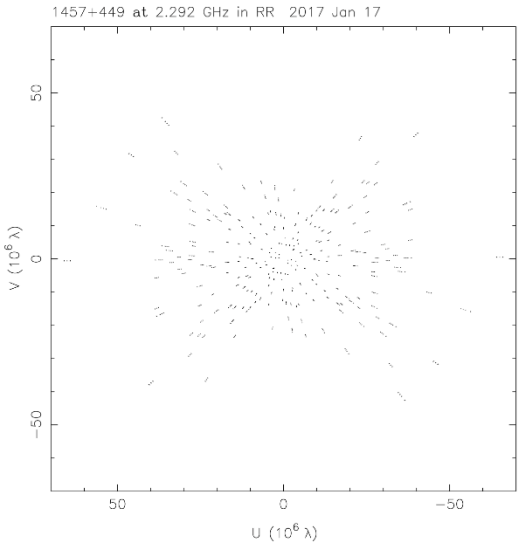

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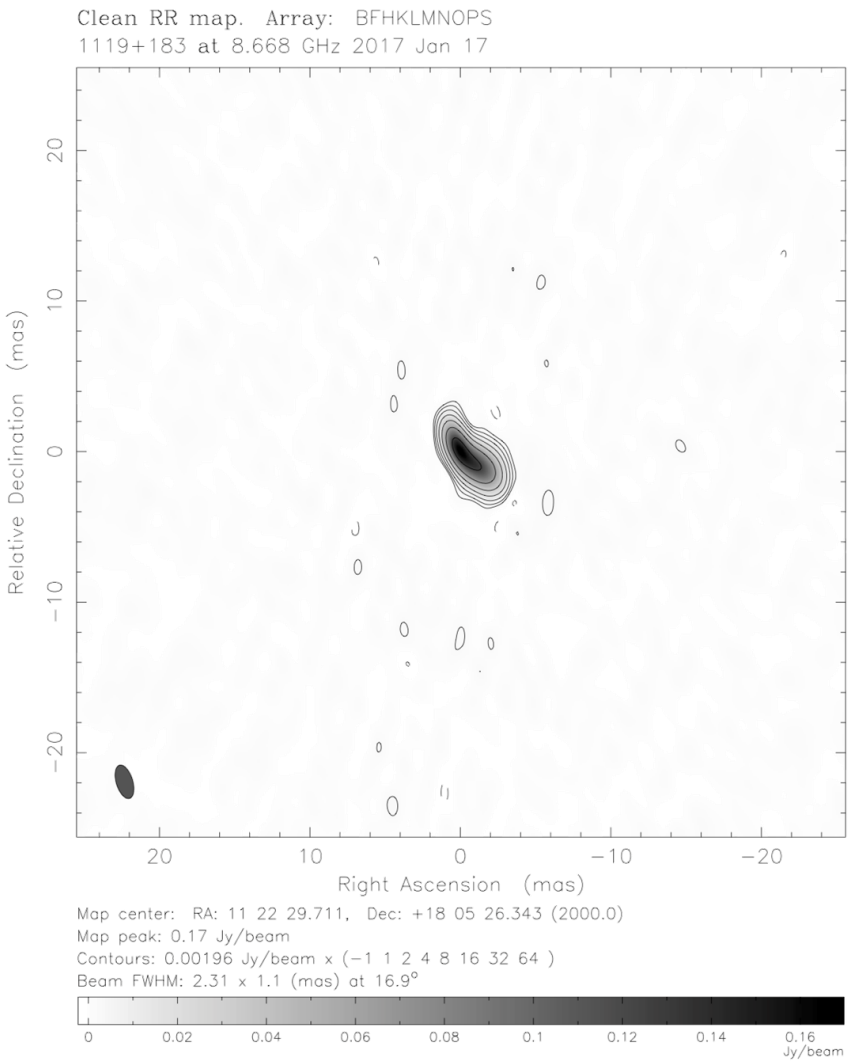

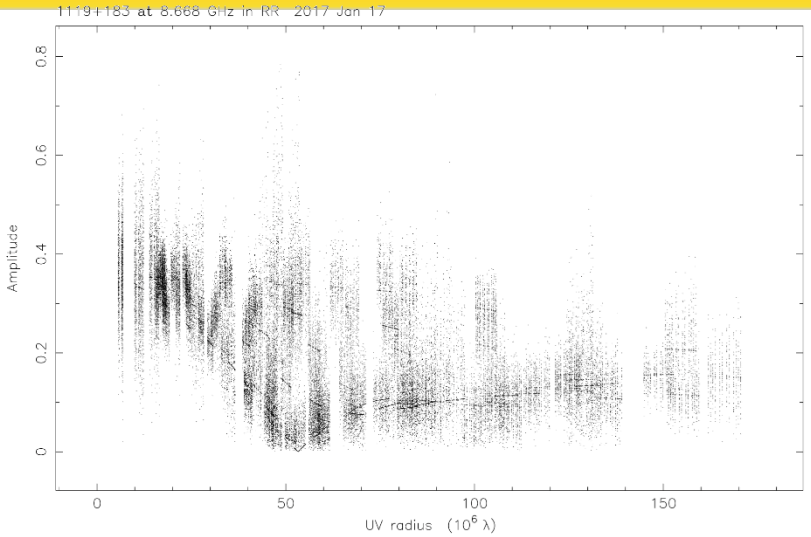

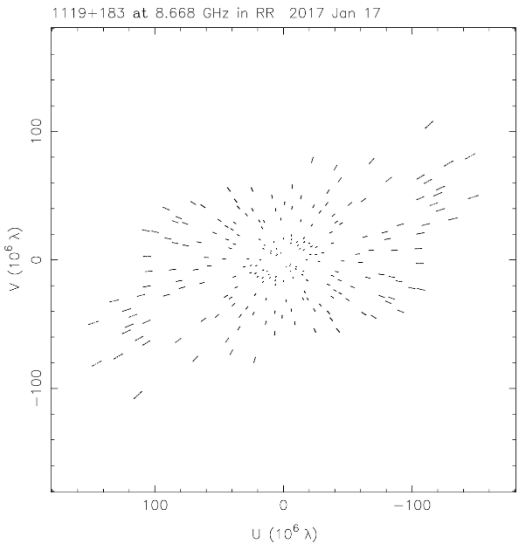

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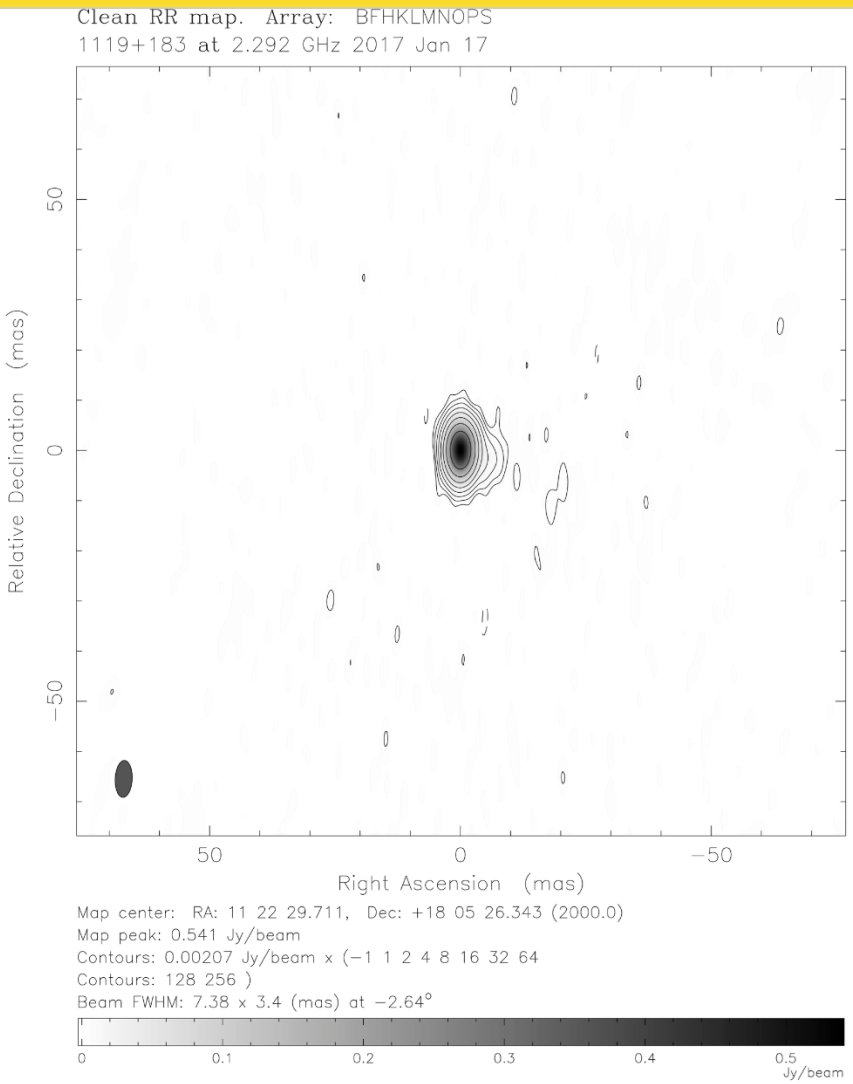

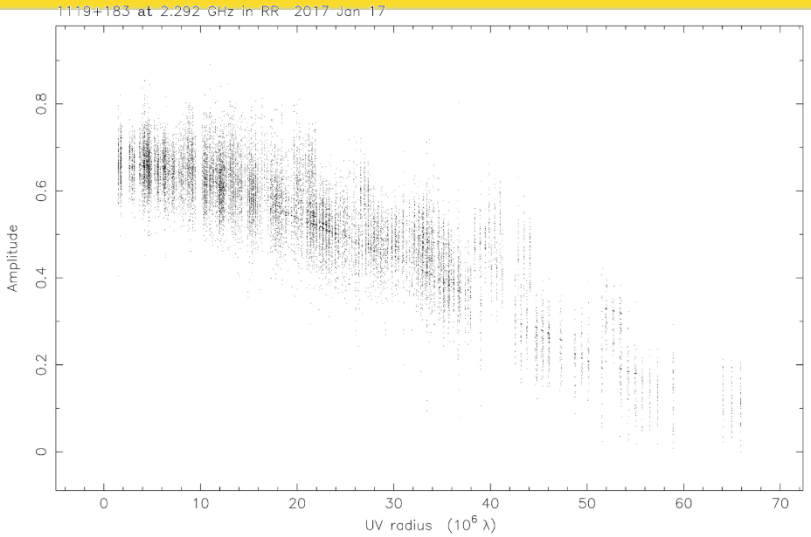

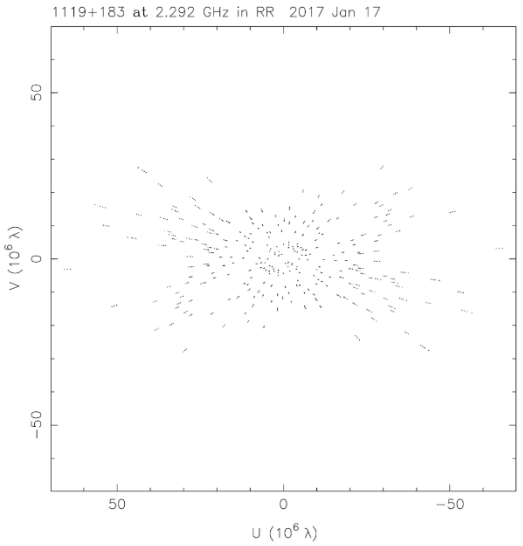

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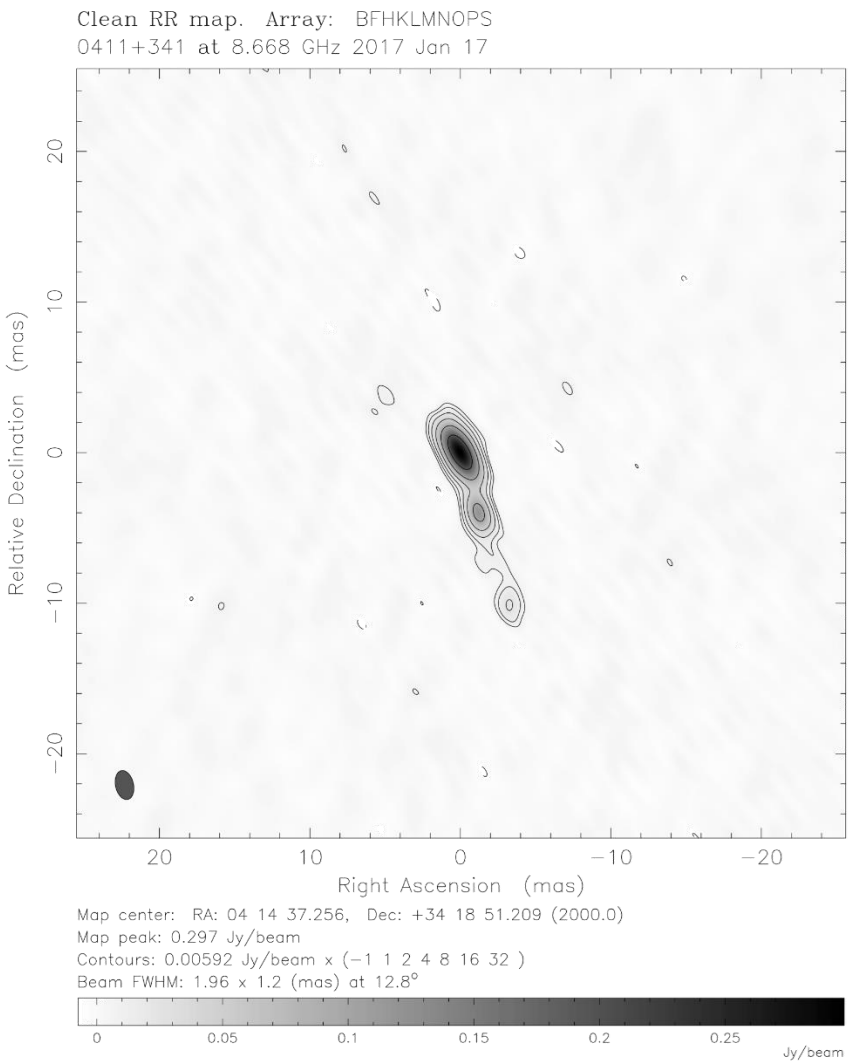

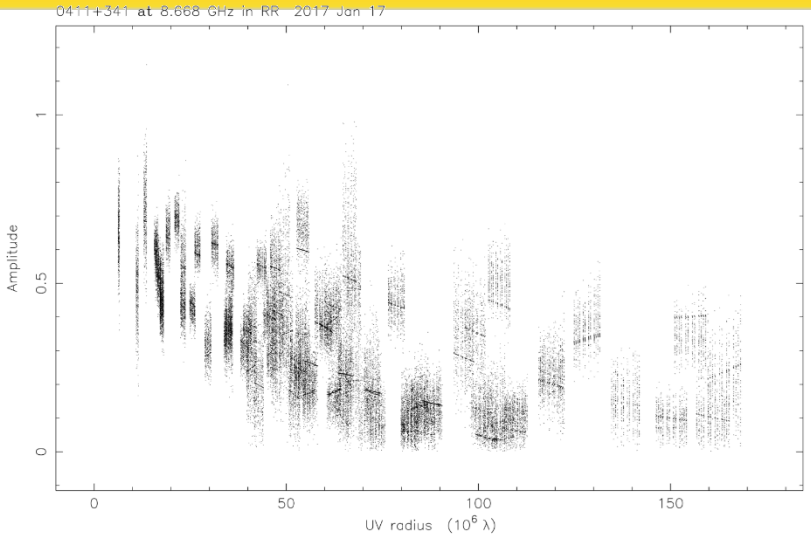

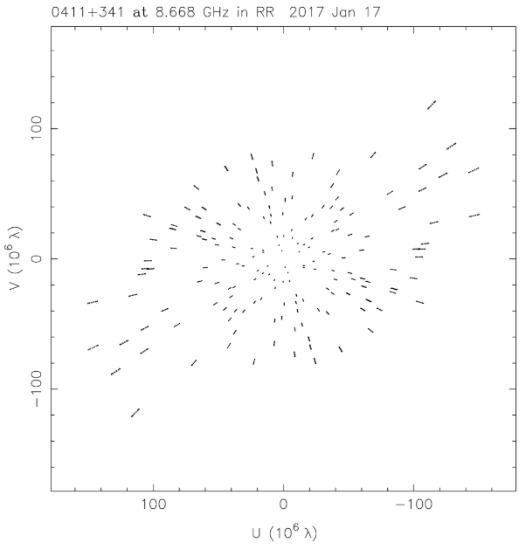

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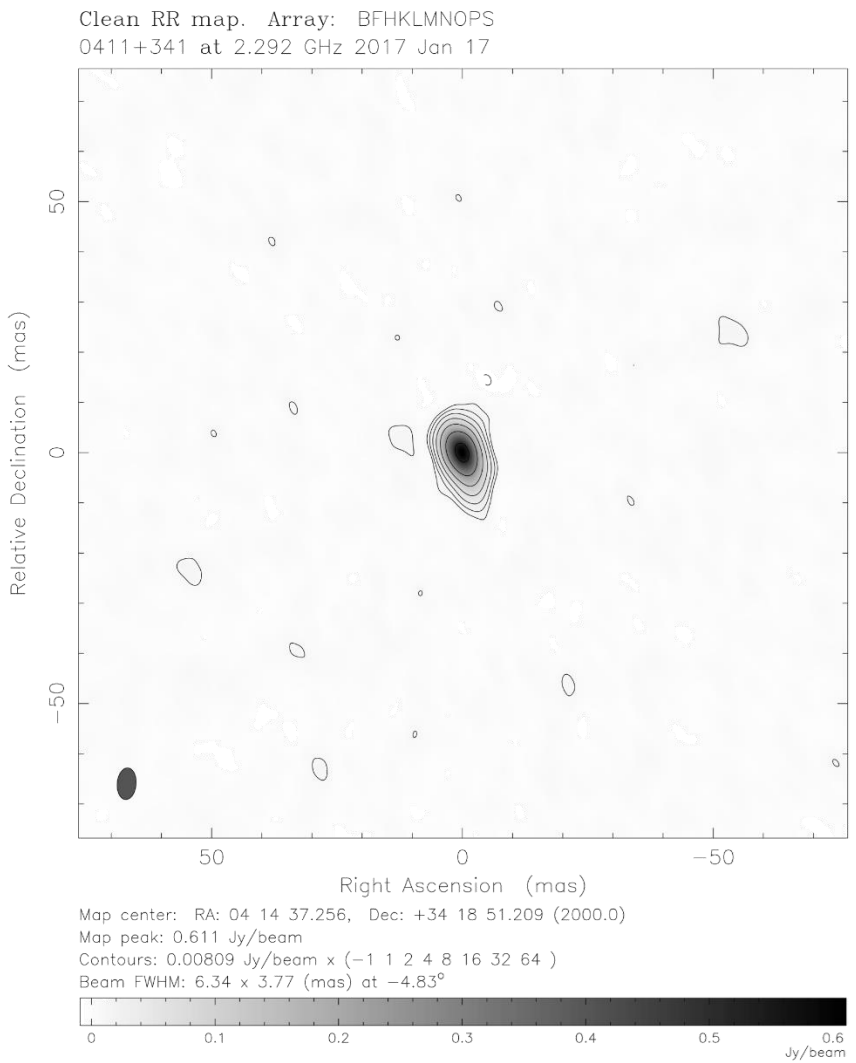

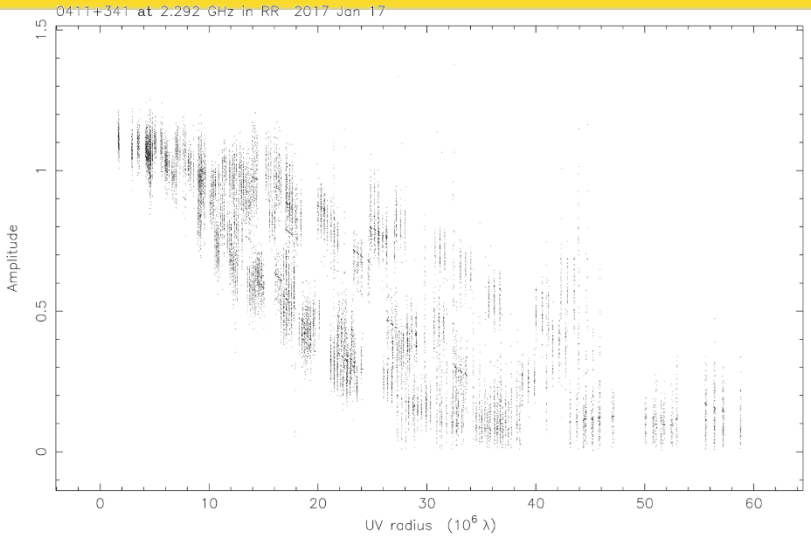

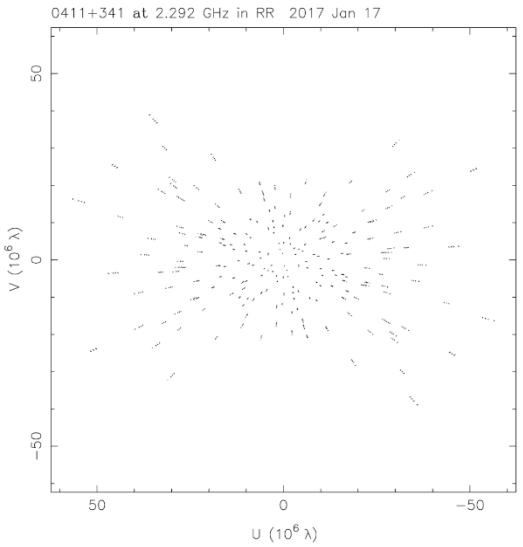

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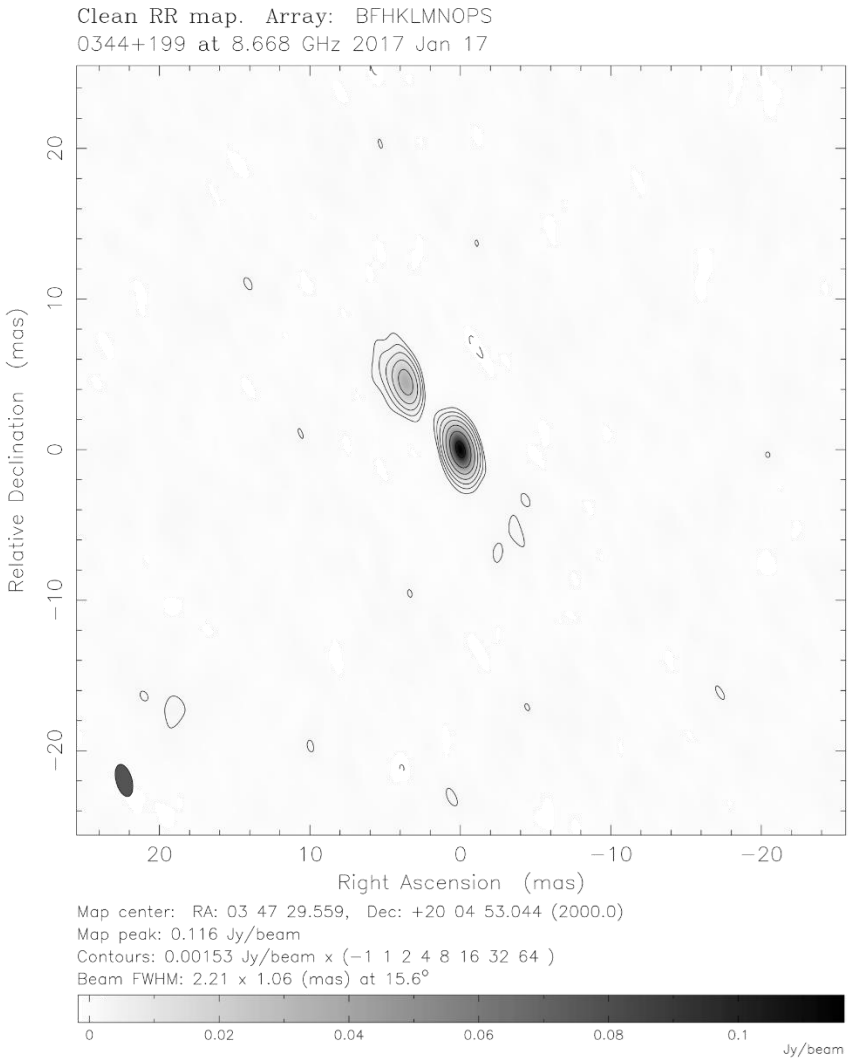

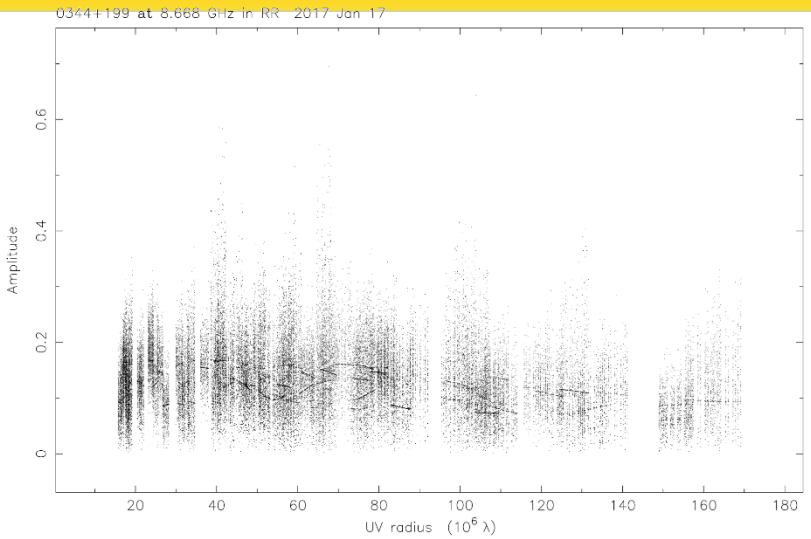

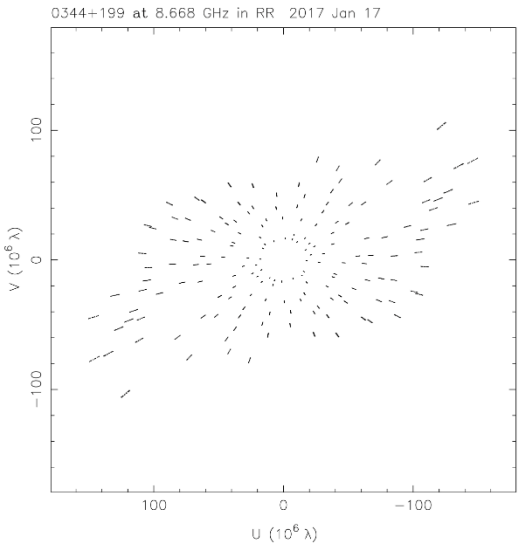

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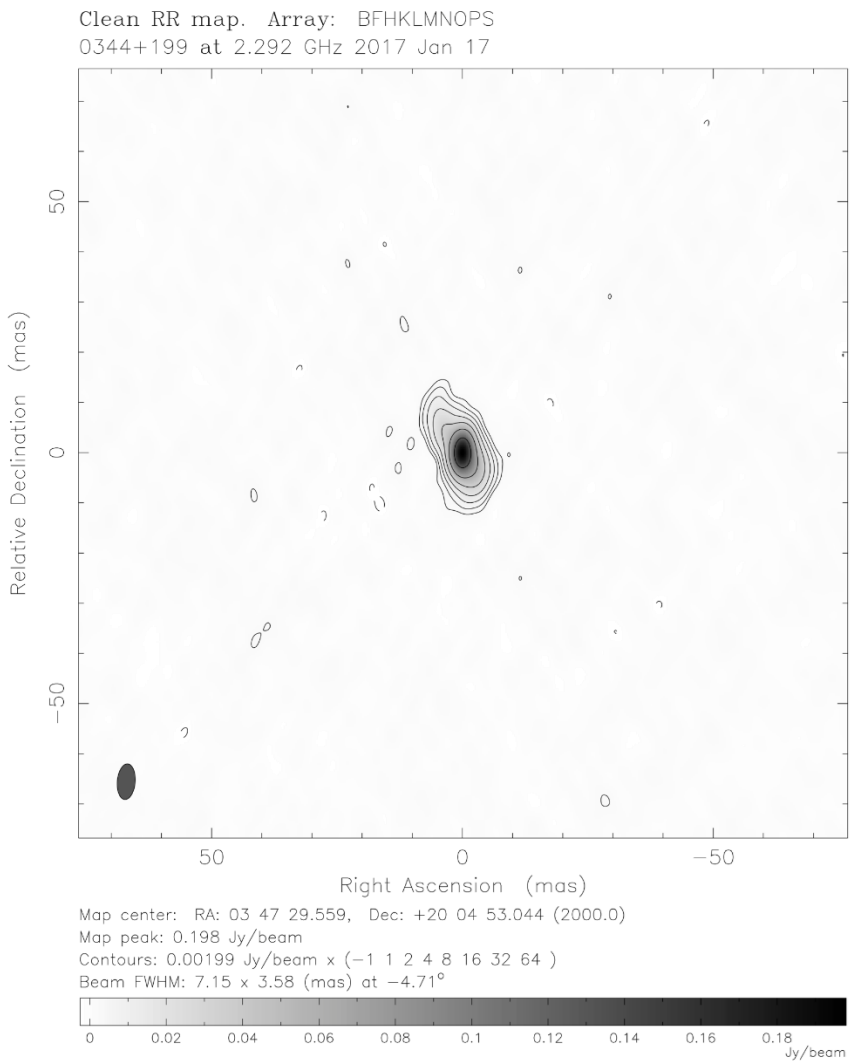

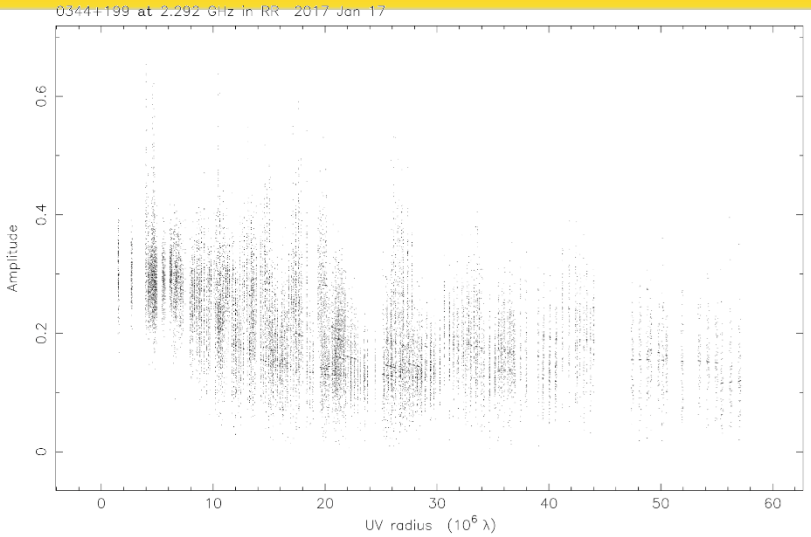

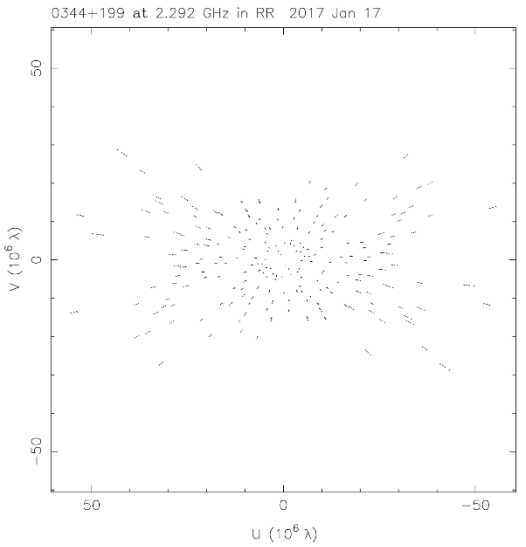

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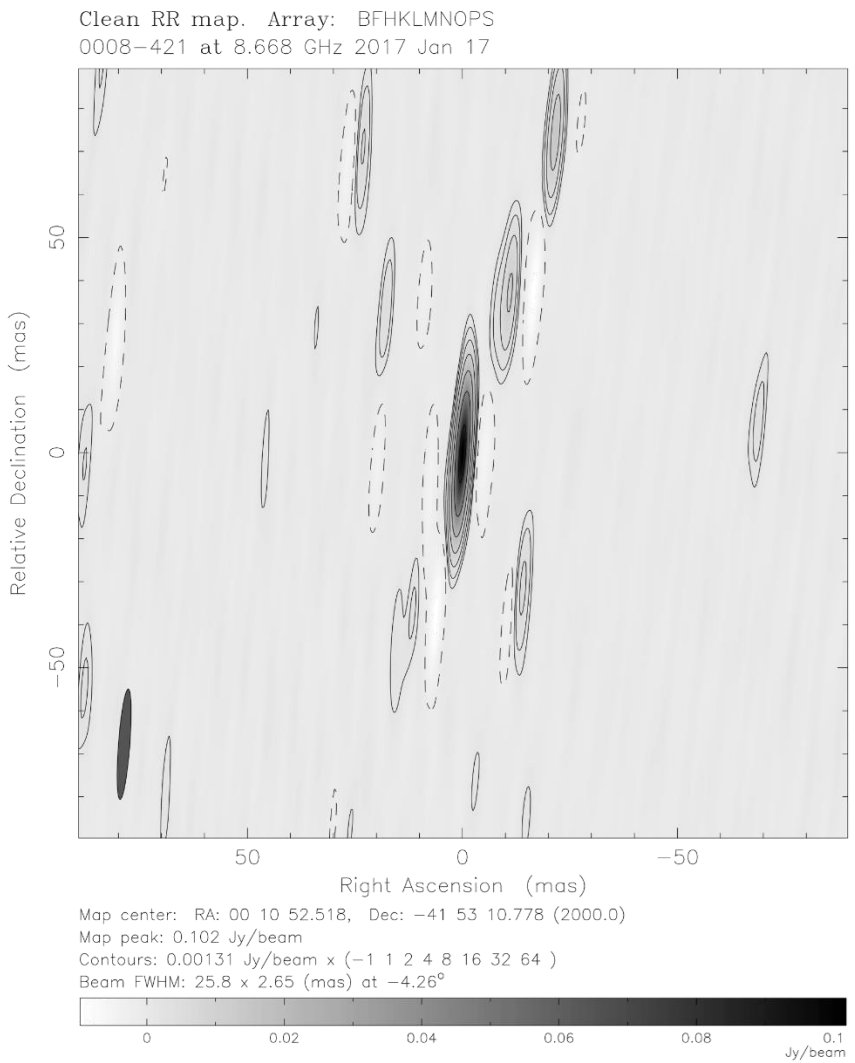

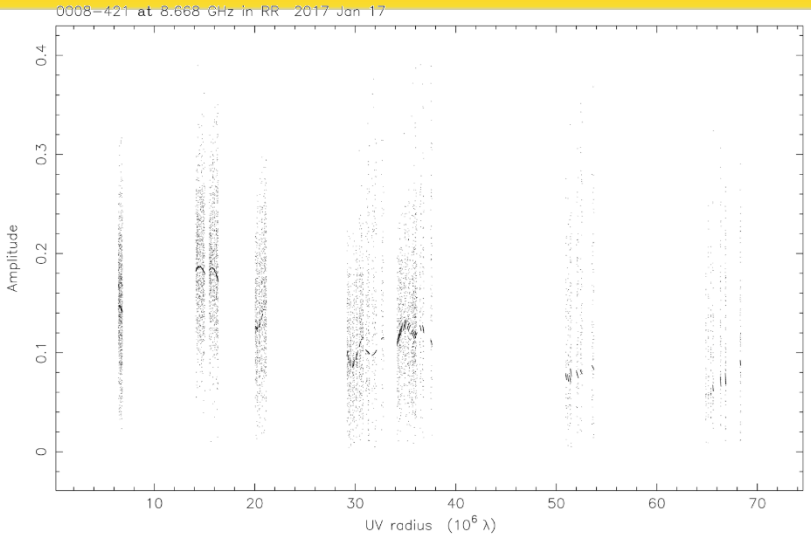

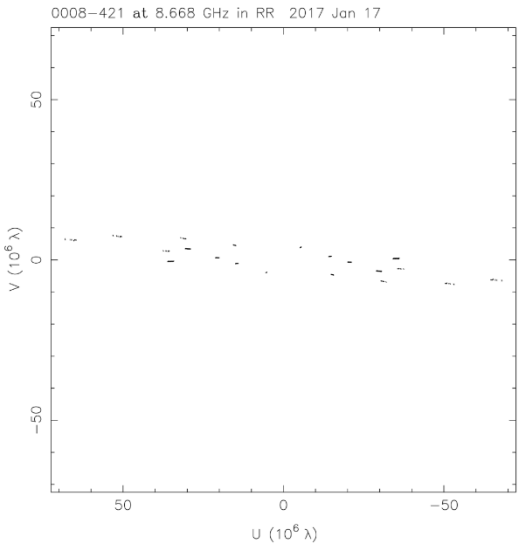

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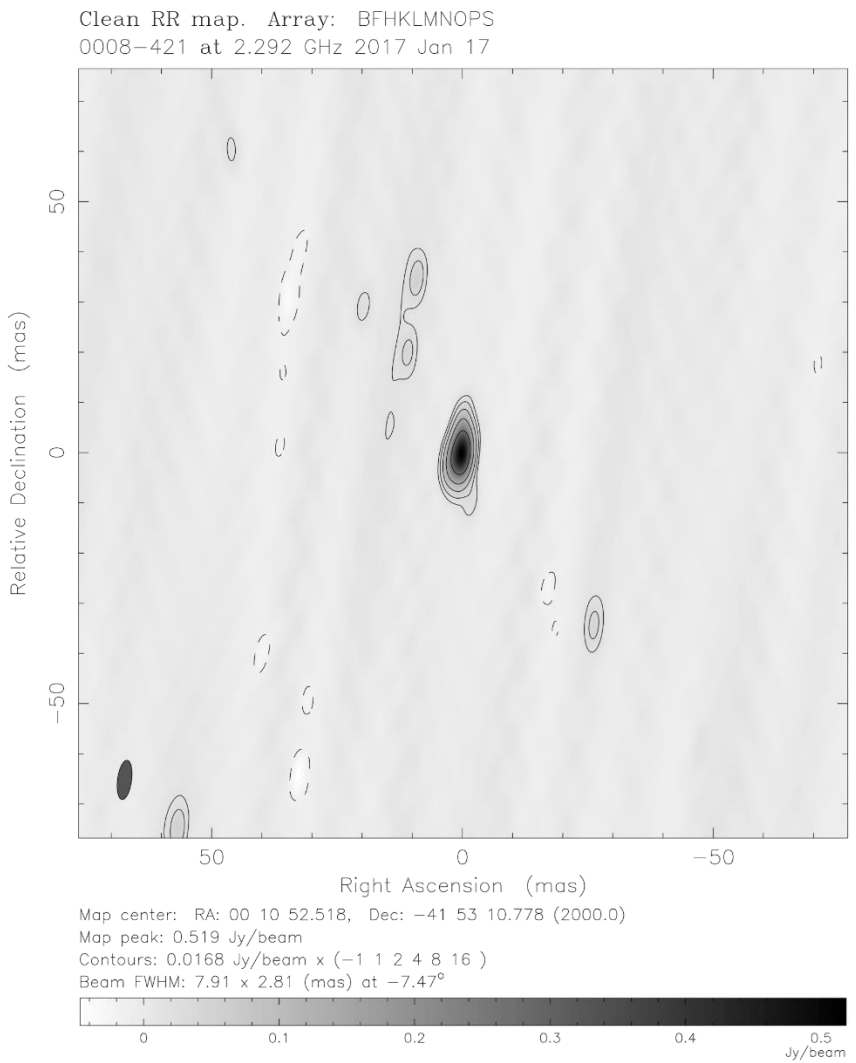
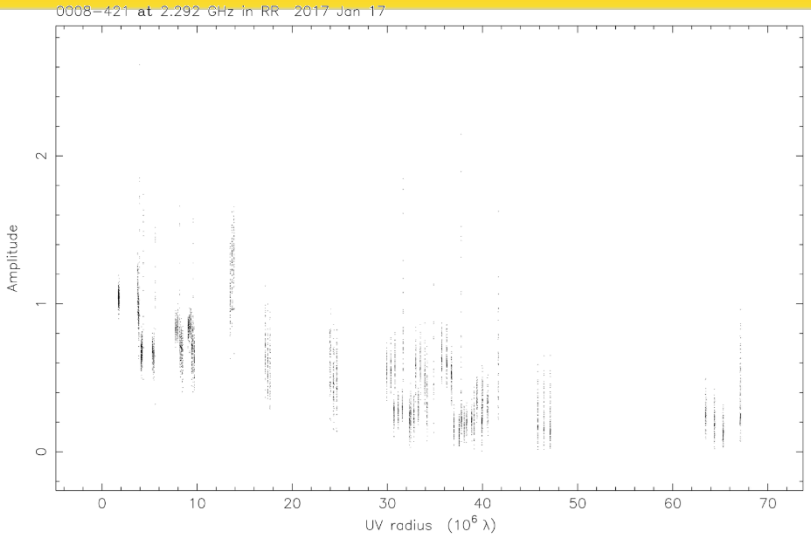
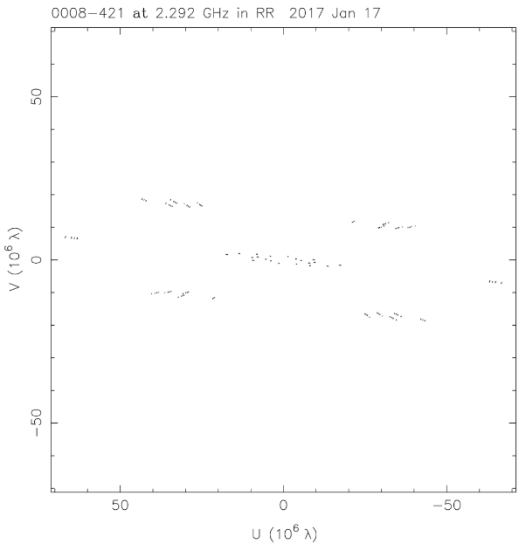






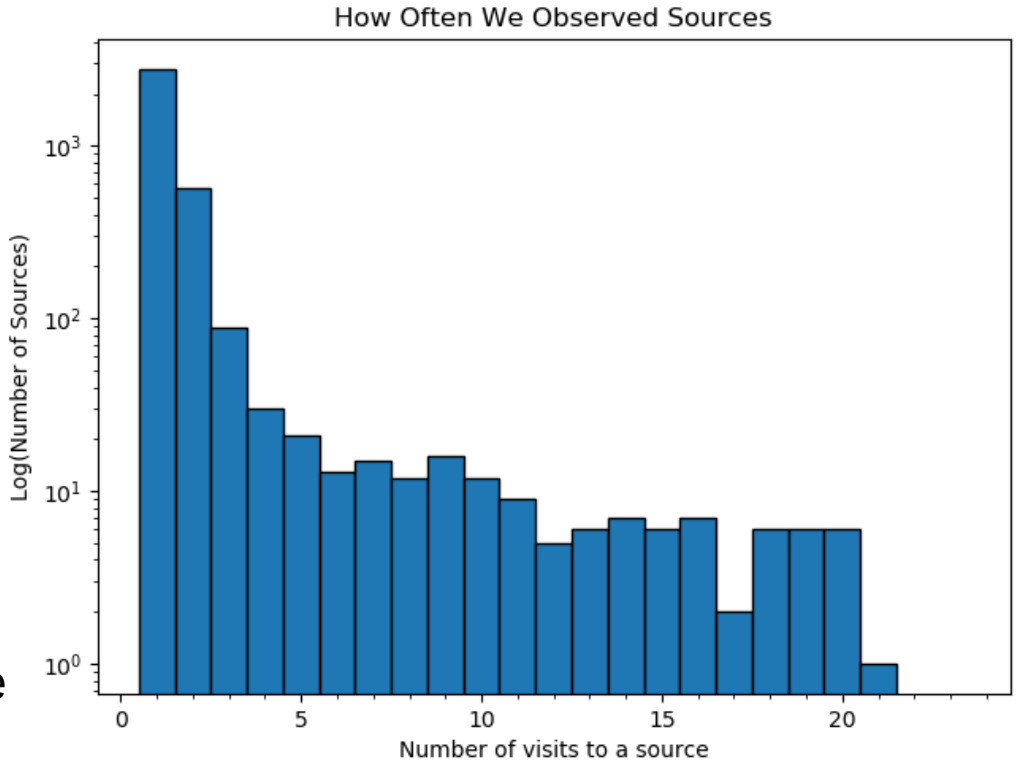
Statistics

All 20 Observations complete

- X-Band
  - 5228/5897 images created
    - ~90% success rate
- S-Band
  - 5664/5897
    - ~96% success rate

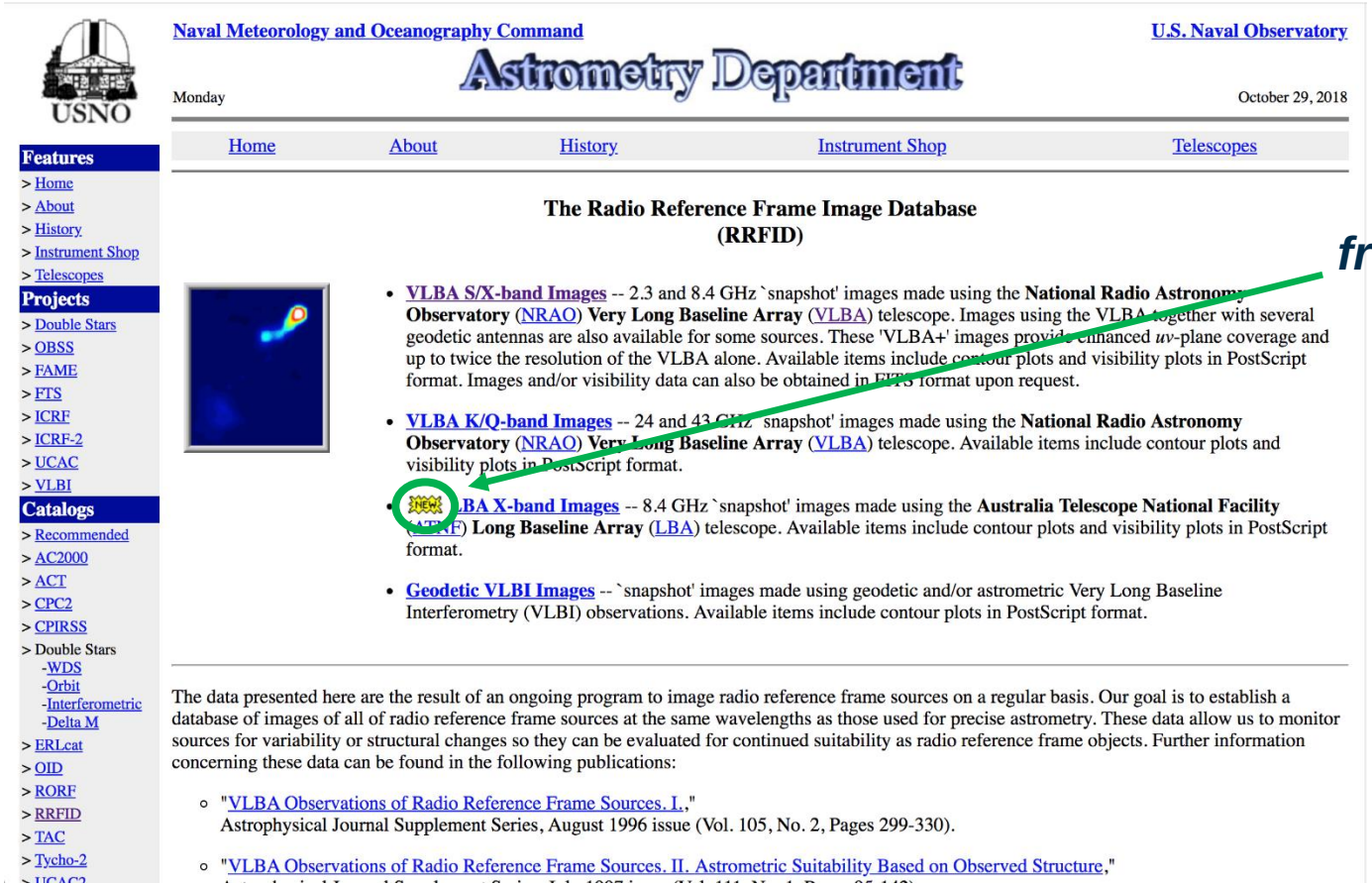
Reasons for failure

- Not observed long enough
- Failed calibration?
  - Assume most objects are point like If not, calibration may not be successful
  - Observing some failed sources with longer integration time and phase referencing to determine intensity and structure



Radio Reference Frame Image Database

Images of all sources in ICRF (685 available at S/X)



USNO

Naval Meteorology and Oceanography Command — U.S. Naval Observatory

Astrometry Department

Monday — October 29, 2018

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> Tycho-2

The Radio Reference Frame Image Database (RRFID)

- **VLBA S/X-band Images** -- 2.3 and 8.4 GHz `snapshot' images made using the **National Radio Astronomy Observatory** (NRAO) **Very Long Baseline Array** (VLBA) telescope. Images using the VLBA together with several geodetic antennas are also available for some sources. These 'VLBA+' images provide enhanced *uv*-plane coverage and up to twice the resolution of the VLBA alone. Available items include contour plots and visibility plots in PostScript format. Images and/or visibility data can also be obtained in FITS format upon request.
- **VLBA K/Q-band Images** -- 24 and 43 GHz `snapshot' images made using the **National Radio Astronomy Observatory** (NRAO) **Very Long Baseline Array** (VLBA) telescope. Available items include contour plots and visibility plots in PostScript format.
- NEW! **LBA X-band Images** -- 8.4 GHz `snapshot' images made using the **Australia Telescope National Facility** (ATNF) **Long Baseline Array** (LBA) telescope. Available items include contour plots and visibility plots in PostScript format.
- **Geodetic VLBI Images** -- `snapshot' images made using geodetic and/or astrometric Very Long Baseline Interferometry (VLBI) observations. Available items include contour plots in PostScript format.

The data presented here are the result of an ongoing program to image radio reference frame sources on a regular basis. Our goal is to establish a database of images of all of radio reference frame sources at the same wavelengths as those used for precise astrometry. These data allow us to monitor sources for variability or structural changes so they can be evaluated for continued suitability as radio reference frame objects. Further information concerning these data can be found in the following publications:

- "VLBA Observations of Radio Reference Frame Sources. I.,"
Astrophysical Journal Supplement Series, August 1996 issue (Vol. 105, No. 2, Pages 299-330).
- "VLBA Observations of Radio Reference Frame Sources. II. Astrometric Suitability Based on Observed Structure,"

This is from 2004

Radio Reference Frame Image Database

Images of all sources in ICRF (685 available at S/X)

U.S. Naval Observatory — Astrometry Department

The Radio Reference Frame Image Database
S/X Band VLBA and VLBA+ Images

(This document is available with and without frames.)

Available items include PostScript format contour plots of Radio Reference Frame source images at frequencies of **2 GHz**, **8 GHz**, and **15 GHz**. Plots of visibility data in PostScript format are also available. Calibration, data analysis, and other information can be obtained by retrieving the files 0000CALIB.ps and 0000README (one for each observation epoch). Visibility data and images are available in FITS format upon request to afey@usno.navy.mil.

Animated GIF format images as well as estimates of the astrometric suitability for many of these sources, based on the images presented here, are also available.

If you make use of these data in any publication, please refer to the citation instructions.

Available Sources

0003+380, 0003-066, 0007+106, 0007+171, 0007-325, 0009+081, 0010+405, 0013-005, 0014+813, 0016+731, 0017+200, 0019+058, 0025+197, 0026+346, 0035+413, 0035-024, 0035-252, 0039+230, 0043-268, 0043-392, 0046+316, 0047+023, 0048-097, 0048-427, 0054+161, 0055+300, 0055-059, 0056-001, 0059+581, 0102+511, 0103+127, 0104-408, 0106+013, 0108+388, 0109+224, 0110-361, 0111+021, 0111+131, 0112-017, 0113-118, 0114-211, 0115-214, 0116+319, 0118-272, 0119+041, 0119+115, 0123+257, 0130-171, 0131-367, 0131-450, 0133+476, 0134+311, 0134+329, 0135-247, 0137+012, 0137+467, 0138-097, 0146+056, 0148+274, 0149+218, 0149-175, 0151+474, 0153+744, 0159+723, 0201+113, 0202+149, 0202+319, 0202-172, 0208-512, 0209+168, 0211+171, 0212+735, 0215+015, 0219+428, 0220-349, 0221+067, 0224+671, 0227-369, 0229+131, 0234+285,

2000JUL06	2 GHz+ , 8 GHz+	2 GHz+ , 8 GHz+
2000OCT23	2 GHz+ , 8 GHz+	2 GHz+ , 8 GHz+
2001JAN29	2 GHz+ , 8 GHz+	2 GHz+ , 8 GHz+
2001MAY09	2 GHz+ , 8 GHz+	2 GHz+ , 8 GHz+
2002JAN16	2 GHz+ , 8 GHz+	2 GHz+ , 8 GHz+
2004FEB15	2 GHz , 8 GHz	2 GHz , 8 GHz
2004JUL14	2 GHz , 8 GHz	2 GHz , 8 GHz
2006JUL11	2 GHz+ , 8 GHz+	2 GHz+ , 8 GHz+
2006SEP13	2 GHz+ , 8 GHz+	2 GHz+ , 8 GHz+
2007JAN24	2 GHz+ , 8 GHz+	2 GHz+ , 8 GHz+
2007JUN26	2 GHz+ , 8 GHz+	2 GHz+ , 8 GHz+
2008JAN23	2 GHz+ , 8 GHz+	2 GHz+ , 8 GHz+
2008MAY14	2 GHz+ , 8 GHz+	2 GHz+ , 8 GHz+
2008SEP03	2 GHz+ , 8 GHz+	2 GHz+ , 8 GHz+

Newest image from 2008

Snapshot Images come from RDV sessions
Only image and UV plots available
(Other products available by request)

Radio Reference Frame Image Database (update)

Images from all available sources

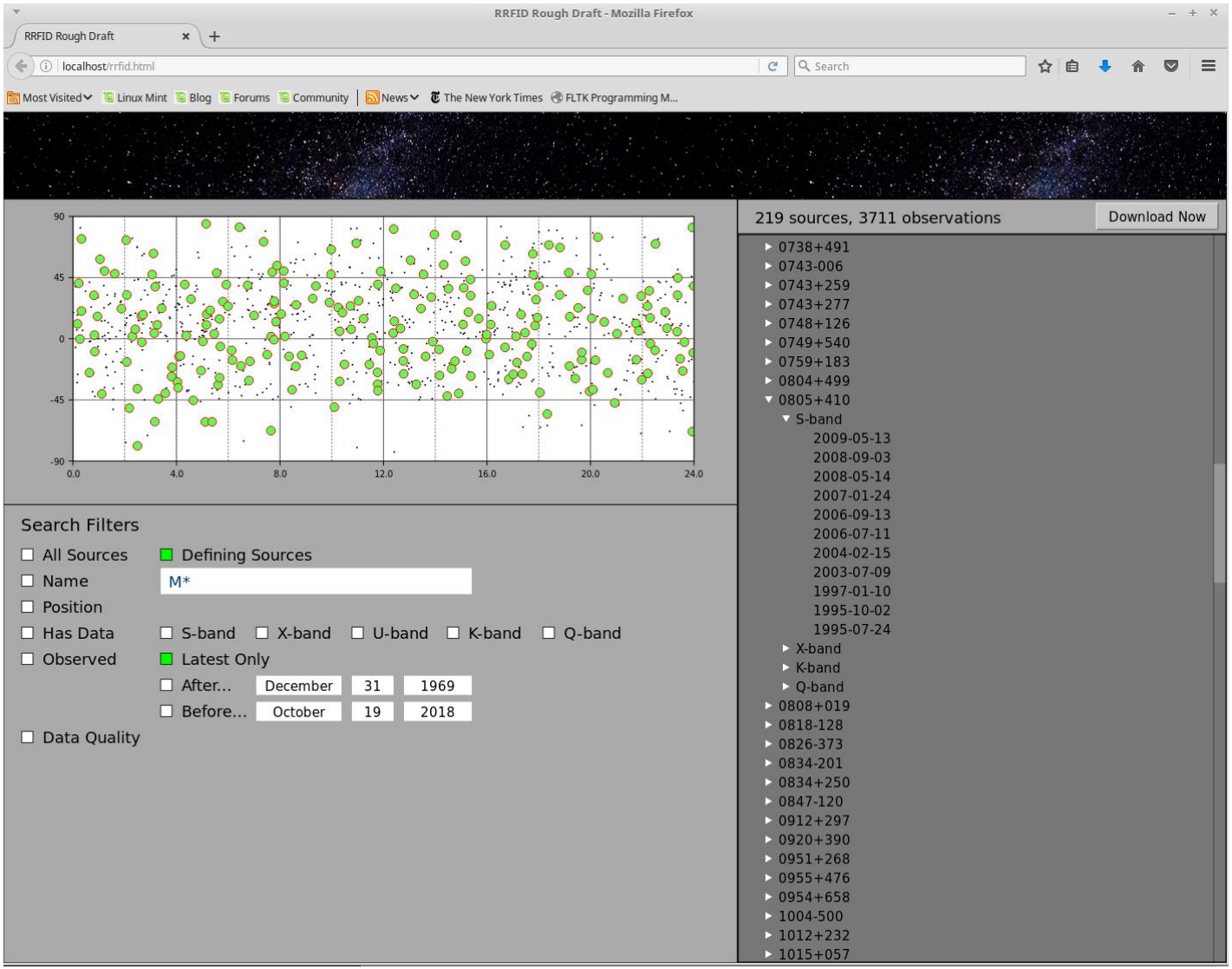
- Images from RDV experiments
- Images from USNO VLBA survey
- Cover S-band through Ka-Band

Other information

- .fits, model, log, par, contour plot, amplitude/uv distance plot

Easier Search

Radio Reference Frame Image Database (update)



Future Work

Determine Source Structure Index/Correction Maps

- Suitability of source for astrometry

Explore Flagging options!

- Some automated flagging algorithms available
  - Pieflag, AOFLAGGER, RFLAG, TFCROP

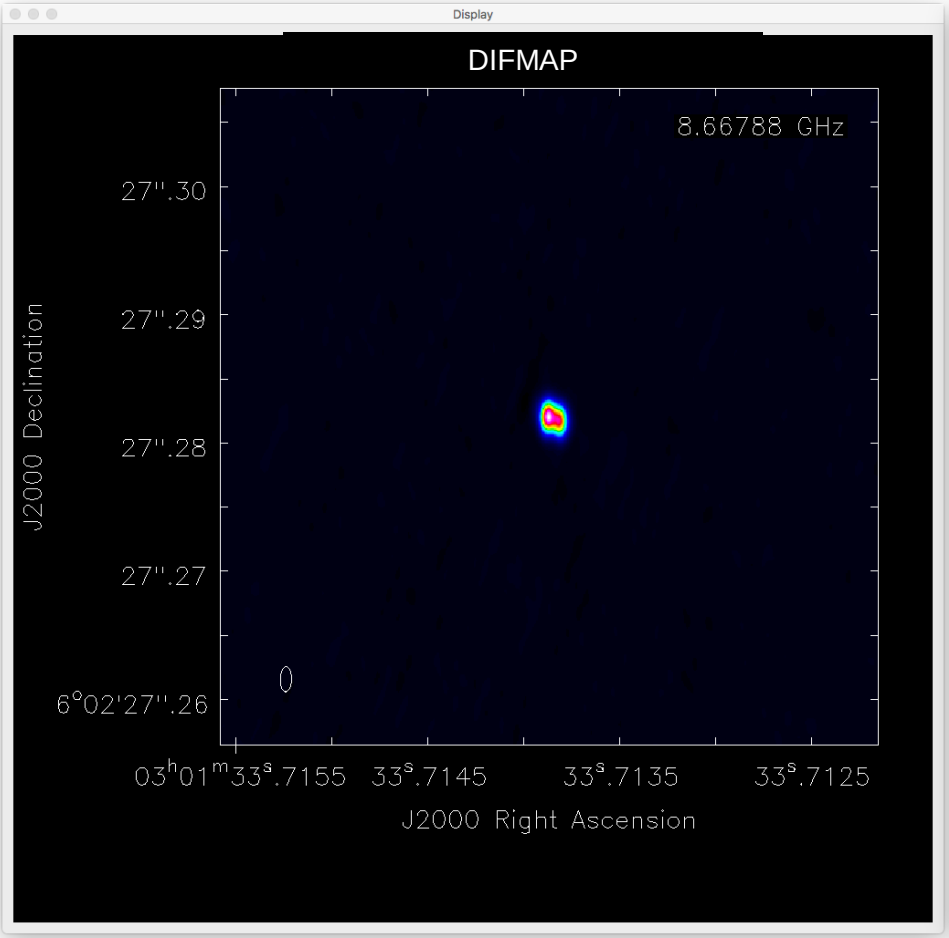
Continue imaging

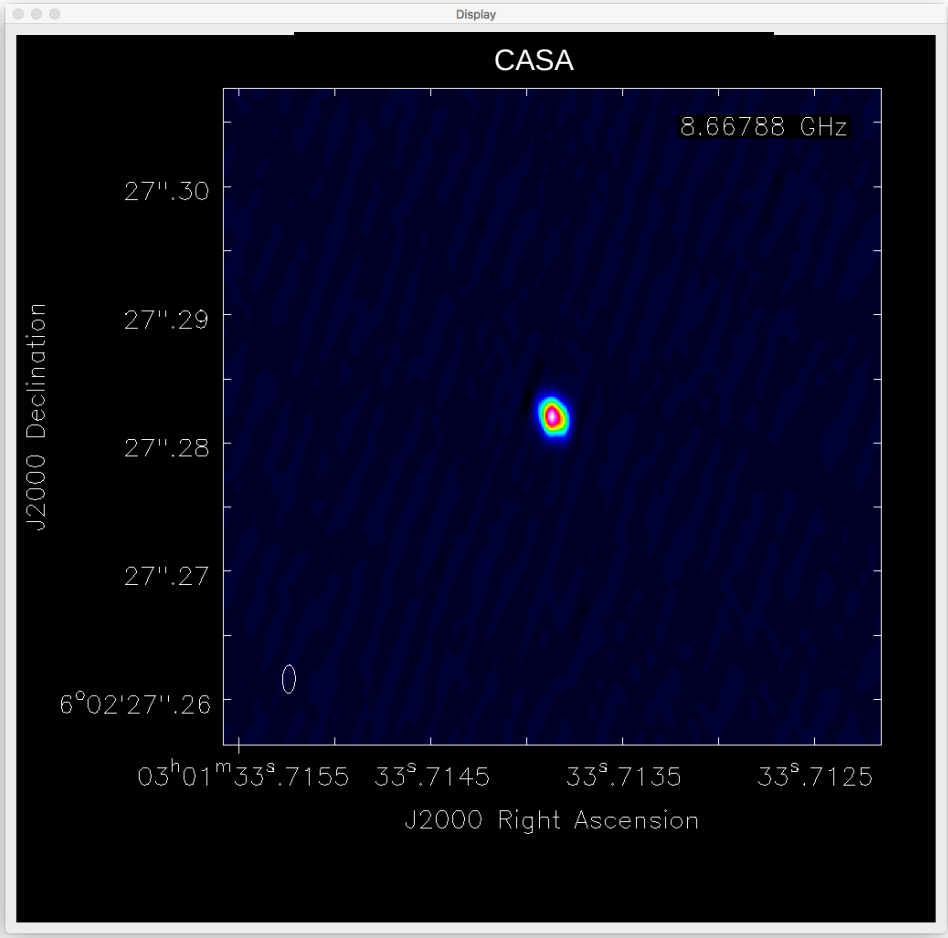
- Similar VLBA observations have continued in 2019

Explore Imaging Options

- AIPS
  - Requires too much interaction=Too much time for large survey
- CASA
  - Has automated imaging routine (tclean)
  - Self-Calibration automatically removes visibilities that don't fit with calibration model

Future Work





RMS=3.9x10^{-4} Flux Density=0.35 Jy

RMS=8.7x10^{-4} Flux Density=0.34 Jy

Conclusion

Using USNO VLBA time to observe ICRF sources

- More observations improve astrometric accuracy
- Images will tell us about source compactness/suitability as calibrator and variability
- Cover >3000 objects included in ICRF3
- Observations continuing into 2019

All data will be publicly available

- Searchable database
- Include contour and amplitude/uvdistance plots
- Information to reproduce images
- Updated database coming soon

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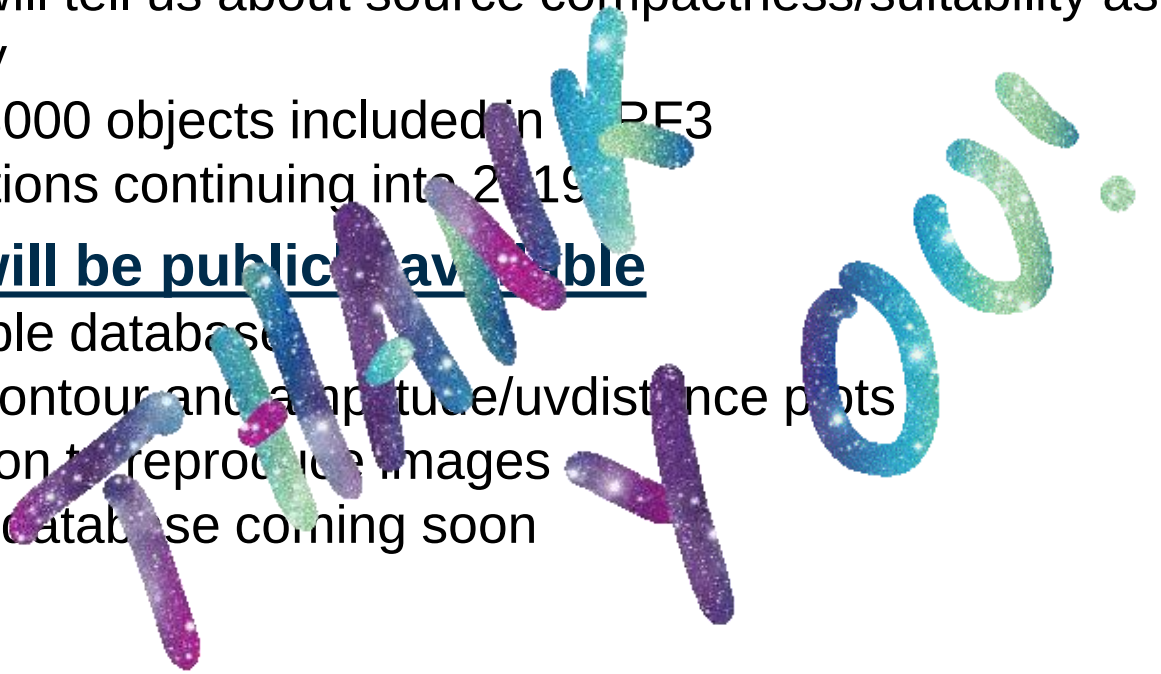

References

Thompson, A.R., Moran, J.M. & Swensen, G.W. 2004, "Interferometry and Synthesis in Radio Astronomy" 2nd edition (Wiley-VCH)

Synthesis Imaging workshop proceedings

- Perley, R.A., Schwab, F.R., Bridle, A.H., eds. 1989, ASP Conf. Series 6, "Synthesis Imaging in Radio Astronomy" (San Francisco: ASP)
  - Ch. 6: Imaging (Sramek & Schwab), Ch. 8: Deconvolution (Cornwell)
- http://www.aoc.nrao.edu/events/synthesis
  - Imaging and Deconvolution lectures by Cornwell 2002, Bhatnagar 2004, 2006

For more information see Synthesis Imaging Workshop Lectures (NRAO)