*Radio Interferometry: Theory, Techniques and Applications,*
*IAU Coll. 131, ASP Conference Series, Vol. 19, 1991,*
*T.J. Cornwell and R.A. Perley (eds.)*

# STATE-OF-THE-ART VLBI IMAGING: 3C345

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ABSTRACT Most VLBI images have low dynamic range because they are limited by instrumental effects such as calibration errors and poor $u,v$-coverage. We outline the method used to make a new image of the bright quasar 3C345 which has very high dynamic range (peak-to-noise of 5000:1) and which is limited by the thermal noise, not instrumental errors. Both the Caltech VLBI package and the NRAO AIPS package were required to manipulate the data.

## INTRODUCTION

For many years, VLBI images have consisted of several Gaussian components in a small field. Numerical jet models now show considerable detail within the jets (eg., K. Lind 1990 in *Parsec-Scale Radio Jets* ed. Zensus, J.A. and Pearson, T.J. (Cambridge University Press: Cambridge)). It would be useful to test these new jet models against very detailed VLBI images. The availability of new antennas, more sensitive receivers, and powerful "mini-supercomputers" has encouraged us to push our 5 GHz observations of 3C345 as close as possible to the thermal noise limit. We outline the method used to obtain a thermal-noise-limited image of 3C345 in this paper. The physical interpretation of the 3C345 image itself will be presented elsewhere (Unwin and Wehrle, in preparation).

## METHOD

Our method can be broken into three major stages: conventional imaging, removal of egregious non-closing errors, and model-derived correction of subtle non-closing errors. For simplicity, individual steps are numbered sequentially.

### Conventional Imaging

1. We used as many antennas as possible, and observed with full tracks. All 15 antennas were successful: Onsala, Bonn, Medicina, Jodrell Bank, Westerbork, Torun, Haystack, NRL Maryland Point, NRAO Green Bank, Iowa, Fort Davis, VLA, VLBA-Pietown, Owens Valley and Hat Creek. Crossing points in the $u,v$-plane were used to make consistent calibration between antennas: by using the Caltech program UVCROSS we derived relative gains ("fudge factors") to apply to the amplitudes.

2. We measured system temperatures often (30-60 minutes). We used computer-readable system temperatures for each antenna, available on the NRAO $\mu$VAX in Socorro. All antennas provide this service except the NASA Deep Space Network, Torun and Crimea.

3. We used gain curves provided by each antenna's Friend of VLBI. Flat gain curves at 5 GHz work well for new antennas like Medicina, Noto, the VLA, and all VLBA antennas.

4. We phased up Westerbork often (every 180 minutes). Amplitude "ripples" mimicking structure result if arrays are not phased up often enough. (A single dish of the VLA was used in this experiment; the full VLA should be phased up every 20-30 minutes at 5 GHz depending on configuration).

5. We edited very carefully with Caltech program IED (An equivalent task for AIPS is being written by Phil Diamond). Our 15 antennas with roughly 12 hours of observation yielded about 150,000 points to be examined and edited!

6. Our first images were made with the Caltech package which allows easy comparison of the closure phases of data and model (AIPS does not). Our image size was chosen to be large enough to adequately sample the large-scale (10's of milliarcseconds) structure of the source. A 256 x 256 CLEAN map size is required to sample all data adequately at 5 GHz for Global VLBI observations.

[Calculation: For Global VLBI at 5 GHz, the beam will be 1.0 mas FWHM, so the sampling interval should be about 0.3 mas, the uv-gridsize is $1.4M\lambda$. The largest baseline that will be in Global 5 GHz data is about $200M\lambda$, so the minimum CLEAN mapsize is $200M\lambda/1.44M\lambda = 139$ cells. The CLEAN mapsize needs to be larger than this, hence 256 x 256. If we had needed to separate our baselines by gridding smaller than $1.4M\lambda$, we would have to increase the mapsize.]

## Removal of Egregious Non-closing Errors

**After "conventional imaging", most VLBI images will have dynamic range 300:1 or less. In our next stage we removed two substantial sources of non-closing errors: we discarded two baselines that seriously disagreed with baselines adjacent in the $u,v$-plane.**

7. We examined the fit of each baseline's data to the CLEAN component model with Caltech program QFIT. When we found that two baselines

were seriously discrepant (5 – 10%), we deleted them. Our image improved dramatically when we discarded IOWA-FDVS which was very noisy, and JODRELL2-VLA which had an offset in amplitude from an unknown cause (polarization or bandpass mismatch?). Throwing out two bad baselines immediately improved the image by a factor of 3. Dynamic range in our CLEAN image (Figure 1) was now 1500:1, but the noise ( 2 mJy/beam) in the image was still a factor of 3 larger than the thermal noise estimated by INVERT.

## Removal of Subtle Non-closing Errors

**The final stage involved "correcting" the data on each baseline to eliminate subtle errors. This work was done with John Biretta (NRAO).**

8. We transferred the data to AIPS. We used the powerful and very fast task MX to clean a large image with several CLEAN boxes. We subtracted the CLEAN components from the data, then clipped remaining data to remove outlying bad points. We added CLEAN components back to the clipped data and remade the image.

9. We derived and applied baseline corrections (with AIPS task BLCAL). In this step, we used our CLEAN component model to derive a correction to amplitudes and phases on each baseline individually. We applied corrections to the $u,v$-data and remade the image. We returned to Step 8 above and repeated the cycle twice. The resulting image is shown in Figure 2. It is critically important to use a long timescale (12 hours) initially and then decrease the timescale to a few hours: a fatal error would be the use of a "point-by-point" (60-second) timescale which would cause the image to be *exactly* the same as the input model.

## CONCLUSIONS

Our final CLEAN image has dynamic range 5000:1, measured as the ratio of the peak to the rms noise off the source. **It is the highest dynamic range image made with 5 GHz VLBI to date.** This image, shown in Figure 2, brings us to two conclusions. **First, we have shown that very high-quality images can be obtained with Mark II VLBI if extra attention is paid to calibration, editing and imaging techniques.** The images presented here were produced with a total "wall-clock" time of about 10 days. We used about 24 cpu-hours of CONVEX C-1 time (detailed guides to the fringe-fitting and imaging VLBI data may be obtained from A. Wehrle at JPL.)

**Second, the "VLA-like" quality of the image makes it clear that the structures in the jet cannot be modelled by simple Gaussian components.** This is one of the first VLBI images of a quasar jet that shows detail across the jet. Like the jets in the radio galaxy M87 (resolved by Reid et al. 1990) and the quasar 3C48 (Wilkinson et al. 1990) it shows complex structures within the jet. We intend to compare our 1989 data (shown here) with new data (June 1990) to study changes within the jet.

## ACKNOWLEDGEMENTS

We are grateful to John Biretta (NRAO) for his efforts with BLCAL. We gratefully acknowledge the cooperation of the U.S. VLBI Network and European Network observatories in obtaining excellent data on 3C345. The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation. This work was supported by the National Science Foundation, grant number AST-8814554.

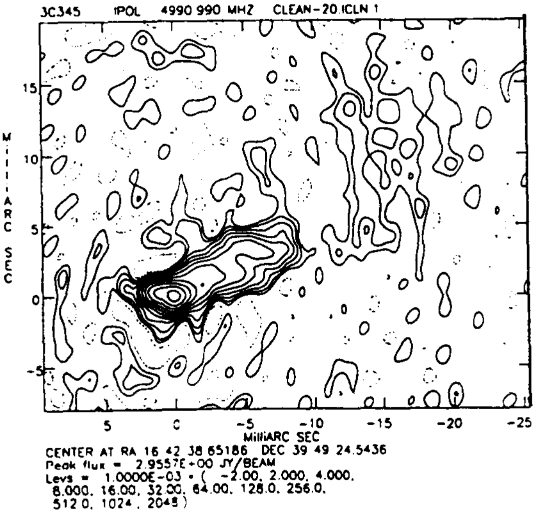

Fig. 1. Image of 3C345 after Step 8.

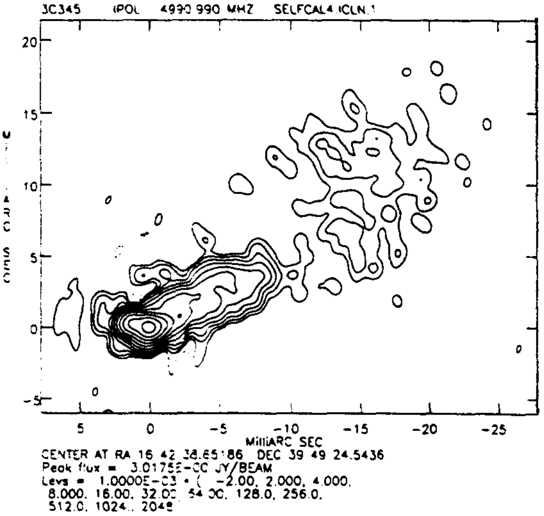

Fig. 2. Image of 3C345 after Step 9.