An Interferometry Imaging Beauty Contest

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ABSTRACT

We present a formal comparison of the performance of algorithms used for synthesis imaging with optical/infrared long-baseline interferometers. Six di erent algorithms are evaluated based on their performance with simulated test data. Each set of test data is formated in the interferometry Data Exchange Standard and is designed to simulate a speci c problem relevant to long-baseline imaging. The data are calibrated power spectra and bispectra measured with a ctitious array, intended to be typical of existing imaging interferometers. The strengths and limitations of each algorithm are discussed.

Keywords: astronomical software, closure phase, aperture synthesis, imaging, optical, infrared, interferometry

1. INTRODUCTION

1.1. Background

Synthesis imaging at optical/infrared wavelengths is a relatively new development. The technique was rst proven possible in 1987 with aperture masking experiments. Following that success several new long-baseline interferometers were designed for imaging, and their rst images were produced in 1995 and 1996. Very few images have so far been published in the refereed literature. All of these images have relied on radio interferometry software.

One of the longstanding problems in this eld, is that the available radio astronomy software is unsuited to optical data. Imaging interferometers at optical/infrared wavelengths measure only visibility-squared and bispectra — from which we can determine closure phases, and closure amplitudes — and their respective errors. The baseline phases are so corrupted by random atmospheric time-delays at each telescope that the baseline

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phases are useless, but the closure quantities remain good observables. At radio wavelengths, on the other hand, the visibilities and phases are the observables; software that processes radio data requests this data as input. It follows that in order to use software packages such as the Astronomical Image Processing System (AIPS) the optical data *must* be transformed: visibilities must be estimated from visibilities-squared, and baseline phases derived from closure phases. Although this may work well for bright sources, the assumptions are problematic when dealing with faint sources at low signal-to-noise level. For example, the errors expected from visibility-squared measurements cannot be easily converted to visibility errors. Moreover, optical closure-phase measurements typically have errors of several degrees, whereas radio closure-phase measurements are assumed to have no errors! It follows that images derived from optical data, processed through radio interferometry software, may have artifacts and statistics that would not otherwise be there.

Recognizing the above problems, it has been evident for many years that new software is needed that is speci cally taylored to optical data. In June 2000, the National Science Foundation hosted a meeting in Socorro, New Mexico, to address issues speci c to imaging in optical inteferometry. A rst modest step forward, suggested at the meeting, was to establish a common data format for calibrated optical/infrared interferometry data. This exchange format was released in 2003, and is described by Tom Pauls, elsewhere in these proceedings. At the 2001 meeting of the IAU Working Group on Optical/IR Interferometry, David Buscher suggested that the existing software suites should be compared with controlled data sets, and so the subject of an imaging beauty contest was born.

2. MOTIVATION AND FRAMEWORK OF A BEAUTY CONTEST

There are several motivations for the imaging beauty contest: 1) Encourage the use of the Exchange Format, identify problems in its de nition, and revise it as necessary; 2) Engage the interferometry community in a formal assessment of existing software; 3) Encourage the development of new software taylored to the needs of optical interferometry.

2.1. Choice of contest data

The data sets for the contest should be relevant to concerns that are speci c to optical/infrared long-baseline interferometry, and ideally each set of contest data should test something very speci c. The data sets should faithfully represent data from a plausible long-baseline stellar interferometer. The following characteristics were considered:

The contest data should have about N(N-1)/2 u-v points per hour of observing and fewer bispectrum points. This would be consistent with array of 3 or 4 apertures, recon gured one or more times.

The observables will be power spectra and bispectra, which is to say visibility-squared and closure quantities.

The test data should represent a source with a complicated symmetry so that measurements of closure phases are essential for image reconstruction. Parametric imaging (modelling) should not recover all of the source structure in the abscence of a priori knowledge. Such an example might be, one or more compact sources imbedded in an extended asymmetric shell.

The data might have some, perhaps all, samples in the low signal-to-noise regime.

The data might include incomplete or sporadic measurements of closure phases and visibilites, due to telescopes that are sometimes present and other times absent in the data.

The relationship between u-v coverage and bispectrum should not be as straightfordard as in the radio regime. VLBI algorithms/software should not be not well suited to reduce the optical long-baseline data used in the contest. This might arise if visibilities were missing at times when closure quantities are measured, or visa versa.

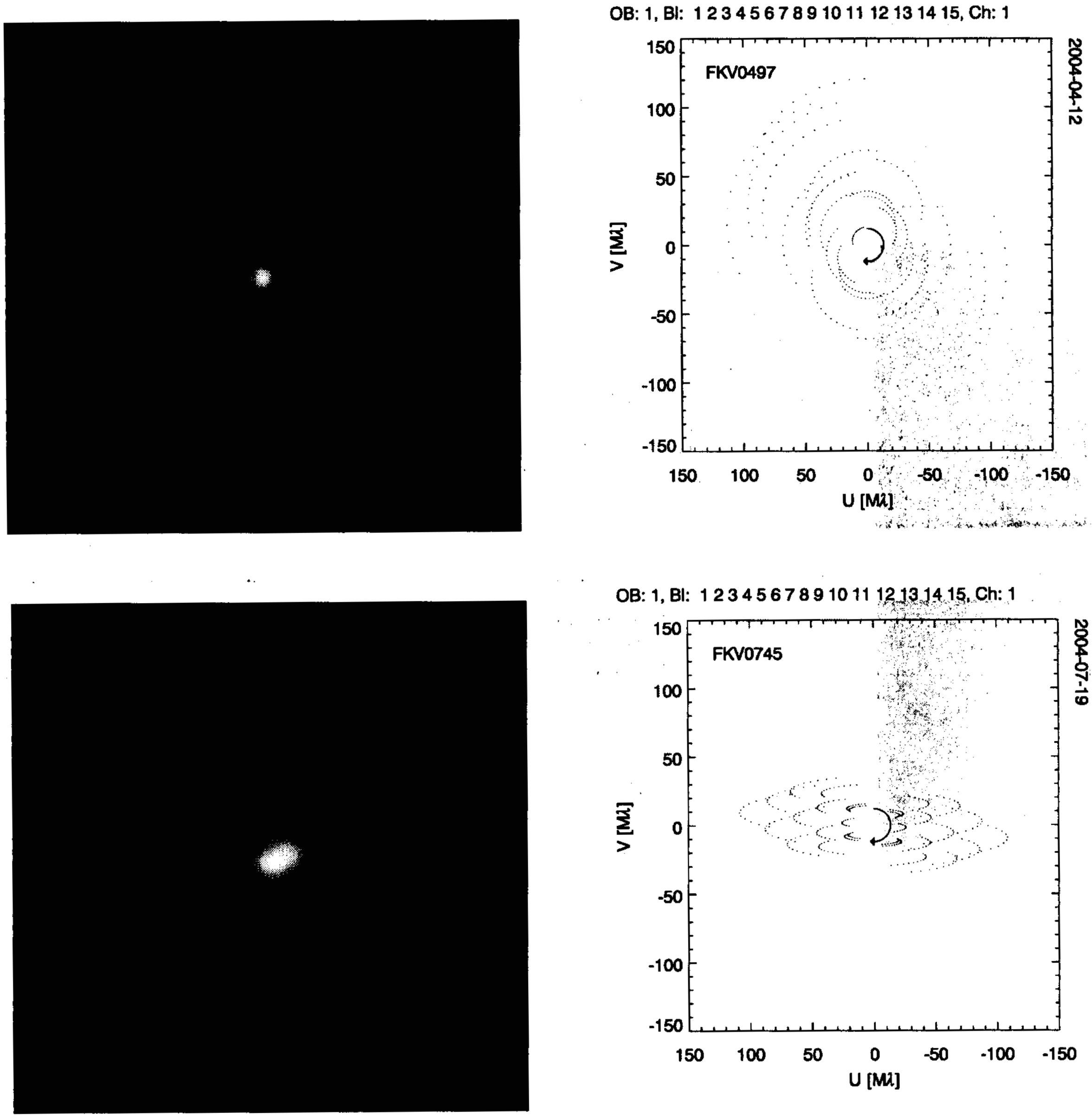

Figure 1. The sources les for the two contest images and their respective u-v plane coverage.

The above concerns are noted for future contests, because this complicated and challenging task was rendered straightforward by necessity. There was no obvious agreement between participants as to what should be tested, and only one of the organizers, Christian Hummel, volunteered to create the data. Christian produced sets of data by his own choosing, using his data reduction suite OYSTER, simulating a 6-station Navy Prototype Optical Interferometer.

2.2. Contest Rules and Guidelines

It was agreed amongst the organizers that the contest data sets would only be provided in the OI-DATA format. This would oblige contestants to work with the data format before using the data in their programs. Test data were provided as a preliminary to the contest itself. This would allow contestants to see if their software could reproduce a simple image, in this case a binary star with a given separation, magnitude di erence, and orientation.

The contest data was then presented without any information as to what it represented. This would provide a blind test. As part of the contest the participants were asked not only to produce images, but to interprete in the images what they believed to be true features and what they believed were artifacts of the imaging process.

Deadlines were imposed to provide a consistent schedule compatible with the timetable of the conference.

3. EXISTING SOFTWARE SUITES

It is useful prior to presenting the results to review the major software suites.

3.1. VLBMEM

VLBMEM has an interesting pedigree. It was developed speci cally for the rst optical aperture synthesis observations in 1987. It it a self-contained Fortran implementation of self-calibration which uses MEM for the deconvolution step. It was written by D.S. Sivia at Cambridge University, as part of his Ph.D. thesis under the supervision of S.F. Gull. It makes use of MEMSYS, a proprietary software package sold by Maximum Entropy Associates. Data is read into VLBMEM in MERGE format. The program was used for many of the publications by the Cambridge group,[1–6] and continues to be used by Cambridge alumnus P.G. Tuthill and collegues for aperture masking work with the Keck-I telescope.

The nomenclature is confusing, because the CITVLB suite (described next) also contains a program called VLBMEM, which was written by S.F. Gull in 1989. This VLBMEM is a stand-alone program that performs only the MEM deconvolution, and requires other CITVLB programs to complete a self-calibration loop.

3.2. Caltech VLBI Package

The Caltech VLBI Analysis Programs, CITVLB, were written for radio very long baseline interferometry. The package contains a large number of separate Fortran programs that are used sequentially for data display, calibration and editing, model- tting, and imaging. Self-calibration is possible using either CLEAN or MEM for the deconvolution. Data is read into the programs in MERGE format, and the suite of software includes programs to translate data into MERGE format from other formats, noteably UVFITS — the standard data format for radio interferometry.

CITVLB was supported by Tim Pearson at Caltech, until the software was superceded by DIFMAP around 1995. The programs assumed that a small number of telescopes were used in the array, and the data was limited to single-frequency and single-polarization data. These limitations, which ultimately halted the development of CITVLB, made the programs particularly well suited to optical interferometry, where small single-frequency data sets are typical. It broke the data processing into simple steps, allowing easy inspection of the data at each step, and providing greater quality control. CITVLB was used by the group at the Cavendish Laboratory in aperture masking experiments,[7] and in long-baseline measurements with the COAST interferometer.[8,9]

Hani 1992 used this (MEM and CLEAN) for observations of Mira.

3.3. DIFMAP

DIFMAP was initially a wrapper for all the steps in CITVLB and has evolved since then. This is an integrated di erence mapping environment in which almost all of the functionality of the Caltech VLBI package incorporated within a single program. It is written in ANSI C, and runs on Sun, IBM, and HP workstations and possibly other UNIX workstations with X-window graphics.

Table 1. Software Packages for Synthesis Imaging by Self-Calibration

Facility Acronym	Author	Deconvolution Algorithm(s)	File Format	Comment	Website (http://)
VLBMEM	D.S. Sivia (Oxford Univ.)	MEM	MERGE	Requires MEMSYS4	Maintained by P.G. Tuthill
CITVLB	T.J. Pearson (Caltech)	CLEAN, VLBMEM	MERGE	Unsupported since 1995	http://www.astro.caltech.edu/ tjp/citvlb/
DIFMAP	M.C. Shepard (Caltech)	CLEAN	UVFITS	Ver. 2.4d (7 Jan 2004)	ftp://ftp.astro.caltech.edu/pub/difmap/
OYSTER	C.A. Hummel (ESO)	CLEAN	UVFITS	Ver. 5.28 (20 Feb 2004)	http://www.sc.eso.org/ chummel/oyster/oyster.html
AIPS	NRAO AIPS Group	CLEAN & MEM	UVFITS	Ver. 31DEC04	http://www.aoc.nrao.edu/aips/
AIPS++	NRAO AIPS++ Group	CLEAN & MEM	Meas. Set	Ver. 1.9	http://aips2.nrao.edu/docs/aips++.html

3.4. OYSTER

The name OYSTER was derived from OISDR (Optical Interferometer Script Data Reduction). OYSTER was created when three collections of scripts written rst in PV-WAVE Command Language and then also in the Interactive Data Language (IDL is a trademark of Research Systems Inc.) were merged into one to provide a comprehensive data analysis package for the Navy Prototype Optical Interferometer (NPOI).

OYSTER uses the di erence mapping algorithm, also implemented in DIFMAP and originally invented at Jodrell Bank (UK). This algorithm assembles a model (i.e. image) and a self-calibrated set of phases in increments, each one preceded by run CLEAN just for a few iterations on the residual map of the previous cycle. This allows the user to inspect the residual map for areas of unCLEANED ux, and possible sidelobe structure resulting from calibration errors.

3.5. Astronomical Image Processing System (AIPS)

AIPS is the most widely used imaging processing software for radio astronomy data. Written mostly in Fortran by groups at the National Radio Astronomy Observatory (NRAO), development began in 1978 and is still ongoing. Since 1981 AIPS has been the principal software suite for reducing data from the Very Large Array. It has since grown to support both the Very Long Baseline Array (VLBA) project as well as space-based VLBI missions. AIPS includes routines to calibrate raw radio data as well as performing data reduction and other tasks too numerous to mention. Interested readers are referred to the AIPS Cookbook for details.

Calibrated data can be imported into AIPS in UVFITS format. Self-calibration can be run using CLEAN for the deconvolution.

3.6. AIPS++

In 1992 the AIPS++ project began e orts at NRAO to reprogram the functionality of AIPS and extend it to support observing modes of the upcoming millimeter array, ALMA. The AIPS++ consortium, involving contributions from several countries, was o cially disolved in April 2003, although development of AIPS++ remains ongoing within NRAO.

4. BSMEM: J.S. YOUNG AND H. THORSTEINSSON

BSMEM is a model-independent approach to imaging using principles of Baysian data analysis and non-linear image reconstruction. This software suite was developed especially for optical interferometry. Baye's theorem tells us quantitatively the best thing to do with uncertain information. In particular it allows us to predict the probability of a particular model representing a given data set, this being proportional to the prior probability of the model and the probability of such a data set given that model. The general recipe is as follows:

Generate all possible models (tedious but possible)

Find the likelihood that each model would have generated the data (easy).

Select the model that best predicted the data (modulo the prior information).

The closure phases are used as constraints on the set of all possible images, and there is no need to convert closure phases to phases — as is the case with standard self-calibration packages. The other constraints include amplitude information, source positivity, and a finite source extent. A gradient-descent method is used to efficiently find the best-fit image. Maximum entropy is used to enforce positivity. All constraints are applied simultaneously (deconvolution and phase retrieval in one step). An early version of BSMEM was used to produce an aperture masking image of the surface of Betelgeuse.[2]

5. WISARD: S.C. MEIMON *ET AL.*

WISARD was written to support aperture synthesis imaging with the VLTI instrument AMBER. Instead of considering the closure phases as the only phase data, the unknown atmospheric phases are also treated as variables to be solved for in inverse problem. The object is reconstructed by minimizing a particular metric describing the object and then similarly treating the atmospheric phases. This metric is minimized alternatively with the object and atmospheric phases. Several suck calibration cycles are done, each including a step for the object with a known set of phases and a step for the phases with a known object. The metric is designed such that the minimization problem is convex for given atmospheric phases while accurately modelling the noise statistics. A global minimum of the data likelihood criterion is computed for the phase step, in spite of the fact that the latter is very non-unimodal. This is achieved by exploiting the separable structure of the phase metric.

6. DIFMAP AND VLBMEM: J.D. MONNIER AND M. ZHAO (UNIVERSITY OF MICHIGAN)

DIFMAP (reference) and VLBMEM (Sivia, reference) were used to produce images. DIFMAP uses a CLEAN-based method (reference) and the VLBMEM uses a Maximum Entropy Method (MEM; Gull & Skilling, reference); both algorithms incorporated closure phases in a self-calibration loop (Cornwell/Pearson, reference).

6.1. Creation of MERGE and UVFITS data files

The data sets were supplied in the OI-DATA format, and needed to be converted into formats compatible with VLBMEM and DIFMAP, which use only complex visibility information, not closure phases, V^2, or triple amplitudes. This conversion was the most difficult and unpleasant part of the work. Unpleasant because it involves a retrograde step, degrading the quality of the data. The data formats required were 1) MERGE format for VLBMEM, and 2) UVFITS format for DIFMAP. The data conversion pipeline described below is based on the well-worn track from early aperture masking work by the Cambridge group (Baldwin, Haniff, Buscher, et al) and later by the Berkeley group (Tuthill, Monnier, Danchi). The difficulty lay only in the creation of one of the two formats, because conversion from MERGE to UVFITS format is then automatic using the program MERGEFITS from the Caltech VLBI suite. Fortunately, the MERGE data format is well documented in the Caltech VLBI Programmer's Manual, whereas UVFITS is very poorly documented.

VLBMEM is used routinely to process data from Keck aperture masking experiments, and IDL software already existed to create MERGE files for that task. However, significant enhancements to existing IDL software were required for this project. This included new support for telescope positions, coordinate conversion, array geometry, sidereal motion, Earth-rotation synthesis, and multiple time-stamps.

After reading in the OI-FITS data using a library of IDL routines (reference, monnier website), an IDL script was created to create a set of complex visibility data consistent with the OI-FITS data products. For each time stamp, a set of phases were generated that were most consistent with the closure phases, using the "fix cp" algorithm described by Monnier (1999, thesis). This phase information, along with the visibilities and array information were then written into a MERGE file.

A UVFITS file was then created from the MERGE file using the Caltech VLBI program MERGEFITS.

6.2. DIFMAP

The UVFITS format data are processed with the Caltech DIFMAP package. The data are uniformly weighted and the images have 1024 pixels with cellsize of 0.2 milli-arcseconds. The images are processed following standard CLEAN/self-calibration procedures, suppressing amplitude calibration since closure amplitudes are not good observables for the OI-DATA test files.

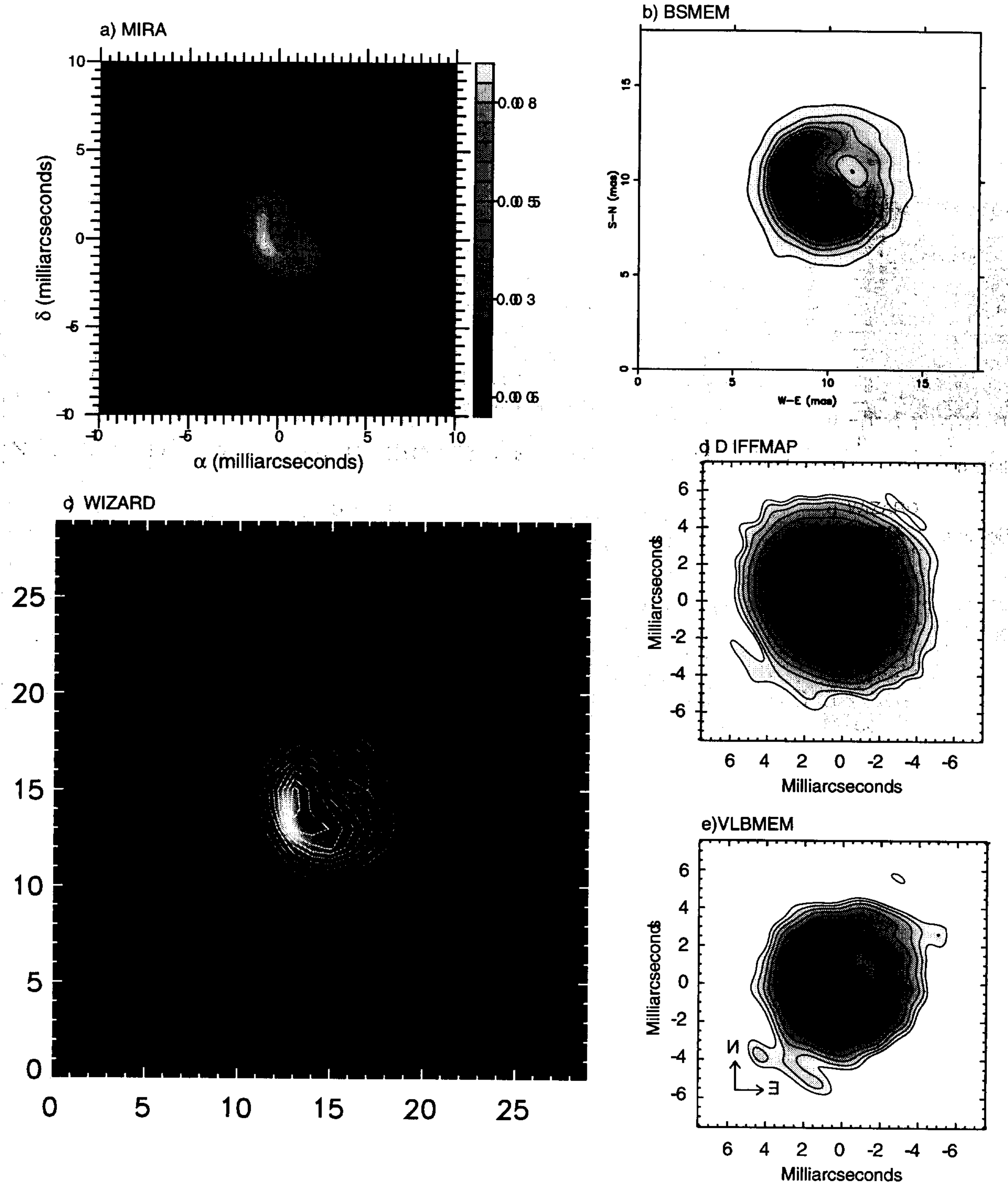

Figure 2. Contest entries for data reduction from the rst set of data. The scale of the images has been adjusted in each case so that vertical and horizontal scales are identical.

6.3. VLBMEM

The VLBMEM package was used to create images as well. For data1, a 128x128 pixel map with 0.1 mas pixels was used, employing a 0.4 mas correlation length. There were problems converging for this dataset when using a uniform prior. Good image reconstructions were possible by using Gaussian and Uniform Disk priors which were t to the raw visibility data; we present only results for Gaussian prior here, but all major image features were present in both. For dataset2, a 256x256 pixel map with 0.25 mas pixels and 0.4 mas correlation length was used. Uniform prior was used and convergence was not problematic.

6.4. Analysis and Comparison of Results

In Figs. 2d, 2e, 3d, and 3e we present our results. We have chosen contour levels such that the lowest-level reveals background artifacts in the maps. Critical image features above the lowest-level contours are present in both methods. The VLBMEM package creates images with higher angular resolution than CLEAN, but with a higher level of background artifacts. These artifacts are typically easy to identify but do pose an obstacle for straight-forward astrophysical interpretation.

A few features are worth brief mention. The bright spot in the middle of Figure 1 is easily seen in the VLBMEM image (right) but hardly visible in CLEAN (left) – this feature is at the edge of believability and may represent noise. Note the low-level ring of emission for the VLBMEM image of dataset2 – this is most likely an artifact of the limited Fourier coverage of the observations.

In conclusion, there is good agreement between the two image reconstruction methods. Furthermore, the images show details which appear robust based on their presence in both CLEAN and MEM maps, an impressive result given the limited uv-coverage for the simulated data. Indeed, this is quite remarkable given the data represents merely one night of observing with a realistic 6-element interferometer (albeit the data had quite high signal-to-noise ratio). We look forward to imaging real objects in the near future with long-baseline optical interferometry!

Image reconstruction algorithms that employ directly the OI-FITS data are under development, and were not ready in time for inclusion in this study.

7. MIRA: ERIC THIEBAUT

MIRA (Multi-aperture Image Reconstruction Algorithm) is one of the image reconstruction algorithms being developed at the Jean-Marie Mariotti Center (JMMC). MIRA is designed to deal with optical interferometry data (sparse u-v coverage and weak Fourier phase information provided by phase closure).

7.1. Data Reduction

The principle the MIRA algorithm is to perform image reconstruction by minimization of a penalty criterion under positivity constraints. The penalty reads:

$$f(\mathbf{x}) = {}^{2}_{\mathrm{vis2}}(\mathbf{x}) + {}^{2}_{\mathrm{cl}}(\mathbf{x}) + \mathcal{R}(\mathbf{x}) \qquad (1)$$

where

- $\mathbf{x}$ are the parameters (intensity of the image pixels);
- is the likelihood term with respect to the squared visibility data;
- is the likelihood term with respect to the phase closures (de ned so as to be insensitive to the modulo 2 in phase di erences);
- $\mathcal{R}(\mathbf{x})$ is the regularization;
- is a Lagrange multiplier tuned so that, at the solution, the likelihood terms are equal to their expected values.

The constrained minimization is done by VMLM-B (Thiebaut, 2002). At this time, MIRA is written in C and in Yorick (`ftp://ftp-icf.llnl.gov/pub/Yorick/`).

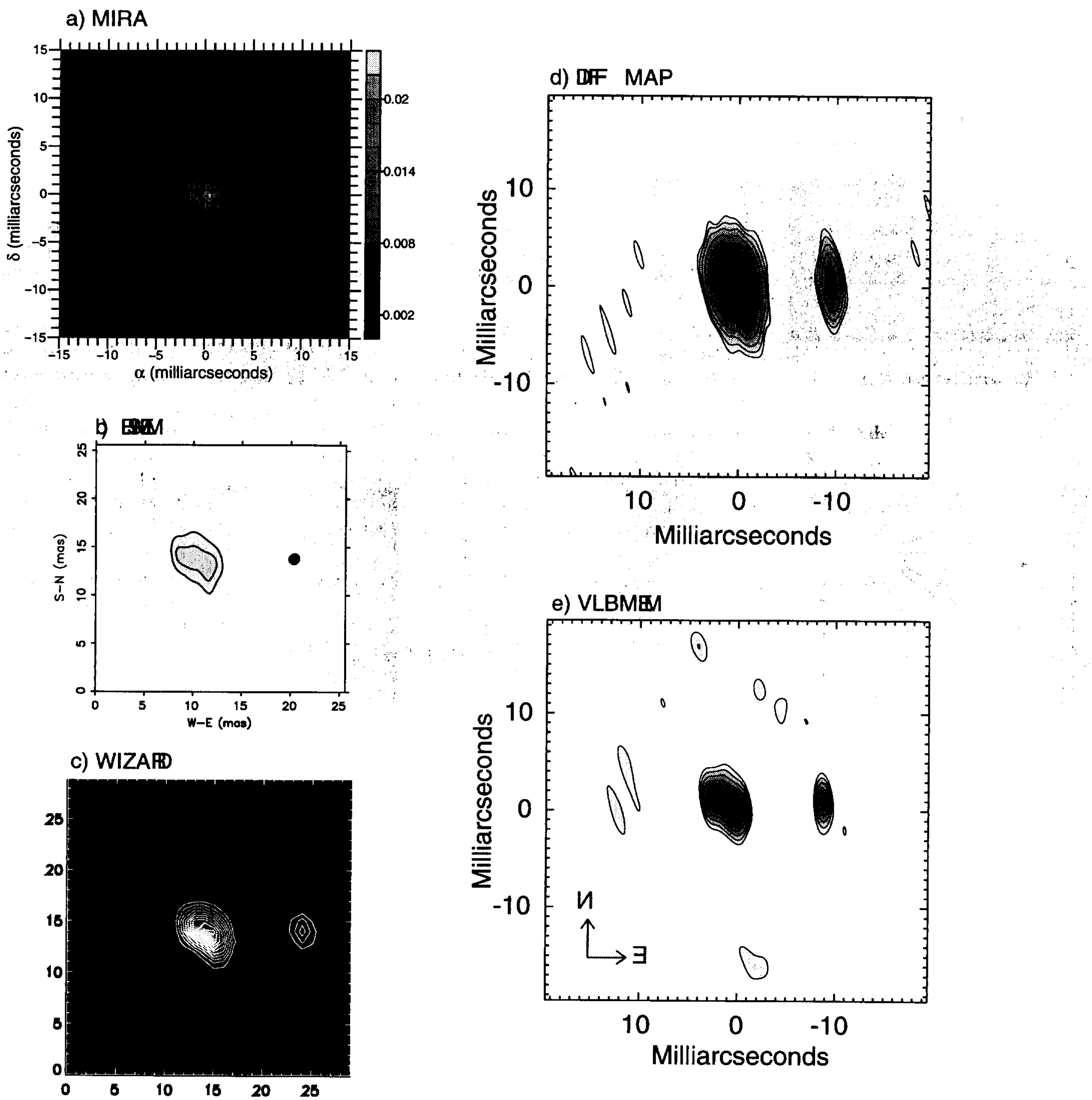

Figure 3. Contest entries for data reduction from the second set of data. The scale of the images has been adjusted in each case so that vertical and horizontal scales are the same.

7.2. Results

For the Imaging Beauty Contest data, the starting solution of the algorithm was an isotropic Gaussian tted o teh squared visibility data. This starting solution is also used as the prior for the maximum entropy restorations with a xed prior). Several di erent regularizations were condired:

1. Quadratic isotropic smoothness;
2. Maximum entropy with a xed prior equal to the starting solution (an isotropic two-dimensional Guassian);
3. Maximum entropy with a oating prior equal to the current solution smoothed to a lower resolution.

The use of di erent types of regularization is essential to assert the consistence of restored features — being aware of the bias induced by the particular choice of regularization. However, for the two data sets, maximum entropy with a xed prior is the method which seems to give the best results.

The resolution of the restored images was chosen to oversample the data by a factor of roughly two: 0.4 10^{3} and 0.5 10^{3} arcseconds per pixel for data sets 1 and 2 respectively. The regularization levels were tuned (by hand, although plans are underway to automate this process) so that at the solution, the likelihood terms are equal to their expected values. The widths of the synthesized elds of view were chosen to avoid aliasing (because of the space of the sampled frequencies in the u-v plane): 20 and 30 milliarcseconds for data set 1 and 2, respectively.

The vertical elongation of the secondary component in the image reconstructed from data set 2 is certainly due to the reduced cuto frequency in that direction (see u-v coverage).

8. COMPARISON OF RESULTS

It became evident when the contest entries were received by the organizers that most images were closely identical, reproducing recognizable details of the original source images. However, it was also obvious that the DIFMAP results of Fig. 2d and Fig. 3d lacked the high-resolution detail contained in the other entries. DIFMAP was the only software suite to use CLEAN for the deconvolution, all other software packages having used maximum entropy. Noticeably absent in Fig. 2d is any trace of the central bright core. Similarly the shape of the primary star in Fig. 3d is likewise poorly reproduced in comparison with the other entries. However, it is much more di cult to judge the winner without a more formal comparison.

Numerical were necessary to evaluate the winner. The tests calculated the total ux in the images and the rms deviation from the source images. Based on these test, the scores for the entries were found to be 1) BSMEM 2) VLBMEM 3) MIRA 4) WISARD and 5) DIFMAP.

9. CONCLUSION

The organizers of the contest are pleased to announce BSMEM as the winner of the 2004 Interferometry Imaging Beauty Contest. The winning team, John Young and Hrobjartur Thorsteinsson, were presented with a certi cate of their achievement on 25 June 2004 in front of the audience at the SPIE conference on *New Frontiers in Stellar Interferometry* in Glasgow, Scotland.

APPENDIX A. SELF-CALIBRATION AND OPTICAL LONG-BASELINE INTERFEROMETRY

Self-calibration is an iterative approach to imaging used in radio interferometry to solve for random phase and amplitude errors that occur at each telescope in the array.

At radio wavelengths the major source of phase error is due to gain uctuations (amplitude and phase) in the radio receivers. At optical wavelengths the principal source of phase error is due to uctuations in the index of refraction of the atmosphere above each telescope. The radio antenna gain errors and light arrival-time uctuations are analogous, and self-calibration can be applied to both radio and optical data.

Why is it termed self-calibration? A model of the source — an image derived at each step in the iteration — is used to re-calculate (calibrate) the amplitude and phase errors of each antenna. With each iteration, a new model of the source is derived along with new gain errors for each antenna/telescope. The process is repeated until there is evidence of convergence or some gure of merit has been met.

Phase up your data: attribute phases to each baseline that are consistent with the measured closure phases. Initially it doesn't really matter how its done, although a global minimization might be an appropriate approach.

1. *Make a image by inverting the data.* This is a straightforward and almost trivial step, which will produce a horrible image full of artifacts. The interferometer measures the Fourier transform of the source, but typically there are only a small number of samples at irregular intervals in the Fourier plane. So the image thus derived is full of artifacts of the poor sampling — high sidelobes and grating lobes seen around the brighter structures. This map is almost useless.

2. *Deconvolve the image.* This step is non-trivial and gives rise to much heated debate. There be dragons here. The aim at this stage is to remove all of the artifacts due to sampling and reconstruct an image consistent with the original data and with a an appropriate spatial resolution. Because there were such huge gaps in the sampling, this involves lling in data in the u-v plane where no data was ever sampled. Standard approaches to this inverse problem include using the CLEAN or MEM algorithms, or any of the numerous variations of these routines. Take your pick, then create a corrected image.

3. *Apply constraints.* A trivial but necessary step. This is a further re nement to make the deconvolved image consistent with real images. Typically, this involves setting any negative parts of the image to zero and truncating the eld of view. This is now your new model of the source.

4. *Estimate new baseline phases:* Attribute phases to each baseline that are consistent with the measured closure phases and the new model you obtained with the previous step. This is the self-calibration part: sample the Fourier components of your new model at baselines corresponding to your original data and compare them with the observed data to re-estimate the phase errors at each telescope. The new baseline phases can then be found.

5. Return to step 1.

APPENDIX B. DOUBLE-STAR DATA SIMULATION

```
; Global parameters:
starid          ='FKV0745'
wavelengths     =[0.650]
rv              =0.0
;
; Star parameters (for each star):
name(0)         ='A'
mode(0)         =3      ; limb-darkened
diameter(0)     =5.5
ratio(0)        =0.7
pa(0)           =120.0
teff(0)         =7000
logg(0)         =4.0
spot(*,0)       =[1.5,2.5,150,1.0]       ; Teff multiplier, offset, pa, size [mas]
;
name(1)         ='B'
mode(1)         =1
diameter(1)     =0.5
teff(1)         =25000
logg(1)         =5
```

```
magnitudes(*,1) =[0.0]
;
; Binary parameters (for each binary):
component(0)    ='A-B'
method(0)       =2
rho(0)          =10.0; [MAS]
theta(0)        =90.0
```

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