The 2012 Interferometric Imaging Beauty Contest

Fabien Baron, William D. Cotton, Peter R. Lawson, Steve T. Ridgway, Alicia Aarnio, John D. Monnier, Karl-Heinz Hofmann, Dieter Schertl, Gerd Weigelt, Éric Thiébaut, Férréol Soulez, David Mary, Florentin Millour, Martin Vannier, John Young, Nicholas M. Elias II, Henrique R. Schmitt, Sridharan Rengaswamy

Univ. of Michigan, 941 Dennison Building, 500 Church Street, Ann Arbor, MI 48109, USA; National Radio Astronomy Obs., 520 Edgemont Road, Charlottesville, VA 22903, USA; Jet Propulsion Lab., California Institute of Technology, Pasadena, CA 91109, USA; National Optical Astronomy Observatory, Tucson, AZ 85726-6732, USA; Max-Planck Institute for Radio Astronomy, 69 Auf dem Hügel, Bonn, Germany; CRAL, Observatoire de Lyon, 9 av. Charles Andre, F-69561 Saint Genis Laval Cedex, France; Laboratoire Lagrange, Univ. de Nice, CNRS, Observatoire de la Côte d’Azur, Nice, France; University of Cambridge, JJ Thompson Avenue, Cambridge, CB3 0HE UK; National Radio Astronomy Obs., Array Operation Center, Socorro, NM 87801-0387, USA; European Southern Obs. Casilla 19001, Santiago 19, Chile.

ABSTRACT

We present the results of the fifth Interferometric Imaging Beauty Contest. The contest consists in blind imaging of test data sets derived from model sources and distributed in the OIFITS format. Two scenarios of imaging with CHARA/MIRC-6T were offered for reconstruction: imaging a T Tauri disc and imaging a spotted red supergiant. There were eight different teams competing this time: Monnier with the software package MACIM; Hofmann, Schertl and Weigelt with IRS; Thiébaut and Soulez with MiRA; Young with BSMEM; Mary and Vannier with MIROIRS; Millour and Vannier with independent BSMEM and MiRA entries; Rengaswamy with an original method; and Elias with the radio-astronomy package CASA. The contest model images, the data delivered to the contestants and the rules are described as well as the results of the image reconstruction obtained by each method. These results are discussed as well as the strengths and limitations of each algorithm.

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

1. INTRODUCTION

The IAU Interferometry Beauty Contest is a competition aimed at encouraging the development of new algorithms in the field of interferometric imaging, by showcasing the current performance of image reconstruction packages. The contest is being conducted by the Working Group on Image Reconstruction of IAU Commission 54.

The principle of the contest is the following. One or several science cases are first selected by the organizers, then realistic models of the science targets are used to generate synthetic images. These “truth” images are then turned into data sets, by simulating the acquisition of interferometric observables by a typical interferometer. Finally, the contestants attempt to reconstruct images from the data sets without knowledge of the original truth images beyond the nature of the target. The reconstruction closest to the truth image is then declared the winner.

The previous contests took place in 2004, 2006, 2008 and 2010, thus the 2012 Interferometry Beauty Contest described here is the fifth contest. The contest results were announced on July 5th during the 2012 SPIE Astronomical Telescopes and Instrumentation conference in Amsterdam.
2. CONTEST MODEL, DATA AND GUIDELINES

2.1 Original model images

In this 2012 edition of the Interferometry Beauty Contest, the focus was to assess the potential of current reconstruction packages on very resolved objects, under realistic observing scenarios. The organizers identified two science cases for which the reconstruction performance is deemed critical for interpretation: imaging Young Stellar Objects and imaging spotted stars. Consequently two models were generated for the Contest. A T Tauri “star + disc” system that was nicknamed Alp Fak, and a red supergiant with bright spots named Bet Fak.

The Alp Fak image was modeled by Alicia Aarnio at the University of Michigan, using the TORUS\(^5\) 3D radiative transfer code written by Tim Harries at the University of Exeter. The parameters for the T Tauri simulation were loosely based on that of v1295 Aql. The scaling of the image was set to be slightly larger than the extent of the disc. The outer radius of the disc was about 200 AU, with the inner radius at 40 AU. The central star, of radius \(3R\odot\), was offset by about 1.3 AU in the \((X,Y)\) coordinates of the image, but left in the midplane of the disk \((Z = 0)\). The mass accretion rate was chosen low, as was the magnetospheric temperature, so that their effects on the image are negligible. The resulting image was then rotated by 63.5\(^\circ\) to obtain the final truth image shown on Figure 1 (left). Our main expectations from reconstructions of this object were: the detection of the central source, a correct global orientation of the target, as well as smooth flux and sharp transitions at the right locations.

The Bet Fak image is (to our knowledge) the first image in the Beauty Contest that was partially derived from real data. This original data came from 2011 observations of the Red Supergiant AZ Cyg, that presents clear asymmetric features that may be spots or convection cells. Several images were reconstructed from the original data, using complex combinations of regularizers (total variation, \(\ell_1\ell_2\) regularization and limb-darkened disk prior of 3.9 mas), and keeping the reduced \(\chi^2\) below 1.0. A particularly “good-looking” image was picked amongst this one to be the truth image of Bet Fak, shown on Figure 1 (right). Our main expectations from reconstructions of this object were: a smooth circumference without artefacts (knowing that contestants would most likely use priors), and approximate locations for the bright spots/convection cells.
2.2 Data set generation: \((u,v)\) coverage and signal-to-noise

Both data sets were simulated as if they were acquired by the MIRC-6T\(^6\) instrument (see Che et al., 2012 in these proceedings), installed on the CHARA Array\(^7\) atop Mt. Wilson, CA, USA. The H-band low spectral resolution mode of MIRC-6T was chosen for the simulations. In this mode the star light is spectrally dispersed onto eight spectral channels. Because very few software packages are able to handle multi-spectral reconstructions, we chose not introduce any spectral dependency in the data. For a similar reason, no temporal dependencies were assumed in the data beyond aperture-synthesis due to Earth’s rotation.

The \((u,v)\) coverage of the contest data is presented on Figure 2. With MIRC-6T, the instantaneous “snapshot” Fourier coverage provided is 15 baselines – i.e. 30 \((u,v)\) points – as well as 10 closure phases. For Alp Fak, the complete \((u,v)\) coverage was chosen to correspond to 5 hours of observation, with snapshots acquired every 15 minutes. For Bet Fak, the \((u,v)\) coverage was directly copied from the original AZ Cyg data. Compared to the previous Contest in 2010 that assumed the use of 10 VLTI stations, the \((u,v)\) coverage is much sparser. In particular, there is hole at low frequencies due to the absence of CHARA baselines below 30 m. On the other hand, the use of six CHARA stations simultaneously (instead of e.g. only three with VLTI/AMBER) allows to recover twice the amount of phase information.

Once the Fourier sampling determined, the complex visibilities were computed via Discrete Fourier Transform from the model images. The contest data consisted of the conventional interferometric observables, i.e. power spectra (squared visibilities) and bispectra (triple amplitudes + closure phases). These were computed directly from complex visibilities, and modified using realistic noises. For Alp Fak our current best empiric noise model for MIRC-6T was applied: typically a few percent errors on power spectra, 1° to 5° on closure phases for short baselines, and 10 to 80° on longer ones. For Bet Fak the signal-to-noise was directly copied from the original AZ Cyg data, thus reflecting the actual MIRC-6T noise. As shown on Figure 2, visibility amplitude values are very low for both objects. In the case of Alp Fak, out of 1320 power spectra, only 162 are greater than 0.01.

The noisy data were then packaged into OIFITS\(^8\) data files, and these were validated with the JMMC online validation tool (http://www.jmmc.fr/oival).

Note that in addition to Alp Fak and Bet Fak, synthetic data of a binary star with very high signal-to-noise and excellent \((u,v)\) coverage was provided. This data was solely meant for contestants to to check whether their software were able to reconstruct a simple model, and to help them determine the orientation of their reconstructions with respect to the default contest convention (North up, East left). The binary separation was 4.0 mas, with a principal axis of 40° East of North (from the bright star to the faint one) and a flux ratio of 5.0. The uniform disk sizes were 1.0 mas for the primary and 0.75 mas for the secondary.

Note that all these data sets (Alp Fak, Bet Fak, and the test binary) are available on the Interferometry Beauty Contest website\(^*\).

2.3 Contest guidelines

In the past Beauty Contests, the contestants were free to choose the field of view and pixel scale of their submissions. While this certainly made the contests more challenging (in 2010, this freedom allowed the organizers to “hide” a point source far from the main target), this also raised the concern that submissions had to be rescaled/convolved to the truth image pixellation. In particular any super-resolution achieved by the reconstruction algorithms was likely to be destroyed by such a procedure. Therefore, in this 2012 edition of the Beauty Contest, both pixel scale and image sizes were explicitly recommended. For both targets, the suggested pixel scale was 0.15 mas, with an advised field of view of 64 × 64 pixels.

3. CONTEST SUBMISSIONS

The 2012 Interferometric Imaging Beauty Contest enjoyed a record participation, with eight teams in competition (compared to 4-5 for its previous editions). In the following sections (3.1 to 3.8), the contestants present the procedure they used for reconstruction, as well as the features they believe to be real in their images. The reconstructions submitted by the contestants can be found on Figure 3 for Alp Fak and Figure 4 for Bet Fak.

\(^*\)http://olbin.jpl.nasa.gov/iau/2012/Contest12.html
Figure 2. Contest data characteristics for both targets Alp Fak and Bet Fak: \((u, v)\) coverage (top), visibility amplitudes as a function of spatial frequency (middle), and closure phases as a function of spatial frequency (bottom). Note: because most squared visibilities are below 0.01, visibility amplitudes are shown here instead.
When more than one entry per team was submitted for the same software, the best image was chosen for display. Also, for the first time since the creation of the Beauty Contest, one team (Millour & Vannier) submitted reconstructions with two packages they are not actually developing (BSMEM and MiRA). Thus their approach was that of non-expert but experienced users: it was particularly interesting in that it allows to assess the similarities (or lack thereof) between reconstructions arising from different user choices.

3.1 MiRA
by Thiébaut and Soulez (Observatoire de Lyon)

For both data sets Alpha Fak and Beta Fak, due to the lack of short baseline on CHARA, the \((u, v)\) coverage is quite weak for low spatial frequency. Consequently, the global shape of reconstructed objects is quite difficult
Figure 4. Co-aligned contest submissions for Bet Fak, using the same greyscale table as the truth image of Bet Fak presented on Figure 1.
to recover, and strongly depends on the regularization and on the starting solution (as the objective function is not convex due to the type of interferometric data: squared visibilities and phase closures).

The first data set is a T Tauri star. As the squared visibilities as a function of baseline doesn’t show lobes, we supposed that the star is not resolved by the interferometer. For that reason, we began the image restoration with a Dirac smoothed to the resolution of CHARA (approx. 0.5 mas = 3 pixels in the restored image). In accordance with Renard et al.\textsuperscript{9} (2011), we choose total variation for the regularization. To avoid getting stuck in local minima, we introduced some perturbations when the algorithm seemed to have converged: e.g. by soft thresholding or by doing several iterations using squared visibilities only, or squared visibilities and closures only. We consider some kind of global convergence achieved when the reduced $\chi^2$ is between 0.9 and 1.0 for the combination of square visibilities and closures, square visibilities and triple amplitudes, and square visibilities and bispectra. The reconstructed object presents a square background of $6 \times 6$ mas that seems to be the size of the simulation box. At the center of this square background there is the unresolved bright star. This star is surrounded by the half of an elliptic bright ring with a major axis of about 3 mas oriented at about PA = 65° (counted from North to East).

The second data set, Beta Fak, is a red supergiant. As (u,v) coverage is very sparse for low spatial frequencies, we estimated the global shape of the star using a linear limb darkening model. We fit the parameters of this model by minimizing the same data cost function as the one used by MiRA. These parameters (diameter = 4.0 mas, limb darkening parameter = 0.42) have been confirmed by LITPro.\textsuperscript{10} For the contest, we produced two images which have been obtained from the square visibilities and closure phases (we did not use triple amplitudes for this data set), starting with the limb darkening model and with total variation or quadratic regularization. This latter regularization is taken as the total quadratic difference between the image and the initial model. In spite of using different regularizations, the two images are very similar. This is a (weak, because the problem is non-convex) confirmation of the reality of the recovered structures at the stellar surface. The regularization weights have been tuned to have a final normalized $\chi^2$ of 0.93 per data sample.

3.2 CASA
by Elias (NRAO)

CASA\textsuperscript{11} is a radio interferometry package. It requires visibility amplitudes and baseline phases, not the squared visibilities and closure phases provided by the Beauty Contest organizers. CASA can operate directly upon uvfits or measurement set (MS) format files, not OIFITS format files. The MS is the native CASA file format.

Many radio interferometers employ “fillers” to convert their file formats to MSes. NME2 is in the process of creating an OIFITS to MS filler within CASA now, but it is not yet ready. For the beauty contest, the OIFITS format files were converted to uvfits by the OYSTER package\textsuperscript{12} and in turn the uvfits files were converted to MSes by CASA. OYSTER also estimated the baseline phases from closure phases before the file format conversion. For an array of six telescopes the number of closures phases is 1/3 less than the number of baseline phases, so the system of equations is degenerate. OYSTER determined the singular-value decomposition (SVD) of the design matrix and formed the “minimum-norm” pseudo-inverse (infinite inverted singular values are set to zero).

The minimum-norm pseudoinverse is among the simplest and works well for ensembles of a few point sources but not as well for extended emission. This technique will be available for the first version of the OIFITS to MS filler. Additional model constraint inputs will eventually become available. This task has the highest priority for the next Beauty Contest as well as other advanced imaging techniques such as full-Stokes optical interferometric polarimetry (OIP).

Once the Beauty Contest data were filled into CASA, they were imaged. The main imaging algorithm\textsuperscript{13} was an advanced version of CLEAN employing multispatial scale (MSS) and multifrequency synthesis (MFS). Standard CLEAN determines and removes source components in the image plane using a delta function, while MSS employs a configurable extended function. MFS inserts data from all frequencies into a single uv plane before imaging. The frequency dependence for each pixel can be selected. The Beauty Contest data had flat spectra, so only a constant was fitted.
Several rounds of iterative CLEANing were interleaved with self-calibration, where deviations between the model and observed visibilities are considered to be calibration errors. Many imaging trials were performed with different CLEANing depths. Each trial led to a different final image, which is symptomatic of ill-defined initial phases from the minimum-norm pseudo-inverse.

3.3 IRS
by Hofmann and Weigelt (Max Planck Institute für Radioastronomy)

The iterative Image ReconStruction algorithm (IRS) uses the measured bispectrum to reconstruct images. IRS uses the non-linear optimization algorithm ASA-CG detailed in Hager & Zhang\textsuperscript{14} (2005) and Hager & Zhang\textsuperscript{15} (2006). ASA-CG is a conjugate gradient based algorithm. The advantage of IRS is that it is much faster than the Building Block algorithm (Hofmann & Weigelt,\textsuperscript{16} 1993).

The reconstructions are images of $64 \times 64$ pixels with a pixel scale of 0.15 mas and not convolved with a PSF. For the red supergiant Bet Fak, we reconstructed a disc with bright and dark spots. The intensities outside the disk are probably artefacts. For the T Tauri disc Alp Fak, we see an inclined circumstellar disc with weak extensions above and below the inclined disc. The long disc axis is approximately (but not exactly) horizontal.

3.4 MIROIRS
by David Mary and Martin Vannier (University of Nice)

We present here our contribution to the Beauty Contest, using the prototype software MIROIRS (Methods for Image Reconstruction in Optical Interferometry with Regularizations based on Sparse priors), which is still in an early phase. Starting from scratch, our progresses so far have led to a preliminary version based on the following very simple principles. From an initial image (obtained using the LITpro model-fitting software), we produce a gradient map of a criterion including the target visibilities and phase closures. In this map, we consider a patch of pixels (of possibly varying size, say, 5 by 5 to 20 by 20 pixels) around the location of the strongest value of the gradient. This patch is used to define the location of the image pixels where the flux should be changed to decrease the criterion. The flux is changed by small increments which are proportional to the gradient value within the patch, only for gradient values above a predefined threshold. This gives the new image, from which the process is iterated, with possible adjustments of the parameters (size of patch, gradient threshold, increment) to ensure that the cost function is iteratively decreased.

Our motivation for participating in the Beauty Contest was originally to inject in the reconstruction algorithm models based on sparse representations. This is done here in a very crude but fast way. We do not impose any particular synthesis dictionary for the reconstruction. Instead, the synthesis "atoms" are formed by analyzing and thresholding the gradient of the cost function, and they come only as corrections to the initial image, in a greedy manner. Optimization-wise, the adopted descent method is very basic and largely empirical with respect to the tuning of the various parameters involved. The relevance of the reconstructed image at the end of the process also heavily depends on how close the initial image is to the ideal solution. The prototype method is currently written in Matlab language. It is not at all optimized and thus quite slow, but not prohibitively slow for the present data set and output format.

As for our analysis of the presented result for the Beta Fak reconstruction: we are confident that the circular structure is reconstructed with a fairly correct diameter. The few tests we could make starting from different initial images chosen as perturbed versions of a uniform disk indicate that the reconstruction surface brightness distribution is relatively stable under perturbations of the initial image. This suggests that the bright and dark spots that are visible on the surface may be real. We believe however that the faint structures around the disk are reconstruction artefacts.

Concerning Alpha Fak, we also believe that the general shape we obtained is not wrong (a large, elongated diffuse object oriented SW-NE), and we think that some internal structures might look what we reconstructed. But, here also, the $(u, v)$ coverage and the SNR at mid and high-frequencies does not allow us to be very much confident about it.
3.5 MACIM

by John Monnier (University of Michigan)

I used MACIM using a “uniform disk” regularizer, which is the $\ell_1$ norm of the spatial gradient of the image. Fabien Baron and I invented this metric in 2011 – it gives all uniform disks the same regularization if they contain the same flux, irrespective of diameter. Just as the total variation regularizer, this regularization prefers sharp boundaries, but is agnostic on the size of the spot or feature. As for total variation, it will prefer “round” spots compared to elliptical ones.

For the Alp Fak reconstruction. Based on inspection of the visibility curves and expectation of a central unresolved source, I introduced a uniform disk model containing 1.4% of the flux. MACIM included this model component in the imaging process, but the amount of flux in the point did not effect the regularization. This had the effect of creating a “hole” in the disk emission, likely coming from a dust-free inner region in the model.

I ran MACIM with a range of regularizer weights and for different amounts of time, creating 3 different possible images. I did not spend more than a few hours on this and chose the image that showed approximately mean zero residuals for the short baselines, which are easy to get wrong because there are relatively few short baselines (i.e., one can iterate too long and get a lower $\chi^2$ but the residuals show overfitting of long baselines and underfitting of short baselines). There are some intriguing asymmetric structures in the disk but do not expect much of it is real. More could be done to symmetrize the images but I thought it was better to just leave the MACIM result in a rather raw state. For a real dataset, I would assess the fidelity of features by using bootstrap methods or splitting up my data into independent chunks. Note that for my entry I just used a single pixel in the center to represent the central star contribution, which is not exactly that same model as MACIM used, but quite close.

For the Bet Fak reconstructions, I generate candidate limb-darkened disks (with power law based on Lacour et al. 2008, with coefficient 0.26) between 3.9 and 4.30 mas in diameter. I used these as weak priors in MACIM along with “uniform disc” regularizer. I got similar structures in all images, but found the best agreement with the expected limb-darkening profiles and with the short-baselines residual using the image reconstruction based on the 4.30 mas limb-darkening prior. I note that imaging spots of complex geometry is very difficult. I would not publish this without additional independent datasets. I also note that by increasing the regularizer strength I could smooth out most of these structures with only a minor effect on the global $\chi^2$, emphasizing the difficulty of this effort.

3.6 Original (unnamed) method

by Sridharan Rengaswamy (European Southern Observatory)

The method used for reconstruction is the following:

- The closure phases (CP) are solved for visibility phases $\phi$ using singular value decomposition (SVD) method. The phase solution is not unique. The uncertainty in the solution is also estimated.
- Complex visibilities are obtained as $\sqrt{V^2} \times \exp i\phi$ and weighted according to their signal-to-noise ratio.
- The Dirty-map is obtained as the direct Fourier transform of the 2-d visibility function. It is first multiplied by an apodization function in the image domain, Discrete Fourier transformed, multiplied by an apodization function that is equivalent to the transfer function of a telescope with diameter equal to the maximum baseline. The Dirty-beam is obtained in a similar manner, replacing the complex visibilities at the measured uv points are by unity.
- The Dirty-map is then deconvolved with the dirty beam, using the Maximum Entropy method (MEM). MEM iterations are stopped when the relative increase in entropy is less than 1% or when the entropy stats to decrease after reaching a maximum.
- Images were obtained in each spectral channel, as described in previous steps. The final images were registered by cross-correlating the images with the reference image (longest wavelength spectral channel image) and then added together to obtain the final image.
The submitted images followed the Contest recommendations in terms of size and pixellation. We found that only the morphology of the images (and not their photometry) seem to be reliable.

For Alp-Fak, the flux (sum of pixel intensities) increases with the spectral channel (higher flux at longest wavelength) alluding to the fact that the object has a disk. Only the central disk like structure (in log-scale) is reliable. The faint unresolved features in the lower half at about 5.9 and 8.7 mas from the center are unreliable. For Bet-Fak, the flux slowly increases but remains almost constant at longer wavelengths (spectral channels). A bright granule of size $4.95 \times 2.5$ mas is clearly visible. There is also another small granule on its left, separated by a dark lane. Other point like features in the images are not reliable.

3.7 BSMEM
by John Young (University of Cambridge)

The BSMEM (BiSpectrum Maximum Entropy Method) software was first written in 1992 to demonstrate image reconstruction from optical aperture synthesis data. It has been extensively enhanced and tested since then, although there have been no changes of late. The code used for this year’s contest entry is essentially identical to that employed for the 2010 contest. The algorithm applies a fully Bayesian approach to the inverse problem of finding the most probable image given the evidence, making use of the Maximum Entropy approach to maximize the posterior probability of an image. An important advantage of BSMEM is the automatic Bayesian estimation of the hyperparameter alpha that controls the weighting of the entropic prior relative to the likelihood. BSMEM can also perform a Bayesian estimation of missing triple amplitudes and their associated errors from the power spectrum data. BSMEM is available free-of-charge to the scientific community on submission of the academic license agreement at [http://www.mrao.cam.ac.uk/research/OAS/bsmem.html](http://www.mrao.cam.ac.uk/research/OAS/bsmem.html).

BSMEM uses a trust region method with non-linear conjugate gradient steps to minimize the sum of the log-likelihood ($\chi^2$) of the data given the image and a regularization term expressed as the Gull-Skilling entropy $\sum_k [I_k - M_k - I_k \log(I_k/M_k)]$. The model image $M_k$ is usually chosen to be a Gaussian, a uniform disk, or a delta-function centered in the field of view, which conveniently fixes the location of the reconstructed object (the bispectra and power spectra being invariant to translation). This type of starting model also acts as a support constraint by penalizing the presence of flux far from the center of the image.

The reconstruction of the T Tauri disk (Alp Fak) used a circular Gaussian default image (with FWHM found by fitting to the short-baseline squared visibility data). For the reconstruction of the supergiant star (Bet Fak) surface, I found it necessary to use additional prior information to constrain the radial distribution of flux. This was obtained by fitting a circular limb-darkened disk (Hestroffer model) to the squared visibility data (elliptical models did not fit significantly better). The image corresponding to the best-fit limb-darkened model was convolved with a 0.3 mas FWHM Gaussian blur, in order to avoid penalizing slight deviations of the disk edge from circular symmetry, before being used as the default image in BSMEM. Following the advice of the contest organizer, a pixel size of 0.15 mas was selected for both contest objects.

For the supergiant star (Bet Fak), I am confident the following features are real: the three brightest spots (S, W, and E) in the central region of the stellar surface; the protrusion at the NE edge of the star; the ”cut-out” at the W edge of the star. I am not convinced that the possible companion with position angle 100° E of N is real. Certainly all of the other features outside of the star are artefacts.

For the T Tauri object (Alp Fak), I am confident in the overall shape and orientation of the disk (quasi-rectangular outer contours and elliptical inner contours). At the centre of the image there are possibly two sections of a bright inner disk rim and a central star.

3.8 BSMEM and MiRA
by Florentin Millour and Martin Vannier (University of Nice)

We tried to place ourselves from a user point of view, i.e. we wished to use several (ideally most of) available image reconstruction software, and compare the obtained results. Therefore, our plans were initially to reconstruct images using image reconstruction software that are available: MiRA and BSMEM. We also tried to use the WISARD software, using complementary low-frequency data derived from model-fitting. However we
noticed some incoherency in the way WISARD reads this data. This probably stems both from some inconsistency in our home-made OIFITS file, and from a lack of robustness of the WISARD conversion routine from the OIFITS format. As this problem could not be tackled in time, we could only obtained flawed reconstructions from WISARD, which we chose not to show here.

The presented MiRA and BSMEM images have 64 pixels, and 0.15 mas per pixel, supposedly increasing with increasing alpha and delta. They are centered around the photocenter of the image. Our method consisted in the following:

- We first fitted the datasets in the first visibility lobe using the softwares fitOmatic (home-made) and LITpro (developed by JMMC).
- A synthetic OIFITS file containing squared visibilities (and closure phases) was generated out of this fit result, for each object, with uniformly and randomly spread baselines in this same first visibility lobe. This synthetic dataset was added to the original dataset. The idea here was to strongly limit the field of view of the image reconstruction to the effective size of the object.
- from this point on, different procedures were used depending on the image reconstruction software:
  - for MiRA, 300 images were generated with a random initial guess (either a uniformly random image, a random-width Gaussian, or a random-width uniform disk). These were sorted by increasing $\chi^2$, and any image with a $\chi^2$ larger than 2 times the minimum one was discarded. All other images were kept and averaged in the result image. This first image run was used as a prior for a second run of 300 generated images, the same way. The result was averaged and produced the presented result. We estimate that the centering process involved in the averaging decreases the effective resolution of the image to 0.45 mas. For more information on our procedure, see Millour & Vannier (2012) in the same proceedings.
  - For BSMEM, we used the default method and reconstruction parameters. We just considered for Alp Fak a Gaussian prior with the size of the fitted model we have done previously (3 mas), and for Bet Fak a uniform disk of diameter 3.5 mas. There was no subsequent convolution with a beam, so the resolution is supposedly 0.15 mas (whereas the effective details would show up at a resolution of approximately 1 mas).

Our interpretation of these datasets is the following:

- for Alp Fak: the model fitting provides an overall elongated Gaussian shape with major axis 4.2 mas, minor axis 3.1 mas, and position angle 66 degrees. The attempts to reconstruct images (and also the model fitting) indicate that there are other, finer structures, like 2 or 3 ”clumps” near the Gaussian center, but we were unable to locate them clearly. Our guess would be one clump in the center (the star) plus 2 clumps on both sides, along the major axis, which would represent an hypothetical inner rim.
- for Bet Fak: The model fitting (and the shape of visibilities vs spatial frequencies) indicates us a circular uniform disk plus 1 or 2 bright spots. Indeed, we are able to get spots in the reconstructed images, but we believe only MiRA is able to locate them correctly, whereas BSMEM tends to produce symmetric images of these spots.

4. COMPARISION METRICS AND CONTEST RESULT

The judge of the 2012 Interferometric Imaging Beauty Contest was William Cotton. The scoring of the Beauty Contest data was done through the following (and now standard) procedure:

1. the submissions are aligned using features in the images. This is done by correlating the submissions with the truth image. This also includes image flips if required, as contestants did not necessarily use the Beauty Contest orientation conventions. The Beauty Contest adopts the standard convention for optical interferometry: East to the left, and North up.
| Team                  | Software | Alp Fak score | Bet Fak score | Total score |
|-----------------------|----------|---------------|---------------|-------------|
| Monnier               | MACIM    | 37.8          | 242.5         | 280         |
| Hofmann, Schertl & Weigelt | IRS    | 28.2          | 285.1         | 313         |
| Millour & Vannier     | MiRA     | 27.7          | 299.8         | 327         |
| Thiébaut & Soulez     | MiRA     | 24.8          | 337.6         | 362         |
| Mary & Vannier        | MIROIRS  | 29.4          | 381.9         | 411         |
| Young                 | BSMEM    | 40.2          | 659.9         | 700         |
| Millour & Vannier     | BSMEM    | 32.3          | 871.7         | 903         |
| Elias                 | CASA     | 41.2          | 1285.9        | 1327        |
| Sridharan Rengaswamy  | SR       | 235.6         | 1636.6        | 1872        |

Table 1. Official results of the Beauty Contest 2012.

2. the submitted images are interpolated onto the pixellation grid of the master images, if needed. For contestants that submitted images at the recommended pixellation of 0.15 mas, this step was skipped.

3. All images (including the truth images) are normalized to unity in a given box. For Alp Fak this was the rectangle defined by corners [7, 7] and [119, 119], representing more than 90% of the emission. For Bet Fak this was the box within 14 pixels of the center, that included essentially all emission.

4. For each object, the score is computed as $10^6$ times the RMS pixel-by-pixel difference between the submission and the truth image in the boxes defined in 3).

5. The scores for Alp Fak and Bet Fak are added. The best scores are the lowest.

If more than one image was submitted per object and per team, the one achieving the best score was retained for scoring (e.g. Thiébaut and Soulez submitted images of Bet Fake regularized with total variation and a quadratic regularizer).

The official 2012 Interferometric Imaging Beauty Contest scores are given in Table 1. In light of the results, John Monnier (University of Michigan) was declared the winner of the contest for his MACIM entry and was awarded the contest prize by the jury (see Figure 5).

5. DISCUSSION AND CONCLUSION

The general agreement amongst contestants is that both targets were hard to reconstruct. This gave rise to more variance in reconstruction quality than what was witnessed during previous contests; but also demonstrated that decent imaging quality can be obtained on very resolved objects in realistic conditions.

Alp Fak was a difficult target, being probably too resolved for any current software to reconstruct it very well. MiRA and IRS obtained the best results, managing to reconstruct a smooth central star. The regularization used by MACIM favored uniform patches of fluxes, and thus was most probably not adapted to recover the original distribution.

Bet Fak was overall reconstructed well in terms of size, but the actual location of the spots was very dependent on the algorithm. Perhaps because stellar surface imaging is a more familiar application, image priors such as limb-darkened disks were used by most reconstruction. As both the \((u,v)\) coverage and signal-to-noise of Bet Fak were derived from real CHARA/MIRC-6T data, these results demonstrate caution will be needed when reconstructing spots from real data. MiRA achieved the best scores on Alp Fak, but its lower performance on Bet Fak (as well as the current specificities of the Beauty Contest metrics that put more weight on this target) prevented it from getting the best overall scores.

With record participation and overall convincing reconstructions, most contestants felt that the fifth Beauty Contest was successful at showcasing the diversity and strengths of the current imaging packages in monochromatic mode. As several packages are planed to add multi-wavelength imaging capabilities in 2012-2013, this contest may be indeed the last one to figure only monochromatic data. As multi-wavelength image reconstruction is both a difficult algorithmic problem and a necessity for new science, the next Beauty Contests should definitively prove exciting...
ACKNOWLEDGMENTS

Work by Fabien Baron was supported by the National Science Foundation through awards AST-0807577 to the University of Michigan. Work by Peter R. Lawson was undertaken at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. Work by William D. Cotton was supported by the National Radio Astronomy Observatory, a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

REFERENCES

1. Lawson, P. R., Cotton, W. D., Hummel, C. A., Monnier, J. D., Zhao, M., Young, J. S., Thorsteinsson, H., Meimon, S. C., Mugnier, L., Le Besnerais, G., Thébaut, E., and Tuthill, P. G., “The 2004 Optical/IR Interferometry Imaging Beauty Contest,” Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series 5491, 886 (2004).
2. Lawson, P. R., Cotton, W. D., Hummel, C. A., Baron, F., Young, J. S., Kraus, S., Hofmann, K.-H., Weigelt, G. P., Ireland, M., Monnier, J. D., Thébaut, E., Rengaswamy, S., and Chesneau, O., “2006 interferometry imaging beauty contest,” Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series 6268 (2006).
3. Cotton, W., Monnier, J., Baron, F., Hofmann, K.-H., Kraus, S., Weigelt, G., Rengaswamy, S., Thébaut, E., Lawson, P., Jaffe, W., Hummel, C., Pauls, T., Schmitt, H., Tuthill, P., and Young, J., “2008 imaging beauty contest,” Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series 7013 (2008).
4. Malbet, F., Cotton, W., Duvert, G., and Lawson, P., “The 2010 interferometric imaging beauty contest,” Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series 7734, 77342 (2010).
5. Harries, T. J., “An algorithm for Monte Carlo time-dependent radiation transfer,” MNRAS 416, 1500–1508 (Sept. 2011).
6. Monnier, J. D., Anderson, M., Baron, F., Berger, D. H., Che, X., Eckhause, T., Kraus, S., Pedretti, E., Thureau, N., Millan-Gabet, R., Ten Brummelaar, T., Irwin, P., and Zhao, M., “MI-6: Michigan interferometry with six telescopes,” *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series 7734* (July 2010).

7. ten Brummelaar, T., McAlister, H., Ridgway, S., Baguolo, W. J., Turner, N. H., Sturmann, L., Sturmann, J., Berger, D. H., Ogden, C. E., Cadman, R., Hartkopf, W. I., Hopper, C. H., and Shure, M. A., “First results from the CHARA Array. II. A description of the instrument,” *The Astrophysical Journal 628*, 453 (July 2005).

8. Pauls, T. A., Young, J. S., Cotton, W. D., and Monnier, J. D., “A Data Exchange Standard for Optical (Visible/IR) Interferometry,” *The Publications of the Astronomical Society of the Pacific 117*, 1255–1262 (Nov. 2005).

9. Renard, S., Thiébaut, E., and Malbet, F., “Image reconstruction in optical interferometry: benchmarking the regularization,” *Astronomy & Astrophysics 533*, A64 (Aug. 2011).

10. Tallon-Bosc, I., Tallon, M., Thiebaut, E., Béchet, C., Mella, G., Lafasse, S., Chesneau, O., Domiciano de Souza, A., Duvert, G., Mourard, D., Petrov, R., and Vannier, M., “LITpro: a model fitting software for optical interferometry,” *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series 7013* (July 2008).

11. Reid, R. I. and CASA Team, “CASA: Common Astronomy Software Applications,” in [American Astronomical Society Meeting Abstracts 215], *Bulletin of the American Astronomical Society 42*, 568 (Jan. 2010).

12. Hummel, C. A., “QC and Analysis of MIDI Data Using mymidigui and OYSTER,” in [2007 ESO Instrument Calibration Workshop], Kaufer, A. and Kerber, F., eds., 471 (2008).

13. Rau, U. and Cornwell, T. J., “A multi-scale multi-frequency deconvolution algorithm for synthesis imaging in radio interferometry,” *Astronomy & Astrophysics 532*, A71 (July 2011).

14. Hager, W. W. and Zhang, H., “A New Conjugate Gradient Method with Guaranteed Descent and an Efficient Line Search,” *SIAM Journal on Optimization 16*, 170–192 (Jan. 2005).

15. Hager, W. W. and Zhang, H., “A New Active Set Algorithm for Box Constrained Optimization,” *SIAM Journal on Optimization 17*, 526–557 (Jan. 2006).

16. Hofmann, K. and Weigelt, G., “Iterative image reconstruction from the bispectrum,” *Astronomy & Astrophysics 278*, 328–339 (1993).

17. Lacour, S., Meimon, S., Thiebaut, E., Perrin, G., Verhoelst, T., Pedretti, E., Schuller, P., Mugnier, L., Monnier, J., Berger, J., and Others, “The limb-darkened Arcturus: Imaging with the IOTA/IONIC interferometer,” *Astronomy & Astrophysics 485*, 561–570 (2008).