Delft Testbed Interferometer
Homothetic mapping and astrometric performances

P.M. Gori[a] , C. van der Avoort[b], R.S. LePoole[a], H. van Brug[c]
[a] Sterrewacht Leiden, Nielsbohrweg 2, NL-2333 CA Leiden, The Netherlands
[b]TU Delft, Julianalaan 134, 2628 BL Delft,The Netherlands
[c]TNO TPD, DOI/OP, Stieltjesweg 1, 2628 CK Delft, The Netherlands

ABSTRACT

A special case of optical aperture synthesis, homothetic mapping, is the topic of this paper. It allows for a wide field of view for interferometric instruments, interesting for astrometric measurments of wide objects. This paper describes a testbed constructed and tested in TNO-TPD in Delft (the Netherlands). This testbed is intended as a tool to investigate the ins and outs of homothetic mapping. The homothetic mapping approach is explained, the whole setup is specified and results are shown.

1. INTRODUCTION

Astrometry can provide can provide accurate angular distance measurements between objects. At the moment, narrow field astrometry is developed for exoplanet detections for instance. But astrometry also concerns globular clusters and the galactic center, which need a wide field of view.
Homothetic mapping is a way to achieve astrometry in a large field of view.
The Delft Testbed Interferometer (DTI) has been created as a facility to experiment with homothetic mapping, a special case of optical aperture synthesis. DTI was designed and constructed in Delft (the Netherlands) by TNO-TPD. Homothetic mapping is a form of image plane interferometry where the beams and the pupil images in front of the beam combiner have the same configuration as the collecting telescopes (but typically on a smaller scale). This assures a wide field of view in the image plane. This wide field of view is the key advantage of the homothetic mapping approach and is the future of optical interferometry

2. OPTICAL

For the DTI the scale factor between light gathering apertures and beam width entering the combining telescope is one; the pupils feeding the beam combiner have the same size and arrangement as the collecting telescopes. At DTI the collecting telescopes are positioned in a configuration, which is similar to that of three of the VLTI telescopes, but on a smaller scale (scaled down by a factor of 800).
The bench is set upon a vibration-isolating table to ensure a high stability.
DTI uses a Xenon lamp (emitting in the visible) and optical monomode fibres to simulate the stars. The fiber ends are placed in a special holder, allowing the configuration of stars to be changed. The light emerging from the optical fibres

New Frontiers in Stellar Interferometry, edited by Wesley A. Traub,
Proceedings of SPIE Vol. 5491 (SPIE, Bellingham, WA, 2004)
0277-786X/04/$15 · doi: 10.1117/12.551407

Downloaded from SPIE Digital Library on 21 May 2010 to 131.180.130.114. Terms of Use: http://spiedl.org/terms

is collimated by a parabolic mirror, 600 nm focal length, and then redirected by a folding flat. This assembly forms the sky simulator. From the emerging collimated beam three sub apertures are 'selected' by 3 holes in a plate, simulating the telescope positions. The beams from these sub-apertures are directed into the beam combiner using six mirrors.

The first mirror is flat not movable and just redirects the beam into the delay line, a simple roof type delay line, consisting of two flat mirrors placed under right angle.
This delay line is actuated by a linear motor and is used for the course optical path difference (OPD) corrections. After passage through the delay lines the light arrives onto piezo actuated correction mirrors to enable fine alignment (pointing, beam arrangement, and OPD).

A final fixed flat then redirects the beam into the beam combiner. The beam combiner optically is the inverse of the sky simulator, except for the telescope design. This telescope has a focal length of 5 meters. The three beams are forming an isosceles right-angled triangle. One beam is chosen as the reference beam, which saves 2 piezo-actuators for alignment and one motor for a delay line.
A CCD camera is used to record the flux distribution in the image plane.
Software has been developed to computer-acuate teh 12 piezos (3 per alignment mirror) and the 2 movable delay lines.

The mechanical and optical elelments of the whole system were completed mid-July 2003 and white light fringes were obtained one month later, after alignment. Recent measurements of fringes using two and later three stars indicate that the alignment is well in hand and that homothetic mapping experiments are possible using DTI.

Currently, tests are ongoing to establish the system stability and the repeatability of the alignment. Also the piezo actuators are being calibrated. Over the next few months we hope to work on fringe tracking and software modelling. In the near future an enhanced DTI+ is planned which will allow to laterally move one of the 3 apertures in order to simulate baseline changes due to earth rotation.

3. ERROR BUDGET

From documentation of PRIMA, a sentence has been reminded: ‘The distance of the white light fringe from the position of zero OPD, in addition to their contrast, is the key to interferometric imaging’.

That’s why the baseline system requirement was set to be V=0.8.
This means that the fringe visibility should be 0.8. The definition of visibility is on Eq. 1.

$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \quad (1)$$

Where Imax and Imin are the maximum and the minimum of intensity in the fringe pattern.

Many elements contribute to decrease the visibility.
The intensity of the source is a determinant factor. Although it does not change the visibility, it does dictate the integration time. The noise in the system, due to vibrations and air turbulence is also disturbing the light interferences. The drift in the system also deteriorates the visibility with time. Pointing error (the different beams should perfectly overlap) must be considered, and finally changes in the layout result in changes in OPD.

The value of the required visibility depends on the accuracy required for phase calculations from the recorded fringe patterns, and on the integration time, which is limited by the system drift, pointing error and OPD control.
According to this analysis, the error budget shown in Table. 1, has been determined.

Downloaded from SPIE Digital Library on 21 May 2010 to 131.180.130.114. Terms of Use: http://spiedl.org/terms

Table. 1. Error budget allowing a visibility of 0.8.

Error source	Allowed	Per item	Comment
Unbalance	0.5	0.5	Pair wise (three sub beams)
Polarization	0.3 rad	0.3 rad	Pair wise
Lateral pupil shift	3 µm	2 µm	three pupils
Longitudinal pupil shift	0.8 mm	0.5 mm	three pupils
Magnification	1×10^{-3}	0.6×10^{-3}	three pupils
Pupil rotation	1 mrad	0.6 mrad	three pupils
Pointing	3 µrad	0	controlled
OPD	50 nm	0	controlled
Wavefront	λ/30	λ/90	about 10 mirrors (RMS)
Vibration	1.5 µrad	1 µm	three pupils
Drift	1.5 µrad	1 µm	three pupils
Off-axis	λ/30	λ/50	three pupils (RMS)
Stray light	7 nW/cm²	5 nW/cm²	three pupils
Noise	5 nW/cm²	2 nW/cm²	measured on CCD

To reach this goal, the alignment requirements Table. 2, have been established.

Table. 2. Required alignment accuracies.

Lateral pupil position	3 µm	Aligned
Longitudinal pupil position	0.5 mm	Static
Pupil rotation	1 mrad	Aligned
Pupil magnification	2×10^{-3}	Static
Pointing	3 µrad	Controlled
OPD	20 nm	Controlled

Downloaded from SPIE Digital Library on 21 May 2010 to 131.180.130.114. Terms of Use: http://spiedl.org/terms

4. HARDWARE / MECHANICAL

The DTI system was designed and a drawing from the mechanical design tool is shown in Fig 1.

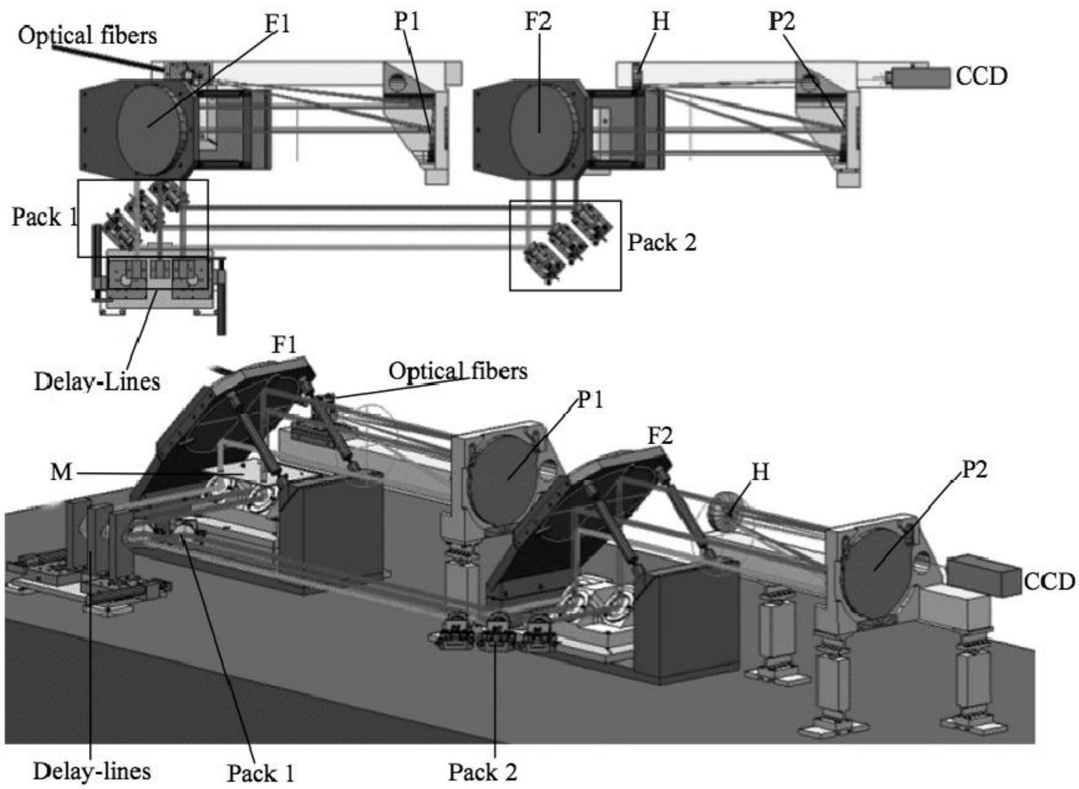


Fig 1: In this drawing the whole DTI setup is shown. The light from the optical fibers is reflected by the parabolic mirror P1, and by the first flat mirror F1. Then it is directed through a mask M used to select 3 beams. Theses beams arrive on the first block of 3 fixed mirrors B1 and are reflected in direction of the delay-lines. Then the light arrives on the first pack of 3 pointing mirrors Pack 1 and then on the second identical Pack 2. Finally the beams are reflecting onto the second block of 3 fixed mirrors B2 to be directed into the second flat mirror F2 and then on the second parabolic mirror P2. Then they are coming onto the hyperbolic mirror H to finally reach on the CCD camera.

Downloaded from SPIE Digital Library on 21 May 2010 to 131.180.130.114. Terms of Use: http://spiedl.org/terms

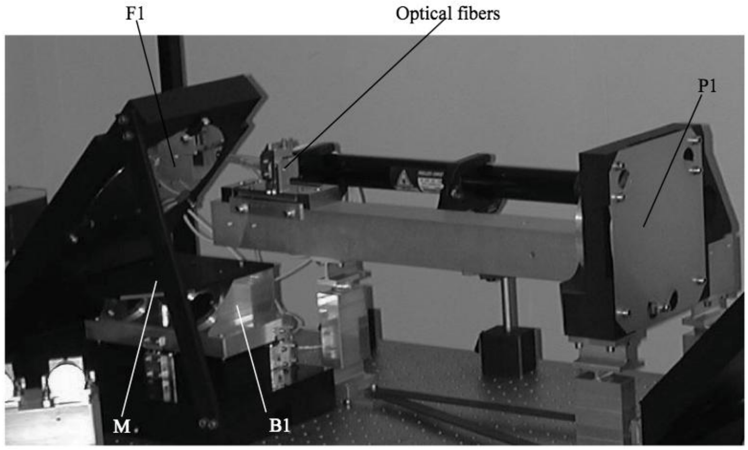


Fig. 2. The star simulator is composed of optical fibers on the left, a parabolic mirror P1 on the right, a flat mirror F1 on the left, a mask M below the flat mirror and under this mask a block of 3 fixed mirrors B1.

This design can be split into three main parts. For each part a photograph of the created hardware is shown:

- First the star simulator Fig. 2,
- Secondly the mapping Fig. 3,
- And thirdly the beam combiner Fig. 4.
-

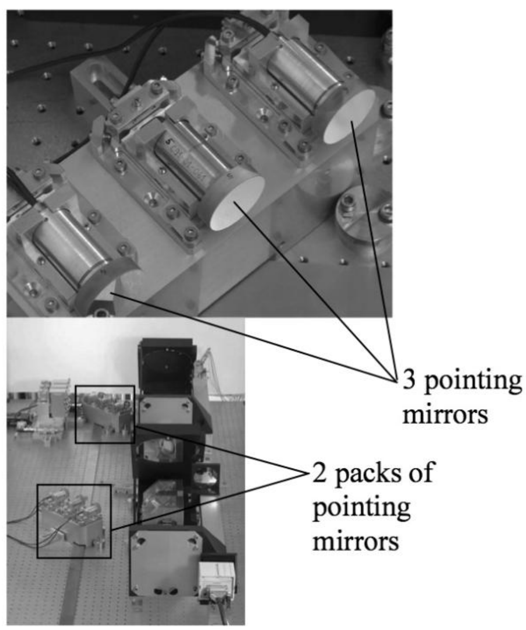


Fig. 3. On the top part is the first pack of 3 pointing mirrors. The central one is not actuated by piezo. On the bottom part are shown the 2 packs determining the homothetic mapping. The piezo actuators allow tip/tilt and piston (required for accurate OPD control) adjustments.

Downloaded from SPIE Digital Library on 21 May 2010 to 131.180.130.114. Terms of Use: http://spiedl.org/terms

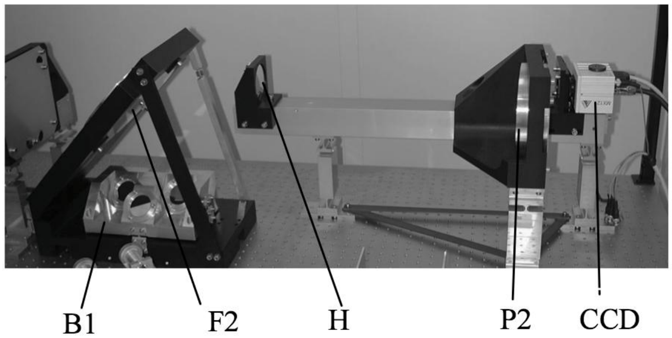


Fig. 4. The beam combiner is composed by the flat mirror on the left F2, the block of 3 fixed mirrors below it B2, the parabolic mirror on the right P2, the hyperbolic mirror in the center H and the CCD camera on the right.

The star simulator is composed of three optical fibers of which the output is reflected by the parabolic mirror (P1 on the image). These optical fibers are fed by Xenon lamp (500-1000 nm). After the reflection on this mirror the three beams are collimated and feed a flat mirror F1. Both the parabolic and large flat mirror have been fabricated in-house using our SPDT machine. Then each beam is going through a mask M. This mask has three holes of one-centimeter diameter. It is the representation of the three telescopes collecting the starlight. The center point of the three holes has been chosen to represent three from the four U.T. positions on VLTI. The defined triangle is the entrance baseline of the system. Below this mask, three fixed mirrors B1 are reflecting the light to redirect it on the mapping elements.

The mapping system contains three Delay-Lines Fig. 5, which are set on the same plane. The central delay line is fixed; the two adjacent Delay-Lines are driven by linear motors. The delay line can be tip tilted. This allows for pupil rotation correction and experiments. Then the light is sent into the first pack of three mirrors Pack1. As the Delay lines, the three mirrors are on the same plane and, the centre mirror fixed while the two adjacent mirrors are actuated by piezos. Then after reflection on this pack of mirrors, the beams arrive at the second identical Pack 2. The exit baselines are formed on the fixed block B2 by controlling the actuated mirrors in Pack 1 and Pack 2. The pattern defined by the pupils must be identical as the entrance baseline to make a homothetic mapping.

Fig. 5. These are the three delay-lines. A pair of flat mirrors composes each delay-line. The disposition is forming a right angle. The light is coming into the top mirror, is reflected onto the second mirror and then is leaving the delay line on the same vertical plan as it was coming. The left delay-line and the right one are actuated by piezo.

Downloaded from SPIE Digital Library on 21 May 2010 to 131.180.130.114. Terms of Use: http://spiedl.org/terms

The first element of the beam combiner collecting the light is a block of 3 fixed mirrors B2 on which the beams are directed in an equal arrangement on the aperture mask. Also these mirrors were created using SPDT. These mirrors send

the three beams into a flat mirror F2 and then the light is going into a parabolic mirror P2 and feeds a hyperbolic mirror H to end on the CCD camera.

All the components are fixed on a stabilized table and the system is open air. So a lot of air fluctuation is coming into the three beams. To investigate the stability, a test has been made. It appears on this test Fig. 6, that during the non-active schedule of the company (roughly between 9 pm and 8 am) each beam is stable with respect to the two others. During office hours the beams tend to drift. Since all beams show on equal movement this does not hinder the operation of DTI. In the near future a cover over the DTI system is planned to allow operation in a daylight environment.

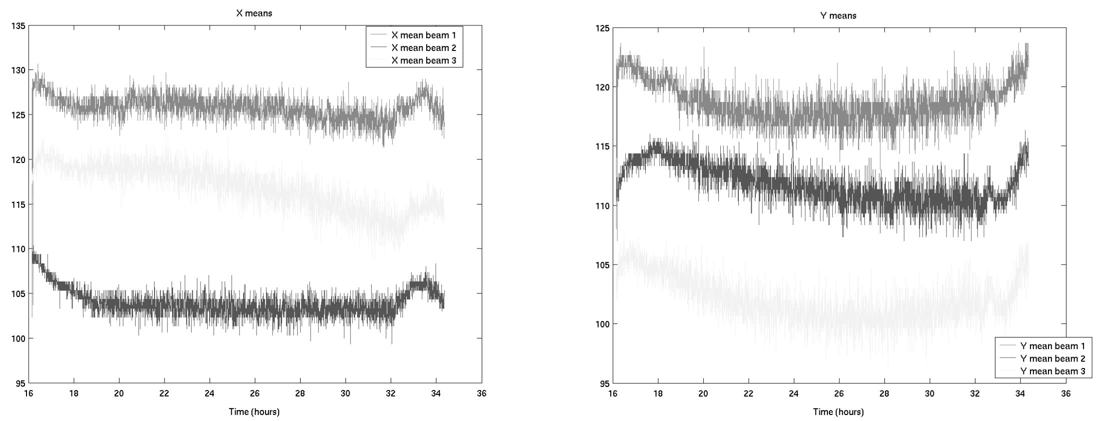


Fig. 6. On the top part is displayed the X-axis stability curve for the 3 beams and on the bottom part is shown the Y-axis stability curved. They are both recorded during a whole night.

5. EXPERIMENTS

As shown before, a stability test has been made on DTI to characterize the instrument. It is important for further experiments to know how the beams behave with time in order to realize what we really observe in using this interferometer. Fringes have been obtained on all three stars. The system is not yet perfectly homothetic mapped at the moment as can be seen from the fact that the fringe crossing is not exactly centered on the underlying Airy pattern. Using the piezo actuators we have already shown that we can shift the position of the fringes with respect to the Airy pattern envelope. This means that a perfect mapping is feasible. At present we are working on an algorithm to automatically align the fringes with respect to the star images, by adjusting beam position and OPD. The fringes can be seen not to be centered exactly on the three stars in Fig.7.

Downloaded from SPIE Digital Library on 21 May 2010 to 131.180.130.114. Terms of Use: http://spiedl.org/terms

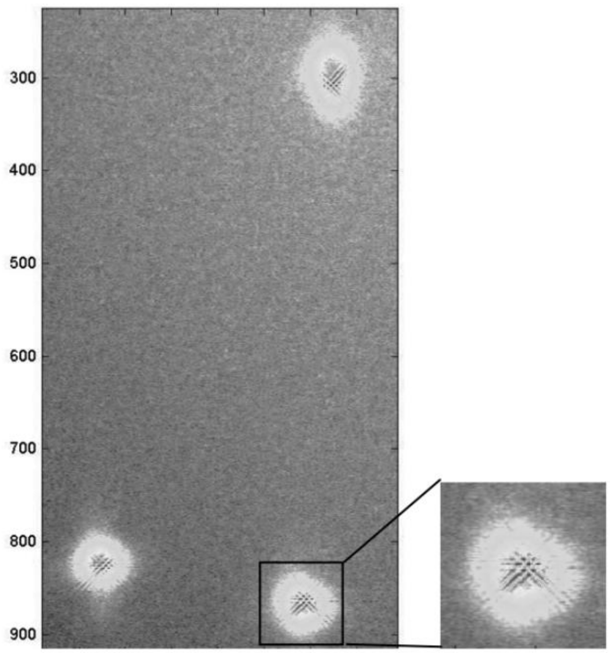
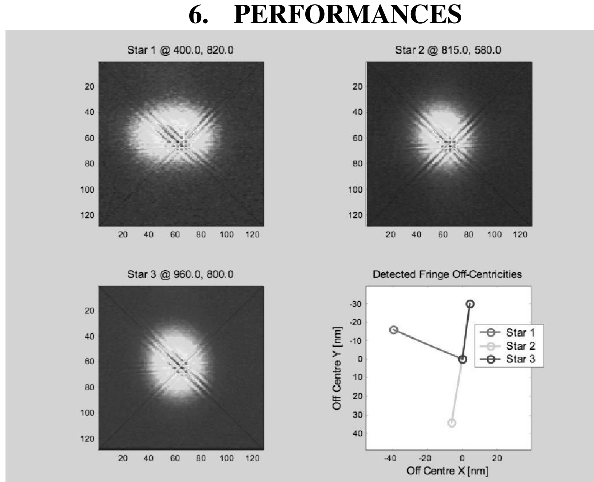


Fig. 7. Three stars observed within DTI with fringes on them simultaneously. On the right hand part it is shown that the fringes, are almost centered on the envelope. The presence of the fringes already indicates the good health of the setup. Having fringes on the three stars shows that by using homothetic mapping, we obtain fringes over the whole field of view without moving any Delay-lines. A fringe tracking experiment has also been done successfully and the resolution reached is 25 nm.

6. PERFORMANCES



Mapping conditions (fringe centering) at the accuracy obtainable by the algorithm.Typically lambda/10.

The 3 stars are represented, with 3 set of fringes in each star resulting of the presence of 3 baselines. The bottom right plot is composed of 3 vectors. The module each represents the distance separting the fringe center and the envelope center for each star. The argument indicates the direction of this separation. The accuracy obtained is about 50 nm.

Downloaded from SPIE Digital Library on 21 May 2010 to 131.180.130.114. Terms of Use: http://spiedl.org/terms

7. OUTLOOK

In the near future, the two blocks of fixed mirrors (B1 and B2) will be substituted by two blocks of movable mirrors Fig.8.

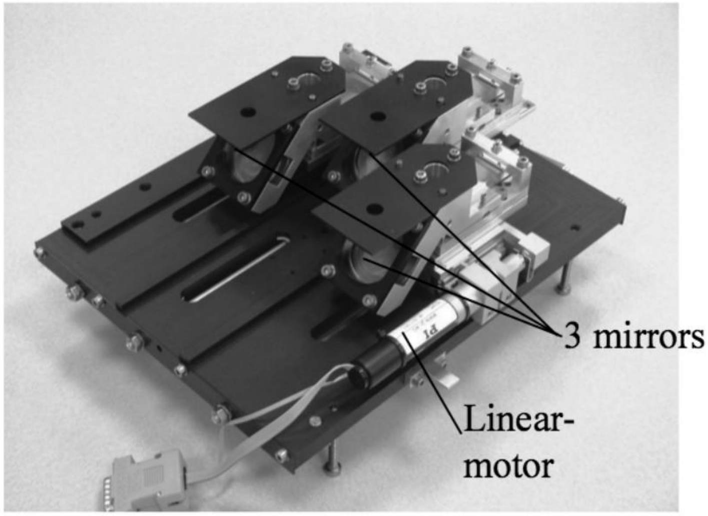


Fig. 8. This is one of the blocks of three movable mirrors. One of the mirrors + apertures is actuated by a linear motor. All mirrors can be shifted manually.

On each new block, one mirror is actuated by piezo. This new version of DTI, DTI+ permits to change the telescope baselines and move the beam positions at the entrance of the beam combiner. It allows ground application experiments, in simulating the earth rotation by moving these mirrors. It is also foreseen to use DTI to observe the real sky by applying it on an actual interferometer.

8. CONLUSIONS

DTI was designed and has been entirely constructed by TNO-TPD. The layout has been presented and the alignment tolerances have been given. We have fringes for three stars in the whole field of view. At the moment, with a static configuration, the homothetic condition is satisfied. This instrument shows that homothetic mapping is possible.

9. REFERENCES

1. H. van Brug, T. van den Dool, W. Gielesen, P. Giesen, B. Oostdijck, and L. d'Arcio, "Delft Testbed Interferometer - layout design and research goals-," Interferometry for Optical Astronomy II, SPIE volume 4838, pp.425 – 429

2. H. van Brug, B. Oostdijck, T. van den Dool, P. Giesen, and Wim Gielesen, "Delft Testbed Interferometer: a homothetic mapping test setup," SPIE Annual meeting 2003 San Diego, in print. 8 pages.

3. B. Oostdijck, H. van Brug, T. van den Dool, P. Giesen, and W. Gielesen, "Delft Testbed Interferometer: a homothetic mapping test setup," EOS Topical meeting on advanced imaging techniques 2003, pp.78 – 80

For further information contact: Hedser van Brug
brug@tpd.tno.nl
+31 15 269 24 89

Downloaded from SPIE Digital Library on 21 May 2010 to 131.180.130.114. Terms of Use: http://spiedl.org/terms