Delft Testbed Interferometer
-layout design and research goals-

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ABSTRACT

The Delft Testbed Interferometer (DTI) will be presented. The main purpose for the DTI is to demonstrate the feasibility of homothetic mapping, both fixed and under scanning conditions. The driving design issues behind the DTI will be presented together with a list of experiments to be conducted with the DTI system in the field of wide field imaging.

Keywords: Multi aperture interferometry, wide field imaging, homothetic mapping

1. INTRODUCTION

The search for earth like planets requires telescopes with a high resolution. The image of a point source is broadened due to diffraction, and its width is given by the telescopes diameter (d), its focal length (f), and the wavelength of the light used (λ), via

$$d_{\mathrm{Airy}} = 2.44 \times \frac{\lambda \cdot f}{d}. \tag{1}$$

As can be seen from Eq. (1), the resolving power of a telescope with fixed focal length can be improved by decreasing the wavelength or by increasing the diameter of the primary mirror of the telescope. Since the wavelength is dictated by the experiment one wants to do the only real option is to increase the diameter. For very large telescopes the useful diameter is limited to e.g. what can be made and the turbulence in the atmosphere. The effects due to atmospheric turbulence can be nullified by applying adaptive optics.

In stead of using larger telescopes one can also use more telescopes. In the case of coherent combination of the light contribution, fringes will be formed within the central peak of the Airy distribution obtained with a single telescope. The width of these fringes is given by

$$d_{\mathrm{fringe}} = \frac{\lambda}{2 \cdot \sin\left(\arctan\left(\frac{b}{2 \cdot f}\right)\right)} \approx \frac{\lambda \cdot f}{b}, \tag{2}$$

with b the so called baseline, the separation between the two telescopes. The use of this approach, indicated as optical aperture synthesis (OAS), enables the creation of telescope systems with very high resolving powers and with hight light gathering powers owing to the large integral surface of all the combined telescopes.

Optical aperture synthesis has a drawback. The light originating from a star is not automatically imaged coherently. Using a single telescope, the light from a single star will be captured and imaged onto a camera. Using separate telescopes and combining their optical signals will require additional elements, i.e. delay lines

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for each telescope signal to ensure that all contributions are combined coherently, having zero optical path difference (OPD). The amount of optical delay that is required depends on the viewing angle, i.e.

$$\Delta\text{OPD} = b \times \cos(\alpha), \tag{3}$$

where α is the viewing angle with respect to the earths normal and where the telescopes are taken to be arranged within a horizontal plane. From Eq. (3) it follows that for observation on a star that stand directly overhead the telescopes ($\alpha = 0$) no delay is required. For each other viewing direction an OPD correction is required. Suppose that an OAS system is used to observe a star at a certain angle α. After pointing the telescopes this will be the on-axis star. For the on-axis star the OPD can be corrected for. Suppose next that there is another star nearby the first star within the field of view (FOV) of the telescope system, an off-axis or science star. For a single telescope system this off-axis star will be imaged coherently together with the on-axis star. For a multiple aperture system the off-axis star will require an additional OPD correction such that the enhanced resolution of the multi aperture system can not be used over a large field of view. One of the possibilities to widen the field of view of optical aperture systems is to use homothetic mapping for the combination of the light beams from the separate telescopes. When homothetic mapping is applied fringes can be observed simultaneously for objects within a large FOV.

2. HOMOTHETIC MAPPING

The principle behind homothetic mapping, see Fig. 1, is to combine the light coming from several large telescopes within a 'small' imaging telescopes where the beams from the different telescopes are arranged such that they are in the same configuration as the large telescopes. In this way all images of observed stars will be imaged with 'white light' fringes in them as long as the stars are within the FOV of the telescopes and the mapping system.

The light beams from the telescopes are combined and form overlapping point spread functions (PSF) on the image plane (the CCD camera). In case of ideal optics and point like stars, the PSF will be Airy discs. The optical path lengths have to be equal for all telescope beams in order to observe fringes within the PSF's. Since the DTI is intended to operate for wavelengths ranging from 500 to 1000 nm the optical path difference (OPD) should be equal to within 50 nm.

Since the DTI system will be a breadboard system we have to construct our own parallel beams to simulate starlight. To this end we will use light from a Xe source that will be guided through several mono mode fibers to create point sources, simulating the stars. The light emanating from those fibers will be collimated by a parabolic mirror, effectively placing the stars at infinity, where the separation between the fibers sets the angle between the collimated beams. One of the fibers will act as guide star and will be placed on axis while the other fibers will be placed off-axis as science stars.

The baseline between the telescopes of the DTI system is set to 125 mm, and a vertical viewing direction is taken for the on-axis guide star (i.e. the baseline is not shortened by an angular effect). The diameter of the beams from the telescopes is set at 10 mm. Three sub beams are selected from the collimated starlight beams, simulating three telescopes, and each sub beam travels towards the combining telescope via an optical path containing delay lines and beam steering elements to arrive at the proper beam arrangement, proper pointing, and approximately zero OPD. The FOV of the DTI system is set to a maximum of 800 arcsec.

3. ERROR BUDGET

Almost independent of the optical design there are certain errors that have to be taken into account. The elements in the error budget will be discussed together with the budget we have assigned to each item. The design driver that we have taken was the phase measuring accuracy $\Delta\varphi$. The goal for $\Delta\varphi$ was set at $\lambda/100$.

The phase measuring accuracy was calculated via

$$\Delta\varphi = \frac{1}{S/N}\frac{1}{\sqrt{\#\text{pixels}}}, \tag{4}$$

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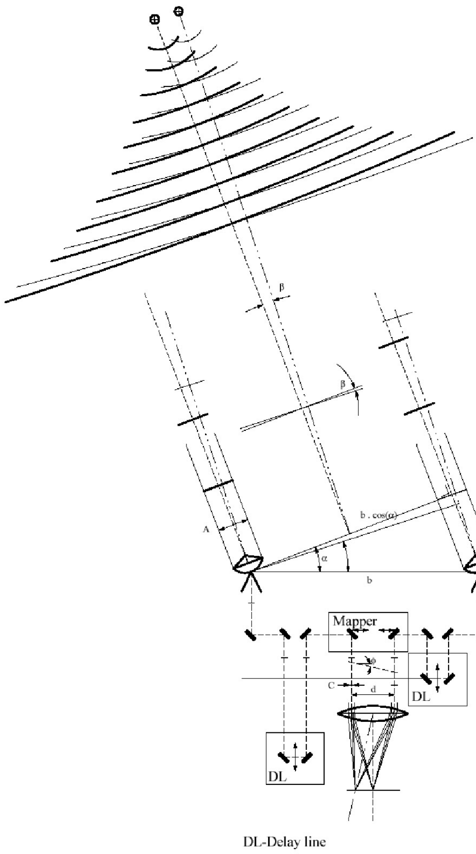

Figure 1. The principle of homothetic mapping. In this figure the viewing angle for the on-axis star is α, and the off-axis star has an angular offset of β. The light collecting telescopes have a diameter of A and a separation, baseline, of $b\cos(\alpha)$. Note that in this drawing the viewing angle is indicated with respect to the horizon. The beams are scaled for the combination to a diameter of C and a baseline of d, both multiplied by the same factor. The off-axis is divided by that factor. The delay lines ensure equal optical path lengths.

with S and N the signal amplitude and the noise, expressed in electrons per pixel, and #pixels the number of pixels covered by a single star image. Since the signal to noise ratio depends on the fringe visibility V via

$$S/N = \frac{2 \cdot V \cdot I_B}{N} \tag{5}$$

with I_B the background intensity of the fringe pattern, we adopted the fringe visibility as design criteria. The value for N is found using

$$N = \sqrt{I_{\text{pixel}} + i_{\text{dark}}/\text{FR} + \text{RON}^2} \tag{6}$$

where i_{dark} is the dark current, FR the frame rate of the CCD camera, and RON the read out noise. For the error budget we have calculated the effect of all possible errors on the fringe visibility. After combining the fringe visibility with the data of a possible CCD camera candidate and the data of the light source we arrived at an achievable phase measurement accuracy. In the following list a summary is given of the most important errors likely to occur in the DTI system, or any other implementation of homothetic mapping, followed by a complete error budget from which an achievable accuracy of $1.8 \times 10^{-3}\lambda$ follows.

Intensity unbalance The visibility will drop below 0.8 when one the light beam intensities differs from one

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of the other beams by more than 25%. For the DTI system the approach will be to select the three sub beams from equal radial positions within the large collimated beam. In that case the intensity matching will be well within limits.

OPD error The OPD control should keep the OPD within $\lambda/10$, i.e. about 50 nm. Hereto the mirror shifts along the propagation direction in the system should be smaller than 25 nm. Since the OPD will be actively controlled by observing the fringes in the on-axis, guide star, no difficulties are expected.

Polarization rotation The sub beams should interfere at the image plane. For good visibility the state of polarization of the beams should be as equal as possible. The polarization rotation of one beam is allowed to be as high as 0.5 rad with respect to the other beams for a visibility of 0.8.

Mapping error Lateral shifts of the beams at the mapping location, there where the input configuration is recreated, result in an OPD error. For the on-axis beams this shift is not critical. For the off-axis beams the requirement is that the OPD error should remain within $\lambda/10$. For a wavelength $\lambda = 500$ nm and an off-axis beam angle of 3.9 mrad (800 arcsec) this means that the lateral displacement of the pupils should be smaller than 12.5 μm. For mapping the entrance pupil layout will be copied to the exit pupil layout. Small layout errors in the order of a few μm can be accepted. A longitudinal shift is less severe than a lateral shift, owing to the small viewing angle. A longitudinal error in the pupil position of 2.5 mm can be accepted. The corresponding lateral shift is then 2.5 mm $\times$ 3.9 mrad, which equal about 10 μm.

Pupil rotation Results in a shift of the Airy spot and a small OPD error. For the chosen setup the allowed pupil rotation amounts to 3 mrad.

Pointing error Results also in a shift of the Airy spot. A shift of about 10 % of the Airy spot is acceptable. For a 5000 mm imaging telescope this means that the pointing error should remain smaller than 12 μrad.

Magnification error Although the DTI system will be constructed as a unit magnification system, small errors can be expected due to surface flatness errors. A magnification result in a change in pointing direction and in a required shift in the 'mapper mirror' location. Due to these effects the relative magnification error should remain below 1×10^{-3}.

Wavefront error We aim at a Strehl ratio of 0.8. In order to achieve this the wavefront errors should remain below $\lambda/10$.

Off axis error e.g. field curvature. This means that the PSF (Point Spread Function) will be deformed. Due to aberrations in the system the changes in the PSF can be field point dependent. These effect should remain within $\lambda/10$.

The allowed errors as given in the descriptions above are for a change in visibility of 0.2, purely due to one contribution. In the error budget table, Table 1, all error sources are weighed to arrive at the phase accuracy goal of about $\lambda/100$. These data have been combined with the Xe source data and the CCD camera data to arrive at the error budget as presented in Table 1. With the shown error budget the visibility that is expected for the DTI system will be approximately 0.3 and the phase measuring accuracy will be 1.8×10^{-3}, well below our target.

The main error contributions come from the wavefront errors due to shape errors in the parabolic and flat mirrors. Another critical point is the relative magnification of the light beams traveling from the entrance telescopes to the mapping stage.

4. OPTICAL DESIGN

One of the difficult issues to resolve for a real homothetic mapping system is the tracking of stars over a longer period of time. Due to the rotation of the earth the effective baseline changes and therefore also a different mapping layout is required. The movement of the mapping stages can be very complicated and can even result in entangled mirror holders or collisions.

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Table 1. Error budget for the DTI system

Error source	Allowed	Effect on V ($\times 1000$)	Remark
Wavefront error flats (λ/N)	20	120	9 per path
Wavefront error parabolic mirrors (λ/N)	5	277	3 per path
Off-axis errors (λ/N)	50	40	
Unbalance I_1/I_2	0.7	16	per two beams
OPD (nm)	20	80	
Turbulence and vibrations (nm)	10	40	
Polarization rotation (rad)	0.2	20	per two beams
Lateral beam shift (μm)	3	48	
Longitudinal beam shift (mm)	1	64	
Beam rotation (mrad)	5	33	per two beams
Pointing (μrad)	5	33	
Magnification (ΔM/M)	1×10^{-3}	96	
Stray light (nW/cm^2)	1	57	
Drift lateral shift (μm)	2	32	
Drift pointing (μrad)	20	33	
Total visibility:	0.314	$\Delta\varphi$:	1.8×10^{-3}

We have designed a system that eliminates this mapping problem. Due to the fact that a patent is pending on our idea the optical design can not yet be presented. We hope that the patent issue is solved by the time of the conference such that the proposed layout can then be presented.

The main design issue is stability. The system can be controlled by observing the fringes in the guide star but in order to arrive at the possibility for fringe integration on the off-axis stars, the system should be free of drift within the errors given in the error budget.

5. PLANNED EXPERIMENTS

Once the DTI system has been built and aligned several experiments relevant to homothetic mapping will be conducted. Among these are:

Star tracking To demonstrate the possibilities of the patented layout star tracking will have to be demonstrated. The angle of incidence of the collimated beam will be scanned, just like starlight direction changes due to the rotation of the earth, and the mapping condition will be maintained.

Field of view map The complete field of view will be investigated to observe all possible off-axis optical errors in the system.

Drift As one of the main difficulties in a homothetic mapping system will be the stability of the system one of the most important experiments is to monitor the drift in the system by observing the fringe visibility as a function of time without active steering of the pointing.

Signal to noise ratio In real life experiments it is standard to use a guiding star to control the OPD. We plan to lower the intensity of the science stars (off-axis stars) to investigate the possibility for phase calculations in extreme low-light situations.

6. CONCLUSIONS

The main objectives of the Delft Testbed Interferometer have been presented together with the research goals. A complete error budget has been given and it has been shown that the fringe measuring accuracy can be better than one hundredth of the wavelength.

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