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# Optical Interferometry with SCASIS.

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# Chapter 14: Conclusions

*This final chapter summarizes what has been achieved with SCASIS. It also discusses what more could be achieved with the present system, and what options there are for further involvement in High Resolution Imaging. A simple facility for systematic spectral observations at intermediate resolutions is described.*

## 14.1 Evaluation of SCASIS in terms of project goals

The work covered by this thesis was intended as a feasibility study for the application of a redundant multiple shearing pupil plane interferometer. In this section we summarize the results of that study.

In the first place it turned out to be possible to construct such an interferometer using the concept of shifted segmented lenses, as described in Chapter 5. The final prototype includes options for atmospheric zooming and monitoring of the seeing. However, the special segmented lenses, and the amount of supporting optics needed for the pupil plane configuration, make the optical layout complicated. Setup and alignment are difficult, and need to be checked repeatedly. The instrument cannot be left on the telescope for general use. Initially we used an eight aperture system. The reduction of several objects showed that it is much safer to work with a five aperture system, which is still over-redundant, but gives more pronounced visibility peaks. This allows for more accurate calibration and in particular makes the correction for the photon bias less critical.

Secondly, it turned out that the proposed video detector system, using a CCD camera and two Intensified TV cameras as described in Chapter 6, was feasible for the observations. The detective quantum efficiency of the intensified cameras allows observations of objects down to 6th magnitude. Initially, the darkcurrent turned out to be too high to observe the faintest sources. An appropriate reduction of the darkcurrent could be achieved with a simple cooling system. The storage on video tape allows efficient storage of large quantities of data, with sufficient accuracy in terms of geometric distortions, contrast degradations and stability of eventshapes. Large numbers of video frames can be digitised and prepared for processing using the multi-pass retrieval system. The fixed integration time turned out to be not critical in terms of limiting magnitude, but made it impossible to get high signal to noise in single frames (Chapter 10). Detector systems put severe limitations on optical interferometers, mainly in terms of quantum efficiency and local dynamic range. Comparison of the video system with the digital IPD system (section 6.5) shows that the video system is in many aspects better suited for use in an interferometer like SCASIS (with isolated visibility peaks). The countrate is much higher and the MTF is slightly better. The intensified cameras do not suffer from the unrecoverable non-linear effects caused by eventcentring hardware. The additional advantage of on-line moving pictures of pupil and image plane images should not be underestimated. During the alignment of a complex instrument, such direct views are vital. Also, since atmospheric conditions can vary on short timescales, a direct visual impression of the observed material is very helpful for scheduling of observations and selection of recorded material. We were able to develop additional tools to quantify such impressions, in terms of seeing quality and sharpened images (Chapter 7).

In the third place, we were able to develop and code the proper algorithms for the reduction of the measured SCASIS fringes (Chapter 8). In particular, we succeeded in making a proper correction for the photon bias in fringe visibilities and closure phases, as described in Chapter 9 (and in Chapter 13 for line triples). We found various ways to verify the corrections. Instrumental effects could be successfully removed with a point source calibration. Unfortunately, it turned out that delay effects, introduced by the segmented optics, limit our effective integration area more severely than atmospheric turbulence. So we use the flexibility allowed by the pupil plane concept to correct for the instrumental effects. Point source calibration does not cancel the decorrelation over the integration time of the cameras, if the seeing changed during the observations. This introduces a slight dependency on atmospheric conditions that is not removed by the redundancy. It can be removed in the hybrid mapping procedure used for the image reconstruction. The effect results mainly in a lower dynamic range in the final images.

With these boundary conditions of optical instrumentation, detector and data acquisition system and reduction software set, we could study the feasibility of the instrument for actual observations. The ability of a pupil plane configuration to match the coherence area at the reduction stage turned out to be not critical in terms of limiting magnitude (section 10.4). We could still use the matching to get the same known amount of decorrelation in different observations. The other main advantage of the pupil plane system is the option to track seeing cells as they move over the pupil, thus extending the effective integration time. This requires zooming on a dominant layer of turbulence. We found strong indications that multiple dominant layers are present most of the time. We verified this in a specific experiment (section 10.5). We found indeed two well separated layers of turbulence, with different properties. Although the lifetime of seeing cells was shown to be larger than the coherence time (a necessary condition for seeing cell tracking) we concluded that seeing cell tracking cannot be generally used. Making images of stellar objects (Chapter 11), we suffered from additional decorrelations. The main sources were found to be delay errors in the optics, atmospheric turbulence within the fixed integration time and (in some cases) smearing of integrated visibility peak due to wavefront tilts over the apertures. We were able to construct images with more than 1:40 dynamic range for a 3.6 magnitude star, with a five aperture configuration. Imaging of a fainter system (components closer than 0.2 arcsec, total magnitude 4.5) in an eight aperture configuration gave much worse signal to noise, but produced results with a dynamic range of 1:10. This lower value is explained by the loss of contrast due to the larger number of strong components in the source and due to the fact that we used more apertures.

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Summarizing we can say that the instrument has been shown to work indeed. Some of the theoretical advantages of the pupil plane approach turn out to be of less practical value, due to instrumental effects and the nature of atmospheric turbulence. The pupil plane system is in principle well suited for high resolution observations. The complicated optics make it difficult to operate. Although none of the many optical elements (apart from the segmented lenses) is critical, it is very difficult to verify the influence of each individual element experimentally.

Regarding the few imaging results that have been produced so far, a few points should be stressed. During all our sessions on the telescope, we had moderate seeing conditions at best. With better seeing, the instrument can be expected to behave better. The larger coherence volume will give higher signal to noise within a single integration time. Effects of wavefront tilts over the apertures (the *dancing* of peaks mentioned in section 8.3) and scintillation will be less, making the integration of frames more efficient. With the present conditions, we had low signal to noise in individual frames even for the brighter objects. Secondly, we had only two observing sessions with proper segment lenses. Finally, more objects have been observed already. Preliminary examination shows that the observational material is of sufficient quality to allow for proper reduction and image reconstruction. We are currently processing observations of P Cygni, for which we earlier found indications of asymmetry on intermediate resolutions (Chapter 12).

Regarding the spectral imaging approach, we can make only preliminary conclusions. The dual channel setup was tested for the image sharpening observations described in Chapter 12. We also tested the "tilted filter" approach for scanning a spectral line. It is as yet unclear whether we will be able to get a spectral calibration with sufficient accuracy. Also, a number of questions related to combination of the channels require a more thorough investigation.

## 14.2 Evaluation of SCASIS in terms of project development

SCASIS was a rather ambitious project to be started by a small group with little optical experience. This was realised from the beginning, and was a prime motivation in the decision to work on the GHRIL facility. This approach has been successful indeed. The flexibility offered by the optical table and general infrastructure allowed us to align the complicated optics without the additional constraints that are present in more rigid and less accessible prototypes. In four observing sessions the design converged to a stable and working prototype. This is certainly not much time, compared to the normal commissioning of other instruments.

It is true that this same flexibility tempted us to perform tests on the telescope that had better been done in the lab. A lot of effort has gone in correcting the effects caused by manufacturing errors in the segmented lenses. Without the possibilities of GHRIL, we would have been forced to wait for better optics. This certainly would have delayed the project, but would have made observations and reduction more easy. However, without the possibility of on-site experimenting and development, we would not have been able to produce actual imaging results within four years. I should note here that the original GHRIL concept included an off-site laboratory for testing.

In general, the project evolved more slowly than planned. This was partly due to complications in the optical design. We also had to construct the video data acquisition system for GHRIL ourselves, which could not have been anticipated. Data of sufficient quality for imaging were obtained only in 1990. Fortunately, by that time an Alliant FX80 mini-super computer with sufficient disk-space was available at the Kapteyn Laboratory. Networking facilities, especially for transfer of mass data from the PC had improved sufficiently, as was anticipated in the project planning. In this respect, the delays worked out in our advantage, since we could do the mass-processing more efficiently.

## 14.3 Current mainstreams in High Resolution Imaging

Before we can look into possible extensions of the SCASIS project, we need to have a look at the broader context in which such extensions should fit.

High Resolution Imaging is a developing field in astronomy. For a long time, activities in this field were driven by interest in instrumentation rather than by astronomical demands. Currently, there are several instruments in operation, producing results on a routine basis (mainly double star separations and stellar diameters, see e.g. Quirrenbach *et al.*, 1991 and Ridgeway, 1991). Specific astronomical questions can now be addressed.

Historically, there are three distinct approaches towards optical interferometry. Speckle techniques use the full aperture of a large telescope. Multi-element interferometers combine the light from a number of distinct apertures. Single telescope systems like SCASIS closely resemble the multi-element approach, but define subapertures in a single large telescope. They form compact arrays, often with more baselines than multi-element configurations. Phase closure and redundancy techniques have been first evaluated on such systems, and are now being incorporated in a number of multi-element applications.

Rather recently, a different class of instruments is becoming available, where high resolution is obtained on-line in direct imaging systems. These telescopes use so called adaptive optics, with active mirrors correcting for wavefront distortions (eg Rigaut *et al.*, 1991). The wavefront sensors yielding the necessary input information need not to be bandwidth limited. This is a major advantage over interferometric systems. In fringe detecting systems, with the fringe frequency scaling with wavelength, bandwidths need to be small to prevent smearing of fringes (bandwidth decorrelation). The sensitivity is proportional with the coherence volume (aperture size times integration time) and the bandwidth. Adaptive optics systems can be more sensitive than fringe detecting systems.

The Hubble Space Telescope (HST) is also a direct imaging system, where the high resolution is obtained by putting the telescope in orbit outside the atmosphere. It is interesting to see how the spherical abberation in the HST primary mirror causes a PSF that resembles the one for an image sharpening or partial adaptive optics system (Beckers, 1991). The diffraction limited information is present in a sharp peak sitting on a broad plateau. Of course the PSF of the HST is stable in time, whereas the PSF of ground based systems is dependent on atmospheric conditions. The main effect of the spherical abberation is that more time is needed to build up sufficient signal to noise in HST observations. In ground based systems, we need to measure the instantaneous PSF, which is difficult since atmospheric conditions can change on relatively short timescales.

With ground based 8 meter class telescopes equipped with adaptive optics and designed to minimise dome seeing, one can observe most of the sources now being looked at with intermediate size interferometers. Of course, to get accurate information on submilliarcsecond scales, long baseline optical interferometers are needed. Since such telescopes and interferometers become more generally available now, there will be less and less need for complicated interferometric systems that get to the diffraction limit of a conventional 4 meter class telescope.

However, even with the current state of partial adaptive systems there is clearly a future for ground based high resolution imaging on baselines up to a few meters. There exist many objects with interesting structure at scales of 0.1 to 0.01 arcsec (see e.g. Ridgway, 1989). Most of them will not be studies with the HST, and some of them will be hard to study with present day adaptive optics systems. I would like to highlight one possible application for which single telescope interferometers are very well suited: the long term monitoring of specific objects, preferably in a limited number of spectral lines. In my view, such monitoring will be done most efficiently with simple instruments operating on a regular if not continuous basis. Such systems can profit from patches with good seeing in an optimum way. Whether such instruments should use a multi aperture approach is a different question.

## 14.4 Possible extensions and applications for SCASIS

Within the general context thus set, what more can be done with the SCASIS interferometer?

From the summary given in the first section, we can conclude that the SCASIS interferometer in its present state is not feasible for use as a common user instrument. From the previous section we conclude that it is not worthwhile to spend an additional amount of manpower and funding in changing or improving the present set-up. This does not prevent us from using it to observe specific objects of magnitude 6 or brighter with dynamic ranges up to 50. Apart from the observational material that is currently being processed, other objects of astronomical interest could be observed as well. Interested astronomers should realise however, that there is as yet no such thing as "Service Observations with SCASIS". Pilot observations using first order techniques like image sharpening are highly recommended to provide information on intermediate resolution. Observations with three apertures should be made to get a first impression of the extent of the source structure. This is necessary in particular for spectral observations. The object of interest should be observed at more position angles than we used so far (at least eight). Preferably, the object should be observed multiple times during the observing session, allowing for selection of the best data and consistency checks. The over-redundancy present even in a five aperture configuration allows for reconstruction of interferometer phases with a number of internal consistency checks.

It is clear that the concept of spectral imaging with a dual channel system can be further explored. At the moment, only few instruments can make spectral observations with high spatial resolution. Proper evaluation of the SCASIS spectral mode will therefore add information that is not available from other sources. Existing observational material can be analyzed to demonstrate the feasibility of the line triple approach. However, we think that proper implementation of the spectral mode at higher spectral resolutions needs to be driven by astronomical interest in specific sources. As was mentioned above, independent pilot measurements are highly recommended.

The SCASIS interferometer can also be used to analyze the general behaviour of interferometric systems with limited support in spatial frequencies. Such analysis in terms of dynamic range and signal to noise would give relevant information for the design of e.g. telescopes with partial adaptive optics. The over-redundant pupil plane configuration makes the SCASIS interferometer well suited for such experiments, provided delay errors in the segmented lenses can be reduced.

## 14.5 A Twin Spectral Image Sharpening facility

What kind of participation beyond SCASIS could the Dutch astronomical community have in High Resolution Imaging?

Extension of the SCASIS interferometer to a common user instrument is not feasible. As mentioned earlier in this chapter, the development of new interferometric systems on 4 m class telescopes is not very efficient with the increasing number of well designed large telescopes with adaptive optics. The construction of a long baseline multi-element interferometer is a major investment in manpower and funding, and requires a lot of expertise. Such a project could only be started in an international collaboration. An obvious approach would be to look into a Dutch involvement in the VLTI, the interferometer extension of the VLT.

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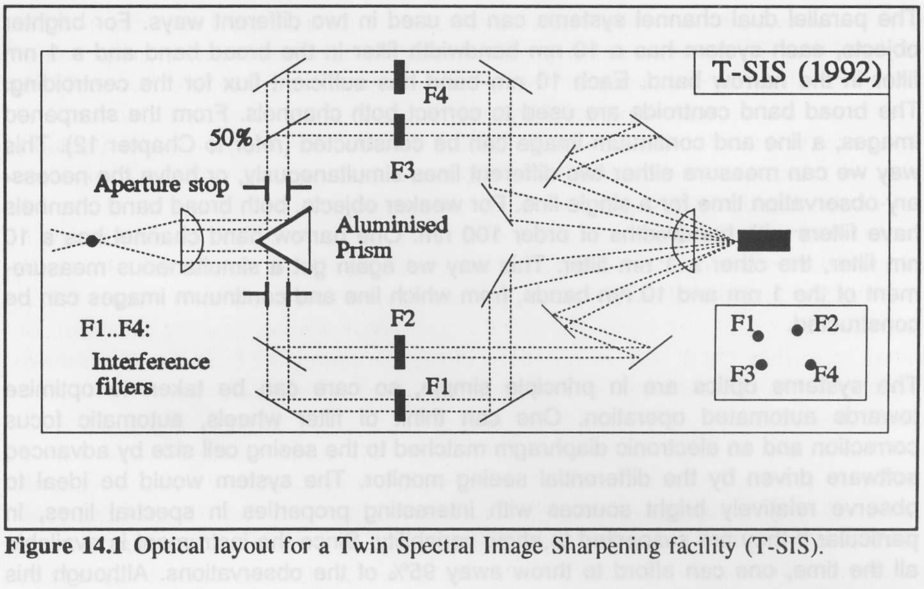

**Figure 14.1** Optical layout for a Twin Spectral Image Sharpening facility (T-SIS).

However, we can think of smaller instruments yielding interesting science at an intermediate resolution for a wide range of objects. At the end of this thesis I would like to elaborate a bit on such an instrument, following a suggestion originally made by Jan Noordam. Although the instrument is not an interferometer, it incorporates many of the tools developed for SCASIS.

Suppose we have a 1 meter class telescope, with a focal station that is available to us all the time. On that focal station a simple two aperture dual channel setup can be made (Figure 14.1). The system closely resembles the Spectral Image Sharpening setup described in Chapter 12. An image is formed in each quadrant on the detector. Since the system has two apertures, we have in fact two dual channel systems operating simultaneously.

The system will primarily be used for Spectral Image Sharpening of a selected number of objects. On-line analysis of differential motion of the two broad band channels gives continuous seeing estimates. Experience with SCASIS learns that even though the apertures are rather large (matched to $3r_0$) the seeing estimates are accurate enough to be used for e.g. long term site evaluation. Primarily however, the seeing and scintillation data will be used to find the patches with the best seeing, and flag them for processing. I suggest that the instrument stores the video data continuously during the night and makes on-line seeing analysis. The best few hours of observations found for a night are sharpened during daytime. This brings down the datarate from five videotapes per night to some ten sets of images. Selected patches of data could be copied to a backup videotape or video disk for further off-line processing.

The parallel dual channel systems can be used in two different ways. For brighter objects, each system has a 10 nm bandwidth filter in the broad band and a 1 nm filter in the narrow band. Each 10 nm band has sufficient flux for the centroiding. The broad band centroids are used to correct both channels. From the sharpened images, a line and continuum image can be constructed (refer to Chapter 12). This way we can measure either two different lines simultaneously, or halve the necessary observation time for a single line. For weaker objects, both broad band channels have filters with bandwidths of order 100 nm. One narrow band channel has a 10 nm filter, the other a 1 nm filter. This way we again get a simultaneous measurement of the 1 nm and 10 nm bands, from which line and continuum images can be constructed.

The systems optics are in principle simple, so care can be taken to optimise towards automated operation. One can think of filter wheels, automatic focus correction and an electronic diaphragm matched to the seeing cell size by advanced software driven by the differential seeing monitor. The system would be ideal to observe relatively bright sources with interesting properties in spectral lines, in particular if they are suspected to show variability. Since the instrument is available all the time, one can afford to throw away 95% of the observations. Although this sounds like a waste of telescope time, it is certainly more effective than spending a long time to improve intrinsically bad data.

A twin spectral image sharpening facility may not have the flavour and political attractiveness of an eight element long baseline interferometer. However, the advanced software and hardware that are necessary for automated operation are a challenge in themselves. The systematic astronomy that could be done with such a system is so even more.

I would like to stress once more that even a relatively straightforward system like this should be primarily motivated by specific astronomical questions, and be developed such as to give the answers to those questions in an optimal way. The results of Chapter 11 and 12 leave sufficient open questions to motivate further research in the objects mentioned there.