SOLAR OPTICAL INTERFEROMETRY

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Abstract. Optical interferometry has numerous applications in stellar and extragalactic astronomy. It also offers the potential for unique solar observations. This review describes current and planned activity in these areas and some possibilities for the future.

Key words: infrared: stars – stars: imaging – Sun: general – techniques: interferometric – telescopes

1. Introduction

Astronomers recall fondly, in their community memory, Michelson's work at Mount Wilson, in which he achieved optical interference between two apertures to measure the angular diameters of several stars. His feat had long since attained the status of legend before it was revisited by radio astronomers and eventually elaborated into a powerful technique for radio imaging. Now it is the turn of the optical (and infrared) communities. The decreasing cost of computers and electronic control and improvements in detectors have made it feasible to build optical telescope arrays which achieve aperture synthesis and very high angular resolution, far beyond any plausible filled-aperture facility. The same techniques have potential applicability for ground- and space-based solar astronomy.

2. What is Interferometry?

Interferometrists work in Fourier space (the infamous u-v plane), use multiple telescopes or strange aperture masks, and are always worried about determining "phase". They are viewed with something between awe and suspicion, as it is not always clear whether they are specialists of an esoteric technique, or masters of obfuscation.

Perhaps it is worth recalling that image formation through a lens may be regarded as an interferometric process, with a series of Fourier transforms from the source to the telescope pupil and then to the image. Surely nobody would give up the simplicity of image formation with a lens or mirror without a good reason. But in fact there may be good reason, when the desired aperture can not be constructed, or when the atmosphere disturbs the image formation process. Then the only solution may be to disassemble the image formation process into its component parts, and exert greater control over them. Thus, to paraphrase von Clausewitz, interferometry is image formation by more vigorous means. A broad view of high resolution imaging, as seen by nighttime astronomers, will be found in *Diffraction-limited Imaging with Very Large Telescopes* (Alloin and Mariotti, 1989). The most recent major meeting on astronomical interferometry was held at ESO headquarters in Münich in 1991 (Beckers and Merkle, 1992).

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To put solar optical interferometry in context, we will recall briefly the development of radio interferometry for lessons which may apply to optical interferometry and then describe developments in stellar interferometry and recommendations of the Astronomy and Astrophysics (Bahcall) Committee. We will mention some early experiments in solar interferometry, speculate on opportunities for ground-based and space solar interferometry, and describe a specific proposal for space optical interferometry, the SIMURIS mission.

3. Radio Interferometry

It is somewhat more than 4 decades since the first tentative steps toward radio interferometry (Ryle and Vonberg, 1946; Sullivan, 1991). The first efforts simply recorded fringes between two antennas. The first results were visibility curves, obtained from fringe modulation as a function of telescope separation. Visibility curves are difficult to interpret except for the simplest sources, and the first results were merely estimates of or limits on source angular sizes.

Once it was realized that radio interferometry was not particularly difficult to do, at least at longer wavelengths, progress was rather rapid. The addition of phase allowed proper inversion of visibility information to provide first one-dimensional and then two-dimensional maps. The information content of these maps was limited by the amount of information that could be obtained by a small number of telescopes in a reasonable length of time. It was understood, however, that the information content would increase with the square of the number of telescopes; this gave great motivation to construct many-telescope facilities, of which an outstanding example is the Very Large Array, with 27 telescopes in a reconfigurable layout (Thompson *et al.*, 1980). Another imaging radio telescope, familiar to the solar community, is the Culgoora Imaging Solar Radio Telescope in Australia (Wild, 1967).

Since the development of the VLA, much of the progress in observational techniques for radio astronomy has been in algorithms for image reconstruction from noisy data and incomplete coverage of the spatial frequency (u-v) plane. For example, the CLEAN algorithm (Clark, 1980) for deconvolving a "dirty" beam from an observed image has achieved great success in processing of radio images, and has been adopted for many other, non-radio-astronomy applications. Techniques of phase closure and other constraints on image formation have been exploited. The result is that the VLA is now capable of producing mega-pixel, high-dynamic-range maps which, by any definition, deserve to be called images, although they are synthesized in a computer one element at a time.

The "frontier" of radio astronomy now has moved on to ultra-high resolution (VLBI, VLBA) and to other wavelengths (millimeter and sub-millimeter arrays). Some radio interferometrists have even taken an interest in optical interferometry!

4. Optical-IR Stellar Interferometry

Optical interferometry in astronomy began with work by Michelson and Pease to measure the diameters of several bright stars (Pease, 1931). Michelson achieved an optical baseline of several meters, necessary to resolve stars like Aldebaran, by clamping a steel beam across the top of the Mount Wilson 150-cm Telescope and putting some mirrors on it. In a logical follow-up, Pease built a 15-m stand-alone system. It was abandoned after a number of years (and has remained, rusting, on Mount Wilson) apparently because flexures were too great for control techniques available at that time.

The most urgent scientific extension of Michelson's work was the determination of the diameters of some hot stars, and this was achieved by Hanbury Brown, who developed the intensity interferometer (Hanbury Brown *et al.*, 1974). However, the high-order photon correlation observed in the intensity interferometer is too weak for any but the brightest and hottest stars, and is not generally applicable.

The next advance was accomplished by Antoine Labeyrie. Fresh from his triumph in the development of speckle interferometry, Labeyrie decided that interferometry between independent telescopes should be easy to achieve, and he proceeded to demonstrate that, if not trivial, it was at least neither difficult nor expensive.

In the subsequent decade, several groups entered the field with prototype optical and infrared interferometers. The typical prototype project began with a plan to deploy an array of 3 to 5 or more telescopes, but slipped back to 2 telescopes, "just to show feasibility and get the funding flowing." Unfortunately, funding has not flowed liberally for these programs, and more than one has closed its doors shortly after achieving successful operation.

Table 1 summarizes the major features of the optical interferometers which are currently in operation, or are in such an advanced stage of construction that completion is virtually certain. All entries down to SUSI have obtained interferometric operation, though some have since closed due to lack of funds or entered a phase of instrument improvements which precludes operations at this time.

I believe that none of these interferometers has operated on anything except stars (including circumstellar shells). The brightest extragalactic sources are within reach of a 1-m telescope, but may require some degree of wavefront correction – a technique which is still in its infancy.

Figure 1 is a photograph of the Sydney University Stellar Interferometer (SUSI). The white pipe is the enclosure for the optical beam propagation between telecopes. Conceived specifically for measurement of stellar angular diameters and binary orbits, SUSI has an optical baseline up to 640 m, giving an angular resolution of 0.2 *milliseconds* of arc. SUSI is currently operational with baselines to 50 m.

Now having experience with a variety of interferometric techniques at a considerable number of facilities, the interferometric community seems to have agreed with Labeyrie that it is relatively easy to obtain interference fringes between two telescopes. Thus, what might have seemed the greatest obstacle is not such. However, it is considerably more difficult to extract information in volume of adequate quality and with suitable calibration to address a range of scientific problems. Recent work in optical interferometry has emphasized systems issues related to efficient data collection, control of instrument configuration, and monitoring of atmospheric conditions. This work has met with considerable success, but with increased engineering costs.

The phase closure techniques, which are critical for interferometric imaging through the atmosphere at optical wavelengths, require three or more apertures.

TABLE I
Some contemporary optical interferometry projects

Facility Name	Location	Number of Telescopes*	Telescope Aperture	Baseline (Maximum)
I2T	Côte d'Azur	2	27 cm	140 m
GI2T	Côte d'Azur	2	150 cm	70 m
SOIRDETE	Côte d'Azur	2	100 cm	15 m
Mk III	Mt. Wilson	2	165 cm	34 m
ISI	Mt. Wilson	2	8 cm	32 m
IRMA	Wyoming	2	20 cm	19 m
COAST	Cambridge	4	40 cm	100 m
SUSI	Sydney	2	14 cm	640 m
IOTA	Mt. Hopkins	2	45 cm	45 m
BOA	Flagstaff	6	35 cm	470 m
NRL/USNO	Flagstaff	2	100 cm	40 m
VLT-VISA	Cerro Paranal	3	180/800 cm	200 m

*Number (to be) combined simultaneously

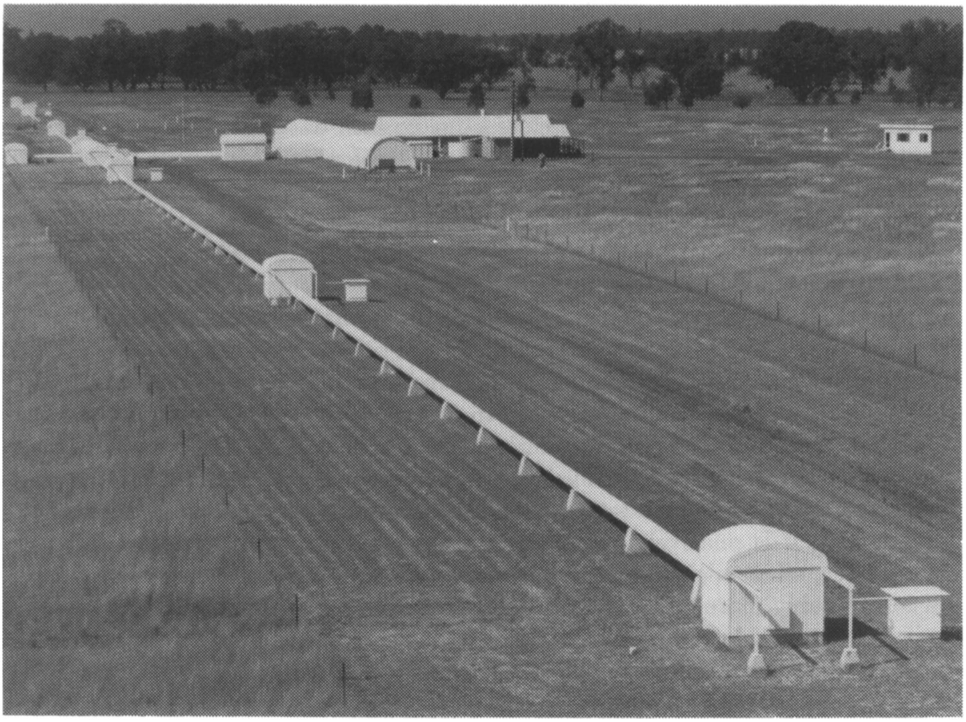


Fig. 1. The Sydney University Stellar Interferometer. The interferometer has many telescope stations, and combines the telescopes pair-wise to obtain one-dimensional visibility, but (initially) no image phase information.

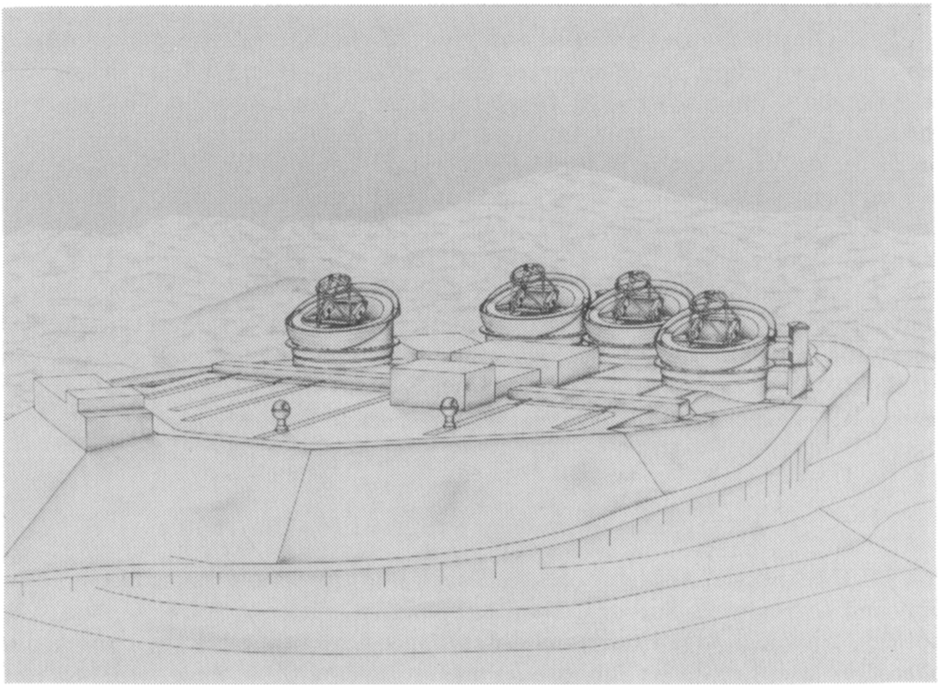


Fig. 2. The Very Large Telescope and auxiliary array to be deployed on Cerro Paranal in northern Chile by the European Southern Observatory.

Such observations have been obtained optically, using masks over large telescope apertures. Somewhere between a simulation and a demonstration, these observations confirm that phase closure works at optical wavelengths and in fact radio astronomy reduction packages can be used for optical data. Unfortunately, no working interferometer yet provides for the combination of three independent telescope beams, owing primarily to limited funding. This demonstration is eagerly awaited, and expected within the next few years.

Of the numerous optical-interferometry projects in progress, the Very Large Telescope array, under construction by the European Southern Observatory, is an outstanding example. The array will consist of four 8-m telescopes, each equipped with adaptive optics to provide a coherent pupil. In addition, there will be (initially) three telescopes of approximately 1.8-m aperture, movable between stations to improve coverage of the u-v plane. Figure 2 shows a line drawing of a layout which is expected to correspond closely to the final design. Ground has been broken and funding for the entire array has been approved.

In spite of the many strong analogies between optical and radio interferometry, one dissimilarity remains, to optical interferometry's detriment. The existence of phase-coherent amplification for radio waves provides for great flexibility in a combination of telescopes. The non-existence of such amplifiers at visible wavelengths (perhaps in principle) means that optical interferometry of faint sources will "gain" only linearly with the number of telescopes.

The scientific programs carried out with optical-IR interferometers are too extensive to review here. A recent survey (Ridgway, 1992) describes work in several areas. The most immediate results are obtained in observations of binary stars, where the model is especially simple. Interferometric observations provide unprecedented precision for binary orbits (Armstrong, 1991). Stellar angular diameters are easily determined, and with careful work excellent results may be obtained (Mozurkewich *et al.*, 1991). The choice of model, especially assumptions about limb darkening, is critical (Quirrenbach, 1992). Circumstellar envelopes may be studied with some ease, as the central "point" source gives a good phase reference. Recent results include observations of details of the dust shells in cool stars of several types (Danchi *et al.*, 1990), and of the gaseous hydrogen disk in a B emission type star (Mourard *et al.*, 1989). Interferometry has also advanced the state of the art in positional astrometry, using interference fringes with respect to a constant telescope baseline (Shao *et al.*, 1990).

5. An Interferometry Program for the 1990's

In 1991 the National Academy of Sciences released the decade report of the Astronomy and Astrophysics Survey Committee. This committee took a close look at new optical technologies, and convened a panel specifically to study the opportunities offered by adaptive optics and interferometry. Both of these areas were prominent in the AASC recommendations (National Research Council, 1991).

In interferometry, two moderate scale programs were recommended. For the ground, the committee recommended support for several optical and infrared interferometers, particularly including one facility of 3-5 apertures of order 2 m, leading into a program for the next decade to build a very large optical array.

In space, the committee recommended an astrometric interferometry mission, with a capability of achieving positional accuracies of a few microarcsec. This was the only new mission specifically recommended by the AASC, which, however, strongly supported several missions continuing from the previous decade. In the longer term (and it seems further away every year) discussion of possible astrophysics observations from the lunar surface commonly mentions interferometry as a possibility, and it is indeed an excellent match, providing a large, firm platform with low temperatures, clear skies and long nights. The scientific case is very strong. Figure 3 shows a NASA artist's sketch of one concept for a short-baseline, ultrasensitive interferometric optical array.

6. Motivation for Solar Optical Interferometry

Interferometric techniques will most likely be of interest for achieving high angular resolution. This could involve interferometric techniques used with a single, filled aperture, in order to achieve the full aperture-limited resolution. It could also be applied to an array of apertures.

Von der Lühe and Zirker (1988) have discussed the scientific goals for solar interferometry and some of the possible limitations. They note, for example, that

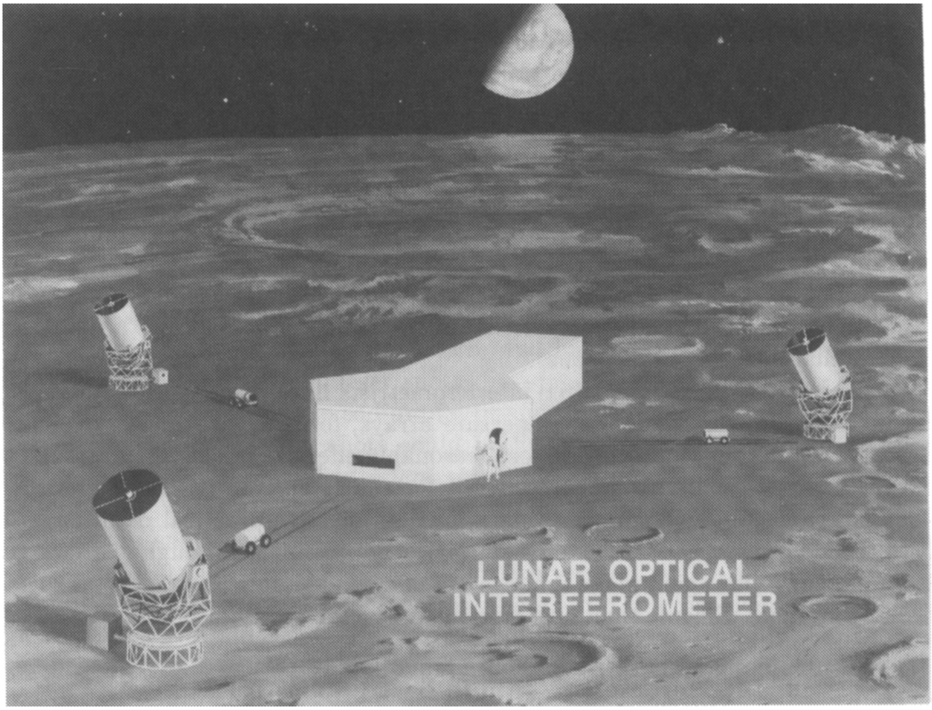


Fig. 3. A concept for a lunar optical interferometer. Not for this decade, but perhaps in the next century.

sub-arcsec resolution will be required to resolve the spatial scales of acoustic waves in the convection zone and that resolution of 0.1″ or better may be required to resolve magnetic flux tubes. They emphasize the requirements for high spectral resolution and polarimetric information. They also provide a very important discussion of the probable lifetime of spatial structure as a function of angular size and conclude that the observation time to construct a single image must be severely limited, perhaps to ~10 s, to avoid change in the structure.

Von der Lühe and Zirker also compute the photon noise-limited angular resolution for several cases, and conclude that achievable resolutions may be only about an order of magnitude better than today's routine capability of about 1″. However, this conclusion is for the specific case of granulation and for $S/N = 1$ in the spatial power plane, which is probably a more severe condition than encountered in typical image structure.

7. Passive Interferometry of the Sun

Interferometric techniques have been used to study solar surface structure for several decades, with increasing instrumental sophistication. Harvey (1972) used short photographic exposures to record fringes formed between a pair of apertures defined with a pupil mask at the McMath solar telescope. Subsequent work with the multi-aperture Michelson technique emphasized understanding of the technique and calibration of the power spectra (Aime *et al.*, 1975, 1977; Aime, 1976).

There has also been extensive work with "speckle" analysis of short exposure images, including one-dimensional images obtained by rapid scanning and conventional electronic images. These observations have emphasized acquisition of properly calibrated spatial power spectra, especially for the study of solar granulation on a scale beyond that which is accessible in direct, conventional imaging. For a recent account with references to earlier work, see von der Lühe and Dunn (1987). Attempts to use speckle analysis to recover two-dimensional images of the solar surface do not appear to have been very productive. The absence of a point source within the isoplanatic angle is a serious drawback in comparison with many successful stellar speckle observations.

In the last few years, nighttime interferometrists have made considerable progress in the use of non-redundant aperture arrays, formed with masks over large telescopes, to obtain phase closure and reasonably effective image restoration. This concept has been explored in some detail for the solar case (Zirker and Brown, 1986; Zirker, 1987) with simulated data, but an effective practical demonstration is still needed. This would certainly appear to be possible, although the lack of a point reference may again make the case of the extended, low-contrast solar surface enormously more difficult than observations in the vicinity of a bright star.

8. Interferometric Ground-based Solar Telescopes

The largest solar telescope today is the McMath-Pierce 1.5-m telescope on Kitt Peak. At this conference we have heard about a proposal to upgrade this facility to a 4-m aperture (Livingston, 1993). A 4-m aperture would have a diffraction limited resolution at 2.2 μm of $0.1''$, or about 100 km at the solar surface. Considering the advanced state of development of 4-m mirror technology at this time and the rapid progress of several strategies for monolithic or segmented 8–10 m apertures, it would seem that the filled aperture telescope would be the natural and preferred solution for high spatial resolution at visible and near infrared wavelengths.

In order to achieve $0.1''$ resolution at 12 μm, a telescope diameter or baseline of 20 m would be required. Thus, very high resolution at long wavelengths is perhaps the most plausible motivation for very large telescope baselines. Livingston (1993) summarizes a number of interesting reasons for achieving high spatial resolution in the 10–12-μm spectral region.

A monolithic interferometric array, such as the MMT or binocular Columbus concept, would be possible at the 20-m scale, but perhaps better suited to a solar furnace than to a solar telescope, with the long focal lengths normally used for solar astronomy. A distributed array would be the natural solution to a requirement for optical baselines of order 10 m or larger. These baselines are very modest compared with the requirements for stellar astronomy (tens to hundreds of meters) and the optical tolerances at the longer wavelengths are somewhat more forgiving than in the visible. Therefore, it is reasonable to believe that a ground-based infrared solar interferometer would be a feasible project and perhaps easier to build than some of the interferometric systems already under construction for stellar astronomy.

8.1. LASER REFERENCE STARS

There is considerable interest in the nighttime astronomy community regarding the possible use of lasers to form artificial reference stars high in the atmosphere (Fugate *et al.*, 1991; Humphreys *et al.*, 1991). For example, a laser tuned to the wavelength of the sodium D line can be focused at the altitude of the layer of neutral sodium atoms in the atmosphere, about 100 km, to form a resonant scattering source with an apparent size from the ground of about $1''$. Of course the Sun has a V magnitude of -26.7, which is considerably brighter than the laser spot. However, in intensity, the laser gains about 16 magnitudes from surface area, about 13 magnitudes from bandwidth, and 0.7 magnitudes in polarization, leaving the Sun at an equivalent magnitude of about $+3$ per laser spot size and bandwidth when the laser is on. This is brighter than current laser spots, but considerably fainter than the spot that would be produced if the sodium layer could be excited to saturation. Lower altitude, Rayleigh scattering spots could be brighter. So an application of lasers for solar adaptive optics and interferometry, while improbable, is not out of the question.

However, a subtlety of the laser guide star technique is that the laser spot gives no direct information about the tilt and piston errors, which probably must be determined from a source above the atmosphere. Also, the problem of isoplanatic angle remains to be addressed. Therefore use of lasers may potentially change some of the parameters, but it doesn't eliminate the fundamental requirement to register wavefronts in space and time using the solar image as a reference.

9. Solar Imaging from Space

In space, the atmospheric turbulence is eliminated, although flexure of spacecraft structure due to tidal and temperature effects may impose analogous disturbances. In space, apertures of even 2 m are currently considered to be large and expensive. An array of small apertures operated as an interferometer might offer an interesting alternative to a large, filled aperture. In fact, one such configuration has been studied in some detail.

9.1. SIMURIS

A concept for a four-aperture spatial interferometer for solar studies (Dame *et al.*, 1987) has been developed in a pre-Phase-A study titled *Solar, Solar System and Stellar Interferometric Mission for Ultrahigh Resolution Imaging and Spectroscopy*, or SIMURIS (Coradini *et al.*, 1991).

The concept incorporates four telescopes of 20-cm individual apertures, arranged in a non-redundant configuration with a maximum baseline of 200 cm. The proposed arrangement is a linear array. The combination of aperture and baseline dimensions is chosen to completely "fill" the u-v plane along one axis – that is, all possible baselines from 0 to 200 cm are available simultaneously in one dimension. Figure 4 shows the geometric cross-section of the aperture, clearly illustrating the extent to which the 2-m synthesized aperture is underfilled by the physical apertures. The instantaneous spatial frequency coverage of this pupil is shown in Figure 5.

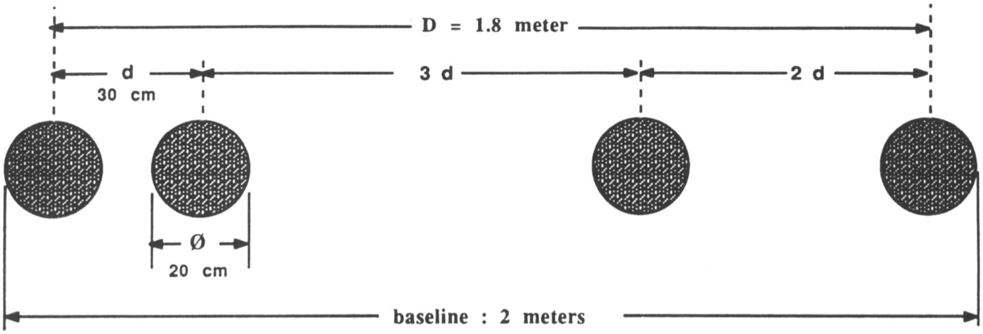
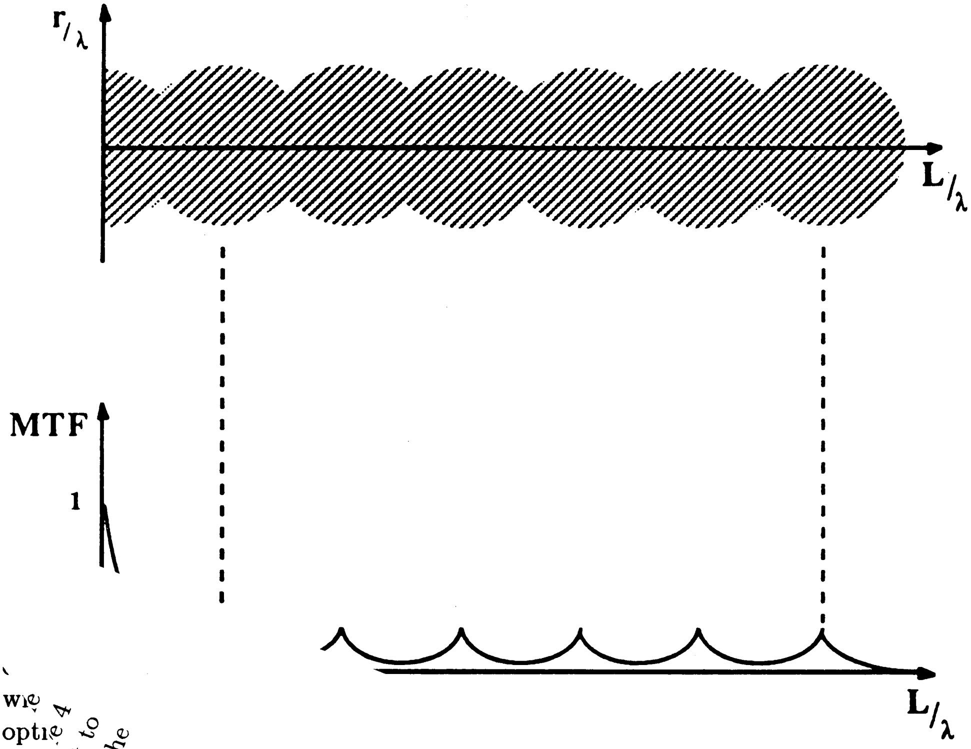


Fig. 4. The input pupil geometry of the SIMURIS high resolution imaging experiment.



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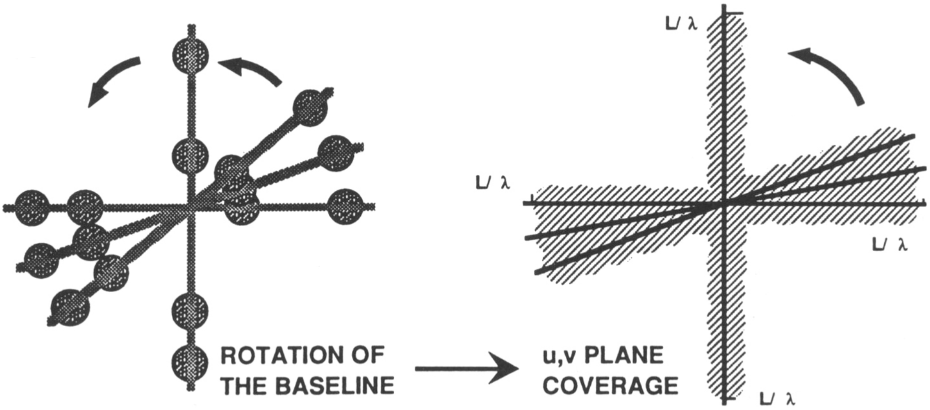

Fig. 6. Continuous baseline rotation fills the *u-v* plane enabling aperture synthesis.

This selection of geometry offers several advantages: Since complete spatial frequency coverage is available in one dimension in a single "snapshot", it is not necessary to change telescope separations, and there are no gaps in the spatial frequency map, which improves the concentration of the point spread function. Complete spatial frequency coverage to the array limit is achieved in two dimensions by rotating the array and recording data at a number of position angles (rotational aperture synthesis). The use of an array of small telescopes makes it possible to obtain the spatial resolution of a 2-m telescope in a package which is much smaller than would be required for a 2-m solar telescope with filled aperture – and hopefully also less expensive. Figure 6 illustrates the mapping of baseline rotation into *u-v* plane coverage. The spatial resolution expected is 30 km on the Sun in the visible, and 10 km in the UV. Observing time is 1 second for a snapshot (with the 20 cm × 200 cm aperture), and one minute for a rotational-synthesis, full-aperture observation.

(The SIMURIS concept also includes other systems and operating modes for imagery and spectroscopy, which are outside the subject of this discussion and will not be recounted here.)

The SIMURIS optical design incorporates beamsplitters to allow pair-wise recombination of the telescopes in 4 pairs. A phased condition is achieved by monitoring and controlling the optical path difference in each pair. In order to have high contrast interference fringes, the four component telescopes must point at the same location on the solar surface to within some fraction of the Airy disk diameter of the 20-cm apertures.

The SIMURIS technical study includes an interesting discussion of two alternate configurations for a space solar telescope: a filled aperture and an MMT concept. The difficulties of these two options are certainly imposing. The interferometric array doesn't have large or expensive mirrors, but it does have a large number of components. Interferometrists and solar astronomers will be interested to learn what the space agencies can do with this kind of system.

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References

Aime, C., Ricort, G., and Grec, G.: 1975, *Astron. Astrophys.* **43**, 313.
Aime, C.: 1976, *Astron. Astrophys.* **47**, 5.
Aime, C., Ricort, G., and Grec, G.: 1977, *Astron. Astrophys.* **54**, 505.
Alloin, D. M. and Mariotti, J.-M.: 1989, *Diffraction-limited Imaging with Very Large Telescope*, NATO ASI series **274**, Kluwer.
Armstrong, J. T.: 1991, in 'Complementary Approaches to Binary Star Research', *Proc. IAU Colloq.* **135** (in press).
Beckers, J. M., and Merkle, F. (eds.): 1992, *High-Resolution Imaging by Interferometry II*, ESO Conf. Proc. No. 39, ESO, Garching.
Clark, B. G.: 1980, *Astron. Astrophys.* **89**, 377.
Coradini, M., Damé, L., Foing, B., Haskell, G., Kassing, D., Olthof, H., Mersch, G., Rutten, R. J., Thorne, A. P., and Vial, J.-C.: 1991, *SIMURIS Scientific and Technical Study - Phase I*, European Space Agency SCI(91)7.
Damé, L., Aime, C., Faucherre, M., and Heyvaerts, J.: 1987, in N. Longdon and V. Davis (eds.), *Optical Interferometry in Space*, ESA SP **273**, 189.
Danchi, W. C., Bester, M., Degiacomi, C. G., McCullough, P. R., and Townes, C. H.: 1990. *Astrophys. J. (Letters)* **359**, L59.
Fugate, R. Q., Fried, D. L., Ameer, G. A., Boeke, B. R., Browne, S. L., Roberts, P. H., Ruane, R. E., Tyler, G. A. and Wopat, L. M.: 1991, *Nature* **353**, 144.
Hanbury Brown, R., Davis, J., Lake, R. J. W., and Thompson, R. T.: 1974, *Mon. Not. Roy. Astron. Soc.* **167**, 475.
Harvey, J. W.: 1972, *Nat. Phys. Sci.* **235**, 90.
Humphreys, R. A., Primmerman, C. A., Bradley, L. C., and Hermann, J.: 1991, *Opt. Let.* **16**, 1367.
Livingston, W. C.: 1993, these proceedings.
Mourard, D., Bosc, I., Labeyrie, A., Koechlin, L., and Saha, S.: 1989, *Nature* **342**, 520.
Mozurkewich, D.M., Johnston, K.J., Simon, R.S., Huffer, D.J., Colavita, M. M., Shao, M., and Pan, X. P.: 1991, *Astron. J.* **101**, 2207.
National Research Council: 1991, *The Decade of Discovery in Astronomy and Astrophysics*, National Academy Press, Washington, D.C.
Pease, F. G.: 1931, *Ergebn. Exact. Naturw.* **10**, 84.
Quirrenbach, A.: 1992, in J. M. Beckers and F. Merkle (eds.), *High-Resolution Imaging by Interferometry II*, ESO Conf. Proc. No. 39, p. 663.
Ridgway, S.: 1992, in J. M. Beckers and F. Merkle (eds.), *High-Resolution Imaging by Interferometry II*, ESO Conf. Proc. No. 39, p. 653.
Ryle, M., and Vonberg, D. D.: 1946, *Nature* **158**, 339.
Shao, M., Colavita, M. M., Hines, B. E., Hershey, J. L., Hughes, J. A., Hutter, D. J., Kaplan, G. H., Johnston, K. J., Mozurkewich, D., Simon, R. S. and Pan, X. P.: 1990, *Astron. J.* **100**, 1701.
Sullivan, W. T.: 1991, in T. J. Cornwell and R. A. Perley (eds.), *Radio Interferometry: Theory, Techniques and Applications*, Astron. Soc. Pac. Conf. Ser. **19**, 132.
Thomasson, P.: 1986, *Q. Journ. Roy. Astro. Soc.* **27**, 413.
Thompson, A. R., Clark, B. G., Wade, C. M., and Napier, P. J.: 1980, *Astrophys. J. Suppl.* **44**, 151.
von der Lühe, O., and Dunn, R. B.: 1987, *Astron. Astrophys.* **177**, 265.
von der Lühe, O., and Zirker, J. B.: 1988, in F. Merkle (ed.), *High Resolution Imaging by Interferometry*, ESO Conf. Proc. No. 29, p. 77.
Wild, J. P.: 1967, *Proc. Inst. Radio Electron. Eng. (Australia)* **28**, 277.