Part VII

Future Ground-Based Interferometry

Chapter 18

Future Ground-Based Interferometry

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As I write, the National Academy of Science Decade Review for Astronomy is in progress. The work has been mostly done and the reports are being written. As input to this once-in-a-decade process, a lot of us working in interferometry thought there should be something on the table for discussion by this group in the area of ground-based interferometry. After asking around, it was clear that nothing was being proposed so François Roddier and I made up some notes and circulated them to colleagues. We received a few responses, and prepared a report which we submitted to the review committee. What I'd like to do in this Chapter is to describe the thinking process we went through and the conclusions we drew, and to lead you through our thoughts concerning what might be done in interferometry in the future. On the scale of the decade review, we won't concern ourselves with minor details but consider the big scale of things.

18.1 Existing Facilities and Scientific Output

The first thing we did was review what has been done in interferometry to date. I have combined in Table 18.1 a couple of tables listing the interferometric facilities that you have been reading about which are in operation, a few you probably haven't heard about, and ones which are coming into operation shortly. It's quite a list and doesn't even include prototype facilities which have closed down, or have done their thing and passed away.

The interferometers listed in Table 18.1 are on the whole, rather special purpose facilities. There isn't anything listed that one would call a general purpose interferometric facility.

Table 18.1: Interferometric Facilities of Today and Tomorrow

Facility	Name	Number of Telescopes	Aperture (meters)	Baseline (meters)
CHARA	Center for High Angular Resolution Astronomy	6	1.00	350
COAST	Cambridge Optical Aperture Synthesis Telescope	5	0.40	20
GI2T	Grand Interféromètre à 2 Télescopes	2*	1.52	65
IOTA	Infrared Optical Telescope Array	2*	0.40	38
ISI	Infrared Spatial Interferometer	2*	1.65	85*
MIRA-I	Mitaka Infrared Array	2*	0.25*	4*
NPOI	Navy Prototype Optical Interferometer	3*	0.12*	35*
PTI	Palomar Testbed Interferometer	3	0.40	110
SUSI	Sydney University Stellar Interferometer	2	0.14	640
Keck	K1–K2	2	10.0	60
Keck	Auxiliary array upgrade (NASA Origins)	4	1.8	140
LBT	Large Binocular Telescope	2	8.4	23
VIMA	VLT Interferometer Main Array	4	8.0	130
VISA	VLT Interferometer Sub-Array	4	1.8	202

Some examples:

1. The Sydney University Stellar Interferometer was built to measure stellar diameters. In fact, it has long baselines—but only on a single line. It was built under the assumption that stars are circular.

2. The CHARA Array is very well laid out for binary star work. It has large baselines, relatively large apertures for sensitivity, but not very good (u, v) coverage because the number of telescopes versus resolution is not very large.

3. The Palomar Testbed Interferometer is well suited for astrometric tests.

4. The Navy Prototype Optical Interferometer, at least the imaging part, is very well suited for imaging stars, but not for particularly faint sources.

5. The Keck and VLTI Interferometers each consist of one or more large telescopes and a few small ones but with very specific capabilities and limitations. Limitations being small baselines, few telescopes, and limited potential for expansion.

Now, with all those facilities, what has been done? Table 18.2 and Figure 18.1 show an overview of the scientific work that has come out of these interferometers. Much of this material has been described in other Chapters, so there aren't any surprises here.

Most of the work has been stellar diameters. In fact, virtually all the work has been diameter-type measurements; that is, characterization by 1 or 1.5 parameters of a distribution of generally circular, stellar, or shell-type objects. This is of course the stellar bright-source astronomy that best suits these facilities.

Table 18.2: Refereed Papers in Optical Interferometry Science

Papers by facility:		Papers by Topic:	
I2T	14	Stellar Angular Diameter	23
ISI	11	Shells of Late Type Stars	11
MkIII	16	Be/P Cyg Shells	8
GI2T	9	Binary Star Orbits	10
IRMA	3	Stellar Atmospheres	6
IOTA	5	Wide Angle Astrometry	2
COAST	3	Novae	1
NPOI	3	Cepheids	1

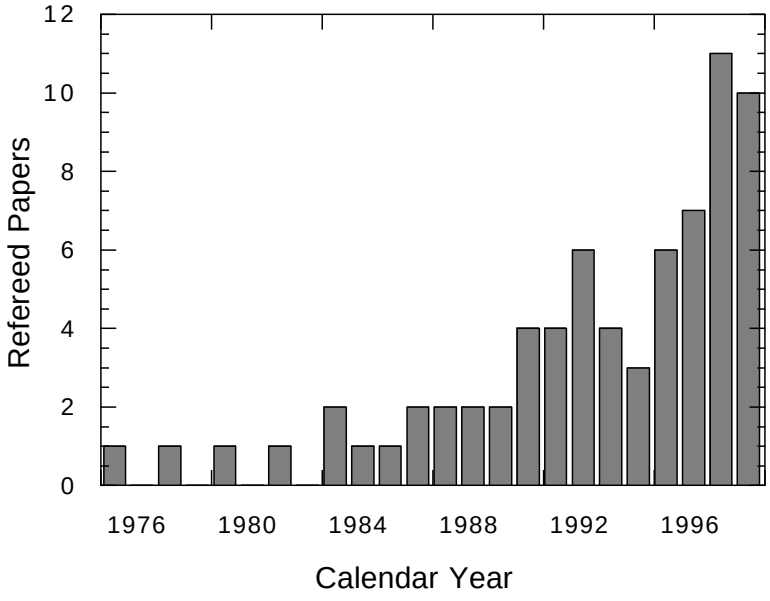

Figure 18.1: Publications of astrophysical results as a function of time.

18.2 Prospects for Astrophysics with Interferometers

We also looked over the literature of the dreams that people have described for interferometry in the future and looked at some of the scientific areas, and tried to lay out, in a visual way, some of the types of sources that one talks about observing.

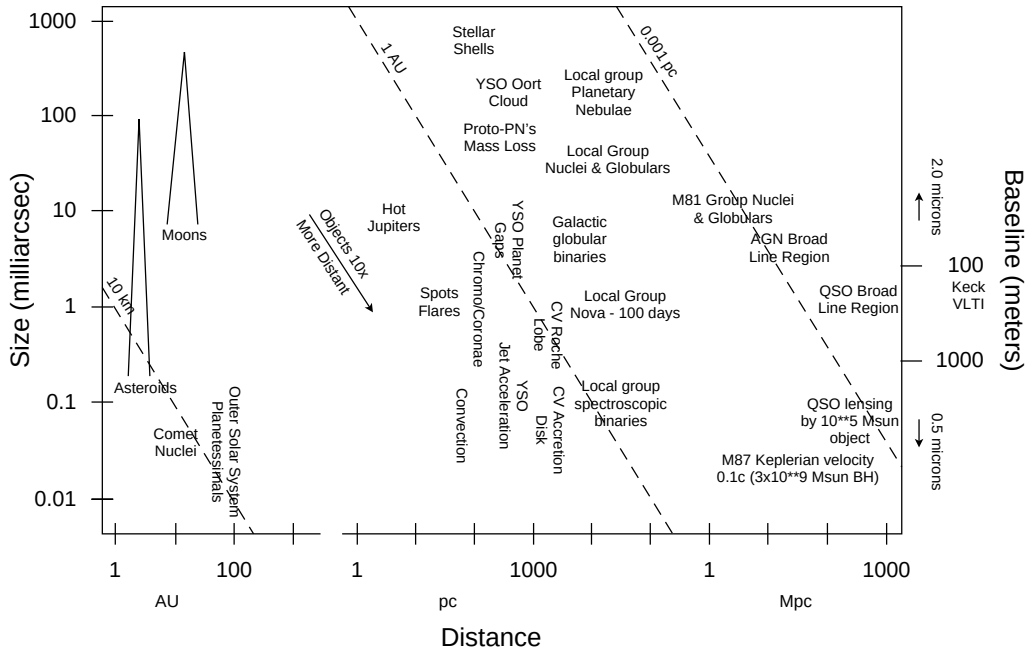

Figure 18.2: Potential astrophysical targets as a function of angular size and distance. [Reprinted from *Allen's Astrophysical Quantities*, Arthur Cox ed. (New York; Springer-Verlag, 2000).]

Figure 18.2 illustrates these thoughts. It is partly astrophysics, partly observational. For various objects the distance, from solar system out to cosmological distances, is shown along with the apparent sizes from microarcseconds to milliarcseconds. On the right-hand side there are tickmarks indicating some typical facilities, with a baseline of 1000 m indicated. Figure 18.2 is scaled for a wavelength of 1 μm, and there are changes in the scale for corresponding changes in wavelength. It is interesting to note and perhaps obvious, that the capability of high resolution beyond the 10-m aperture range (but less than something like a kilometer) does not have an infinitely broad range, and so not all science falls into an area where that particular resolution range is critical.

These are perhaps some of the typical areas we might consider. Interestingly enough, the targets that tend to push the angular resolution are small sources in the solar system and phenomena on the surface of stars. As an extreme example we might consider observations of convection on the surface of lower-luminosity stars. Phenomena that might require driving the resolution up to high or even implausibly high values for ground-based interferometry include the acceleration of jets around stars, high-energy phenomena in close binaries, and interacting binaries. What I've noted here is the resolution to start to resolve a source, but not necessarily to see lots of details on it. It is also interesting to note that a large number of potential targets fall at baselines which are not much greater than baselines provided by a large telescope.

18.3 Next Generation Ground-Based Array

Let me go through the thinking process of developing a concept for a next generation interferometric array. There are all kinds of directions one could go, for example picking an interferometer from the list of existing facilities and expanding it with more telescopes or longer baselines or putting adaptive optics on it. We thought however that we should focus on something that was more of a quantum step in capability and resolution, adequate to encompass a substantial increment in science—which is to say a capability for substantially better imaging than arrays that are now in development.

18.3.1 Near Infrared Capability

We are discussing a ground-based facility, and so it would have to be a near-infrared facility. We would, of course, need high sensitivity, because so much of astronomy deals with faint sources. If it is to be sensitive, it will have to have adaptive optics, which will work well at infrared wavelengths, but only by a stretch of the imagination perhaps at visible wavelengths. On the other hand, at the longer wavelengths as you get into thermal infrared, interferometry on the ground starts to get really tough because of the large number of reflections, and the thermal background is changing—all kinds of bizarre things going on in the facility. So the interferometer would operate at near-infrared wavelengths.

18.3.2 Baseline of ∼1000 m

What maximum baseline is reasonable for a next generation ground-based interferometer? We suggest 1000 m, maybe a little more, perhaps a little less. You don't want to be in a site where the atmospheric conditions are actually hostile to astronomy. You would like to be on the best possible site, so 1000 m is a compromise, but which provides a tremendous resolution—straight brute force resolution of 200 μas at 1 μm. As you have probably seen already, if you want to simply parameterize a source, let's say a characteristic diameter, with a baseline of 1000 m you can easily expect to go a factor of 10 beyond simply resolving it. We're talking about measuring sources of 20 μas size; that is a substantial change.

18.3.3 General Array Capabilities

Now in order to attack a wide range of science, we have to imagine a dual-beam facility so that it can be phased on offset reference stars and integrate on faint sources.

It would have to be configurable. Although, with a large number of telescopes, you might be able to arrange them such that they are well disposed for one science problem, you would have to reconfigure them for a target with an angular size 10 times smaller or larger. Examples that come to mind include the GI2T at the Observatoire de la Côte d'Azur, or the VLA where the telescopes move happily on rails.

The array would have to be a facility dedicated to interferometric observations, and not an array attached to a bigger facility which has a bigger use, such as the Keck or VLT observatories.

The array would have to be affordable, and would probably be a multi-national collaboration.

18.3.4 Number of Telescopes and Array Geometry

An imaging capability requires quite a few telescopes. There are a number of interferometric arrays in progress now with ~ 6 telescopes, which is far fewer telescopes than we would consider.

It would also have to have a snapshot capability with good (u, v) coverage in an instantaneous mode. That implies a large number of telescopes, baselines, and closure phases from one moment to the next. We had a discussion of how rapidly things can be expected to change with these high resolutions, and so you're now in the realm where sources change structure overnight. Furthermore, whereas with the VLA it's customary to build up (u, v) coverage by tracking down to the horizon, that's not as useful for optical arrays where the atmosphere is such a strong factor. So you can't rely on supersynthesis to the extent you can with radio.

We can say a few more things about what an array like this probably would look like. By now you probably understand the problems, probably have read about it repeatedly, involved in phasing an array on a resolved source. If you have a source which is approximately a disk resolved at a baseline Δb, and you'd like to further resolve 10 pixels across the disk, you need to observe the fringe pattern out to baseline b, where $b/\Delta b = 10$. However, if this is a faint source, you're going to have a hard time tracking fringes at baselines comparable to b, so you now require that no two telescopes be separated by more than a distance Δb. Therefore when you start laying out the array of telescopes, you must keep in mind the ratio $b/\Delta b$, and keep to a relation something like

$$\frac{\pi b}{N} \simeq \Delta b, \tag{18.1}$$

where N is the number of telescopes. Now if you want $b/\Delta b = 10$, you need $\sim$30 telescopes to get 10 pixels across your source. It follows that the number 27, even though it is the same as the VLA uses, isn't arbitrary. The configuration of the telescope layout then quite logically drops out to be a circle, because that gives you the short baselines all the way around including an extra closure as you come back to where you started, and the advantages of that have been recognized for a long time—although not before the VLA was built. Tim Cornwell, who studied this analytically, described a family of array geometries such as this that are now called Cornwell circles (Cornwell, 1988).

Let me comment on the large baseline and the number of telescopes, and now compare a facility of that description to the other facilities that are existing or impending. Figure

	ADAPT				PUEO		
	B	V	R	I	J	H	K
Median Strehl =	0.02	0.07	0.15	0.30	0.27	0.41	0.56
Strehl attenuation 50% at magnitude R =		10.0			14.3	15.0	15.7
Strehl attenuation 50% at field angle =					20”	30”	40”

Table 18.3: Demonstrated Performance of Adaptive Optics. Performance of operational natural guide star adaptive optics systems ADAPT at Mount Wilson (Mount Wilson Institute, private communication from C. Shelton), and PUEO (Canada-France-Hawaii Telescope on Mauna Kea, from the CFHT Web pages.)

idea, in what would be a simple-minded sense, of the limiting performance of a facility put together with off-the-shelf parts.

And this can be expected to go a little fainter with further developments in natural guide star adaptive optics. I'm not going to talk about laser-beacon adaptive optics which of course would improve the performance considerably but has not yet been demonstrated.

These are the ideas that we discussed with people in the community. Table 18.4 summarizes the concept that came out as a strawman—no more than that. Something we might call the Infrared Very Large Array, just to give it a designation, with a large total baseline of $\sim$1000 m, 27 telescopes with aperture diameters of 3 to 4 m.

18.3.6 Budget Estimate

Let's do a quick budget. Suppose we have, just to round it off, 30 telescopes. Four-meter telescopes sell for about \$20 million now, and we can probably get a 50% discount for building 30 of them—in this calculation the exact discount doesn't matter. We add to that \$100 million for delay lines and beam-combining laboratory for a subtotal now of \$400 million. The facility is probably going to be at a somewhat exotic site so we'll add a factor of 1.5, and we now arrive at a \$600 million project. That's probably right within 50%. So does this budget make sense? Or does it immediately say that this is just a stupid idea? Well, the answer is not necessarily obvious.

18.4 Astrophysical Potential of an Infrared Very Large Array

The answer depends on what science can be done with the facility, and so it becomes at some level a subjective matter depending on one's ranking of topics in astrophysics. Current astronomical research is strongly leaning towards dark-sky, extragalactic, cosmological areas

Table 18.4: Concept Summary

Infrared Very Large Array (IRVLA)	
Large baseline	1000 m
Many telescopes	27
Large unit telescope apertures	3–4 m
Adaptive optics equipped	Curvature sensing based
Dual beam operation	Similar to PTI/Keck
Reconfigurable	Telescopes on rails (OCA, VLA)
Dedicated facility	
Multi-national collaboration	

and so many astronomers would consider that anything closer than 20 Mpc is irrelevant.

There's been a lot of stellar science during this course, but I don't think that the above budget is going to be applied to stellar astronomy or stellar physics in the real near future. I could imagine a further, more distant future after a couple of time constants and die-off of the cosmologists. There is a seriousness to that; interest and emphasis in sciences do rise, fall, and change. The qualitative era of astronomy gave way to the quantitative era, and stellar physics faded out as people did what they could with high-resolution spectroscopy—what hasn't really started up yet, is people taking advantage of what can be done with high spatial resolution.

Table 18.5 lists a number of characteristic source types for which interferometry would clearly have an interesting application, as well as the typical distances to the sources, and the size of partially and fully-resolved features that a kilometer baseline would give you at a wavelength $\lambda = 1$ μm—partially-resolved in the sense of characterizable.

Take for example Seyfert galaxies, listed in Table 18.5. They are a very interesting area of application for interferometry, which would be of considerable interest to many astronomers. The picture of a Seyfert galaxy as a high-energy galactic nucleus consists of a central source sometimes called a continuum region, or (u, v) continuum, with a size of less than one-tenth of a parsec, probably quite a bit less, but (with more confidence) surrounded by a clumpy region called the broadline region with a size on the order of one parsec. Interferometry is in fact a very good candidate for finding out what's really going on in a source like that. Because not only does it have the potential to resolve structure well inside the broadline region but to even distinguish specific models involving processes that are going on in here, such as orbital motion of clumps of material versus ejection versus other mechanisms and the potential for actually looking at internals and following them with time. And a similar argument applies to the internal workings of quasars.

But of course this type of astronomy involves relatively faint sources and starts to run into the co-phasing and phasing limits for an array based on natural guide-star adaptive optics.

As I indicated, an adaptive-optic system is pretty well guaranteed to work to a visual magnitude of about 16 but then it starts to get tough after that. This limiting magnitude is a little bright for extragalactic exotic-source astronomy. I would like to see that pushing up to 18 or so, but a magnitude limit of 16 is in the ballpark.

Table 18.5: Potential targets for high-resolution infrared interferometry.

Source Type	Typical Distance	Resolved	Partially Resolved
Asteroid	2 AU	200 m	20 m
M dwarf	5 pc	0.5 R	0.05 R
Evolved star	100 pc	0.02 R	0.002 R
YSO	400 pc	0.04 AU	0.004 R
Recurrent Nova	2 kpc	0.4 AU	0.04 AU
Relativistic disk	5 kpc	1 AU	0.1 AU
Local group galaxy	16 kpc	3.2 AU	0.3 AU
M81 group	3.4 Mpc	0.003 pc	6 AU
Seyfert, BL Lac	10 Mpc	0.01 pc	18 AU
Virgo cluster	19 Mpc	0.02 pc	0.002 pc
Quasar	1500 Mpc	1.4 pc	0.14 pc

18.5 Comments and Conclusion

Just to finish off the story, we presented our proposal to the Decade Review Committee, a group of primarily dark sky astronomers, who were predominantly, I would say, somewhat neutral to this general plan. But quite cordial. Their recommendations go into the report which then gets reviewed by the National Academy of Sciences, and the review process takes about 6 months and it's all held in great secrecy.

I wound up my presentation to them by reviewing many of the concepts that have been described in these course notes and showing that there are no technical blocks to the construction of an Infrared Very Large Array. It will work and we can now go ahead. Interferometry has been developing very rapidly for the last decade, a lot of money has been invested in it. The science productivity from interferometers has been been strong and is accelerating. The intermediate facilities are coming on-line now, and it is logical to look at a further more ambitious step in ground-based interferometry. The scientific rationale is, of course, the level of detail that a new array would bring to studies of compact sources. Going from a star that appears as a point-source observationally, to a resolvable source is an enormous advance, and it's also an enormous complication because the physics you need to understand it becomes a lot more complicated—the spherical symmetry, homogeneity, all those assumptions suddenly go away. There's a tremendous jump to actually processing the advances that are possible.

I made the argument that the development of such a facility could begin any time—tomorrow even. My own feeling is that the huge step in capability is so large, and the power of it is so obvious even to a non-scientist, that I'm sure this array will happen.

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