N93-13581

THE CHARA OPTICAL ARRAY

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Introduction

The Center for High Angular Resolution Astronomy (CHARA) was established in the College of Arts and Sciences at Georgia State University in 1984 with the goals of designing, constructing, and then operating a facility for very high spatial resolution astronomy. The interest in such a facility grew out of the participants' decade of activity in speckle interferometry. Although speckle interferometry continues to provide important astrophysical measurements of a variety of objects, many pressing problems require resolution far beyond that which can be expected from single aperture telescopes. In early 1986, CHARA received a grant from the National Science Foundation which has permitted a detailed exploration of the feasibility of constructing a facility which will provide a hundred-fold increase in angular resolution over what is possible by speckle interferometry at the largest existing telescopes. The design concept for the CHARA Array was developed initially with the contractual collaboration of United Technologies Optical Systems, Inc., in West Palm Beach, Florida, an arrangement that expired in August 1987. In late November 1987, the Georgia Tech Research Institute joined with CHARA to continue and complete the design concept study.

The design philosophy has been to specify an interferometric array which incorporates as much off-the-shelf technology as possible and which is capable of making frontier contributions to modern astrophysics. This paper is not intended as a presentation of scientific potential, but two applications in stellar astrophysics clearly indicate the power of distributed arrays. Speckle interferometry at the largest telescopes can now resolve binary star systems with periods of the order of 1 to 2 years and is limited to five or six resolvable supergiant stars. The CHARA Array will be capable of resolving spectroscopic binaries within a few hours. Several hundred thousand stars of all spectral types and luminosity classes will be accessible to diameter measures. Such gains in power by any technique offer the even more exciting aspect of scientific discovery which cannot be anticipated but which, in retrospect, may be the hallmark of the greatest accomplishment by such a facility.

Much of this science can be obtained by strictly interferometric applications of the array while other problems are best approached through imaging. Current activities by several groups around the world are likely to significantly enhance the maturity of imaging methods by the time the CHARA Array is operational. Thus, while the CHARA Array will immediately provide a wealth of fundamentally important images of astrophysical objects of simple geometry, it will also serve as an important facility for the development and use of imaging algorithms applied to more complex objects.

Very high-resolution imaging at optical wavelengths is clearly coming of age in astronomy. The CHARA Array and other related projects will be important and necessary milestones along the way toward the development of a major national facility for high-resolution imaging--a true optical counterpart to the Very Large Array. Ground-based arrays and their scientific output will lead to high resolution facilities in space and, ultimately, on the Moon.

Description of the Array

The CHARA Array will consist of seven 1-m aperture-collecting telescopes in a Y-shaped configuration contained within a 400-m diameter circle. Each telescope beam is relayed to the central station by a separate light pipe so that all seven beams are simultaneously accessible. At the nominal operating wavelength of 550 nm, the Array will achieve limiting resolutions of 0.35 milliarcsec (mas) for single objects and 0.15 mas for binary stars. Uniform and extensive, two-dimensional coverage of the uv plane beyond that which is provided by Earth rotation has been considered essential to many of the scientific goals of the array. It is also considered essential that a high degree of data throughput be maintained to respond to the very large number of potentially resolvable targets. The seven telescopes simultaneously provide 21 baselines to enhance throughput. The proposed array configuration is shown in figure 1 while the uv coverage obtained at $\delta = +20°$ during 1 hour of diurnal motion is shown in figure 2.

Telescope apertures and mountings are important cost drivers. Apertures of 1 m were selected as offering several important advantages. At 2.2 μm, the longest wavelength at which the CHARA Array is intended to be operated, 1 m is likely to the largest aperture which is fully coherent for a short, yet significant, period of time. At visible wavelengths, this aperture also provides a reasonable level of complexity in terms of the adaptive optics needed to correct the incoming wavefront. Smaller apertures, even when made fully coherent by adaptive optics, are not likely to collect sufficient photons to reach even the brightest quasi-stellar objects (QSO), and require longer integration times to reach a particular limiting magnitude, an important throughput consideration. The optical systems will be fast confocal paraboloids to provide an afocal beam, and the telescope mounts will be compact alt-az structures using five mirrors to inject the beam into the light pipe.

A simplified schematic view of the optical path from collecting telescopes to the central beam-combining station is shown in figure 3 for two telescopes. The various subsystems encountered along this path are briefly described in the following paragraphs.

Adopting a 100-cm aperture for the afocal collecting telescopes, a beam reduction factor of five provides collimated beams 20 cm in diameter which must be relayed to the central beam-combining station over path-lengths as long as 200 m. The #5 mirror in a light-collecting telescope must, therefore, accommodate critical pointing conditions to keep the beam from wandering by more than 2 mm when it strikes the #6 mirror in the beam directing periscope system.

The compressed beams from the collecting telescopes will be relayed to the central station through evacuated light pipes to eliminate the potentially severe effects of ground-level turbulence and to minimize the cumulative spectral dispersion that would result from these long air paths. Each of the collecting telescopes will have a dedicated light pipe, a necessity if all beams are to be simultaneously available at the central station. At the exit end of the vacuum pipes, the beams will encounter two-mirror periscopic alignment systems. These mirrors, #6 and #7 in figure 3, serve the purpose of placing all seven beams in a parallel configuration to be fed to the path-length compensation system. It can be shown that there is no differential field rotation among the beams when all telescopes are pointed at the same object. The absolute field orientation can easily be calculated for each pointing.

Of critical importance to the success of an astronomical interferometer is the performance of the system designed to compensate for the variable optical path-lengths from the collecting telescopes to the central station. Each collecting telescope will feed light to a dedicated optical path-length equalizer, or OPLE, system. The OPLEs need not be equal in length. The placement of the collecting telescopes in the array configuration shown in figure 1, combined with a typical maximum zenith angle of 55° and a maximum integration time between baseline resettings of 1 hour, can be used to constrain the relative lengths and placements of the individual OPLE lines. To meet optical coherence length requirements, the OPLE must provide an absolute path-length equality of 2 μm over a range of 70 m and must be free of jitter in excess of ± $\lambda/20$ during a 10 msec time frame. Relaxation of these specifications could occur if a passband narrower than the nominal 8 nm or a shorter time frame were used.

The OPLE concept for the CHARA Array, as shown schematically in figure 4, calls for the movement of a cart along parallel rails assembled from 20-foot lengths of precision rail. The dowelled joints between successive rails are ground to keep joint discontinuities at less than 0.0001 in. The velocity and position of the retroflector cart are controlled by a micro-stepper motor servoed to a control signal generated by a laser interferometer. The absolute position and velocity at any instant for a particular pointing will be determined by a computer-generated model which will be improved through a learning process based on actual experience.

The retroreflector system will be a catseye using 61 cm parabolic primary optics and 21 cm flat secondaries. The control system for the OPLE is essentially that of the very successful SAO/NRL Mark III stellar interferometer, in which a hierarchical division of control signals is distributed to the stepper motor for the lowest frequency, highest amplitude corrections, to a speaker coil driving the mounting of the flat secondary in the catseye system for intermediate frequencies and amplitudes, and to a PZT stack which directly actuates the secondary reflector for the highest frequency and lowest amplitude corrections. Computer control of the servo tasks enables the PZT and voice coil servos to operate at 1 kHz. Preset fiducials along the track can be set with precisions of ±1 μm using magnetic sensor devices.

The emergent beam from an OPLE is directed by mirror #10 toward an optical table on which are mounted the optical systems used for the next stage of beam compression. These systems will be afocal, using confocal paraboloid primary (mirror #12) and secondary (mirror #13) mirrors to reduce the beam by another factor of five to give an output beam diameter $\leq$ 1 cm. As can be seen in figure 5, the output from these beam-reducing telescopes goes to two subsystems: the first for guiding, and the second for relaying light to the auxiliary spectrograph. Convenient access is also given to the central obscuration of a beam prior to reduction. Figure 5 shows how this access can be used to insert a laser metrology beam into the system and pick off light to be used to align mirrors #5 through #10.

The goal of the laser metrology subsystem is to measure the path-length from the #1 mirror, i.e., the primary mirror of a light-collecting telescope, to a fiducial on the optical table containing the beam reduction optics. Presently available laser interferometers easily provide the desired accuracy but lack the range needed in this application. A two-color laser system developed for the University of Sydney Large Stellar Interferometer, with even longer path-lengths than the CHARA Array, could accomplish this function. A possible substitute would be the use of electronic distance meters commercially available for surveying purposes. These devices are becoming available with precisions of ±0.5 mm, although they remain rather expensive. The purpose of this metrology would be to permit rapid accommodation for path-length drifts to quickly meet the coherence requirements and to quickly acquire fringes on new targets. It is expected that such effects, which may be tied to meteorologically induced relative motions between the collecting telescopes and the central station, are repeatable and can be mapped out. Therefore, this type of metrology would only be required to produce the mapping look-up tables which would be updated for secular changes.

The beam alignment subsystem uses a simple scheme in which LED's are mounted in the centers of mirrors #4 through #9. When the LED on mirror $n-1$ is illuminated, the orientation of mirror n can be adjusted to center the point source in the field of a small CCD camera mounted at the focus of the beam alignment telescope. By working out from the beam alignment telescope to the #5 in a kind of "airport landing light" approach, easy alignment can be obtained and checked as necessary.

The guider subsystem will incorporate a beam splitter to extract approximately 10 percent of the light from the object to illuminate a guider sensor, possibly a quadrant type detector or an avalanche photodiode system. The servo system will use the low frequency, large amplitude corrections in a closed loop to the collecting-telescope drives and the high-frequency residual errors to correct for average atmospherically induced tilt by actuating a PZT–driven tilt corrector mirror on the optical table. The beam folding correction provided by mirrors #13 (the tilt corrector) and #14 (a fixed flat) provides for nearly normal incidences while keeping the beams parallel to their original directions.

The first approach at beam combination, as shown in figure 6, uses a system of fixed flats and beam splitters to equally separate each of the seven beams into pairs of beams. A similar arrangement of fixed flats which incorporates beam splitters movable on precision shuttles to preset locations then provides a means for interfering any beam with any other beam. The fixed relative optical delays can be minimized by appropriately laying out this subsystem and the OPLEs. This arrangement provides an easy means for quickly changing baselines, an activity which is mostly dominated in time by the slewing of the OPLE retroreflectors. Slightly more complicated schemes for combining beam triplets for closure phase imaging can easily be configured.

Pupil-plane interferometry offers a wide variety of approaches to detection and analysis. This is an area in which the 0^{th}-order approach will be a straightforward imaging of the interfered pupil planes in a single bandpass onto an array detector. A single detector will provide a sufficient number of pixels so that the two sets consisting of seven interfering pupils each can be accommodated by two detectors. To adequately resolve the pupil-plane intensities, 16 pixels across a pupil would be necessary. Thus the array detector would have a minimum of 256 x 7 x 2 = 3584 pixels. In addition, the output for several other passbands can be located on the same detector, including a wide passband for fringe-tracking.

This detector hardware implementation or "strategy" is a straightforward extension of that used by the University of Sydney for a single r_o system. As additional advantages, it has the ability to vary the detector "footprint" (areas over which photons are counted in computing visibilities) in software and, thus, to obtain an internal estimate of visibility loss due to the finite detector areas.

Several other detector strategies were considered. One is to use footprints with the light fed into 100 to 200 fibers, re-arranged linearly, and then dispersed spectrally to produce visibilities from the fringes. A second is to rely on a higher degree of compensated imaging and to channel the light prior to combining from each aperture into only six fibers, representing six 33-cm sub-apertures. Light from each telescope could thus be combined pairwise with the light from the other six telescopes and then spectrally dispersed. With an even higher degree of compensation, the light from the whole aperture would be used for combination. An evolution in detectors toward the latter detector strategy is envisioned, which would reduce the data burden, increase the limiting magnitude, and facilitate the combining of three or more beams to obtain closure phases for imaging.

Optical Effects and Simulations

Because of the very long light propagation paths in the arms of the interferometer, it was considered necessary to explore the effects of diffraction on visibility measurement. In a series of calculations, the Fresnel approximation to scalar diffraction was carried out to explore the degradation of propagating wavefronts. Of particular concern was the effect of beam reduction on the spread of diffracting waves. For a beam reduction factor of m, these effects were shown to be proportional to m^2. Thus the natural tendency to reduce the beams immediately to a rather small diameter before relaying them to the central station must be given careful consideration. Simulations incorporating realistic atmospheric turbulence models showed that diffraction leads to a kind of scintillation in the pupils, an effect which mimics the presence of interference, itself, in the pupils. This scintillation does become significant for small, r_0 and long propagation distances and may, in fact, surpass the natural atmospheric effects in degrading visibility.

For reasonable values of r_0, the loss in visibility over the longest path lengths of the Array was found to become significant for values of $m \leq 0.15$. To ensure a margin of safety, this analysis has led to the adoption of $m = 0.2$ for the CHARA Array. For the CHARA Array, diffraction effects can be expected to reduce visibilities by no more than a few percent over losses arising from natural atmospheric effects.

The oblique 45° reflections from metallic surfaces can produce differential polarization and phase shifts if the sequence of reflections from the telescopes to the combining house is not the same. In the CHARA Array, an asymmetry occurs in the two mirrors (#6 and #7 in figure 3) that translate light from the telescopes to the OPLEs. Polarization effects can be combatted in two ways: first, by adding one or two mirrors to make the sequence of reflections the same for all telescopes or, second, by only using one polarization for visibility measurement. The second polarization can be used for compensation imaging, etc.

To improve the understanding of the performance that can be expected from an interferometric array, an extensive series of simulations has been carried out. These simulations are based on a realistic model of the spectrum of atmospheric turbulence characterized by Fried's parameter r_0 and the wind velocity. The scalar diffraction theory is used to propagate the beams from the collecting telescopes to the plane of interference. Various detection schemes can be implemented in simulations incorporating wavefront corrections starting with simple tilt compensation and adding high order corrections. This effectively increases r_0 to an appreciable fraction of the aperture. The performance of the array has been evaluated in the high photon flux case as well as in the case of dim objects and for a variety of object types. For example, it has been shown that binary star systems with separations as small as the resolution limit of the array (0.15 mas) can be imaged, using only six baselines, with relative geometric and photometric accuracy comparable to that obtainable from speckle interferometry, a method providing continuous uv coverage. The understanding gained through these efforts makes a substantial case for the feasibility of the proposed array.

The simulations show that a multi-r_0 interferometer working in the pupil plane provides the expected advantages over an image plane interferometer, particularly in the requirements imposed on the detection scheme. Using reasonable performance parameters for the array, we find that the limiting magnitude under typical seeing conditions (r_0 = 10 cm) is m_v = +11.4 extendable to m_v = +13.9 by mutliplexing ten 8–nm–wide passbands simultaneously. The use of relatively simple adaptive optics based on 15 actuators for compensated imaging provides up to 2.2 magnitudes of improvement for these two cases. The importance of relatively simple wavefront compensation (i.e., that which requires no more that 10 to 15 actuators) when extending the limiting magnitude to a value permitting detection of extragalactic objects provides a role for the continuing development of such adaptive systems. Such systems are likely to become available at relatively modest expense compared to those now being developed for fully compensated imaging at the largest telescopes and will provide advantages in data reduction and multiple beam combinations for closure phase imaging. But even without compensated imaging beyond simple average tilt correction, these simulations show that the CHARA Array can meet and exceed specifications required to carry out the basic scientific program.

The Array Site

Anderson Mesa, near Flagstaff, Arizona, has been selected as the proposed site for the CHARA Array. A region of the Coconino National Forest has been designated as an astronomical preserve since 1961, when Lowell Observatory negotiated with the U.S. Forest Service for access to a permanent dark site outside of Flagstaff. The "Lowell Use Area" is currently being renegotiated, and new boundary lines are being defined which will more than adequately accommodate the array.

The selection of Anderson Mesa resulted from a detailed site selection process. An initial list of 10 candidate sites was culled to three possible locations following the first evaluation. Other sites which were finally considered in detail were Mt. Fowlkes, adjacent to the Mt. Locke facilities of the McDonald Observatory, and Blue Mesa near Las Cruces, a site developed by New Mexico State University's Department of Astronomy. The process considered a number of parameters judged to be critical to the selection of a site. These parameters included suitability of terrain to a distributed array, meteorological conditions (particularly cloudcover), degree of night sky illumination, geology (particularly seismic background level), atmospheric seeing, and logistics. As with any astronomical site selection, the accumulation of relevant data is a challenging task due to the heterogeneity of the data types. The one category in which homogeneous data was secured was the question of relative cloudcover. Satellite observations of cloudcover were obtained from the National Climatological Data Center for the southwestern U.S. covering the time interval from January 1984 through September 1987. These data showed, somewhat to our surprise, that northern Arizona offered the clearest skies during this time period.

Probably the most critical of the above issues is the question of seeing conditions at a variety of candidate sites. To provide measurements of seeing on Anderson Mesa, the only one of our candidate sites which had never been evaluated for seeing, an inexpensive seeing monitoring system was assembled from a commercial CCD video camera system and PC–based frame grabber board. Tests with this system during the spring of 1988 permitted the tie-in to a more extensive series of seeing measurements carried out from the U.S. Naval Observatory (USNO) Flagstaff Station. The mean seeing on Anderson Mesa during this period was 1.24 arcsec, and we expect that the Mesa will exhibit long–term seeing similar to that of the USNO station. Considering the conditions at Anderson Mesa, we can expect median FWHM seeing profiles of 1.1 to 1.2 arcsec during 30 percent of all nights. We can also expect the poor seeing tail to yield seeing worse than 2.0 arcsec for another 30 percent of the time. Thus, while Anderson Mesa does not compete with Mauna Kea in the category of superior seeing, it can be expected to provide very acceptable seeing conditions in addition to the very favorable ratings in other categories.

Conclusion

A feasibility study and an initial design concept have been completed for a multiple telescope array for very high spatial resolution astronomy. The success of current programs in long-baseline optical interferometry and the development of critical technology as a result of these efforts argue strongly for increased activity in this field.

The CHARA Array will be open to visiting astronomers from other institutions who can conduct their own scientific programs or develop alternative detection and analysis schemes. The facility's role of serving as a test bed for the development of imaging techniques and auxiliary instrumentation, such as compensated imaging devices, will allow it to play a dynamic role in the continuing development of high resolution imaging with national and international participation.

Acknowledgments

This project has been a collaborative effort with the major participation of William G. Bagnuolo, Jr., and William I. Hartkopf. We plan to publish more detailed reports of the various aspects of this study. The National Science Foundation provided major support for this effort through NSF Grant AST 84-21304, and we gratefully acknowledge this critical support.

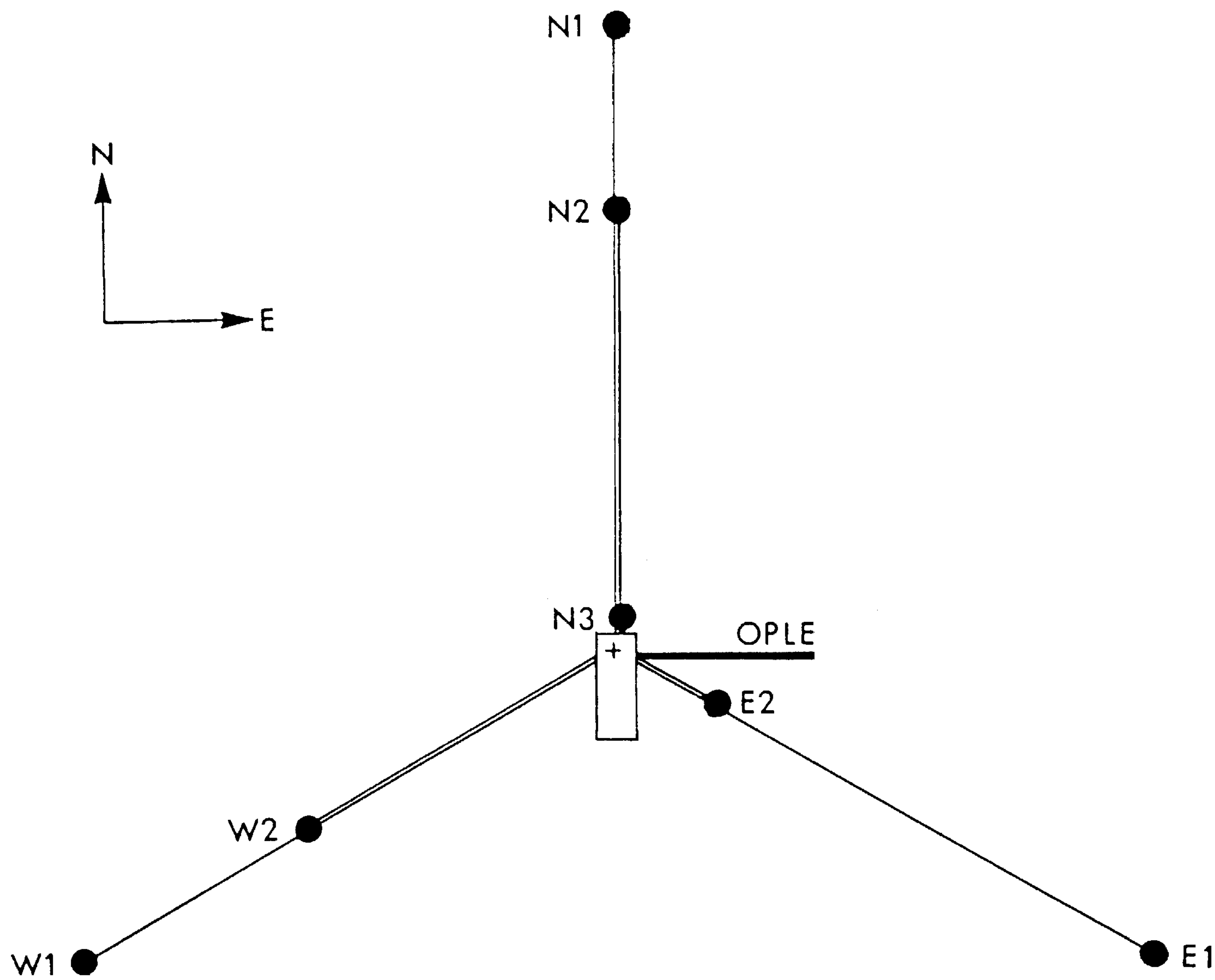

Figure 1: The baseline configuration for the CHARA Array is shown. The three telescopes at the extreme limits of the array are 200 m from the central station.

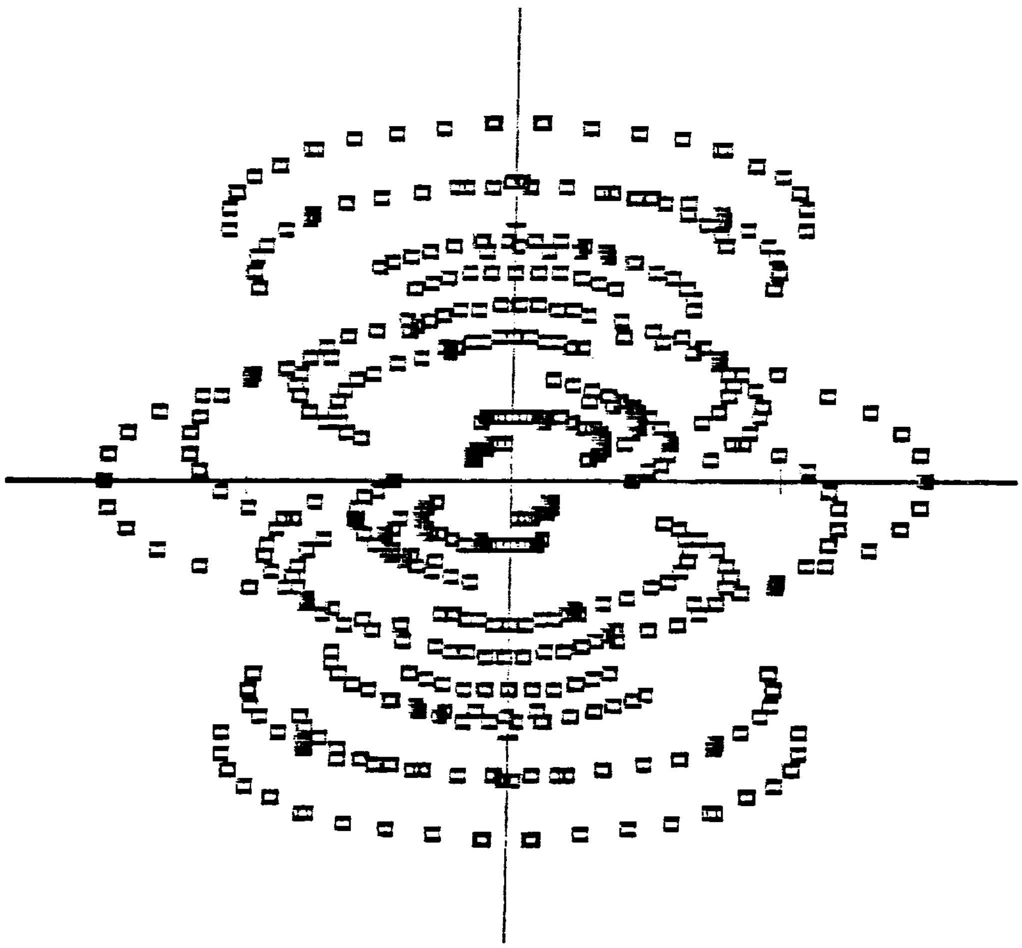

Figure 2: The uv coverage for the selected array is shown for the case of $\delta = +20°$ after 1 hour of Earth rotation induced synthesis.

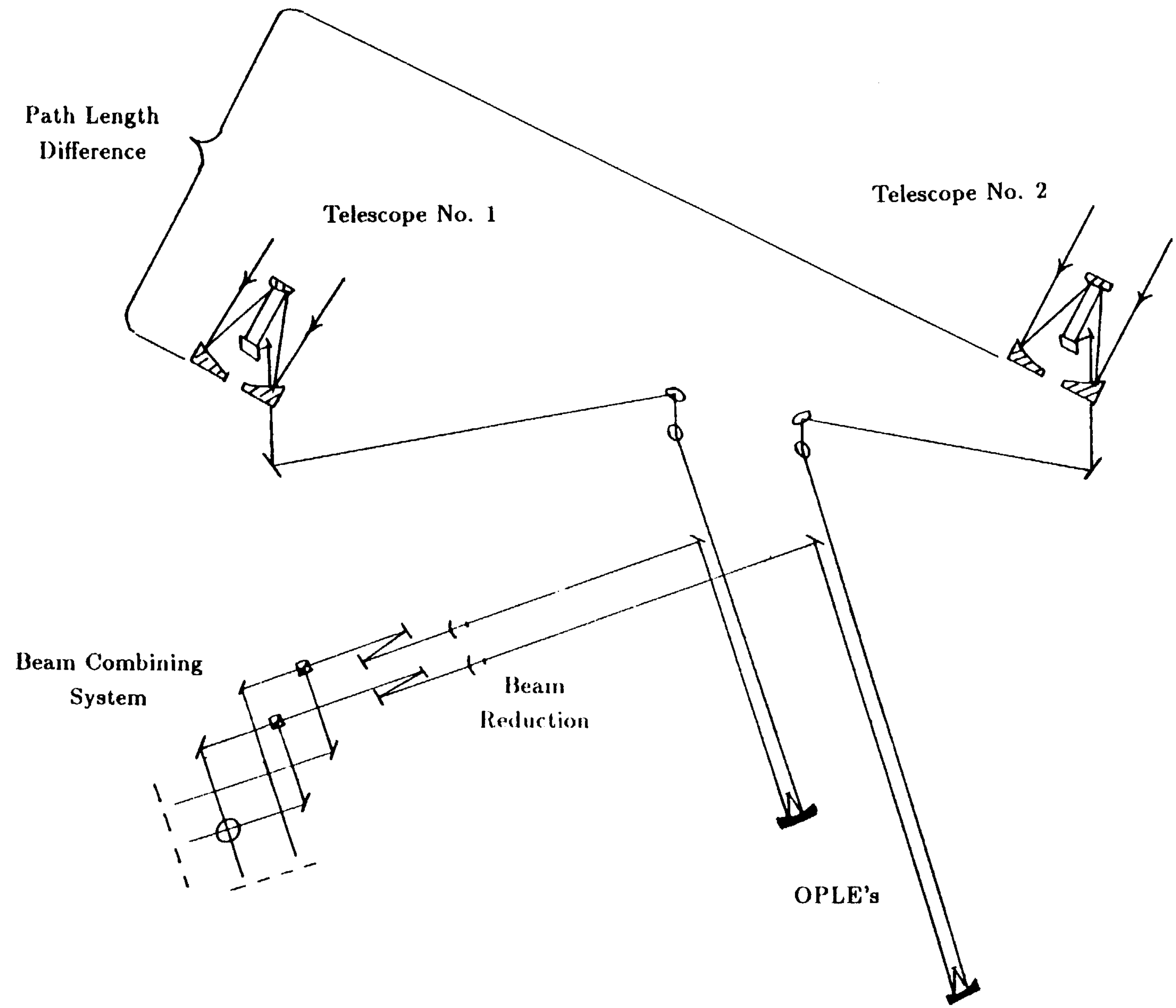

Figure 3: The simplified overall optical layout of the CHARA Array is shown for two collecting telescopes.

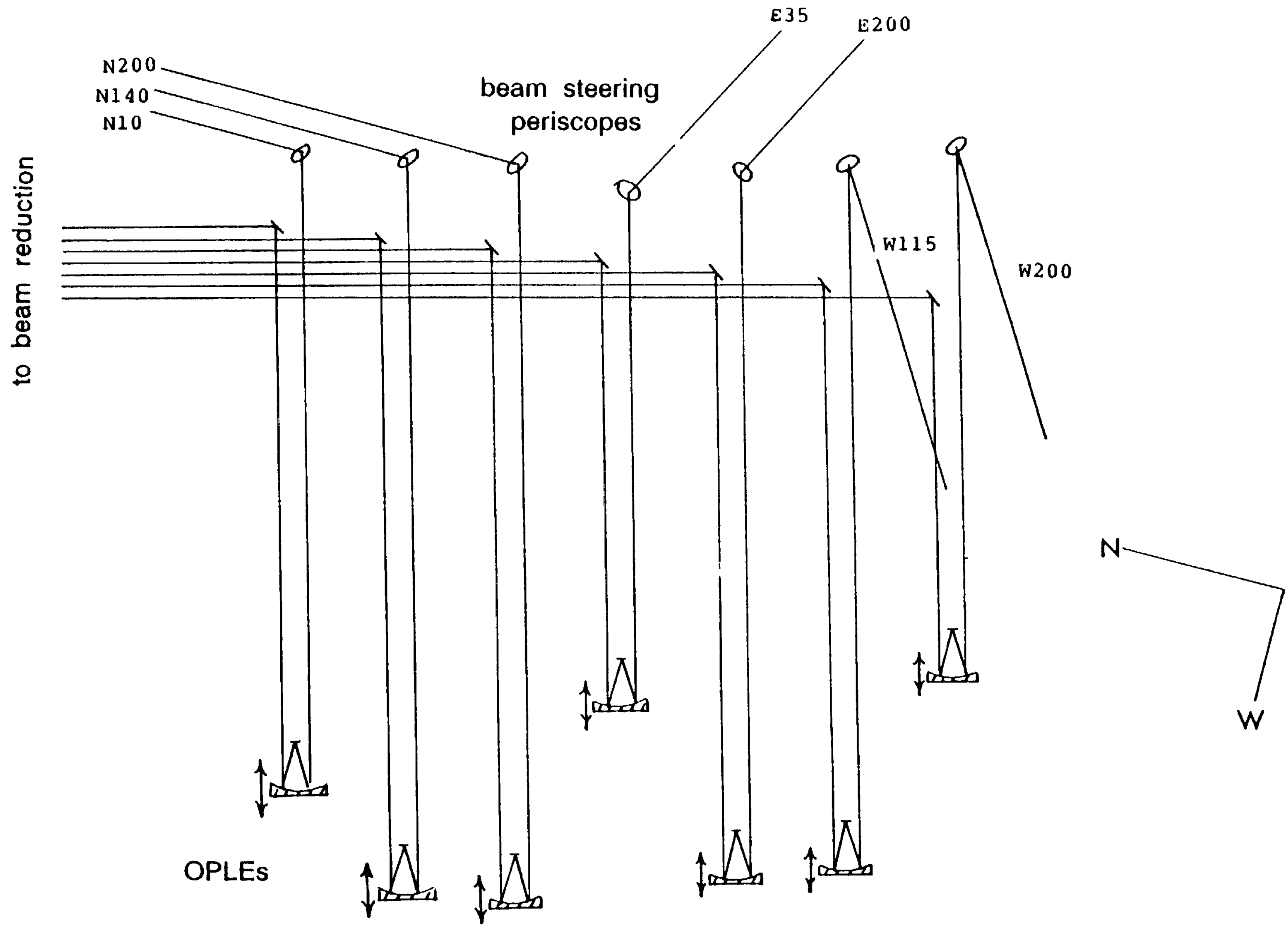

Figure 4: The path length compensation subsystem is shown for all seven telescopes including the insert periscope subsystems for aligning the beams and the #10 mirrors which relay the beams from the OPLEs to the beam combining table.

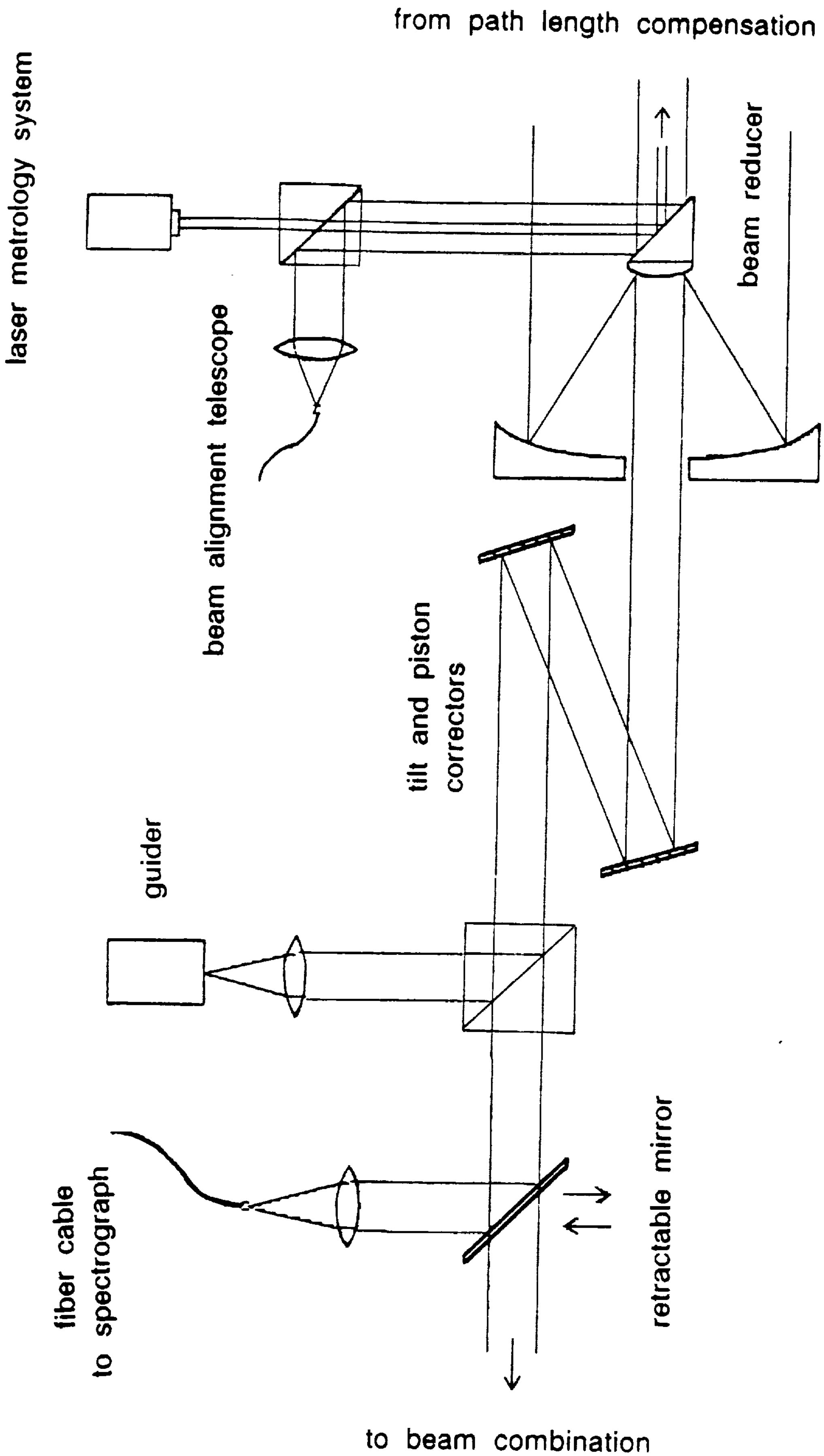

Figure 5: The beam reduction and guiding subsystems are shown for a single light-collecting channel.

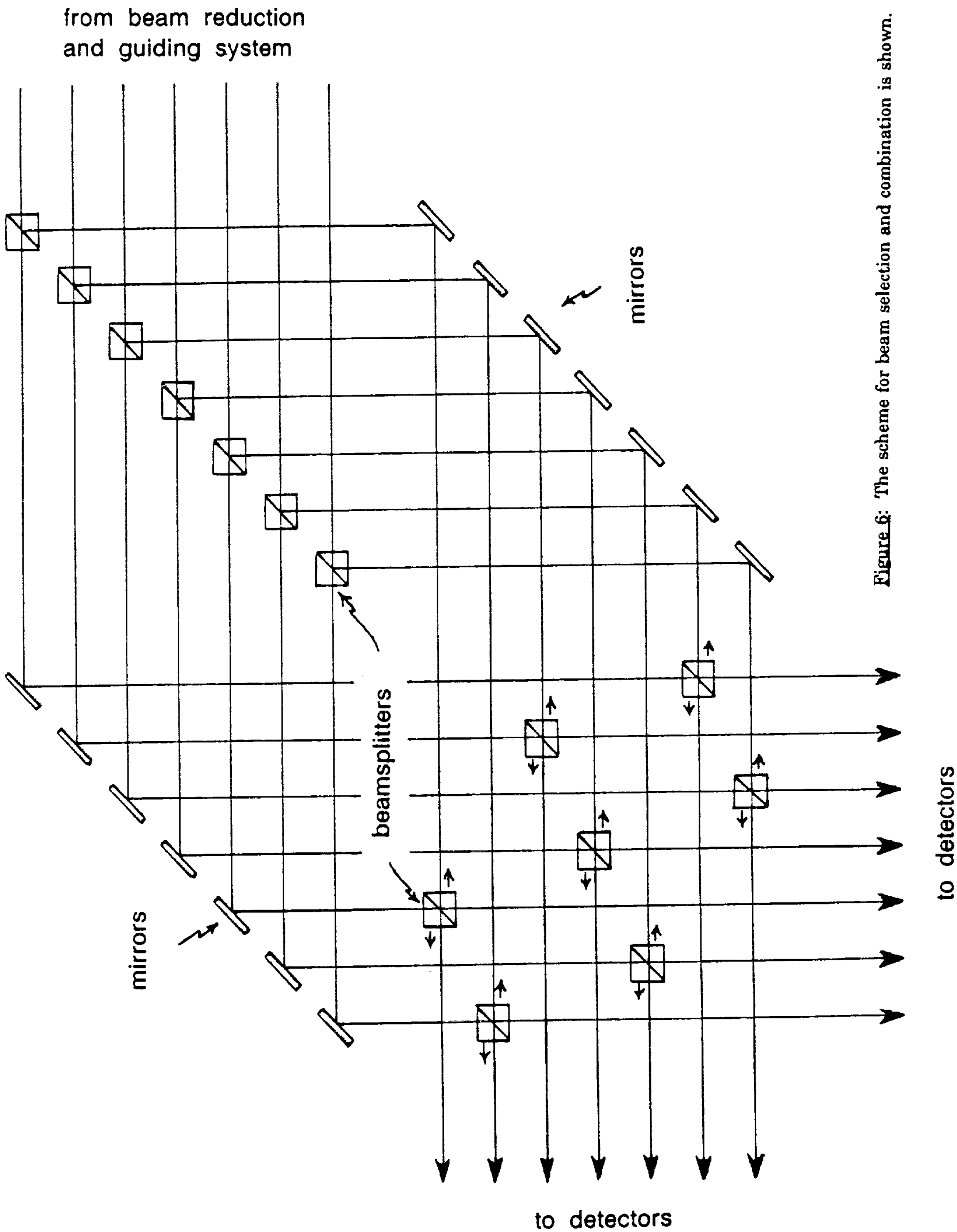

Figure 6: The scheme for beam selection and combination is shown.