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INNOVATIVE RESEARCH IN THE DESIGN AND OPERATION OF LARGE TELESCOPES FOR SPACE: ASPECTS OF GIANT TELESCOPES IN SPACE

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I. SUMMARY

Continued progress in many areas has been made during the second year of the contract. Perhaps the most striking advances have been made in our capability and understanding of how to finish the reflector surfaces needed for large space telescopes. We have also made a big step in the technology for making very light glass substrates for mirrors.

Other areas of development have been in wide field imaging design for very fast primaries, in data analysis and retrieval methods for astronomical images, and in methods for making large area closely packed mosaics of solid state array detectors.

In the third year we propose to concentrate largely on demonstrating a new concept for polishing fast aspherics and on continued development of innovative techniques for automated analysis of very large numbers of CCD frames with 16 bit pixel accuracy.

II. PROGRESS REPORT

1. Reflector Surface Finishing (Angel and Parks). This work divides into three domains -- producing machined glass surfaces with the highest possible accuracy, suitable for LDR or longer wavelength as machined; methods of lapping and polishing to improve surface finish to the accuracy for diffraction limited optical performance; still better finish for X-ray reflectors.

(a) Machining. The most accurate machining is done by making in situ measurements of the surface, and applying appropriate corrections. Using a 'swing arm' generator of the type described by Angel and Parks (1982) we have demonstrated that it is possible to generate off-axis parabolic segments with a figure accuracy of 2 μm rms. The off-axis segments were made with one-half meter in overall dimension, segments of an F/1.2 parent. The surface finish obtained on these segments was sufficiently good that the segments could be tested interferometrically with a CO_2 laser interferometer in a double pass autocollimating configuration. This meant that immediately after a generating run it was possible to detremine the figure accuracy of the segments. If they met the specification then the next step of lapping was done, if not an error correction tape was made to the computer controller and a new generating run made. All this was done in near real-time. In fact the generating run took only five hours.

After generating, the segments were lapped with a diamond abrasive material bound into flexible pads. We found that the lapping material worked very progressively, did not cause scratching, and did not cause contamination in going from one grit size to another. We feel that the use of this type of material is a great step forward over tradiational loose abrasive lapping. The accuracy already demonstrated could be adequate to finish LDR panels for diffraction limited operation at 60μ. A factor two improvement would reach the goal of diffraction limit at 30μ.

In order to make panels of ~ 2m a larger generator is needed. Continued work in this area will be conducted with a new large optical generator by Campbell, now installed in the Optics shop at Optical Sciences Center (Shannon and Parks 1983). This generator is large enough to do an 8 meter diameter symmetric mirror or segments of up to a 15 meter dish. It appears from initial work that the large optical generator (LOG) should be able to produce work with an accuracy of 2 to 3 μm rms over 2 meter size segments. Work will continue to improve the accuracy of the LOG for doing contour work. Initial generating runs with the LOG have been very promising, a plano pass on the back of a 72-inch borosilicate glass mirror was sufficiently uniform and regular so as to produce a diffraction pattern from the grinding marks. While this is a common occurrance in diamond turned optics it is the first time we have heard of this phenomenon in glass and it is even more unusual in that it occurred in a generating pass where 10 h.p. were being applied to the grinding spindle. Usually in diamong turned optics or diffraction grating ruling the greatest forces involved are at the most a few grams.

(b) Lapping and Polishing

Diffraction limited optical performance in glass requires polished surfaces. Conventional polishing methods are very good for making spherical surfaces, but can become extremely difficult and tendious if fast or off axis aspheres are needed. Following our work on optical designs of the past two years of this contract, which has yielded good solutions for wide field imaging from very fast primaries, we have now devised a method to make them. This is described in the attached preprint by Angel "A Method for Polishing Aspheres as Fast as f/1".

In order to accommodate the varying curvature of an aspheric surface, current methods use either flexible or small laps. Flexible laps polish highs and lows alike, and so the pitch distribution must be varied to correct figure errors. This is very tedious. Small laps also have no tendancy to correct errors, but must be driven by computer to work on highs identified by metrology. The problem is that very fast aspheres require very small laps, and figuring times which increase as the inverse cube of focal ratio become very long. Our proposed method is to use a rather stiff lap, fitted with hydraulic or motor driven actuators that can change its curvature as it moves over the work. We have demonstrated a practical arrangement of actuators that is capable of inducing accurately the changes of shape needed to conform to conic sections of revolution. The huge advantage of this method is that the dynamically stressed lap will tend to form the asphere as naturally as it would a sphere if it were used passively. While the principles of this method have been proven by our static test, the method needs to be tested by actually polishing a fast asphere.

The stressed lap method should be particularly valuable for future space telescopes and optics, allowing the use of compact fast designs that otherwise would be prohibitively difficult. Thus it should allow optical polishing of LDR panels, to give the "light bucket" mode at 2μ, even if the reflector is f/0.5. It also will be a powerful method for polishing to the diffraction limit 8m monoliths that are now under consideration for launch in the shuttle fuel tank.

A further application we have recently considered is in the polishing of the AXAF mirrors. Resolution in this telescope is not diffraction limited, but limited by the surface finish. Presently this is expected to give about 1/2 arc second images. Stress lap polishing could improve this to perhaps 1/10 arc second.

2. Mirror Substrates (Angel -- shared funding with NASA Ames)

Last year we reported the development of a new process to fuse lightweight honeycomb. Taking manufactured cylindrical glass tubes as a starting point, these were close packed and filled with free-flowing refractory sand. On firing, the sand pressure formed the tubes into a monolithic hexagonal honeycomb.

This year we have made a very substantial improvement in the process, and it is now of great practical interest to glass manufacturers. A copy of an invention disclosure of the new process, attached, is now under consideration by the Research Corporation. The new idea is to use air pressure instead of sand pressure to press the tubes together.

This is done by first heating a complete assembly of tubes between face sheets until the sheets seal to the tubes top and bottom. Then compressed air is introduced into each sealed tube from a small hole in the back plate. The tubes seal together to form an internal monolithic honeycomb, while the face plate is prevented from bubbling up by a flat refractory restraining plate. Gaskets of ceramic fiber prevent the glass from sticking to the restraining plates.

The new process has the advantages of (1) low thermal inertia, so the process is fast and the fused glass joints do not fog due to crystallization, (2) a complete flat sandwich blank is formed in a single furnace firing, (3) the starting plates and tubes need no elaborate machining. In fact we simply use the scribe and snap method to cut the tubes, using a precision jig to get them all the same length.

While the process forms flat blanks directly, curved blanks can be formed by slumping in a separate heating cycle. As a demonstration we slumped to f/1.6 and finished a 70 cm honeycomb blank, which was then used in the CCD transit telescope.

All the large blanks made by this method have been of borosilicate glass, which softens and fuses at about 840°C. The thermal properties of the finished blanks are very good, and they have been finished to diffraction limited performance quickly. Their thermal time constant is so rapid, the optician does not have to wait to get a stable figure to test. We expect that there will be applications in space for borosilicate honeycomb, particulary if their thermal environment is not too severe, and if optical diffraction limited optical performance is not required. Nevertheless, it would clearly be very desirable to show the process could be used for ULE and silica, for which the softening point is about 1600°C.

We have made a series of experiments with these materials. The main problem is to find gasket material to eliminate chemical reaction and sticking of the silica at such high temperatures. Zirconia fiber paper looks promising. The alternative is graphite, but this requires the use of inert atmospheres or vacuum. We have discussed this approach with Corning, and they have the equipment to do it. At present we are not planning to use or develop vacuum furnaces, and we would be happy to see an outside manufacturer pick it up.

3. Optical Design (Epps, Woolf, Angel)

This year has seen a careful exploration by Epps of the limits of high resolution imaging that can be achieved with refracture correctors used at Cassegrain or Ritchey-Cretien foci. These may have an important role in ST successor telescopes. The uncorrected RC focus is quite limited in field because of uncorrected astigmatism. We earlier explored 3-mirror systems which can be superbly corrected, but are inconvenient in inascessible foci. Epps design goal was a 1° field, an enormous advance on the ST field of 2.7 arc minutes. The achromatic correction is extraordinarily good, and the monochromatic images very small. Thus the worst RMS image diameter anywhere in the field is 0.12 arc seconds, and the worst energy concentration is 98% into 0.25 arc seconds.

Although not reaching the diffraction limit for a large reflector, the huge field will be a valuable asset for many astronomical problems. For an 8m primary diameter, the field diameter would be 24 inches, and the resolution about 17 microns. This presents a challenge for CCD detectors which is addressed below.

4. Physical Optics (Woolf)

In the past year we have studied an analytic approach to the process of obtaining high resolution maps from elongated apertures. The study shows that there is a modest degree of information loss related to the highest spatial frequencies, but that there is no major loss in signal/noise ratio at the resolution of a disk of the same area. In consequence the concept of sending an 18 x 4m monolithic mirror telescope into space using the full size of the shuttle bay still seems attractive.

As the multi-billion dollar cost associated with schemes for large telescopes in space becomes apparent, a solution that provides a single space observatory for UV-O-IR-sub-mm astronomy becomes attractive. The logic for such a scheme is that the high resolution use at any wavelength requires the use of the optical image formed by the telescopes for co-alignment and phasing, and therefore even sub-mm telescopes will benefit from optics of "visible use" quality.

Such an observatory would use a number of monolithic mirrors in configurations that were changeable in orbit. In this way there would be potential for separate use as well as interferometric use for the complete range of wavelengths. Schemes for such individual primary mirrors of such a complete space observatory, include both 7-8m circular mirrors that could be lofted in the shuttle fuel tank, and also the elongated mirrors discussed above. The most interesting technical questions posed by such a concept relate to the forms of synthetic aperture and their relative merits. Both linear arrays of apertures with the axis rotated in the plane of the sky, and Golay like minimally redundant 2-dimensional apertures can be considered. We will explore the possibility of generating some kind of figure of merit to compare the effects of both additing more apertures, and placing them in different configurations.

Additional work this year has explored the possible use of the space shuttle for a test for interferometric long-baseline space studies of the angular structure of objects. It appeared that the shuttle environment does not prohibit such an experiment, but that it requires a major effort to undertake such a project.

5. Image Analysis (McGraw, Cawson)

Funds from the contract have been used to address aspects of building and operating the CCD transit telescope that are relevant to space telescopes. Thus the lightweight secondary and tertiary mirror blanks were made with contract support. The full instrument had first light in June, and now after very careful optical alignment is about to start regular operation, producing 400 megabytes of pixel-data each clear night.

The challenge now is now shifted to that of handling this huge amount of very high quality data, extracting lists of objects with properties such as coordinate, colors, variability, shape, etc. The software for making and handling of these lists will be an extraordinary powerful tool not only for astronomical research and statistical studies but for the next generation of automated guide star selection, and the analysis of data from wide field space telescopes.

(a) Software Development

With partial support from this contract, software is being developed as described below. We have benefitted from the experience of Mike Cawson, a postdoc from Kibblewhite's group at Cambridge, England, which is currently a world leader in the digital analysis of full Scnmidt plates. The system being developed represents a substantial advance both in software and hardware.

The raw pixel-data is to be archived in such a way that each pixel can be extracted in its original form -- this requires data-compaction to reduce most 16-bit pixels to 8-bit differences (making use of the fact that most of the sky is realtively flat), and the use of optical discs as a storage medium. The raw data will be analyzed in real-time to detect new or changing objects. This analysis will produce lists of parameters for all objects detected each night, and these lists will be used to update master-list summarizing every measurement of each object, to produce a history-list of the time-sequence of brightnesses of every object, and to compile a list of 'objects of interest'. Periodically, the raw pixel-data from many different nights' observations will be coadded to reduce the photon and read-out noise, producing an ever deeper image of the region of sky being surveyed. These coadded frames of data will themselves be analyzed to detect objects fainter than the nightly detection threshold whose parameters will be measured and stored in another list.

The four CTI lists, together with other 'user' lists produced by further processing of CTI or external data, will be accessible through a single data-channel so that any application program may address any type of data transparently. In a similar manner the CTI pixel-files (raw and coadded), together with 'user' pixel-files may be accessed through a second single data-channel. This data-management scheme, whilst being relatively simple in concept, provides great flexibility for defining new file-types which are supported and extreme ease of use for astronomers who wish to develop new analysis algorithms without having to learn about a complex data-management package.

An interrogation program has been written which provides integration for extracting sub-sets (or super-sets) from the CTI or user lists of object parameters, and which allows selection criteria to be defined interactively using graphical input and output.

The CTI telescope and its associated data-bases provide an ideal test-bed for the development of a data-management scheme (including considerations such as data-compaction, storage media, felxibility and usability) which will be required more and more as other optical instruments (such as Space Telescope) start to produce extremely large volumes of data on a regular basis.

(b) Hardware

A dedicated Data General MV 10,000 computer will form the nucleus of the system. It has been our intention to use funds from the second year contract toward the purchase of peripheral image processing hardware, capable of carrying out useful functions on full 16-bit CCD images. A survey of available equipment has revealed that no product currently on the market has the required architecture or capability. However, Dipix of Canada is about to release a new product (the MPX-3) which at last seems to here the architecture necessary for processing large volumes of optical data.

Up to now the development of image processing systems has been driven by the seismology, remote sensing and earth resources markets which typically have 8 or 12-bit pixel data. The Dipix product will have an extremely fast 32-bit ring-bus archetecture (42 M words/sec) with the capability of hadling several special purpose arithmetic/logic cards for genuine 16-bit image processing and up to 128 Megabytes of image data. This will be the first time that it will be faster to extract data from 16-bit optical images in a special purpose image processing unit than in a conventional computer. We plan to use funds still remaining from the second year to buy part of a Dipix system as soon as it is available.

6. <u>CCD's</u> (Leach, Lesser, Angel)

During the past year we have addressed the problem of making very large focal plane mosaics of CCDs, in the 0.5m class. To obtain the highest filling factor the connections and local electronics should all occupy an area no larger than the sensitive area. Our concept is one in which the individual devices are bump-bonded to lands on a passive silicon block (to match thermal expansion). Printed leads on this block pass through a central hole to circuits and a connector underneath, all no larger in area than the CCD area. The devices would be thinned after being mounted to the blocks, so they would be optically flat and with exactly controlled dimenisons relative to the block. The blocks in turn would be exactly registered on a large optically flat substrate.

This concept has evolved from the work of graduate student Mike Lesser, who has made lab tests of many kinds of bonding. We have also thinned some imaging devices. Largely with other support, Leach has put into operation TI and GEC CCDs, with extremely flexible clocking to allow noiseless co-addition of adjacent pixels. We plan to use this set up for further tests in the coming year.

PUBLICATIONS FUNDED BY NGW-121

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INVENTION DISCLOSURE

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