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QUANTITATIVE ASSESSMENT OF THE SCIENCE RETURN FROM AN ORBITING, IMAGING, OPTICAL INTERFEROMETER

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ABSTRACT We describe an investigation of the science potential of the filled Mills cross orbiting, imaging, optical interferometer proposed by Synnott *et al.* and the constraints that science places on the design of the instrument. Imaging simulations were performed with this design in order to determine its capabilities in the area of spatial resolution, dynamic range, and sensitivity. In addition, specific astronomical objects of high interest were chosen as candidate program sources to determine what science was desired for these objects, what spatial resolution, *etc.* was needed to perform that science, and whether or not this interferometer design could do the science.

I. THE FILLED MILLS CROSS CONCEPT

Synnott *et al.* have proposed a filled Mills cross dilute aperture interferometer as a possible observatory-class follow-on mission to the Hubble Space Telescope. This design provides excellent radial (u,v) coverage and good off-diagonal coverage in a single snapshot, without having to rotate or reconfigure the interferometer. A spacecraft with two crossed 30m × 1m paraboloids can be deployed in a single shuttle launch. When the instrument is phased to $\sim 0.05 - 0.1$ wavelengths, the dirty map can be formed directly in the image plane on the CCD detector (a Fizeau interferometer). All spatial frequencies sampled by the filled arms are represented, creating a completely filled aperture. Synnott *et al.* call this mission concept the Fizeau Filled-arm Telescope (FFT).

II. IMAGING SIMULATIONS

Imaging software was developed for Fizeau interferometers. Simulations of point source observations were performed in order to determine the interferometer's dynamic range response, and of a complex source, in order to study detection of low surface brightness features, multiple weak point sources in the field, *etc.* Values of 10^{-3} counts s^{-1} pixel^{-1} for the background noise, 50% quantum efficiency and 1.0 count pixel^{-1} readout noise for the CCD

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detector, 100 Å bandwidth, and three pixels per main interferometer lobe (beam) were chosen.

Results of point source simulations indicated dynamic ranges of 700 N, 100 N, and 6 $N^{1/2}$ for sources of 10^3, 10, and 10^{-2} ct s^{-1} m^{-2} (*i.e.*, $m_V \sim 15$, 20, and 25), respectively, where N is the number of snapshots rotated by 180/N degrees and averaged together. Dynamic range is defined as the ratio of the map peak to the brightest error in the map Note that only the weakest source is limited by the noise. The other two are limited by (u,v) coverage errors.

The complex source used was that devised for imaging studies of the QUASAT orbiting radio astronomy mission (Readhead *et al.* 1984), representing a variety of objects including quasars, novae ejecta, stellar jets, *etc.*, depending on the assumed flux and size. For these simulations we gave it the size (0.″1 × 0.″3) and flux of $m_V \sim 17$ Seyfert (10^{43} erg s^{-1}) and $m_V \sim 12$ quasar (10^{45} erg s^{-1}) emission line regions 200 Mpc distant. The simulations studied single 17 minute snapshots of this source with the FFT, as well as "full synthesis" images formed by averaging eight snapshots, separated by 22.5 degrees rotation. (See Meier 1990 for more details.) The original image was almost fully recovered, even though the point sources were as faint as 27th magnitude each. From these simulations we have determined the RMS noise level for the FFT to be $\sigma \sim 1.5 \times 10^{-3}$ ct s^{-1} m^{-2} bm^{-1} (29.5 magnitudes per beam) with the detection limit at about 6σ.

III. SCIENCE WITH THE 30m FFT

A. Solar System Science. The filled-arm interferometer functions as a planetary camera with resolution sometimes better than the best Voyager images (see Table I). Blurring due to planetary rotation or atmospheric motions is not a problem as the exposure times needed to reach 100:1 signal-to-noise are $10^{-4} - 10^{-2}$ times shorter than the estimated blurring times (at an assumed 3 milliarcsecond resolution at 5000 Å). Required dynamic ranges are also only on the order of 10-100. Long term monitoring of atmospheric flows, vulcanism, *etc.*, as well as images of Pluto and asteroids 30-60 beams across, would be possible with such an instrument.

TABLE I. SOLAR SYSTEM SCIENCE WITH A 30m FFT

Solar System Object	Maximum Voyager Resolution	FFT Beam Size	Surface Brightness (ct s^{-1} m^{-2} bm^{-1})	Blur Time (sec)	Time to Achieve S/N ∼ 100
Mars	–	1 km	200	4	0.003 sec
Asteroids	–	4 km	200	–	0.001
Jupiter	14 km	9 km	60	0.6	0.01
Saturn	2 km	18 km	18	1.8	0.03
Neptune	11 km	60 km	1.5	24	0.4
Pluto	–	75 km	1.6	6000	0.4

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B. Stellar Astronomy. Crude images (3-10 beams across) of nearby giant and supergiant stars and a few dwarfs will be possible. This will allow detection of large starspot systems and measurement of polar vs. equatorial rotation rates. Because of the high brightnesses and low required dynamic ranges, it may be possible to perform spectroscopy of the resolved stellar surfaces with the snapshot dirty image, allowing the measurement of a variety of properties (velocity, magnetic field, temperature, abundances) at several locations on the surface. Imaging in the ultraviolet will allow the study of stellar chromospheres (with 10-30 beams across at 1500 Å). Monitoring in both UV and visible light could verify the suspected pulsations which heat and extend the atmospheres of cool supergiants. UV observations could also be used to study the structure of winds from O/B stars, which should be imageble out to 400 pc.

TABLE II. STELLAR ASTRONOMY WITH A 30m FFT

Star	Max Distance for 3-beam Image	Imaging S.B. ($ct\,s^{-1}\,m^{-2}\,bm^{-1}$)	Spectr S.B. ($ct\,s^{-1}\,m^{-2}\,bm^{-1}$)
Solar	$<$ 1 pc	10^8 (100 Å)	10^5 (0.1 Å)
K/M Giants	$<$ 13 pc	10^7 (100 Å)	10^4 (0.1 Å)
O/B S-giants	($<$ 40 pc)*	10^{10} (100 Å)	10^7 (0.1 Å)
M S-giants	$<$ 140 pc	10^7 (100 Å)	10^4 (0.1 Å)

* When observed at 1500 Å wavelength. Nearest O/B Supergiants are too distant for disks to be imaged with the 30m FFT.

C. Explosive Events. Three or more novae with magnitudes of 2 - 8 appear each year. These will be prime candidates for study with high resolution instruments because they are so bright ($\sim 10^4\ ct\,s^{-1}\,m^{-2}\,bm^{-1}$ in the 30 Å wide emission line at 5007 Å line of OIII), and they become more resolvable as they expand. Producing a crude 3-beam image as early as 10 days after the explosion, the FFT could be used to study explosion asymmetry, detailed flow in the ejecta, the formation of dust, and abundance gradients with spectral resolutions much smaller than the emission line widths.

Supernovae are not imageble until some 50 years after a typical event 10 Mpc away. (SN 1987A is, of course, a notable exception.) Echoes of the maximum light burst are imageble as early as 1.5 year after the event and may provide a primary distance indicator for determining H_o.

D. Extragalactic Astronomy. The FFT will produce detailed images of active galactic nuclei narrow line regions. 100 pc narrow line regions will remain imageble, with about the same surface brightness, out to 2 Gpc, allowing detailed study of many objects. 1 pc broad line regions will not be resolved even at the 1 milliarcsecond resolution obtainable at 1500 Å. (See Table III.)

The FFT may also be able to detect the 15 pc luminosity cusps created by $10^8\ M_\odot$ black holes in the centers of galaxies. The cusps' faint broad band surface brightness ($10^{-1} - 10^{-2}$ ct s^{-1} m^{-2} [1000 Å]$^{-1}$ beam^{-1}) indeed

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would be detectable with the FFT instrument. To determine a velocity of dispersion as a function of radius at this resolution with the Fourier method, at least 10^5 total photon counts are needed at each radial point in the galaxy – barely achievable in an 8 hour snapshot exposure in a 1000 Å bandpass. This could be improved if all photons in each annular region could contribute to the spectrum. Rotation of the interferometer would not be necessary as the 100:1 dynamic range achievable with a snapshot will be more than sufficient.

TABLE III. EXTRAGALACTIC ASTRONOMY WITH A 30m FFT

Object	Max Dist for 3-beam Image	Req Dyn. Range	Line Widths	Imaging S.B. ($ct\ s^{-1}\ m^{-2}\ bm^{-1}$)	Spectr S.B. ($ct\ s^{-1}\ m^{-2}\ bm^{-1}$)
$10^8\ M_\odot$ B.H.	300 Mpc	10	5 Å	10^{-2} (1000 Å)	(see text)
N.L.R.	2000 Mpc	10^{1-3}	30 Å	1 (30 Å)	0.3 (10 Å)
B.L.R.	(70 Mpc)**	10	150 Å	300 (150 Å)	100 (50 Å)

** When observed at 1500 Å wavelength. Nearest A.G.N. or QSOs are too distant to have their broad line regions imaged with the 30m FFT.

IV. FUTURE WORK

Future imaging simulations should include the effects of phase errors and finite bandwidths, both of which will reduce sensitivity. (We note that practical image restoration experience is being provided by the Hubble Space Telescope.) Issues of wavelength coverage, polarization capability, and methods for producing two-dimensional spectra still need to be treated before a baseline mission with a complete science program can be established.

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