What is beyond the Current Generation of Groundbased 8m - 10m Class Telescopes and the VLT-I?

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ABSTRACT

The tremendous growth in the building of large 8m and 10m telescopes, which give substantial gains in sensitivity over the current 4m telescopes, presents a significant challenge to the builder of a future 21st Century groundbased telescope. To try and explore the possible scientific motivations that may drive a future groundbased facility, I have chosen a current observational project whose completion is beyond the capabilities of our new generation of telescopes. By examining what is required of a groundbased facility to undertake spectroscopy on the majority of the objects in the Hubble Deep Field (HDF), it becomes apparent this project will need a Very Large Imaging Infrared Array (VLIA) or a 50m telescope. The main conclusion of this comparison is that any groundbased facility capable of undertaking this project is likely to cost *at least one billion dollars*. The choice between the two differing approaches should therefore be driven by the scientific aspirations of the 21st century community of astronomers. Superficially, the "scientific edge" probably belongs to the VLIA facility, with its ability to probe structures at infrared wavelengths down to the milli-arcsecond scale. The more profound issue is whether it is time for groundbased astronomers to begin looking to space for the placement of their next 21st Century telescope.

1. INTRODUCTION

The last twenty years has seen an unprecedented explosion in telescope building. So much so, that at the start of the 21st century, there will be more 8 to 10m class telescopes in operation than there are currently 4m telescopes today. What has driven this enormous investment? There are probably three factors:

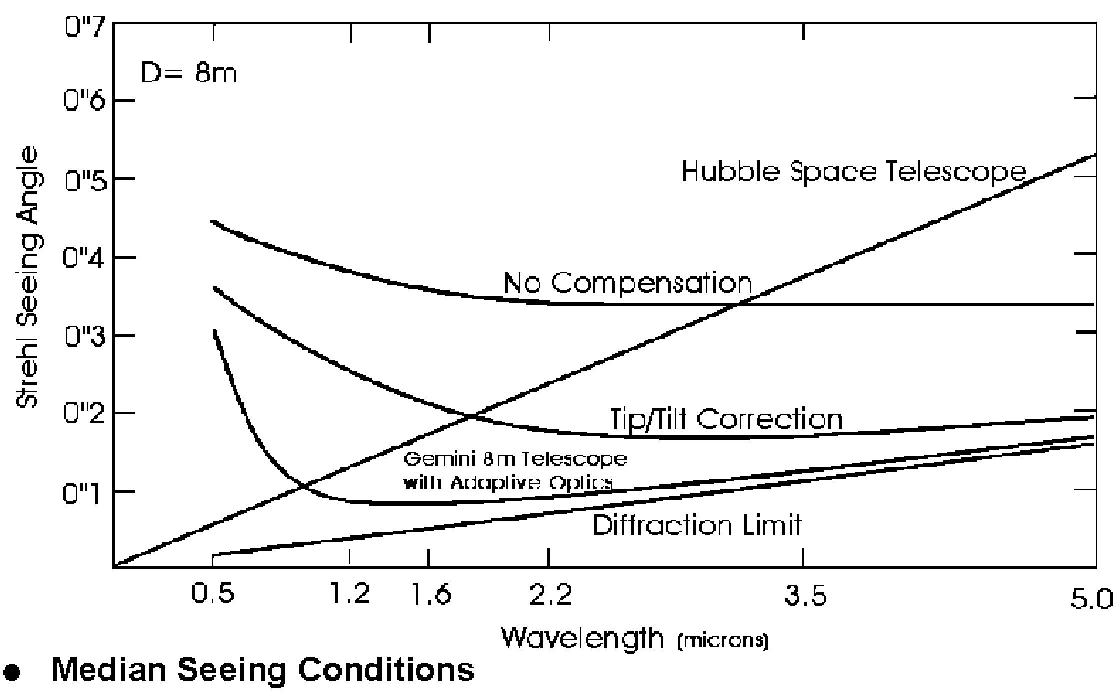

Figure 1. The expected delivered image quality at near infrared wavelengths using both simple 'tip/tilt" correction and low order adaptive optics, adapted from Roddier et al [1].

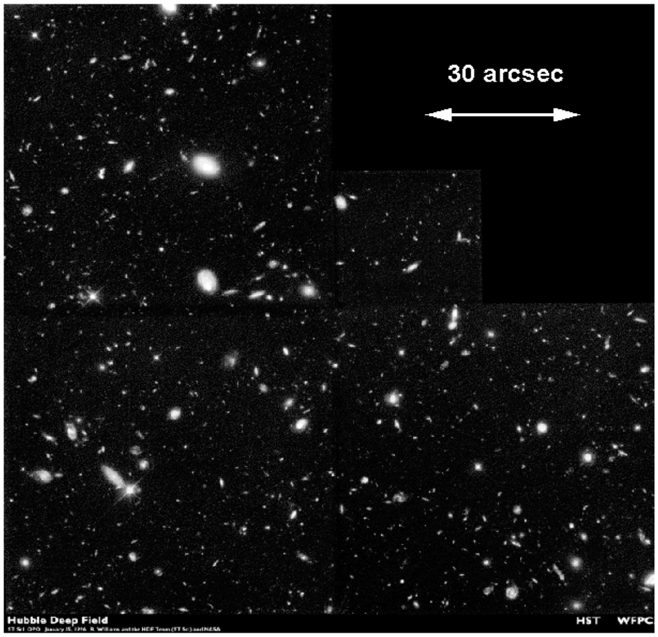

Figure 2. The Hubble Deep Field (Williams et al 1996a) [2] -- A target list for 21st Century Astronomy.

Science - The culmination of this millennium of astronomy is a tremendous growth in our understanding of the scale of the Universe and the range of astrophysical phenomena which underlies its apparent structure. Space missions such as IRAS and the Hubble Space Telescope, with their tantalizing views of a previously unrevealed cosmos from stellar nurseries, to the morphology of galaxies at redshifts of three or more, has simply reinvigorated our curiosity.

Technology - the revolution in computer and materials technology has enabled new approaches to building large telescopes and instruments. This has encompassed the detailed analytical modeling of complex structures to the construction of large, fully active primary mirrors and the deveopment of near perfect detectors with quantum efficiencies approaching 100%.

Atmospheric Physics - perhaps the most profound change in our groundbased perspective has been the realization that the turbulent structure of the atmosphere is amenable to analysis and correction. Figure 1 from Roddier shows that at near infrared wavelengths, we can build large telescopes that will be essentially diffraction limited, combining the resolution of HST with the collecting area of a 8 - 10m telescope.

It is the combination of the last two factors, the ability to manufacture and support large mirrors combined with adaptive optics, which has given the new generation of large telescopes such tremendous gains over the previous 4m telescopes. For example, an 8m telescope delivering 0.1 arcseconds images can observe point-like objects 10 times fainter than a conventional 4m telescope delivering 0.5 arcsecond images. Are we going see such gains in the next generation of groundbased telescopes?

2. DEFINING A 21ST CENTURY OBSERVATION

To try and explore the possible scientific motivations that may drive a future groundbased facility, I have chosen a current observational project whose completion is beyond the capabilities of our new generation of telescopes. A key first step in understanding galaxy evolution will be obtaining spectra of galaxies and their constituent parts for a range of morphological types stretching back to the earliest epochs observable. Figure 2 shows one of the deepest views of our Universe, taken by the Hubble Space Telescope and if we are viewing galaxies at high redshift, then the Hubble Deep Field (HDF) (Williams et al 1996a)[2] provides an ideal target list for this project. The magnitude range of the objects in the Hubble Deep Field (HDF) is shown in Figure 3 (Williams et al 1996b)[3] along with the current spectroscopy limits achieved by the Keck telescope.

Over 90% of the objects in the HDF have yet to be measured or dissected by spectroscopy. To reach this remaining 90% of galaxies will require at least 4 magnitude increase in sensitivity or an instrument which can deliver at least 40 times the signal to noise ratio of the Keck I telescope and its spectrographs. If I assume that we try and observe these high redshift objects in the IR, where we can obtain images of comparable size to HST, from Figure 4, the I - H colors of the high redshift galaxies in the HDF are likely to be about 2 -3 magnitudes. Given that we expect IR spectrographs on telescopes Gemini to reach H magnitudes of 22 - 23, will still need a signal to noise gain of at least 40 (~4 mags) over what we will expect to achieve with H band spectroscopy on an 8m telescope using 0.1 arcsecond apertures.

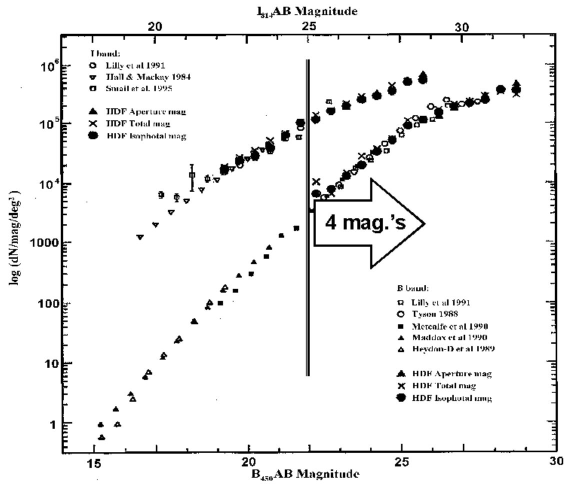

Figure 3. The number density with magnitude for galaxies in the Hubble Deep Field both at R and I. (Williams et al 1996b)[3]. The solid line shows the current spectroscopy observation limit on Keck-1.

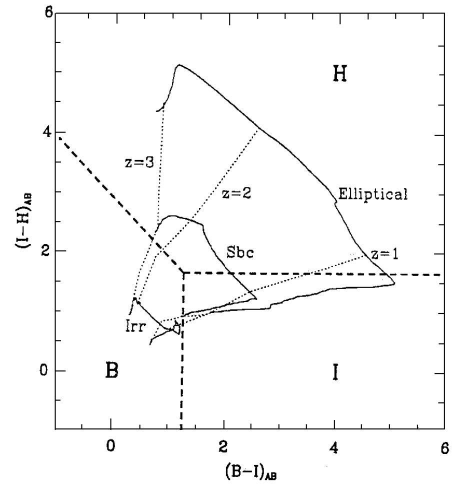

Figure 4. The expected I-H colors of high redshift objects from Lilly (1995) [4].

In the background limited regime like the IR, the signal to noise ratio of a measurement of a point-like source can be expressed as follows:

For background or sky noise limited observations:

$$\frac{S}{N} \approx \frac{(Effective\ collecting\ area)^{1/2}}{Delivered\ image\ diameter} \frac{\eta^{1/2}}{\varepsilon^{1/2}}$$

Where η is the effective throughput of the telescope to the focal plane and ε is the effective emissivity (or relative background) of the telescope.

Which for background or sky noise limited spectroscopy becomes simply:

$$\frac{S}{N} \approx \frac{(Effective\ telescope\ diameter)}{Effective\ aperture\ width} \frac{\eta^{1/2}}{\varepsilon^{1/2}}$$

The challenge therefore is to design a groundbased facility which will offer a gain in this ratio of at least 30 - 40 over current and future 8m - 10m telescopes or,

S/N ~ 40 x S/N of a 8m ~ 10 m Telescope

Simply increasing the telescope diameter by a factor of x40 is not a viable option. Consequently, a future groundbased facility will also have work at higher angular resolution than current facilities. This means we will be spatially “dissecting” the majority of the objects we hope to observe rather than simply collecting the integrated flux from objects in the Hubble Deep Field (HDF).

3. OPTIONS FOR A 21ST CENTURY GROUNDBASED TELESCOPE

A pragmatic way to look at which type of facility may achieve the observing gain we need is to extrapolate from what we have (or are planning to have) in operation by the turn of the century. Looking at Table 1, there will be a substantial number of large groundbased facilities worldwide against which a 21st Century observatory will have to demonstrate a significant gain to justify any further investment. By simply plugging in the numbers for a 20m telescope, using near diffraction limited spectroscopic aperture of 0.04 arcseconds, assuming an adaptively corrected

Strehl ratio of ~0.5 at 1.6 microns, gives a Signal/Noise gain of 6 - 7 over an equivalently corrected 8m telescope. To realize a gain of 20-40 will require a more radical and ambitious approach than "simply" building a 20m telescope. I look at two options here, a very large optical/IR array and a 50m telescope.

3.1 A kilometer baseline large imaging array

Table 1 shows one possible extrapolation to a large IR imaging array (VLIA) with the equivalent collecting area of a 32m telescope.

The key characteristics of such an array is that it should have a large effective aperture, combined with a scientifically interesting angular resolution. As Table 1 shows, the proposed Very Large Imaging Array (VLIA) gives an increase in effective aperture over the latest facility by about a factor of 4 and an increase in angular resolution by a factor of 5. To gain any advantage over conventional telescopes in background limited spectroscopy, a fully corrected "image" must be delivered to the focal plane. Consequently, a "facility" Very Large Imaging Array (VLIA) is envisioned as at least 16 -20 adaptively corrected 8 meter telescopes operated in the near infrared, arranged in a "snap shot" configuration, for example as in Figure 5.

Table 1

Facility	Baseline(m)	Collecting Area(m^2)
• SUBARU	8	50
• Gemini 8-M	8	2x50
• CHARA	354	5.5
• LBT	20	110
• Keck 1 & 2 +	165	157+11
• VLTI +	200	201+20
• Very Large Imaging Array	1000	800

16 x 8m fully adaptive telescopes with 0.01" - 0.001" images at 2.2 μm - 10 μm

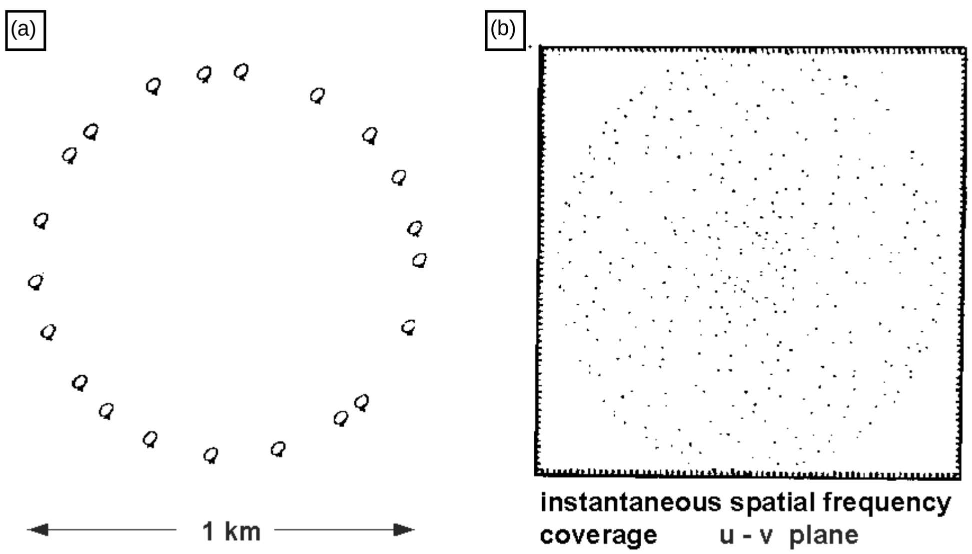

Figure 5(a). A "snap shot" configuration based on a Cornwall Circle (Hjellming[5], Cornwall[6]) and (b) the associated U-V coverage.

In order to achieve a S/N advantage for compact sources compared to an 8m telescope delivering 0.1 arcsecond images, the 1km array must actually transmit 1-5% of the total flux from the 16 x 8m telescopes through a 1 milli arcsecond spectroscopic aperture (1mas). This may be a fairly optimistic fraction given the interferometric dilution that can occur with simple Fizeau combination which preserves the geometry of the input and output puils to give reasonable imaging fields of view (Roddier[7]). However, Labeyrie[8] has shown that this fraction can be significantly improved using Michelson recombination, which in the limit, must approach the radio synthesis domain. In this domain, the point source flux within a diffraction limited core is of the order of S:

$$S \approx \gamma \frac{\sqrt{N(N-1)/2}}{4\sqrt{2}} \pi D^2$$

where N is the number of telescopes of diameter D and $\gamma \approx 1$ for a configuration like that in Figure 4.

In this "radio limit" for N = 16, the fraction of flux from the total collecting area can approach ~40% assuming no recombination losses. However, in this limit, the field of view approaches that of a single 8m telescope. For the type of observations outlined above, a VLIA needs to work in the intermediate regime, using the "zoomed Michelson" described by Labeyrie[8] , with an imaging field of view of at least 5 arcseconds and the fraction of the flux in the diffraction limited core approaching 1%.

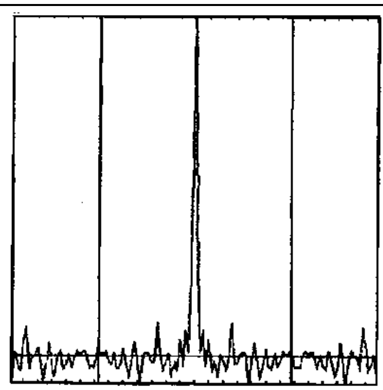

Figure 5(c). The expected instantaneous beam profile (Hjellming [5]).

An estimate of the cost of such a facility (measure of scientific and political feasibility) are given in Table 2. The unit costs are scaled from current 8m projects and assume substantial cost savings from manufacturing the individual elements "in bulk". For example, I estimate an individual adaptively corrected 8m telescope could be built for approximately $80M (in today's dollars), and that by manufacturing 15 more identical copies can reduce the unit cost to $40M. In addition, I assume each telescope is surrounded by simple wind breaks rather than complex enclosures.

Using these fairly rough estimates, the total cost to build 21st Century groundbased infrared interferometer will be of the order of $892M (1996). If it takes 10 years to build an VLIA (with inflation at 3% per year) the total cost by 2006 will be the order of $1,200M.

Table 2

VLIA Facility	**quantity**	**unit cost (1996)**
8m adaptive telescopes	16	$40M
Wind shelters + site work	16	$8M
Optical/IR delay lines	16	$2M
Laser Beacon System(s)	16	$2M
OH rejection Imager/Spec	1	$10M
Beam tubes, combining facilities controls, services, management	1	~ $50M
TOTAL		**$892M**

3.2 A 50m Telescope

An alternative approach to achieving a S/N gain of 30-40 over an 8m telescope is a 50m telescope, shown in Table 3, together with a comparison of current facilities.

Table 3

Facility	Baseline(m)	Collecting Area(m^2)
• SUBARU	8	50
• Gemini 8-M	8	2x50
• CHARA	354	5.5
• LBT	20	110
• Keck 1 & 2 +	165	157+11
• VLTI +	200	201+20
50-M Telescope	50	1963

As has been discussed, good image quality is required to drive down the background in any spectroscopic observation, so the concept I have examined is a fully adaptively corrected 50m telescope. Figure 6 shows the expected Strehl ratios using the extrapolation formulas of Racine[9], both as a function of IR waveband (I through N) and of off-axis angle, for a 1000 actuator AO system in good seeing conditions on Mauna Kea.

What is immediately apparent is that an adaptively corrected 50 m telescope will also have a limited field of view (FOV), over which good images can be obtained, especially in the 1 - 3 micron regime. However, for the envisioned project, imaging spectroscopy of Hubble Deep Field galaxies, FOV ~ 10 - 20 arcseconds is not necessarily a significant draw back.

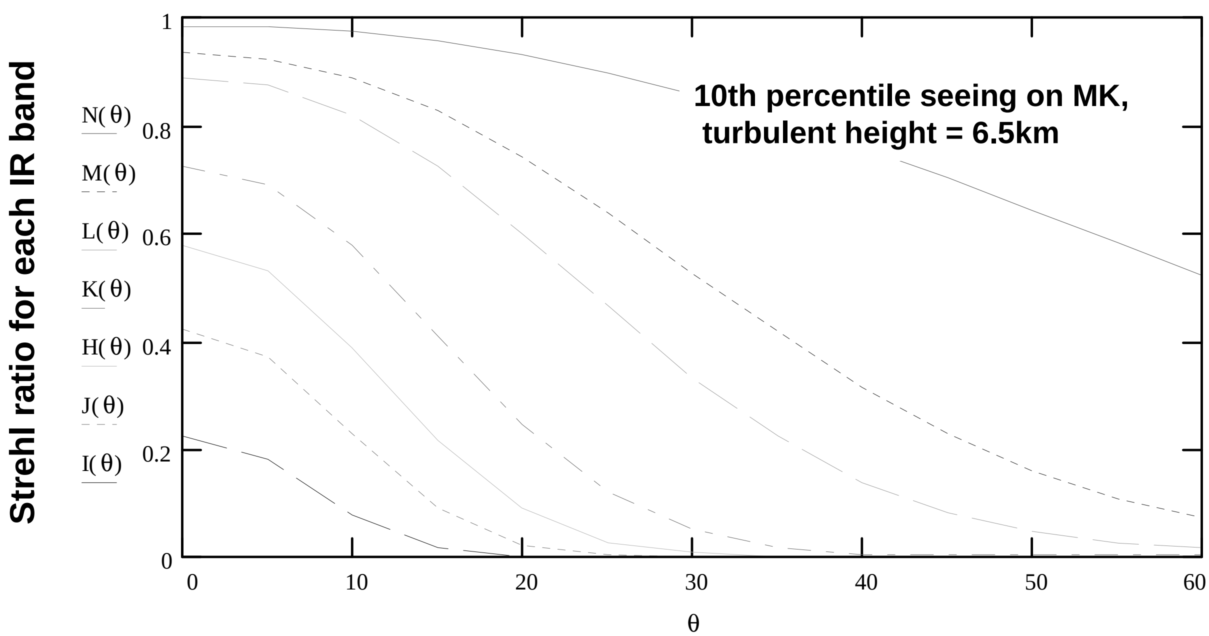

Figure 6. An AO corrected 50m telescope on good seeing, assuming N~1000 actuation system.

Again, to assess the feasibility of such a facility, I have costed the following 50m telescope concept from Oschmann (1996) [10] shown in Figure 7.

The primary is assumed to be a segmented “simple” parabolic surface, to simplify both the manufacture and testing of each segment. In addition, we have assumed limited active support for the primary mirror as wind buffeting, flexure and thermal affects will all have to be corrected by a small (2m diameter) fully active and adaptive secondary mirror with at least 1000 actuators. The focal plane is relayed across the 25m primary radius to Nasmyth platforms using a collimated beam and then brought to a focal surface by a small reflecting telescope. The optical quality of such a configuration can be essentially diffraction limited over a 0.6 arcminute diameter field as shown in Figure 8. The image quality over larger FOV’s is limited by atmospheric isoplanatism.

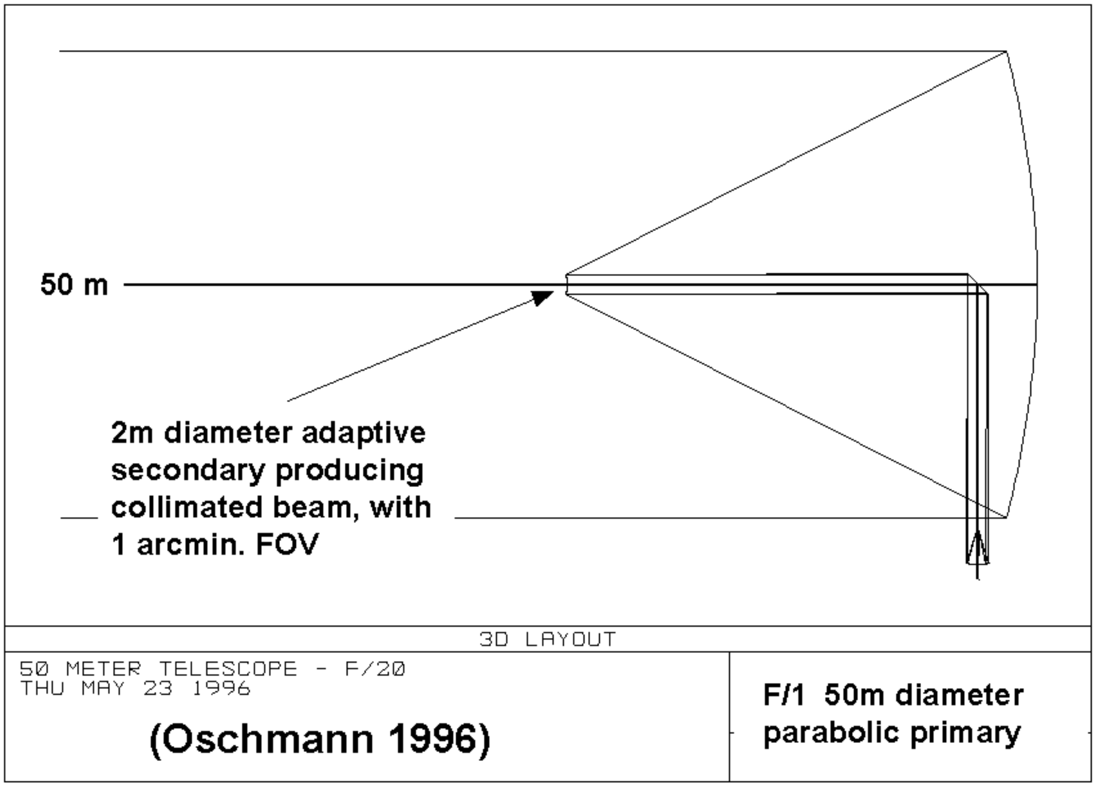

Figure 7. The 50m Telescope Concept.

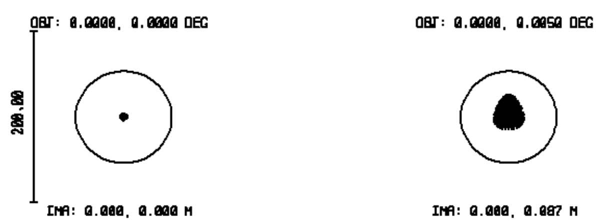

Figure 8. Optical performance of the 50m concept at 2.2 microns.

The cost of such a telescope, partially scaling from current 8m telescope projects is estimated in Table 4.

If the current generation of 8m and 10m telescopes have been designed to be as structurally efficient as possible, cost scaling is more likely to follow the $D^{2.6}$ law (Hjellming[5], or Hoerner[11]). However, the Hobby Eberly Project[12] have shown that by using an “Arecibo” approach to building large telescopes, this cost scaling law can be reduced (Bash et al, 1996[13]). So in Table 4, I have constrained certain costs to keep within a budget of a billion dollars -- assuming such things as; a simplified enclosure, a control system of comparable complexity to Gemini etc. Consequently, I will assume one billion dollars will be sufficient to build a 50m telescope by departing somewhat from our more “traditional” large telescope designs and following the lead of the Hobby Eberly concept.

Table 4

50m Telescope	**costs (1996$)**	
Primary mirror assembly	$622	scaled costs
Telescope structure & components	$190	scaled costs
Secondary mirror assembly	$11	scaled costs
Mauna Kea Site	$78	scaled costs
Enclosures	$70	constrained costs
Controls, software & communications	$26	constrained costs
Facility instrumentation (A&G, AO)	$10	constrained costs
Coating & cleaning facilities	$14	constrained costs
Project office	$40	constrained costs
Total	**$1,061**	

4. Comparisons

To try and contrast the two approaches, I have compared the effective sensitivity of the two facilities in Table 5.

Table 5

$$\frac{S}{N} \propto \frac{Equivalent\ Telescope\ Diameter}{Effective\ \ Aperture\,Width}\,\frac{\eta^{1/2}}{\varepsilon^{1/2}}$$

50 m Telescope	λ = 1.6 µm	1 km Imaging Array
D_{equ} = 50m θ = 20 *mas* η = 80%		D_{equ} = 32m θ = 1 *mas* η = 1%
(emissivity = 5%)		(emissivity = 20%)
S/N = 36 x Gemini		S/N = 52 x Gemini
for ~ 20 *mas* size sources		for ~ 1 *mas* size sources

The first point which needs emphasis is that for an VLIA to be scientifically useful for the Hubble Deep Field imaging project, at least 1% of the collected flux from at least 16 x 8m telescopes must be concentrated into a 1mas scale imaging spectrograph and the imaging field of view must be at least 3 - 5 arcseconds.

The second point is that a 50m telescope will only approach the required sensitivity gains over a limited field of view (limited by isoplanatism) as we will have to rely on adaptively corrected images to probe the faintest sources.

The third point is that although both approaches give a significant gain over current 8-10m class telescopes for point like sources, neither the VLIA of the 50m Telescope will effectively measure the integrated light from an HDF galaxy. In fact, what we will be measuring are the spectra of sources within the galaxies on either 20mas or 1mas scales.

Figure 9 compares the scale of various astrophysical phenomena. What is apparent is that at the 1 mas scale, we will be able isolate structures such as giant molecular clouds, globular clusters and AGN's in high redshift galaxies. At this type of resolution, the integrated light is actually distributed into fairly compact sources. A simulation of a 2.2 micron image using a 8K x 8K imager using 0.001 "/pixel of NGC 253 redshifted to z = 3 is shown in Figure 10 (adapted from Metzger et al 1996[14]). Figure 11 taken from Stockman[14], shows the expected magnitude of a range of astrophysical sources in high redshift objects, and as can be seen, it will be possible to detect such structures if we can get down to a limit of 29-30 magnitudes. Given also that on Galactic scales 1 mas resolution should allow most nearby planetary systems and star formation regions to be observed in great detail, the VLIA may have the scientific edge over a 50m telescope. However, the challenge of a VLIA will be the ability to actually make scientifically

Footnote:

1. Quoting from von Hoerner (1987): "When scaling a design to other sizes, different members scale with different exponents of the telescope diameter D. Omitting all details: the many small members keep the bar area fixed and just go with D. Longer ones without much load keep the slenderness fixed and go with D^2. All those which carry the main loads of survival winds (ice, snow) keep the stress fixed and go with D^3. If a few members must be beefed-up for observational winds, they keep the deformation fixed and go with D^4. Altogether, we found from some examples an exponent of about 2.6 for the whole telescope."

useful images of the type shown in Figure 10.

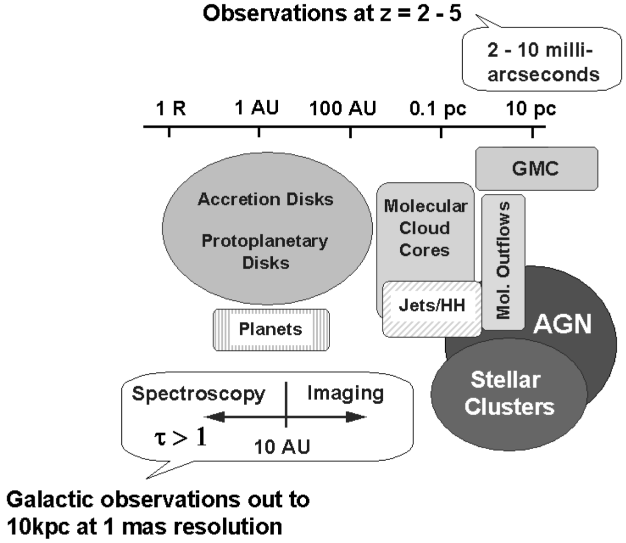

Figure 9. The scale of several astrophysical phenomena.

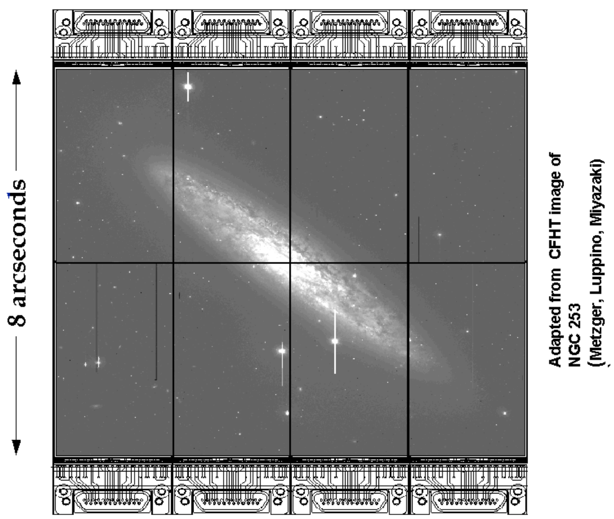

Figure 10. A simulation of a 8K x 8K image of a z~3 galaxy taken at 2.2 microns (adapted from Metzger et al 1996[14]) the type of image we should aim to obtain on a future 21st Century facility.

5. CONCLUSIONS

The main conclusion of this comparison is that any groundbased facility capable of undertaking spectroscopy of the majority of the Hubble Deep Field objects is likely to cost *at least one billion dollars*. The choice between the two differing approaches should therefore be driven by the scientific aspirations of the 21st Century community of astronomers. Superficially the "scientific edge" probably belongs to the VLIA facility, with its ability to probe structures at infrared wavelengths down to the milli-arcsecond scale. However, the real performance of VLIA will depend on the ability to concentrate a significant fraction of the flux collected by the equivalent of a 32m telescope (1%) into 1mas apertures while maintaining a scientifically interesting imaging field of view.

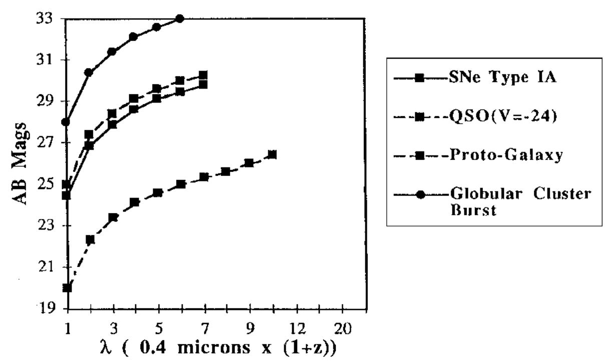

Figure 11. The expected magnitudes of several astrophysical sources within high redshift objects, from Stockman[15].

Given that the Bahcall Committee Report[16] and the "Hubble and Beyond" Reports[17] reflect a continuing desire to extend our scientific interests along the directions I have outlined above, perhaps the more profound issue is whether either of the above approaches, a 50m groundbased telescope or a groundbased VLIA is in fact the correct direction to pursue these scientific goals. If, as I believe to be the case, it will take at least one billion dollars to take a scientifically significant step from the ground beyond our current generation of large telescopes, then space telescopes become reasonable alternatives. The main driving parameters I have chosen are to increase collecting area and to simultaneously decrease sky background through increased angular resolution. Alternatively, putting a large telescope in space, and exploiting the 10^3 - 10^5 reductions in background is another way to gain large factors in signal to noise over current 8-10m class telescopes. If the NGST proposal (Belly 1996[18]) is shown to be feasible at a cost even comparable to one billion dollars, maybe it is time for groundbased astronomers to begin looking to space for the placement of their next 21st Century telescope.

6. ACKNOWLEDGEMENTS

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