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Memorie della

The VLT interferometer

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Abstract. The VLT interferometer has been operating since the time of first fringes in March 2001 with a pair of 40 cm diameter siderostats at baselines of 16 and 66 m and since October 2001 with a pair of 8 m diameter telescopes (UT1 and UT3) with a baseline of 103 m using the test camera VINCI operating in the K band. In this talk, I will describe the present status of the facility and plans for its future development.

Key words. instrumentation: interferometers – techniques: interferometric

1. Introduction

The important milestones in the history of optical long baseline interferometry (OLBIN) are all quite recent. The first successful use in astronomy was the measurement of the angular separation of Capella (Anderson 1920) and the diameter of Betelgeuse (Michelson & Pease 1921) both with the Michelson interferometer on Mt. Wilson. The first use of OLBIN with 2 telescopes to measure diameters of MS dwarf stars was accomplished by Hanbury-Brown & Twiss (1956) with the intensity interferometer at Narrabri, Australia. The first direct combination of light from 2 telescopes by Labeyrie (1975) occurred at Nice Observatory while the first optical synthesis imaging of Capella took place with COAST (Baldwin et al. 1996). Finally, the first combination of very large telescopes (Keck 10 m, VLT 8 m) occurred in 2001 and the first 6-way beam combination at NPOI, Flagstaff in 2002. Thus, clearly, OLBIN is just getting started but the pace is rapidly picking up. Currently, OLBIN projects seem to be sprouting everywhere. The list includes the VLTI on Paranal (4×8 m + 3×1.8 m, $B = 200$ m), the Keck interferometer on Mauna Kea (2×10 m + 4×1.8 m, $B = 140$ m), the CHARA array on Mt. Wilson (6×1 m, $B = 350$ m), the LBT on Mt. Graham (2×8.5 m, $B = 23$ m), SUSI in Australia, (3×0.15 m, $B = 640$ m), the NPOI in Flagstaff, AZ, (10×0.5 m, $B = 440$ m) and, last but not least, SIM, Darwin, TPF in space.

The reason for all this activity is not difficult to discern. A typical OLBIN project would have 50-100 times the spatial resolution of Keck and HST, 30 times that of ALMA, 2-3 times even that of OWL for a tiny fraction of the cost (and also, unfortunately, of the sensitivity and field of view!). This situation is dramatically illustrated in

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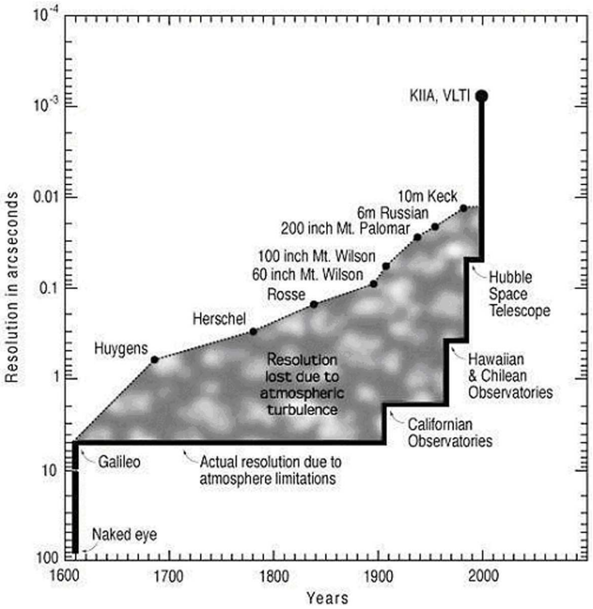

Fig. 1. The evolution of resolution in astronomy from Galileo to the present. Most of the increase in the 20th century has been solely due to the better locations of telescopes to minimize or eliminate altogether atmospheric seeing not to any technical breakthrough. Recently, AO techniques have allowed a narrowing of the gap at least for small fields.

Fig. 1 that shows the history of the evolution of the spatial resolution parameter as a function of time since Galileo's telescope. We presently sit at the very top of a narrow peak afforded by OLBIN techniques.

2. Theoretical and technical background

Four parameters can be obtained, in principle, from an observation of the fringe packet at the zero optical path difference (ZOPD) position:

1. The fringe visibility or the modulus of the degree of correlation between the electromagnetic fields at the two telescopes: $V = (I_{\max} - I_{\min})/(I_{\max} + I_{\min})$ with $0 \leq V \leq 1$, If $V = 0$, the radiation is completely incoherent and the source is resolved If $V = 1$, the radiation is fully coherent and the source is unresolved In between these extremes there is partial coherence. Light at the combination point is a mixture of coherent and incoherent radiation with $V = I_{\mathrm{coh}}/(I_{\mathrm{incoh}} + I_{\mathrm{coh}})$.
2. The position of the fringe packet with respect to the phase reference or phase tracking point gives the phase ϕ of the complex degree of correlation. These two measurements alone completely determine the degree of correlation and, therefore, the source intensity pattern through the Van Citters-Zernike theorem.
3. The fringe period or number of oscillations connected to the spatial angular resolution $\simeq \lambda/B$.
4. The width of the fringe packet giving the bandpass $\Delta\lambda$ and the source spectrum.

So, in principle, that's all there is to it: measure V and ϕ for a number of different pairs of points (baselines lengths and orientations), do an inverse FT and get the source intensity pattern. In practice, unfortunately, the atmosphere above the telescopes adds a random phase that has to be accounted for i.e. the fringe packet moves randomly near ZOPD. Thus, one needs to calibrate the measured complex visibility with a point source (Transfer Function similar to PSF). In the radio ($10-600$ THz), the atmospheric coherence time is $\sim$ 20 min and the size of the iso-planatic patch $\sim 1^\circ - 2^\circ$ while in the optical/IR they are $\sim$ 10 ms and $\sim 30''$, respectively. This means that phase referencing in the radio can be done by off-pointing to a calibrator star but in the O/IR this is essentially impossible! Other practical constraints are that the maximum OPD allowed $= \lambda^2/\Delta\lambda$ which means that the absolute accuracy of OPD compensation has to be $\sim$ 10 μm over 200 m ($\sim$ 1 part in 10^9) at $\lambda \sim 1$ μm. The optical path jitter during observation, moreover, must not smear the fringes i.e. ΔOPD$\sim \lambda/20$ meaning that the dynamic stability of OPD compensation has to be $\sim$ 10 nm. This goes a long away towards explaining why OLBIN has taken such a long time to implement! In addition, one needs to consider some other serious limitations that only recently have been partly overcome. The interferometer $S/N \propto NV^2$ where N = number of photons detected/subaperture/integration time and V = measured visibility. Thus, detection becomes increasingly difficult for spatially complex sources as: $m_{\rm resolved} = m_{\rm unresolved} - 2.5 \log V^2$. So, for example: if V=10%, $V^2 = 0.01$ and $m_{\rm resolved} = m_{\rm unresolved} + 5$. Integration times are limited to the atmospheric coherence time (10 ms in O/IR) without a fringe tracker. The background is high (especially at 10 μm) due to detector noise, sky and thermal emission from telescope etc. Adding all these factors up one gets shockingly low sensitivities! One must increase sensitivity by using large collecting areas, adaptive optics and fringe tracking. The new large telescope interferometers are an attempt to couple the high spatial resolution afforded in principle by up to 200 m baselines ($\sim$ 1 mas at 1 μm) with high sensitivity due to the large collecting areas of 8-10 m telescopes. But the problem then becomes (u, v) plane coverage since these beasts are not movable (only earth rotation synthesis) and OLBIN requires many and/or movable smaller auxiliary or outrigger telescopes since the number of baselines is proportional to $n(n-1)$.

3. Present status

Since the corresponding times of first fringes in March and October of last year, the VLTI configuration we have been using is shown schematically in Fig. 2. In particular, this means the use of the UT1 and UT3 8-m telescopes on a 103 m roughly NE-SW baseline both equipped with Coude' optics and tip/tilt sensors and 2 40-cm diameter siderostats on 16 and 66-m baselines oriented almost orthogonally as shown in Fig. 2. In the 120-m long delay line tunnel, 3 60-m long stroke delay lines allow access to most of the available AT stations and the required tracking and OPD compensation. In the beam combination laboratory, pupil plane combination of the two beams is implemented by means of the test instrument VINCI operating in the K band at 2.2 μm. The whole system together with its scientific objectives is described in greater detail in the ESO web site[1].

The currently achieved delay line precision is remarkable: flatness of rails better than 25 μm over 65 m, an absolute position accuracy of the carriages of $\sim$ 30 μm and a relative position error of $\sim$ 20 nm RMS over 50 ms. It is this phenomenal precision and stability that makes the VLTI possible and unique. The sensitivity and precision achieved with the test camera VINCI and the two UTs is shown in Fig. 3.

4. First science results

First fringes with the siderostats were obtained March 17, 2001 and with UT1 and

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[1] `http://www.eso.org/projects/vlti/`

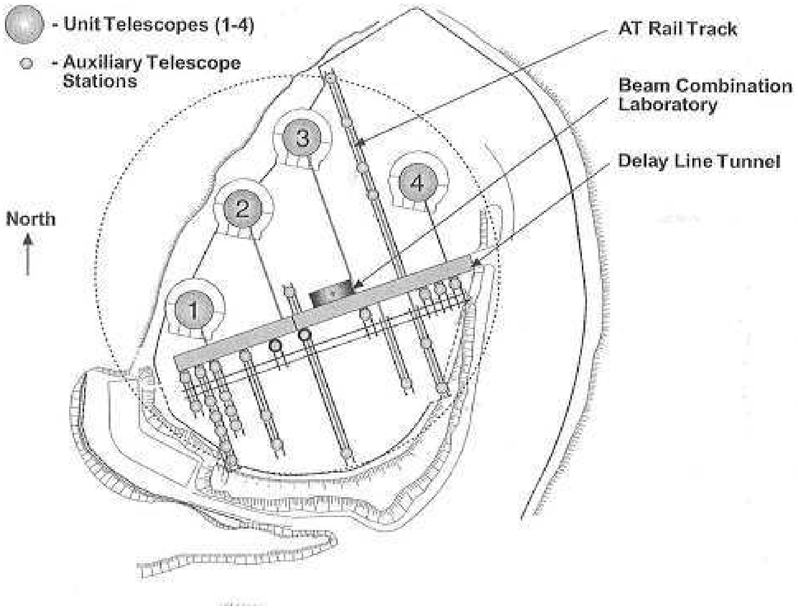

Fig. 2. Schematic layout of the VLT Interferometer facility on Cerro Paranal. The dotted circle has a diameter of 200 m for scale. The small circles indicate the auxiliary telescope (AT) and siderostat stations. The original siderostat positions with a 16 m almost E-W baseline are marked in bold relief. The current positions correspond to the W siderostat remaining where it is and the E siderostat moved to most Southerly station on the same track for a 66 m almost N-S baseline.

3 on October 30, 2001. Technical commissioning is ongoing with highest priority. During natural pauses, observations of scientifically interesting sources take place. An internal science group decides on sources to be observed and the list is approved by the project manager responsible for commissioning. All scientifically interesting data taken in the period from March 17, 2001 and March 25, 2002 have been released to the community and are currently available from the ESO archive[2]. About 25 ESO community scientists have availed themselves of the opportunity and are presently working on data taken so far. We encourage everyone to try! Data release is expected about every 3 months. VINCI and the siderostats have also been made available in service mode to the community on a shared risk basis starting on October 1, 2002 (Period 70). The deadline was April 3, 2002 and 39 proposals were received by that date. The total number of objects measured so far is 140 (most of them repeatedly), 57 for the first time! The breakdown: 1 AGN, 1 W-R star, 1 LBV, 1 symbiotic nova, 1 S star, 3 Cepheids, 3 YSO, 3 emission line stars, 3 shell stars (IR excess), 6 C stars, 10 MS dwarfs, 12 Spectroscopic binaries, 39 Late-type giants, and 56 Miras. The Cepheids are used to obtain a distance determination as precise as 1% or better by accurately measuring the variation of the star's diameter through the full pulsation cycle. The corresponding measurements of the radial velocity variations yield the dis-

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[2] `http://www.eso.org/projects/vlti/instru/vinci/vinci_data_sets.html`

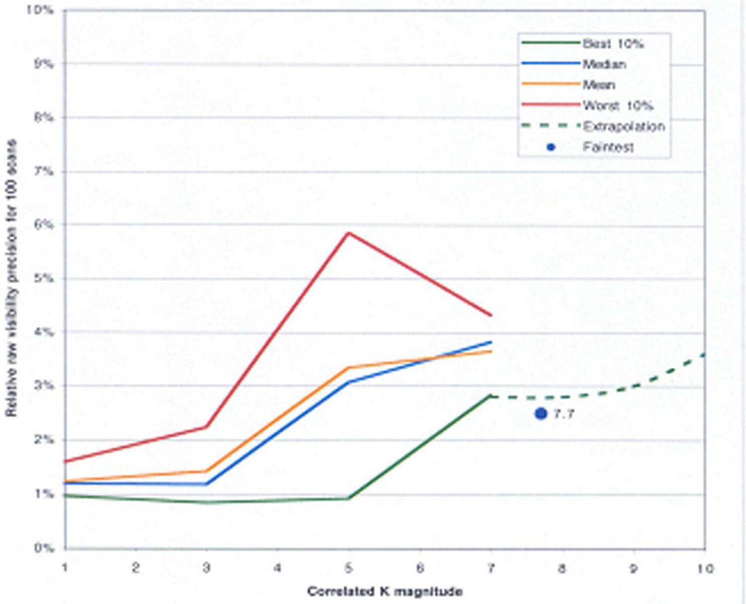

Fig. 3. Visibility precision vs. source correlated K magnitude achieved so far with VINCI and UT1 and UT3.

tance to the object since both the physical and the angular sizes of the motion are determined simultaneously. Observations of the Cepheid Zeta Gem ($K = 2.1$, $D \sim 2.2$ mas, $d = 360$ pc, $P = 10$ d), for example, have shown that the required observing precision to track the pulsation has been achieved (1.78 ± 0.02 mas) and that all that remains to be done is to follow the 10 d period to extract the distance. K velocimetry is limited mainly by the projection factor which is model and limb darkening dependent. Currently, the precision with which this parameter can be obtained is $\sim$1% which corresponds approximately to the final accuracy on the distance. Sampling over many baseline orientations and beyond the first null for limb darkening effects should push this accuracy down to $\sim$0.1%. With these accuracies, the anchor of the distance ladder that is based mainly on the Cepheids will take a huge leap forward in usefulness and confidence. The LBV Eta Carinae was also observed at the 3 different baseline lengths and orientations available with excellent results as the measured visibilities were all >20% and relatively easy to measure. Less straightforward is the interpretation of the measurements. Some success has been obtained with wind models coupled to a disk to reconcile the observations with ISO spectra and high resolution AO images of the nuclear region. A similar study is ongoing on the symbiotic nova R Aquarii whose diameter is being monitored carefully to detect variations due to the Mira's 387 d pulsations. Measurements taken at different times cluster around the value of 16.13 mas as expected for a typical Mira of this type. The variations of the visibilities in time will be carefully monitored for signs of the possible hot white dwarf secondary. The scientific objectives of this first phase of the VLTI development are:

1. High precision visibility measurements at K (no phase information but $\phi \equiv 0$ for axial symmetry).
2. Distance and mass determinations with binaries.

3. Diameter, T_{eff} determinations with stars across the H-R diagram
4. Several hundred measurements at 1% or better precision (much better than thousands at 10% since theoretical models unconstrained at 10%).
5. First look at the brighter complex systems: YSO and debris disks, envelopes and shells, torii etc.

5. Future prospects

Two new instruments (see Tab. 1) will become available in $\sim$ 2003 to extend wavelength coverage to 10 m and 3-way beam combination:

The spectrograph of AMBER (SPG) is being built at the Osservatorio Astrofisico di Arcetri. It is shown schematically in Fig. 4. It is contained in a 77 K liquid–nitrogen cryostat and accomplishes the following set of functions in the near-infrared bands J, H, and K', from 1.0 to 2.4 μm:

- formation of an image of the fiber outputs at cryogenic temperature and filtering of thermal radiation by means of suitable spatial filters;
- formation of a parallel beam;
- accurate spatial filtering of the pupils;
- separation of spectroscopic beams from photometric beams;
- spectral analysis at three resolving power values (50, 1000, 10000);
- formation of images on the detector plane.

A fringe tracker (FINITO) will be available by beginning of 2003 for on-axis fringe tracking in H for bright sources ($H < 12$) observed at longer wavelengths. This is a collaboration between ESO and INAF Osservatorio Astronomico di Torino with the financial support for the three-beam upgrade from the Consorzio Nazionale per l'Astronomia e l'Astrofisica - CNAA FINITO (Fringe-tracking Instrument of NIce and TOrino) measures the optical path difference (OPD) variation, induced by atmospheric turbulence, on three telescopes, measured pair- wise, providing the information required by the delay line control loop to compensate the perturbation. FINITO supports the closure phase measurement capability and significantly improves on accuracy and sensitivity of each VLTI instrument (AMBER, MIDI), increasing their coherent exposure time from few milliseconds to several minutes. Its conceptual layout is shown in Fig. 5. Adaptive Optics on the UTs is expected by end of 2003. This will remove all aberrations except piston (Strehl $\sim$50% in K for $V < 13$ guide star, $\sim$25% for $V < 16$) and, therefore, increase sensitivity by several magnitudes. Three 1.8-m Auxiliary Telescopes will be ready by May, 2003 allowing an enormous increase in (u, v) plane coverage. Finally, three more delay lines will be available by mid 2003 allowing coverage of >90% of AT stations. The scientific objectives of the second phase of VLTI development (> 2003) are the following:

- direct detection of RV exoplanets;
- the binary fraction in nearby clusters;
- size, temperature structure and features of nearby stellar and protoplanetary accretion and debris disks;
- stellar surface features (spots, acoustic waves);
- mass and distance of isolated, microlensed BH;
- structure of CSE of mass losing giants
- morphology of dust torii in nearby AGN;
- "real" (model-independent) imaging with 3-way beam combination and phase closure techniques on moderately bright complex sources ($K < 14$).

A little further down the line beyond $\sim$ 2005, phase referenced imaging and as astrometry will be available thanks to the PRIMA facility now in an advanced planning stage. There are two methods for measuring phase for model-independent imaging: closure-phase ($n > 3$ simultaneous beam combination) limited to $K < 14$ sources and phase-referencing using a bright reference star as in AO. PRIMA allows imaging of faint complex sources close

	AMBER	MIDI
Spectral coverage	J, H, K' (1 – 2.4 μm)	N (8 – 12 μm)
Spectral resolution	35, 1000, 10000	100
Beams combined	3	2
Lim. mag. with UTs (ATs)	$K = 13(9.8)$	$N = 5(1.8)$
Field of view	$0.06'' - 0.24''$	$0.26'' - 1.14''$
Min. fringe spacing (λ/B)	1–2 mas	10 mas

Table 1. AMBER and MIDI characteristics.

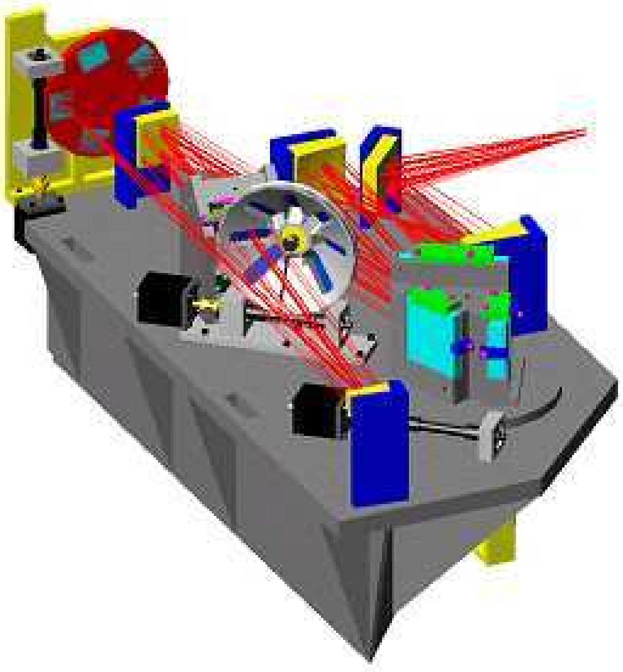

Fig. 4. A schematic view of the Arcetri spectrograph for AMBER.

to a bright reference ($K < 15$) with MIDI and AMBER and narrow angle astrometry at 10 μas accuracy. Prime objectives of the VLTI with PRIMA will be exozodiacal clouds (with the ESA-ESO prototype Darwin nuller in visitor position), the masses of MS and PMS dwarfs, brown dwarfs and hot Jupiters in star clusters out to Orion, the structure and distance of expanding nova shells, the 3D kinematics of the nuclear cluster of the MW and the structure of the nuclear regions of AGN. At this point the beam combination laboratory at the center of the Paranal complex would be packed with instruments as shown in Fig. 6.

6. Conclusions

The past has seen a tremendous amount of work to fire up the VLTI again after the 1993 suspension. The present consists essentially in moving quickly up the

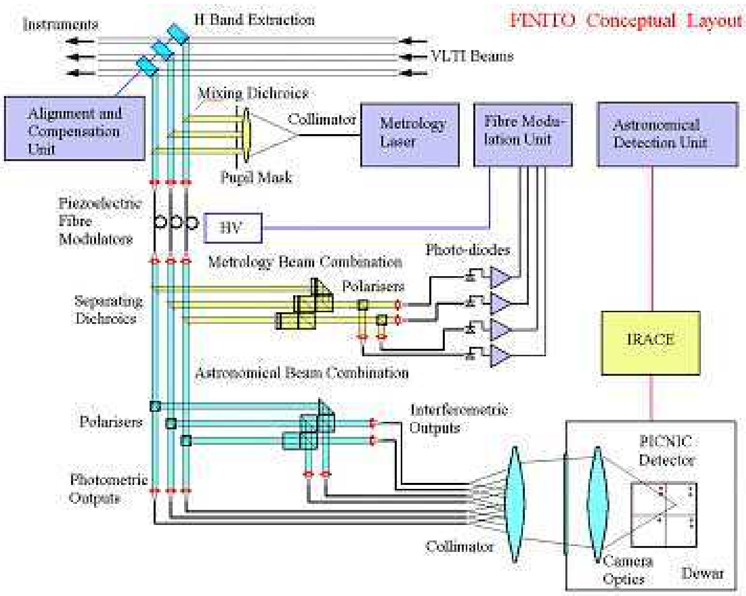

Fig. 5. Conceptual layout of the FINITO fringe tracker for VLTI.

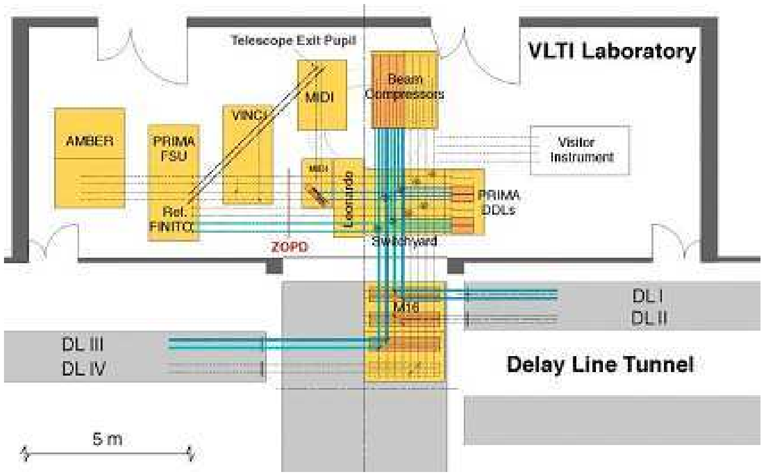

Fig. 6. Schematic layout of the VLTI laboratory at the end of phase 3 of the VLTI development expected around 2005 with the full complement of first generation instruments. The visitor instrument is now expected to be the GENIE prototype of the Darwin nuller.

learning curve and carrying out first steps to compelling science at high angular resolution. The near future holds the exciting prospect of adding a huge array of new equipment to enormously enhance capabilities. Exploiting them fully will require more specialists! Won't you join us? The far future also promises exciting possibilities not only for the second generation instruments that will extend capabilities to the 20 μm region and to the visible with the appropriate AO systems, possibly of the MCAO variety and to more sophisticated imaging techniques based on image plane rather than pupil plane combination. Integrated optics will also simplify and extend possibilities into the large n multibeam combination arena. Clearly, at that point, Cerro Paranal will become cramped and space for a large OLBIN array of km size will have to be found pushing the peak shown in Fig. 1 up another order of magnitude to unprecedented levels.

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