Bulletin de la Socié Royale des Sciences de Liège - Vol. 74, 1-2-3, 2005, pp. 73-78

KEOPS: Kiloparsec Explorer for Optical Planet Search, a direct-imaging Optical Array at Dome C of Antarctica

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Abstract: The future winter operation of the new permanent station on the Antarctic plateau at Dome Concordia is a strong motivation to investigate the potential of the site for astronomical observations. Recent site seeing testing campaigns conducted by our team from University of Nice show that Dome C represents the best site on Earth for astronomical high angular resolution (HAR) observations at optical and IR wavelengths. The dramatic gain over relevant HAR parameters r_0, L_0, θ_0 and τ_0, added to very low temperatures during the polar winter nights ($-70°C$), the dry atmosphere and the possibility of continuous observations during several nights make Dome C the ideal site for deploying a kilometric optical interferometer before the 2015 horizon. Here we describe the concept of Kiloparsec Explorer for Optical Planet Search (KEOPS) that is studied by our group at LUAN. KEOPS is an interferometric array of 36 off-axis telescopes, each 1.5m in diameter. Its kilometric baselines open sub-mas snap-shot imaging possibilities to detect and characterize extra-solar planetary systems specially exo-Earths out to 300 parsecs from the visible to the thermal IR.

Keywords: imaging interferometry, high angular resolution

1 Introduction

The Antarctic continent has been considered as a prospective place for astronomy, thanks to the atmospheric transparency and darkness in the IR and submm domain. However, the first seeing measurement in the visible and close IR domain at South Pole were quite deceiving. In 1999, Marks and Vernin show that the bad seeing at South Pole was only due to the strong wind near the ground on that site, and predicted than the Antarctic plateau where the wind is slow should exhibit incredible seeing. The decision of construction of a new italo-french permanent station at Dome Concordia has been the opportunity to check this assumption.

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There are several reasons why Dome C in Antarctica is considered as the best ground site for astronomy and specially for interferometry (Fossat, 2003, Epchtein, 2003). Daytime monitoring of Dome C (Aristidi, et. al, 2003 and private communication) has shown that the atmospheric seeing Fried parameter can peak at .8m in the visible, stable in the range of 0.3m-.5m over several hours, with a coherence ranging around 0.1s during the same periods. Extrapolating from wind and temperature profiles measured during daytime (Fossat, 2003) and compared to the seeing conditions of the best ground observatories, e.g. Paranal or Mauna Kea, the coherence volume, most critical for interferometry, should improve by a factor of 10 at least. The other fact is that Dome C and its extreme cold (200K) and dry atmosphere (.1 to .25mm H2O) open the K_{Dark}, L', M' IR windows (Epchtein, 2003) otherwise accessible from space. Taking into account that each of the atmospheric limitations improve as $\lambda^{6/5}$ and that going from the visible to the thermal IR benefits from a Sun/Earth contrast dropping from $10^9$to 10^6 makes Dome C an exceptional site to install a DARWIN/TPF-type interferometer for exo-Earth hunting. The good news are that at Dome C (Fig. 1), there is room in principle for a deca-kilometric interferometer on a suitable flat area next to the Concordia italo-french station. The average slope is less than 1m across 100 km so that even much longer interferometers could be built at Dome C (remember the flattening effort for Paranal to attain 200m baselines). For a typical a 1km baseline at $10\mu m$ one achieves 1 mas resolution: exactly what is needed to separate an exo-Earth from its parent star at 1kpc. With even longer baselines the exo-Earth is well separated from its parent sun so that its image can be directly recorded provided direct snap-shot imaging possibilities of the interferometer.

2 Interferometry at Dome C: an evident next step?

Optical Long Baseline Interferometry (OLBI) is now a mature observing technique. 2D maps are being currently obtained by optical arrays: NPOI in Arizona, COAST in Cambridge, UK, CHARA at Mount Wilson, and VLTI at Paranal (see also http://olbin.jpl.nasa.gov/). The next challenge for OLBI will be to directly detect extra-solar planetary systems using nulling interferometers from the ground (Gondoin, et. al, 2003) or from space (Menneson, Mariotti 1997, Beichman et. al, 2002). Indeed large monolithic telescopes using extreme adaptive optics reaching Strehl ratios better than 90% or better could attain this goal. The challenge though of Earth-like planets detection on a statistically significant sample can only be achieved by long baseline interferometry which offers sufficient spatial resolution to do this. Considering the non zero-risk and limited lifetime of space missions however, the question of doing this from the ground can legitimately be debated. In the followings we argue that Dome C in Antarctica meets the best conditions for a ground-based alternative nulling interferometer for ExPNs observations. We outline the generic pre-phase A studies of our KEOPS concept currently studied at the Laboratoire Universitaire d'Astrophysique de Nice (LUAN), following a step-by-step approach to build a kilometric baseline interferometer within the 2015 horizon.

The concept of KEOPS emerges directly as an imaging array of optical diffraction limited telescopes of 1.5m-2m in Dome C conditions. These telescopes are spread over 3 co-centric rings of 200m, 348m and 676m radii: 7 telescopes on the first ring, 13 telescopes on the second and 19 on the third (Fig. 1). These numbers offer optimized possibilities to achieve 1 mas spatial resolution at $10\mu m$ in order to separate an exo-Earth from its sun at 1kpc. KEOPS will search for such targets through a 90 degree opening angle cone pointing from the geographical site of Dome C (75 degree South and 123 degree East). KEOPS is an implicitly co-phased array operated in the so-called hypertelescope mode (Labeyrie et. al, 2003) but using the more efficient nulling arrangement of IRAN recently introduced by us (Vakili et. al, 2004). This

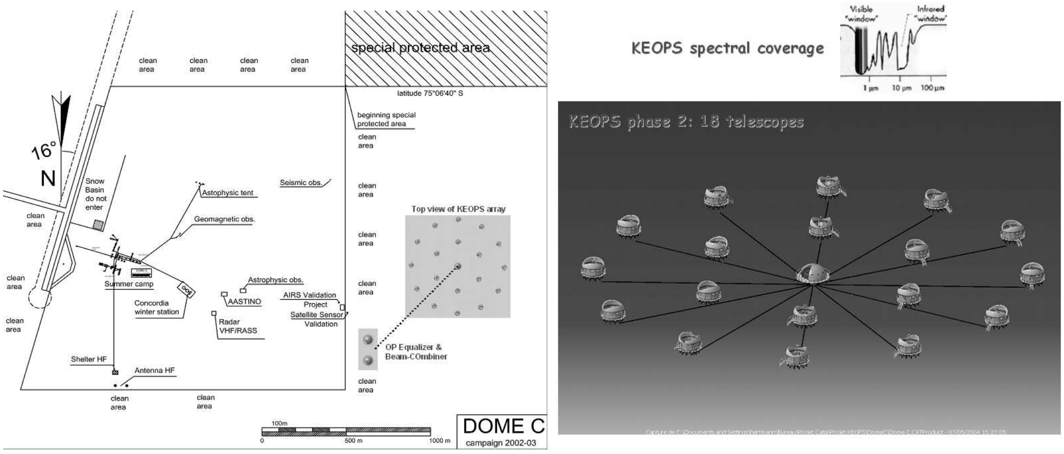

Figure 1: Layout of the Concordia station at Dome C. There is enough space on the North-East square area (bottom-middle) to deploy a kilometric array of 39 telescopes. These telescopes sit on 3 concentric rings ranging from 300m to 1000m in diameter. The sequence of these rings is approximately 7, 13 and 19 elements to maximize the intensity distribution of the co-phased interferometric response. This is done by co-phasing the array is continually them using folded optical delay lines for the sideral motion. Each rings uses its own group of delay lines hosted in tunnels next to the two central domes one for the focal instrument and the second for housing the control and real-time electronics and software.

arrangement is a multi-axial interferometer using an achromatic interfero-coronagraph (Gay et. al, 1998) for nulling the on-axis star and detect the planetary companion (Fig. 3). KEOPS has an equivalent collecting surface comparable to the Keck interferometer but placed in the extreme cold, dry and excellent seeing conditions of Antarctica will easily challenge a 30m class ELT. In its imaging mode with the coronagraph removed, KEOPS provides 741 simultaneous baselines making Fourier Synthesis of extended objects very efficient (twice the VLA number of u,v points). Indeed in the co-phased hyper-telescope mode KEOPS can access to snap-shot imaging across very narrow-fields due to intrinsic properties of the image-densification (Vakili et. al 2004).

2.1 Science Rationale

Different projects than interferometry can benefit from the improved seeing conditions at Dome C like IR wide-field surveys or high resolution spectro-imaging using FTS techniques (Epchtein 2003, F.X. Schmider 2004). The meaning of wide-field imaging is sometimes misguiding. In practice what is important is the number of resolution pixels per field of view where the PSF remains almost constant. Interferometers have intrinsic small optical fields of view. They can access however to a field larger than their optical limits by mosaicing provided the PSF and the scene to be imaged remain time invariant. The bottom-line of an interferometric instantaneous field of view is the Airy disc of the primary telescopes. Considering the 1-2m telescopes used by the kilometric baseline KEOPS, we may expect to obtain sub-mas resolution pixels across a 1" FOV. Thus, unlike classical wide field telescopes, KEOPS offers an Ultra-High-Spatial-Resolution imaging instrument with a reasonable wide field of 2000x2000 resolution elements (resel). The inefficient filling factor ($< 10^{-3}$ due to the small number of simultaneous baselines) of KEOPS could be compensated by earth-rotation synthesis for imaging of compact objects which exactly benefits from the polar long winter nights in Antarctica!

The exo-Earth discovery program of KEOPS will be its primary mission. A rough estimate

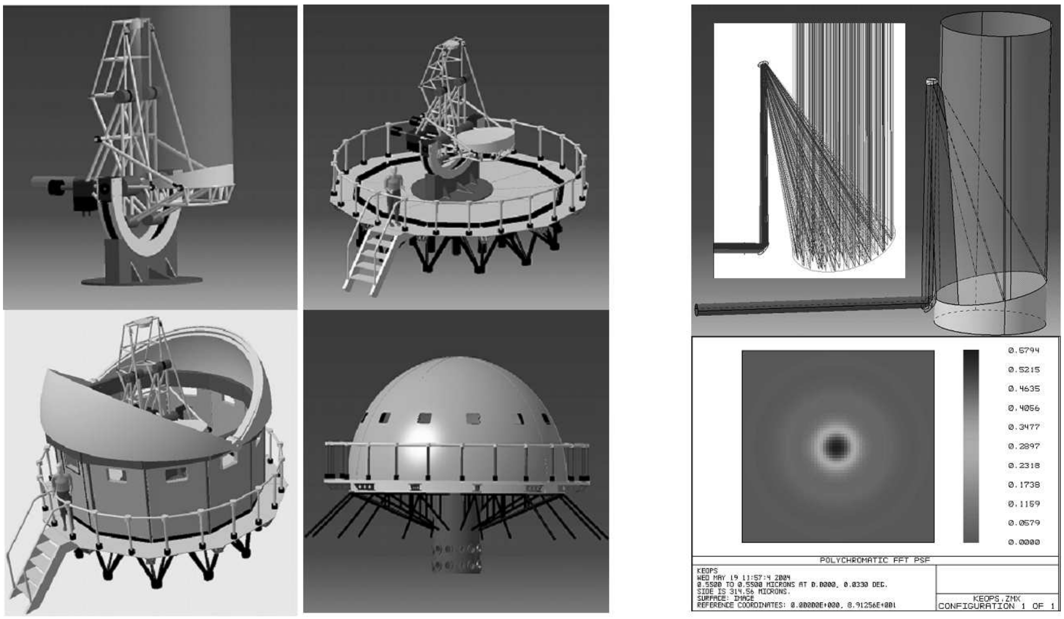

Figure 2: Different components of KEOPS: the off-axis alt-az 1.5m telescope for avoid the diffraction undesirable patterns of a classical on-axis telescope and minimizing thermal emission, its plate-form and dome, the central beam-combiner and the ray tracing for a 20" transported afocal beam within this beam-combiner.

of KEOPS performances, by extrapolating from those of DARWIN (Thomas, 2001), shows that almost 8000 F,G and K dwarves within 1000pc inside a 120 degree cone could be visited during 10 years. Rejecting binary, variable/active stars from this sample will still leave more than 500 potential targets clearly better than the nominal program of DARWIN. Although restricted to a 120 degree cone from Dome C this sample remains statistically significant to detect and characterize potential exo-Earths and understand the scenarios of planetary systems formation and evolution.

In its imaging mode KEOPS could bring significant breakthroughs in studying galactic and extra-galactic objects from visible to thermal IR inaccessible from any other ground astronomical site. These could be the central engines of YSO's or stars in advanced post-AGB or pNP stages of stellar evolution. H2 regions, massive star clusters in nearby galaxies, M & B dwarves angular diameters are among other exciting targets for KEOPS. It has to be noticed that the high values of the isoplanetic angle θ_0 will allow to find a bright enough star to close the loop of AO and fringe tracking on the whole sky, even with telescopes as small as 1.5 meter

Thanks to its snap-shot imaging from the large number of telescopes, KEOPS could make non-interrupted imagery of rapidly variable stars like magnetic stars, RSCVn, Symbiotic stars, colliding winds in WR-O,B binaries, accretion discs in cataclysmic binaries or the structures of TTauri star collimated jets. Combined with Imaging Fourier Transform Spectroscopy (IFTS), KEOPS is able to detect and identify non-radial modes on close star up to the degree $l = 50$, opening a new window in asteroseismology.

2.2 Keops sub-systems

KEOPS Off-Axis Telescopes Optimized for IR Interferometry & Coronography KEOPS primary telescopes are 1.5m off-axis parabola (from master F/D=1 paraboloids) with 3 reflection Cassegrain-Coud afocal optics and 60 zenithal distance pointing. Thus KEOPS can access to

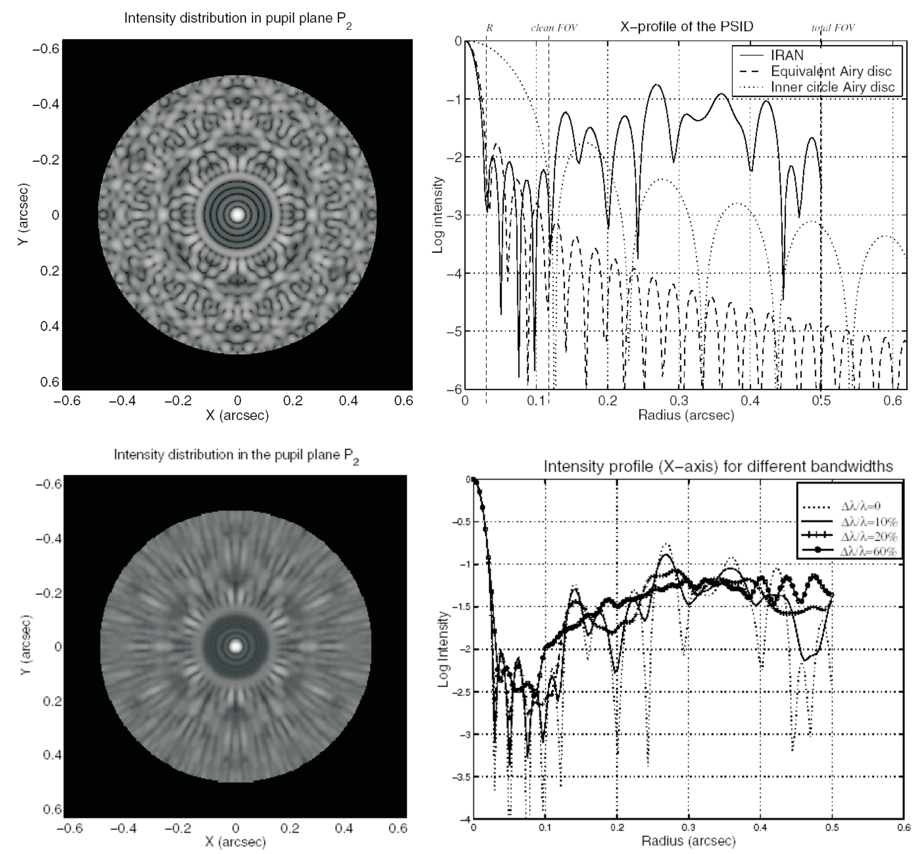

Figure 3: The focal diffraction pattern of KEOPS from 39 co-phased telescopes. Using image-densification (Vakili, et.al 2004), it is possible to reconstruct a pseudo-Airy pattern in the pupil plane, with true convolution relation with the object. On top: monochromatic PSF, bottom: effect of bandwidth.

all sources in a 120 cone from Dome C. The alt-alt mount is similar to the ESO-CAT at La Silla. The optics can be passively cooled to -60 during the winter night. The absence of central obstruction minimizes both the IR background and the diffraction noise for coronagraphy in the nulling mode of KEOPS (Fig. 3). The pointing primary FOV is 1, and 20" at the central hub. Field-rotation is corrected by a K-prism erector.

On the route towards constructing and operating KEOPS and/or alternative concepts to it, a proposal called "Giordano-Bruno Program for Interferometry from Concordia" has been submitted to the french national agency for astronomy INSU. This proposal includes a large number of french laboratories with additional european/international collaborations and should start as early as 2005 to define also a road-map for a full-fledged KEOPS operational optical synthesis array around 2015. Giordano Bruno builds upon the unique scientific results from VLTI and its next generation instruments. An end-to-end plus system level study for a fully automated diluted array like KEOPS is foreseen as a major outcome of this study. Indeed nulling or differential techniques as well as dual-feed astrometry will also be considered. A detailed comparison with a monolithic Extremely Large Telescope with X.A.O. + Coronagraphy is also part of the study package. We think that an ambitious project such as KEOPS at Concordia is complementary of the DARWIN/TPF space missions both for their scientific objectives but also to validate nulling concepts, technologies and strategies to be developed for ExPNs direct detection and characterization at a much lower cost than these ambitious projects and circumventing to put a zero-risk observatory at the L2 Lagrange point!

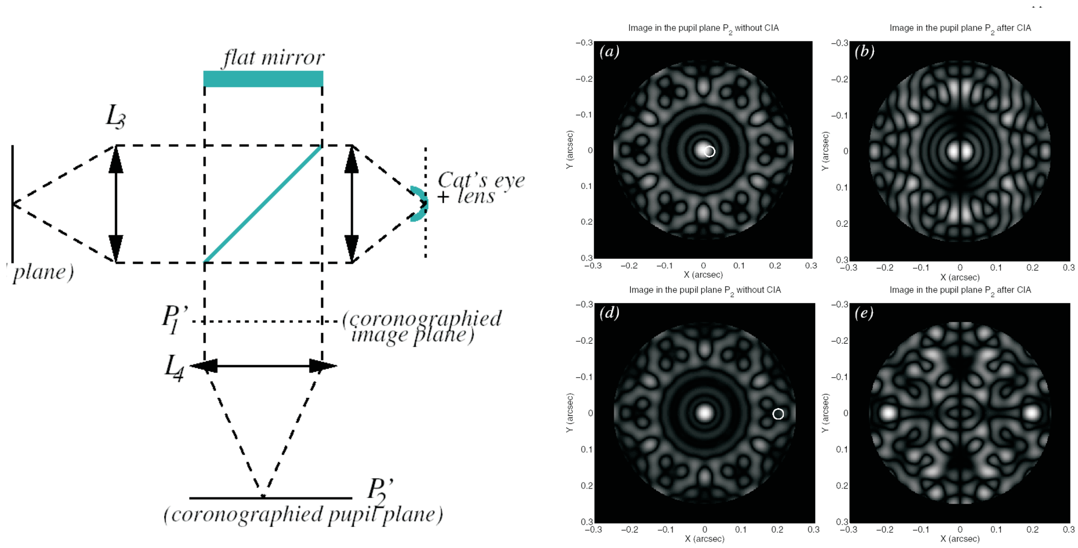

Figure 4: The snapshot imaging capability of KEOPS could be used with an Achromatic Interferential Coronograph (Gay & Rabbia, 1996, on the left). The inversion of the pupil conduct to the total extinction of the star on the optical axis, and the apparition of the faint companion, either very close of the central star (top right) or far from the star (bottom right).

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