A wide-field telescope for MACHO searching at Dome-C

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ABSTRACT

Wide-Field imaging at visible wavelengths with seeing of the order of 0.1-0.2arcsec is believed to be possible from the high Antarctic plateau site of Dome-C by the removal of ground layer effects only. We present a proposal for a 2m-class telescope specifically designed for the science case of short duration (~10s or greater) microlensing events in the crowded central regions of Galactic Globular Clusters and nearby galaxies where the achievement of a spatial resolution of the order of a fraction of arcsec is essential.

The philosophy behind the telescope proposal is discussed in detail. It is emphasized that this is a project with a specific unique science goal in mind and not a large scale facility instrument. A preliminary design for the optics, ground layer removal using a deformable secondary and "static" wavefront sensor and telescope structure is presented. In particular, it is shown that substantial simplification in the design can be achieved by having a specific science goal in mind, so reducing the complexity and increasing reliability. Transport and logistics for the successful deployment and operation of the telescope at the Dome-C site are discussed.

Keywords: Antarctic telescope, Dome-C, Wide field; Ground layer wavefront sensing, Adaptive Optics, Microlensing, Galactic Globular Clusters

1. INTRODUCTION

In terms of atmospheric conditions the Antarctic plateau is well known to be among the best ground based astronomical site for observations from the millimeter to microwave regions, due to the low temperature[1] and the extreme dryness[2]. Shifting towards the visible wavelengths, however, initially proved not to be so rewarding at sites such as the South Pole as one of the key parameters for judging the quality of a site for visible astronomy, the seeing, was measured to be relatively poor[3, 4]. This finding, however, was accompanied by substantial evidence that most of the turbulence occurs because of gravitationally produced katabatic winds very close the ground[5].

The situation changes dramatically on local maxima or domes, isolated peaks on the Antarctic plateau, where the thickness of the ground level turbulence and mean wind velocity are substantially reduced. Such a local maxima is Dome-C, where an Italian-French base is in the last stages of completion and several astronomical activities are already underway[6]. Preliminary differential seeing measurements[7], MASS scintillation data[8] and ground layer turbulence profiles[9] taken during over the past two years have in combination suggested the possibility extraordinary seeing over large isoplanatic angles in the visible exists for the Dome-C site. There are other reasons making Dome-C unique and extremely appealing from the point of view of optical astronomy. These include the low brightness of the coronal sky, the significant distance from Aurorae, and the high of clear time (more than 75%)[10].

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A large facility telescope would require a special effort to be erected at the site or, at the very least, would require a specific, extremely smart and simple design. As work on the site is confined to only a few months in the Antarctic summer it is easy to project that the work needed to construct a telescope like TNG (that was previously engineered in Chile as NTT) will span several decades. This is even assuming the availability of manpower and infrastructure is similar to those in temperate regions (a condition that must be accepted as being far from the truth). The first step into optical astronomy would be, in our opinion, a 2m class telescope that can be built, tested, debugged and only afterwards sent as a complete unit capable of robotic operation. A primary aperture of 2m-class fits well inside a conventional commercial container (assuming a non-folding telescope design) that is used for large mass transfer of material to Dome-C by ice traverse. In summary, we believe the crucial point is to well define the scientific rationale and to then design a precise experiment rather than building a facility instrument.

It is interesting to note that for transport costs alone the size of a segment of a future Extremely Large Telescope (ELT) will very likely be similar in size which leads to the possibility of collaboration under the ELT framework.

2. SUMMARY OF THE SCIENCE CASE

The science rationale for this project required very careful assessment. We think it is of vital importance that such a project must be only doable from Dome-C and no other ground-based location and it should have a high probability of producing unique science. In addition, we think the powerful capabilities of this telescope will aid the wider scientific community with by-product science. The primary science case we propose is the detection of fast (~10s or more) microlensing events using Galactic Globular Clusters (GGCs). This includes the detection of microlensing events where the objects are the stellar sources in the GGCs (the lens is baryonic matter located between us and the GGCs), detection of baryonic matter in the GGCs themselves (where the GGC is the lens magnifying stars in a background galaxy such as the Small Magellanic Cloud (SMC)) and so-called self-lensing events (where the GGC contains both the lens and background star).

This requires the continuous observation of a well-defined region of stars over a reasonably large field of view (~15 arcmin FoV) with an unprecedented resolution. Continuous observation is made possible thanks to the geographical location of Dome-C close to the South Pole that, at least in the Antarctic winter, provides almost uninterrupted observations. As the crowding in the center of a GGC is large (47-Tuc and NGC362 are of primary interest) this can be achieved only through excellent optical quality, of the order of 0.1 to 0.2 arcsec over the FoV, that is compatible with the diffraction limited imaging of a ~1m class telescope at visible wavelengths. A 2m class telescope, however, at the DomeC site can achieve a SNR of the order of five with a 10sec. exposure for an event of magnitude R~23 and for mainly this reason we have chosen a 2m class telescope as the basis of the design. It is noted immediately that such a telescope is not required to provide diffraction limited performance but just to exploit the excellent seeing conditions experienced at Dome-C over a wide field.

Due to the resolution alone the scientific outcome would be unique as the microlensing events can be resolved and detected for a large number of stars located at a well-known distance (removing some of the ambiguities that often occur in microlensing events), not to mention the more exotic possibilities such as self-lensing in the cluster itself. In addition, a substantial amount of data including lightcurves of eclipsing binaries, IMF, deep imaging and possible detection of Neptune-like planets[11], to name a few, will be made available. As microlensing surveys have already existed for many years we must push the parameter space if we wish to produce outstanding science. In particular, as well as the absence of jumps in photometric data due to the use of different telescopes throughout the world in the existing microlensing searches[12], the much higher spatial and temporal sampling (0.1arcsec on 10sec. exposures, for example) should allow for such a survey to reach detection limits otherwise not possible from the ground.

3. OPTICAL DESIGN

The requirements of the optical design are as follows. Firstly, the science case requires 0.1-0.2 arcsec imaging across the visible region over a ~15 arcmin FoV. A 2m diameter effective aperture (required for R~23 detection for a 10 sec exposure) would more than serve the resolution requirement and is, roughly, the largest non-folding design that can be housed inside a standard shipping container (an important requirement for transport reasons). In addition, the optical train must not extend past the dimensions of the container. We reiterate here that the 2m aperture does not necessarily need to be diffraction limited: a 1.26m diameter mirror provides 0.1 arcsec resolution at a wavelength of 500nm, therefore one can consider a segmented aperture even without the need to co-phase if there are substantial design benefits. A ground layer wavefront sensor and corresponding deformable mirror should be provided for in the system.

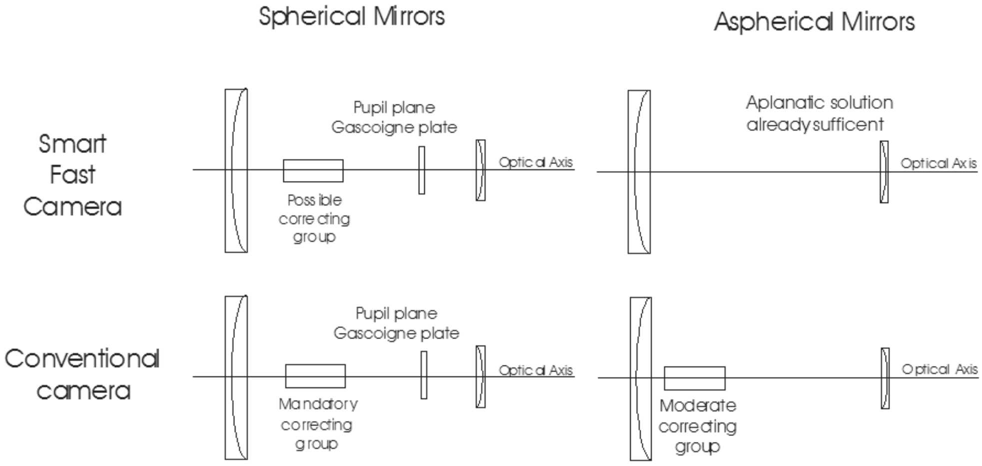

Fig. 1. The four classes of optical design considered. Two of the designs (bottom left and bottom right) adopt a conventional camera at the focal plane whereas the above designs make use of a Smart Fast Camera that eases constraints of the remaining optics (see text for further details). Designs using all-spherical (requiring more complex correcting optics) and all-aspherical mirrors were considered. Gascoigne plates placed at the pupil correct for (mainly) spherical aberration in the all-spherical designs.

Several classes of optical design were studied and the four general types are summarized in Fig. 1. The four designs are divided into two groups labeled Smart Fast Camera and Conventional Camera respectively. The first assumes the use of a proposed wide-field camera design that can produce wide-field coverage with a relatively slow beam input[13]. This feature reduces the constraints placed on the proceeding telescope optics. Both all-spherical and all-aspherical mirror designs were considered. As can be seen in Fig. 1 the adoption of an all-spherical mirror design requires a more complex wide-field corrector, with some elements (the Gascoigne plates) containing aspherical surfaces (not shown in the figure) unlike the all-aspherical mirror designs. The all-spherical mirror system with a conventional camera design was eventually chosen for ease of alignment in a site where this is becomes crucial. The design, with further details of the corrector group and Gascoigne plates, is shown in Fig. 2. A 2m telescope based on this design is shown in the far-left of Fig. 3.

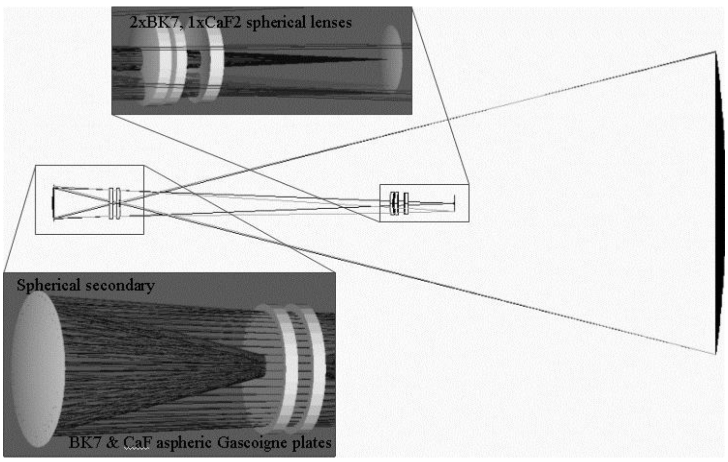

Fig. 2. A schematic of the preferred all-spherical mirror design contains a 2m spherical primary mirror and adaptive secondary mirror. Gascoigne plates are at placed at the telescope pupil (correcting for pupil plane aberrations) and an additional set of corrector lenses prior to focal surface correct the residual aberrations.

A segmented primary approach was considered as a nice way to reduce weight, ease the complexity of the mirror mount and reduce the requirement for a fast primary surface. Recalling that the full 2m diffraction limit even at the shortest of wavelengths is not required for the science case it is possible to use smaller aperture mirrors, the diffraction limit of which matches the required value of 0.1-0.2 arcsec. Shown in Fig. 3 are two segmented designs considered. The central figure contains four ~1m square segments collectively producing a 2m square aperture, specifically chosen to mimic one possible unit of an ELT based on a square aperture configuration (that produces a cleaner point spread function for the purposes of planet detection). The far-right design in Fig. 3 contains six 80cm diameter spherical mirrors arranged in a hexagonal pattern. Whereas the square aperture segments have a resolution matching the required value the 80cm segments are very slightly under (with a diffraction limit of 0.16 arcsec at 500nm).

Given the off-the-shelf nature of the spherical segments, the ease of mounting and the possibility of co-phasing the segments using piezoelectric actuators the six spherical mirror segmented design is the preferred choice and will be discussed further. However, on-going investigation of the feasibility of using a lightweight mirror design is an interesting possibility and does not rule out the use of a single mirror solution in future.

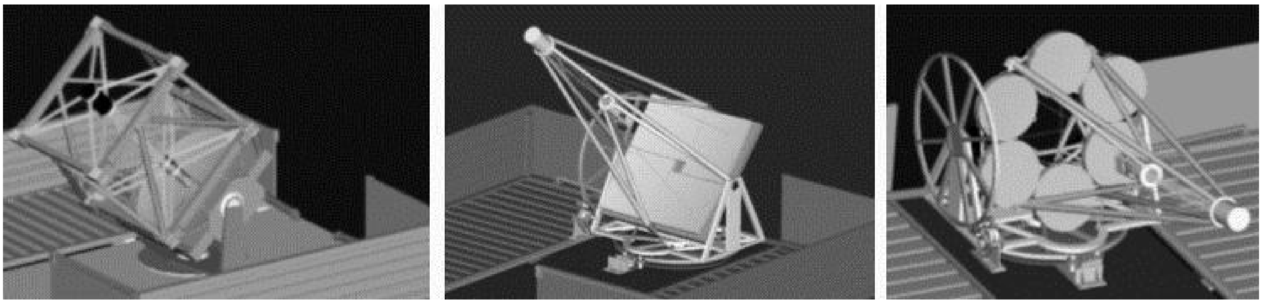

Fig. 3. Three of the mirror configurations considered. Far left: single 2m spherical primary; centre: segmented square aperture and; far right: size 80cm spherical mirrors arranged in hexagonal pattern reduces the weight, risk and cost compared to a monolithic primary mirror.

4. ADAPTIVE OPTICS

4.1. Underlying philosophy behind the AO

Given the science requires a relatively large FoV with very good resolution across the entire field it is very unlikely adaptive optics can be avoided. In the initial stages of this project, before the publication of recent site-testing, discussed below, it was assumed the ground level turbulence occurred across the entire first kilometer, as well as some small but not insignificant high level turbulence. For this correction it was necessary to include 2 adaptive mirrors, not an insignificant task for a telescope we hope to be remotely operated, or at the very least, with minimal human intervention.

Then arrived the remarkable 2003-2004 site testing data from the Dome-C site performed by two groups. The collective results can be summarized as follows. The seeing results measured using a Differential Image Motion Monitor (DIMM)[14] for the first time suggested the raw seeing during summer above the Dome-C site could be lower than 0.2 arcsec for substantial parts of the day when the temperature gradient over the first few hundred metres was reasonably constant. The measurements showed a strong diurnal variation expected during the summer months that would, most likely, disappear during the winter. The results strongly suggested that the image degradation was caused by turbulence occurring in the first few hundred metres only and not by the dreaded high altitude turbulence that is more difficult to correct for a large FoV. For the first part of the following winter season two site-testing instruments were remotely operated from the AASTINO[15] laboratory located at the Dome-C site. The high-altitude turbulence impact on the image quality measured on the ground was determined using a Multi-Aperture Scintillation System (MASS[16]). Measurements showed a ~0.3 arcsec mean value with periods including seeing as low as 0.15 arcsec in the visible[8]. The mean isoplanatic angle, the angle on the sky over which the turbulent effect of the atmosphere is constant, was ~6 arcsec with a corresponding mean Greenwood frequency of ~8 ms. Lastly, a Sonic Detection And Ranging

(SODAR[17]) instrument was operated in parallel with the MASS. This instrument launches sound waves of different frequencies into the atmosphere above the site and from the intensity of returned signals a turbulence profile of the layer 30m to 900m can be produced every 30m at the Dome-C site. For the several thousand winter profiles measured it was found that, for the majority of the time, the variation of refractive index in this layer, if present at all, produced return signals that are beneath the detection threshold of the instrument[9]. In other words there was very little turbulence in this layer.

Whether the majority of the winter turbulence, which most likely produces a small deterioration in the image quality, occurs very close to the ground (below 30m) or at high altitudes requires future measurement with something like a wavefront sensor on a telescope at the site such as the future IRAIT telescope[18]. However, to a certain extent regardless of this, the philosophy we have adopted for this project with regards to Adaptive Optics (AO) is as follows. The AO is not aiming to produce diffraction limited imaging but to correct for ground layer turbulence, when and if it exists. In this way any image degradation can only be caused by high-altitude turbulence. The AO system will consequently not be sensitive to the resulting Greenwood frequency produced by this layer. The resulting PSF over the entire FoV will be seeing-like, but of course we expect of excellent resolution. In addition, we would prefer as few moving parts as possible, in particular for the wavefront sensor, to increase reliability.

4.2. Proposed AO design

We wish to correct for as much of the ground layer turbulence as possible. The deformable mirror and wavefront sensor are conjugated to a specific altitude layer above the ground. In doing so, the effect of turbulence at this layer can be virtually eradicated across the FoV and at other layers, but only for a certain layer thickness[19]. With a median seeing of 0.3 arcsec, corresponding to an r^0 of 0.3m, and combined with a FoV of 15 arcmin, gives an effective corrected layer thickness of 60m. To obtain the full benefits from this we have chosen to select a layer ~40m above the ground given the turbulence from 30m to 900m is very low and, so far, there is no recorded data of the turbulence below 30m. A substantial reduction of the image degrading turbulence can be produced using this method, if and when turbulence exists, as shown in Fig. 4.

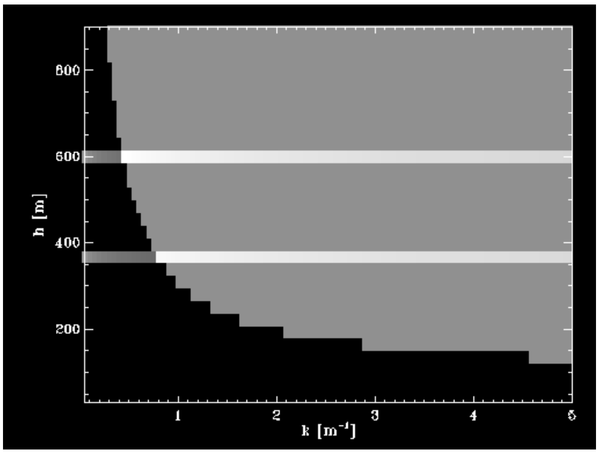

Fig. 4. The partial removal of turbulence effects over the entire the ground layer by conjugating the secondary adaptive mirror to a height of 40m. The x-axis shows the fourier components of the modes present for each of the 30m layers. If the plot were uniformly grey this would represent all fourier modes present at each 30m layer from 30m to 900m above the ground. The black sections represent the fourier modes removed by the 100m conjugation, and therefore, for this layer the plot is black across all fourier modes. Turbulence occurring at other heights (such as 360m and 600m) is also, in part, corrected, the amount of correction a function of altitude distance from the conjugated layer.

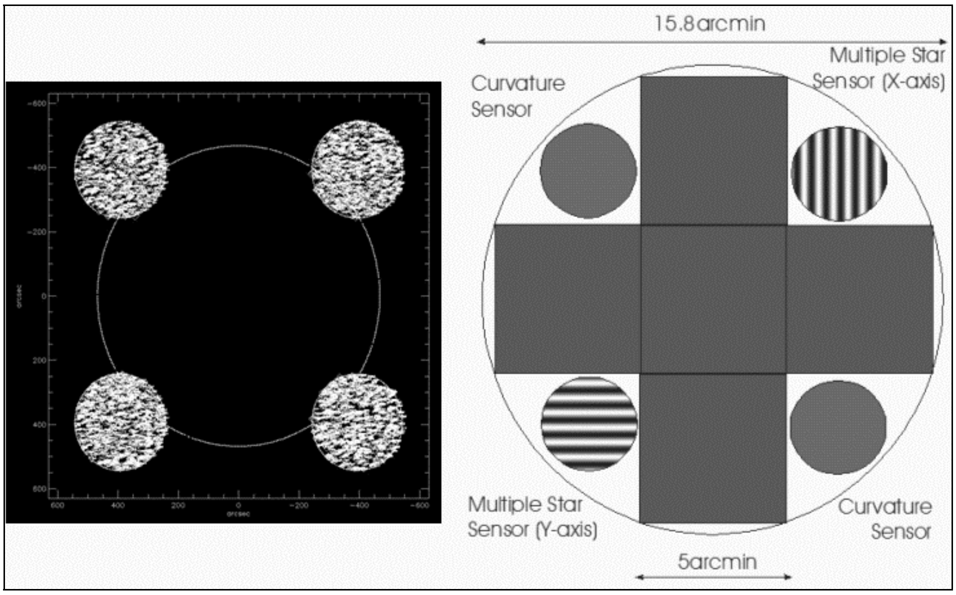

Fig. 5. A possible layout for the focal surface of the telescope is shown in the right-hand sketch. The five CCD chips allow for a total of five 5x5arcmin square zones centred on the crowded central region of the Globular Cluster. The four circular FoV, each roughly 4 to 5 arcmin in diameter located at the corners of the focal surface, are devoted to Adaptive optics assisted wavefront sensing. They are intended to collect the light from a large number of stars appearing in such areas modulated by a grating (shown left).

Given the requirements of the AO summarised above and the large number of stars available for wavefront sensing in the FoV we propose to include the ground layer wavefront system into the focal surface unit as shown in Fig. 5. The ~15×15 arcmin FoV is divided into 2 areas: firstly there are 5 CCDs, each covering ~5×5 arcmin, arranged in a cross shape, that collectively will image the central region of a GGC for the detection of microlensing events. The remaining four corners of the focal surface are dedicated to wavefront sensing. We tentatively envisage that two of the sensors are of the modulated grating type[20], and collectively they measure the 2D correlated motion of the hundreds of stars incident of each of the grating sensors and two curvature sensors. This design requires zero moving parts for the wavefront sensing, a huge advantage given the proposed location of the telescope.

We propose a secondary adaptive mirror that well matches the existing prototype technology developed at Arcetri Observatory for the deformable secondary of the LBT[21]. As discussed above, the mirror will be conjugated to the 40m ground layer.

5. MECHANICAL DESIGN

The mechanical design remains in the early stages so a summary of the progress so far is presented here. The telescope is a redesigned and retro-fitted CLUE[22] structure and therefore will fit into a deployable shipping container, as shown in Fig. 6. Data can be stored on-board and retrieved during the Antarctic summer which reduces the man-power requirement from the staff wintering over at the Dome-C site.

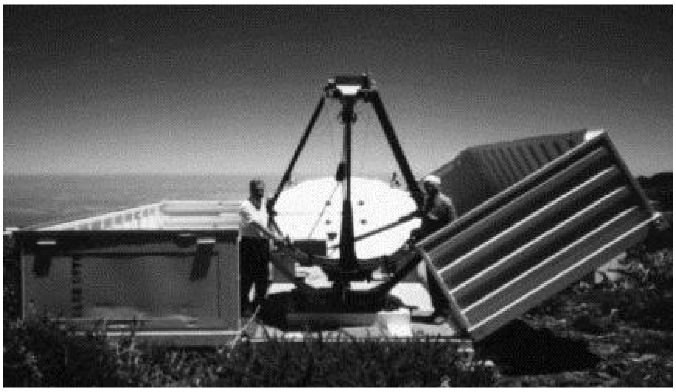

Fig. 6. The remotely operated CLUE telescope housed inside a standard shipping container. This project has heavily influenced the design of GATTO TOM.

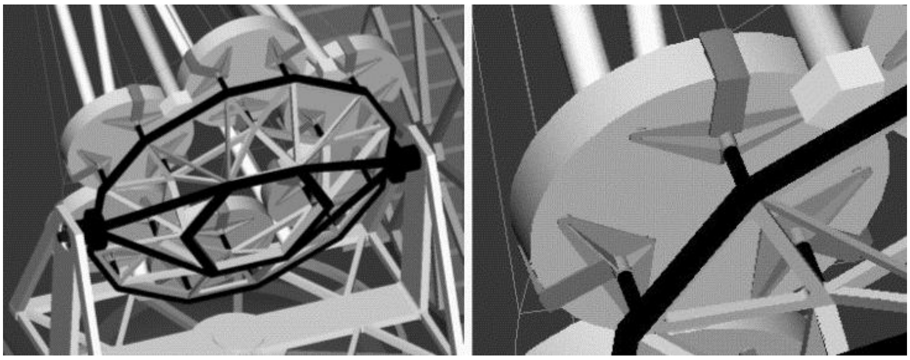

Fig. 7. Details of the mounting of the mirrors. A 9-point Hindle mount is shown, though an 18-point system may be required for this size of mirror.

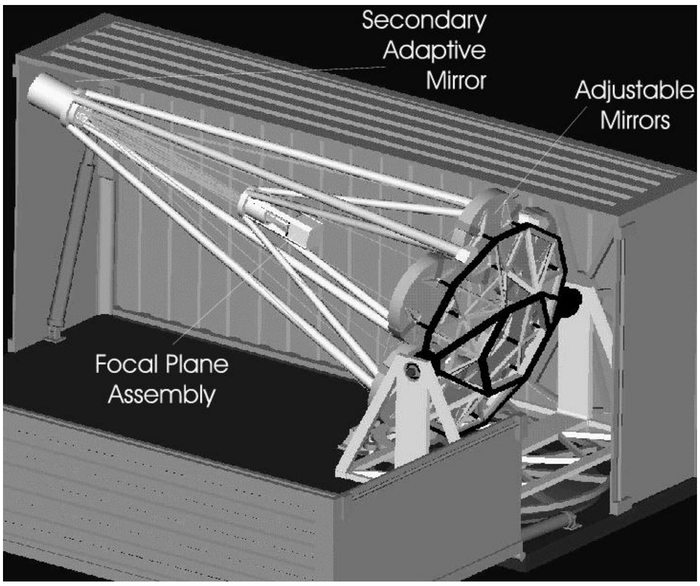

Fig. 8. A schematic of the GATTO TOM telescope hosed inside a standard shipping container. Six spherical mirrors for shape the main mirror to keep overall weight low and to have almost off-the-shelf components.

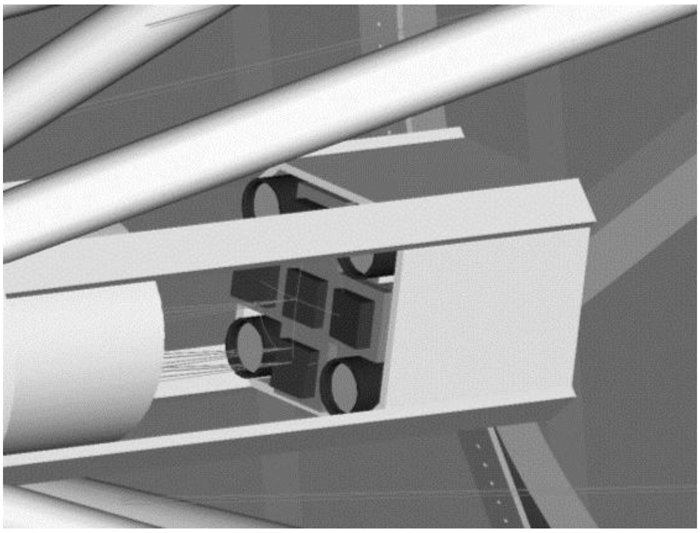

Fig. 9. Details of the focal plane assembly. The five CCDs are arranged in a cross covering an area of 125 square arcmin in total. Wavefront sensing is performed at the corners of the field using a combination of grating and curvature sensors. The wavefront sensors by design contain no moving parts.

6. DESIGNING FOR ANTARCTIC CONDITIONS

This topic covers more areas that can be summarized here. Given the conditions at Dome-C make working outside reasonable hard for long periods of time, though by no means impossible, we prefer to design the telescope for remote operation. Redundancy in the mechanical systems will be considered where possible. The telescope and all peripherals must be reliable, with the aim of no mechanical or software failures and be fully tested at low temperatures in Europe before shipment to the Antarctic plateau.

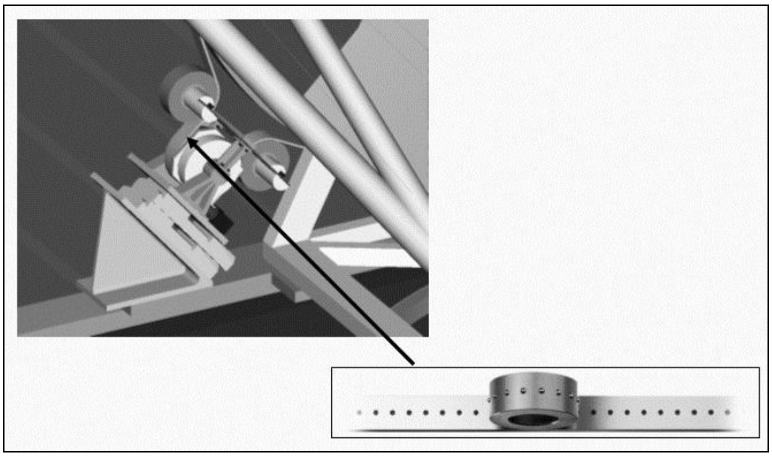

Fig. 10. A suggestion for a simple and reliable drive mechanism (for elevation and azimuth rotation of the telescope) for an Antarctic telescope detecting short duration microlensing events. Course positioning is achieved using a direct driven metallic belt. When the telescope is roughly positioned using the metallic belt the linear drive takes over providing the fine movement required for tracking the required field. As the exposures are relatively short in time a linear drive with constant velocity is adequate (see text for further details).

To this extent the design of the telescope is reduced in complexity by concentrating on the proposed science target. A specific case regards the motor drives of the elevation and azimuth structures. A series of continuous 10sec exposures does not require a tracking system able to achieve precise encoding for all 360 degrees of rotation of the telescope axis but just for a small arc, allowing for technical choices that result in a significantly cheaper, faster to realize and reliable design. We propose a course positioning mechanism (a direct driven metallic belt shown in Fig. 10) to point the telescope to within, say, an arcmin of the target and for tracking purposes a more accurate drive is engaged for the duration of the short observation. The tracking drive mechanism can be an off-the-shelf linear drive with in-built encoder, as shown in a redundant form in Fig. 10. To push the simplification even further it is possible to operate the linear drives at a constant velocity during the short exposures set to be the average velocity of the motors if they were tracking the object perfectly. For an object such as GGC 47-Tuc it was found that one can point the telescope to within 0.1 arcsec of the object for 10s exposures or more (depending on the hour angle) using azimuth and elevation motors operating at a constant velocity.

7. TRANSPORT AND LOGISTICS

Transport of a shipping container to the Dome-C site is routine business during the summer season[23]. There are 3 traverses per year leaving from the coastal base and finishing at the Dome-C station, as summarized in Fig. 11. Substantial infra-structure exists at the Dome-C site in the form of the jointly funded French-Italian Concordia base[6] which for the first time this year will accommodate staff over the winter season. In summary, the telescope will be designed for remote operation but it is extra security to have the knowledge that man-power is available at a short notice all year who have access to the available infrastructure.

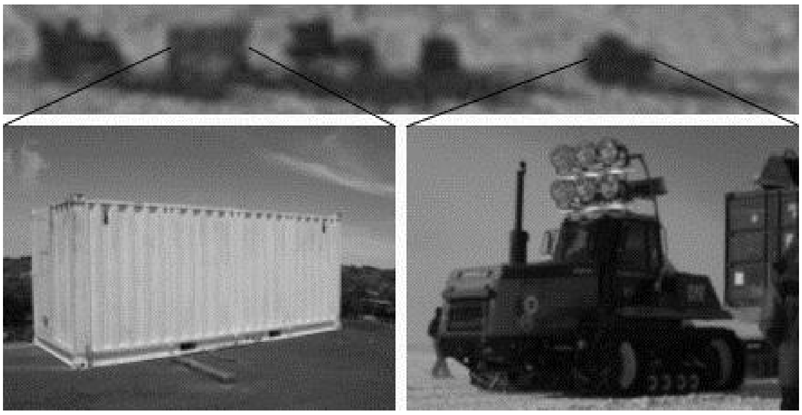

Fig. 11. The method of transporting heavy items from the coastal base to the Dome-C site. There are 3 traverses each summer season, such as that taken from airplane in the above image. GATTO TOM will be housed inside its shapping container such as that shown in the bottom-left image can be transported across the ice by one of the many available tractors (shown bottom-right).

We intend to perform substantial testing of the telescope in Europe before transportation to Dome-C (say 6 months-1 year operation in an Alpine site, for example).

8. CONCLUSIONS AND FURTHER WORK

We present the design of a 2m-class telescope for location on the high Antarctic plateau site of Dome-C. The primary science case of detecting short duration microlensing events (~10 sec) in and by Galactic Globular Clusters is ideally suited to the site and telescope design. The site offers almost continuous observations of a spatially well defined region of stars, with excellent image quality (FWHM in the range 0.1-0.2arcsec). With the inclusion of ground layer adaptive optics we aim to reproduce the excellent seeing over a 15 arcmin FoV by removing the effects of turbulence close to the ground if and when it occurs. It is emphasized that this is not a facility, but rather an experiment.

A concept design is already underway. We eagerly await any future site-testing data from the upcoming winter season. We would like very much to include a wide FoV wavefront sensor on the IRAIT[18] project for prototype test purposes, a medium aperture IR telescope scheduled for operation in 1-2 years. Such data would help to modify the AO system for GATTO TOM (specifically relating to the secondary adaptive mirror). Depending on the degree of complexity of the telescope we aim to be on the sky in 3-5 years from commencement of the project. An assessment of the links between the telescope and future large scale telescopes, either ELTs of Antarctic interferometers, is to be investigated. Possibilities include the base unit for an Antarctic interferometer such as KEOPS[24] that requires co-phasing of the mirrors. The grating base AO system lends itself to future AO systems for ELTs based in Antarctica.

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