A robotic instrument for measuring high altitude atmospheric turbulence from Dome C, Antarctica

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ABSTRACT

To properly characterize the atmospheric properties of a site for a future large telescope or interferometer, it is insufficient to measure quantities, such as the full-width at half-maximum of a stellar image, that have been integrated over the entire atmosphere. A knowledge of the turbulence distribution as a function of height is necessary, since this affects the ease and degree to which adaptive optics systems can improve the telescope's resolution. Furthermore, some astronomical measurements, such as narrow-field differential astrometry at microarcsecond precision, depend critically on the amount of turbulence high in the atmosphere (up to 20km). In order to obtain the necessary site-testing data at remote sites such as those on the Antarctic plateau, we have designed a robust and reliable instrument based on an 85 mm refractive telescope, a gimbal-mounted sidereostat mirror, and a Multi-Aperture Scintillation Sensor (MASS). The instrument uses the spatial structure of single-star scintillation to measure vertical turbulence profiles from 0.5 to 20km. The MASS system is designed to operate completely autonomously throughout the Antarctic winter. It also has potential applications at existing observatory sites for quantifying the turbulence characteristics of the atmosphere in real-time.

Keywords: atmospheric turbulence, site testing, scintillation

1. INTRODUCTION

The possible advantages of Antarctic plateau sites for astronomy have been recognised for many years. It is now well-established that the thermal infrared sky background is significantly lower than that at typical mid-latitude sites[1], and that the precipitable water vapour content is exceedingly low[2], which increases the atmospheric transmission, especially around water vapour absorption lines. One site characteristic that has been very difficult to measure is the atmospheric turbulence as a function of height. Measurements have been obtained at the US Amundsen Scott South Pole Station (altitude 2385 m) via a SOund Detection and Ranging (SODAR) instrument[3], a Differential Image Motion Monitor (DIMM)[4], and balloon borne microthermal probes[5]. These measurements have demonstrated a unique turbulence profile, where the high-altitude turbulence is very low, and the majority of turbulence is confined within 300 m of ground level.

There are reasons to believe that Dome C, at an altitude of 3250 m on the high Antarctic plateau, should have better atmospheric turbulence characteristics than the South Pole[6, 7]. However, obtaining proof of this during night-time is difficult since Dome C is currently occupied only over the summer months (Nov, Dec, Jan)[8], when the sun is continuously above the horizon. To obtain site-testing data through the winter, we developed a remote autonomous laboratory, the AASTINO (Automated Astrophysical Site Testing International Observatory)[9]. The AASTINO was

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installed at Dome C station in January 2003, and provides heat, electricity, communications, and control, for a suite of site-testing instruments. The initial instruments included a SODAR, a sub-millimetre tipping radiometer (SUMMIT), and several cloud detection cameras. During the second half of 2003 we designed and built a MASS instrument to measure the turbulence from 0.5 to 20 km. It is this instrument that we describe here. The Dome C MASS was installed during January 2004 and successfully took data until 17 May 2004, when engine problems caused the AASTINO to shut down.

2. MASS

The MASS concept was developed at the Cerro Tololo Inter American Observatory (CTIO), in collaboration with the Sternberg Astronomical Institute of the Moscow University, as a relatively inexpensive technique for determination of atmospheric turbulence profiles, through single star scintillation[10-13]. The MASS has several advantages over other techniques for atmospheric turbulence monitoring. With MASS, turbulence profiles can be generated (unlike a DIMM, which measures integrated properties), only a small aperture telescope is required (unlike SCIDAR), continuous observation is possible (unlike microthermal balloon probes), and high altitude turbulence can be determined (unlike SODAR). In addition, the MASS does not require good image quality or precise tracking, and can be mounted behind a window of only modest optical quality. Finally, because it is insensitive to turbulence close to the ground, no requirement exists to place it on a tower or away from sources of heat. Disadvantages of the MASS are that only relatively low resolution profiles can be obtained, and it is not sensitive to the surface layer (below about 500 m). For determination of atmospheric parameters important for an astronomical observatory (total atmospheric seeing, isoplanatic angle, coherence time), the MASS must therefore be combined with another instrument type, such as DIMM or SODAR. There are currently several programs investigating the correlation of turbulence measurements between each of these different types of instrument[14].

The MASS instrument, which is fully sealed and has no moving parts, must be mounted at the focal plane of a telescope with an aperture greater than 80 mm, and must observe a sufficiently bright ($m_v < 2$) single star. Optics within MASS re-image the telescope pupil, through a 3 arcmin aperture, onto a circular “segmentator”. The segmentator directs the star flux from four concentric annuli (of projected outer radii 19, 32, 56, 80 mm) onto four miniature Hamamatsu photomultipliers. The photomultipliers each sample the star flux at 1 ms intervals. The normal scintillation index for each aperture, and the differential scintillation index for each pair of apertures, are then calculated as the variance of the intensity (or intensity ratios) normalised by the average intensity (or intensity ratio) over a 1 minute accumulation time. The scintillation indices represent the intensity and spatial structure of the scintillation, which depends on the altitude of the turbulence layers and their strengths. The scintillation indices can thus be used to compute the turbulent intensity, quantified by the refractive index structure constant, within a number of fixed altitude layers[13]. The fixed layer altitudes are centred at 0.5, 1, 2, 4, 8, and 16 km above ground level, with a triangular response function that drops to zero at the altitude of the adjacent layer. Alternatively, the turbulent strength and altitude of three floating layers can be determined. From either of these profiles it is possible to compute the free atmosphere seeing (above 500 m) and the isoplanatic angle. The atmospheric time constant can also be derived. However, the correlation of this parameter with the adaptive optics time constant determined by other methods (such as from microthermal and wind speed balloon measurements) is yet to be determined.

3. DOME C MASS

MASS instruments are currently being deployed at several astronomical sites around the world. They are typically integrated with a DIMM CCD channel and fed off-axis from a ~200 mm alt/az mounted Cassegrain reflector. DIMMs developed by the University of Nice have been collecting data at Dome C over the summer months for the past two seasons. These telescopes are winterised, but not autonomous, and thus require operator presence. The desire to obtain winter-time data on the high altitude turbulence before the Dome C station is manned year round, combined with the difficulties in making a robotic winterised telescope with an aperture large enough for DIMM operation, motivated the development of the Dome C MASS as a stand-alone unit, i.e., without a DIMM channel. Only a small aperture (< 90 mm) telescope is required. Problems such as ice formation, snow accumulation, and electronic or mechanical component failure, are often encountered with instruments located externally in the extreme Antarctic winter conditions. The Dome C MASS is therefore operated in the relatively warm environment inside the AASTINO; this

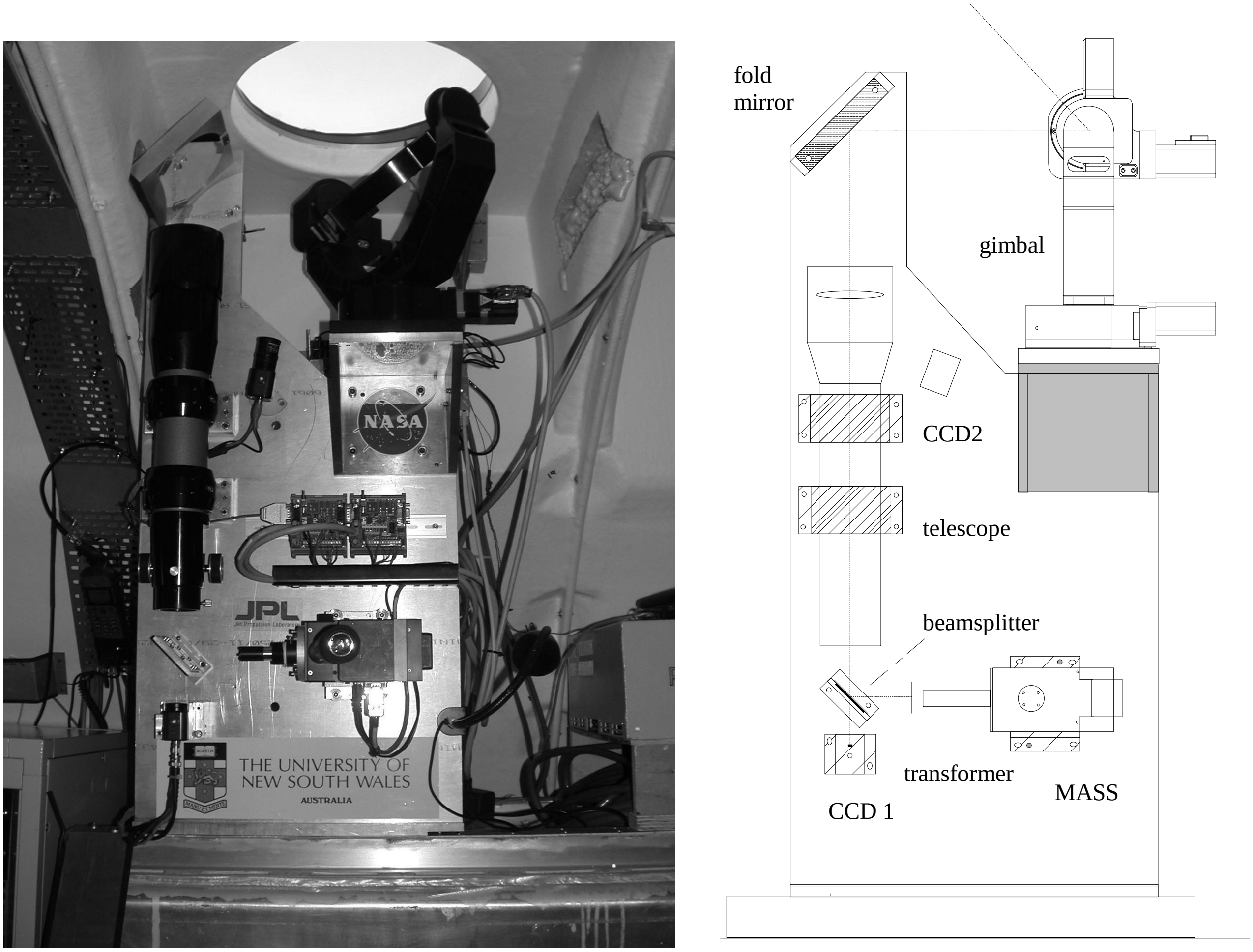

Figure 1. Picture (left) and schematic (right) showing the MASS instrument and feed optics.

reduces complexity, lowers cost, and adds to reliability. Space limitations precluded an alt-az mount, as the swing radius for a telescope of the required focal length (400–700 mm) was too large. A unique MASS feed system consisting of a fixed 85 mm refractive telescope with a gimbal-mounted sidereostat mirror was therefore employed.

The Dome C MASS and feed optics are shown in Figure 1. All components are mounted on a vertical 16 mm thick aluminium base plate attached to one of the internal AASTINO fuel tanks (tests have shown that this is stable to within a few arcminutes over a period of months). Dowels are used to facilitate removal and re-installation of the various components of the instrument, with the only adjustment being the position of the transformer lens immediately in front of the MASS module. Tracking and guiding is achieved with a sidereostat mirror, which looks through a 13 mm thick float-glass window on the AASTINO roof. This window is sloped at ~15 degrees to reduce snow/ice accumulation. The 140 mm diameter aluminium-coated flat sidereostat mirror is mounted in a modified GM-12 gimbal mount (manufactured by Newmark Systems) with a 3:1 spur and a 76:1 worm drive (resulting in less than 1 arcmin backlash on the output shaft). The gimbal mount is driven by two 24 VDC Silvermax #17-3 closed loop servo-motors with in-built incremental encoders and microprocessor control. Three optical limit switches are installed for each gimbal axis for homing. An additional mechanical limit switch is installed to prevent over-rotation of the gimbal azimuth axis.

The gimbal mount directs light to the fixed telescope (a Teleview 85 doublet apochromat refractor of 600 mm focal length) via a flat fold mirror, allowing the telescope to be mounted vertically. An achromatic beamsplitter directs 95% of the star flux to the MASS unit and 5% to a CCD camera (CCD1) for acquisition and guiding. This CCD camera is a

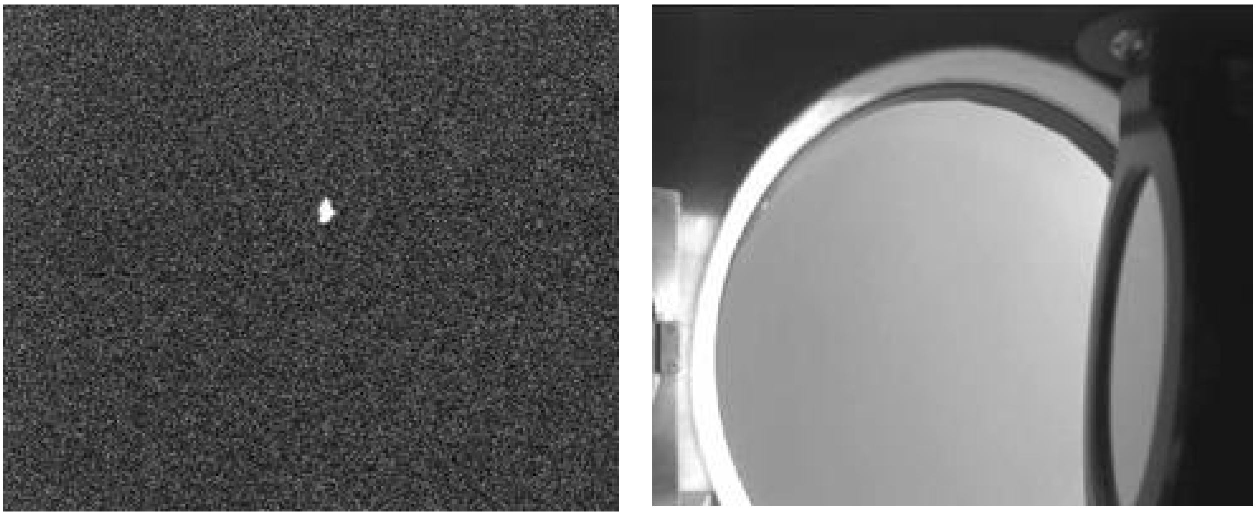

Figure 2. Example of images taken by MASS webcams. Left image is from CCD camera in focal plane of telescope which is used for auto-guiding, and right image is viewing the gimbal mirror and AASTINO window which is used for checking of ice/snow formation.

Watec (WAT902H low light level, 800×600 pixel, monochrome array) and has a field of view of ~20×30 arcmins. A second Watec camera (CCD2) with a 120° wide field lens is installed facing directly upwards to monitor the gimbal and external window for signs of ice or snow accumulation. If ice or snow is detected with this camera, a window heater can be switched on. An example of CCD images taken by the two cameras is shown in Figure 2. Between the beamsplitter and the MASS is a transformer lens pair that matches the telescope beam to the required f/number for MASS. The 400 mm external window aperture limits the range of star zenith angles that can be observed. By observing a number of different stars, however, 24 hour coverage is possible.

4. INSTRUMENT CONTROL

The Dome C MASS instrument has been integrated into the AASTINO remote site-testing laboratory. The AASTINO uses a hybrid Stirling-engine/solar-panel system that provides up to 700 W of electrical power and several kW of heat to keep the internal temperatures above –20° C in mid-winter when the external temperatures can drop below –80° C. A central “Supervisor” computer controls engine and heat management, instrument operation and data collection, and communications. This computer is a DSP TPP3 PC104 system with a 300 MHz Celeron processor, 512 MB of semiconductor memory, and two 1 GB 2.4″ IDE Plus Flash Disks, running a GNU/Linux operating system. The AASTINO communicates via the Iridium satellite network. This provides a low bandwidth (2400 baud) connection, allowing data transfer and some degree of command and control, but is too slow and unreliable for real time control.

Power to the 24 VDC MASS gimbal servo-motors, the 12 VDC MASS instrument, and the 12 V CCD cameras is provided from a power distribution unit that contains a number of DC-DC converters. This allows the MASS gimbal, instrument, and cameras (as well as all other AASTINO sub-systems) to be independently power-cycled. The complete MASS system requires less than 20 W of electrical power, which is only a small percentage of the total AASTINO system power requirement. The Supervisor computer communicates with the two gimbal motors via a single RS485 line from a computer serial port to azimuth and altitude network breakout modules (Quicksilver Controls QCI-BON). These modules also contain digital input/output connections for the optical and mechanical limit switches. The MASS instrument communicates with the Supervisor computer via the Supervisor parallel port through an RS485/LPT converter that includes a microcontroller to reduce the need for real-time response from the Supervisor. The video output of both the acquisition CCD and the window camera is sent to an Axis video server linked to the local AASTINO intranet.

The MASS instrument is controlled via the Turbina software program which is installed on the AASTINO Supervisor computer. This software has two separate interfaces, a local GUI for manual control used for initial set-up and on-site testing, and a command interface for remote operation via a “socket” connection (using TCP/IP or UNIX sockets). The socket connection is run from scripts stored locally that are called from the Supervisor’s crontab file. The software has complete control of the instrument and can perform diagnostics, data collection, and data analysis. MASS data are stored in separate daily log files that record the scientific parameters (flux measurements, turbulence profiles and derived integral parameters), and the statistical moments (used to compute scintillation indices).

The gimbal motors are driven by a Linux device driver that provides position and velocity information at 1 second intervals in order to track the stars. The gimbal pointing is controlled by a custom Telescope Hardware Interface (THI) to the PTCS (Portable Telescope Control System) software package[15]. THI/PTCS uses a 13-parameter model to account for gimbal alignment, axis zero-points, non-perpendicularity of axes, and telescope orientation. The success of our project was in no small part due to the modularity of PTCS and the ease of converting it from its normal equatorial or alt-az configuration to run a siderostat.

MASS observing is controlled via a perl script that is automatically started each day. This script runs a gimbal initialisation routine that power-cycles the servo-motors, loads the control software, and points the gimbal to its home position. The observing script then sets the gimbal to the track an appropriate star. Stars with a range of magnitudes, such as Alpha Eridani (m_v = 0.46), Beta Crux (m_v = 1.25), Beta Carina (m_v = 1.68), Alpha Triangulum Australis (m_v = 1.92), are observed depending on the local sidereal time. Spiral search and peak-up routines then center the star in the middle of the 3 arcmin MASS aperture, based on feedback from the MASS D-channel flux (largest annulus). The MASS is then set in normal operating mode, via the Turbina socket interface, where it computes turbulence profiles and statistics from scintillation measurements in one minute bins. While absolute pointing is accurate to within a few arcminutes, residual errors in the pointing model can cause a slow drift of the star out of the MASS aperture. The gimbal pointing is thus adjusted (independently from the Turbina program) once per minute using the telescope focal plane CCD camera image. The centroid of the maximum flux in the image is computed, and the gimbal offsets are adjusted to re-center the star. Once every hour the Turbina operation is briefly halted, while the star is re-centered (via the spiral search and peak-up routine), and a sky background measurement and detector test is performed. Once every day an automated script downloads the latest MASS data files to a computer at UNSW via the Iridium satellite link, and a separate script analyses these files.

The operating method for the Dome C MASS is designed to provide a robust and completely autonomous instrument, with a minimum of required user input. It additionally has a high degree of flexibility so that the observing strategy can be readily modified, by uploading a new observing script, based on information contained in the MASS data files and the observing log files.

6. RESULTS

The Dome C MASS and optical feed system were set-up and tested at the University of New South Wales in Sydney, Australia during December 2003. These tests were used for system debugging and to determine the required alignment procedures. Nominal operation of the MASS instrument and the tracking and guiding system was confirmed; free atmosphere seeing was demonstrated to be typically 2-3 arcsec in the middle of the city. The instrument was then shipped to Dome C station and installed over January and February 2004. The minimum sun elevation before station close on 8th February was ~5 degrees. Full operation of the MASS at Dome C could not be tested, as the level of sky background at the minimum sun elevation would saturate the MASS photomultipliers. Initial commissioning of the instrument at Dome C thus involved debugging system communications, making accurate measurements of the gimbal alignment, and collecting pointing data with the CCD camera (in full daylight the focal plane CCD was capable of detecting stars brighter than magnitude m_v = 1.8). After station close, the PTCS pointing model was adjusted based on collected data, and the tracking and guiding of the gimbal was tested via automated scripts. The first night’s observation with the MASS instrument was possible in late March when the sun was below the required elevation angle (approximately 10 degrees below the horizon), creating a sky background approximately 5% of stellar flux. The instrument then acquired data until 17 May 2004 when the AASTINO stopped due to engine problems.

7. CONCLUSION

The unique design for the feed optics and control system of the Dome C MASS has proved very reliable, and may find application in other remote areas, or even at established observatory sites where a low maintenance MASS is desired. The gimbal mount MASS system described here requires less observer intervention than other MASS units. Its only moving part is the gimbal, and there is no need for a traditional dome or sliding-roof housing for the instrument, leading to greatly eased automation and no requirement for a weather station to monitor rain. A modified version of our design, perhaps powered by solar-recharged batteries, could readily be deployed as a completely independent unit to remote, uninhabited mid-latitude locations.

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