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# Atmospheric Spatial and Temporal Seeing Monitor Using Portable Amateur Astronomy Equipment

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## ABSTRACT

Accurate knowledge of the spatial and temporal seeing has become increasingly important as AO systems move from being specialised instruments to standard equipment at large ground-based telescopes. While monitors that measure the spatial seeing scale are now commonplace, devices capable of measuring temporal seeing parameters are much rarer since the sampling requirements are severe. Nevertheless, such information is vital if the bandwidth and control requirements for active and adaptive systems at state-of-the-art telescopes and optical/IR interferometers are to be correctly specified. In this paper we describe a cheap, yet robust, Differential Image Motion Monitor Which Is Transportable (DIMMWIT) that can make both spatial and temporal seeing measurements. It samples starlight at rates up to 500Hz but contains no mechanical parts and uses only technology available to amateur astronomers. We review the design and performance of the device and present examples of results from routine use at the Cambridge Optical Aperture Synthesis Telescope (COAST) site in the UK. An identical system is also being tested at the Magdalena Ridge Optical Interferometer (MROI) site in New Mexico.

**Keywords:** DIMM, site testing, seeing, turbulence, speckle, CCD, Linux

## 1. INTRODUCTION

Atmospheric seeing quality affects almost all ground-based optical astronomy, from choice of site to telescope design to interpretation of data. With the advent of larger telescopes and interferometers and the increasing adoption of adaptive optics systems, quantitative seeing measurements are becoming vital to successful ground-based astronomical enterprise.

One popular seeing monitor is the Differential Image Motion Monitor (DIMM) of Fried<sup>1</sup> where a two-hole aperture mask is placed in front of a slightly defocused telescope that is aimed at a bright star. The relative motion due to seeing of the two resulting images is measured, while common-mode effects such as telescope tracking errors are rejected.

DIMM optics are suitable for measurement of Fried's parameter  $r_0$  (the telescope aperture size below which a telescope is diffraction limited) and temporal seeing parameters such as the speckle lifetime, but the majority of such instruments have traditionally only been used to measure  $r_0$ .<sup>2,3</sup> This is a technical constraint—  $r_0$  measurements require only that a large number of short exposures of the image pair are taken, while temporal measurements require that exposures be taken at a sustained rate that adequately samples the image motion due to atmospheric turbulence (hundreds of Hertz). While it has been possible for many years to mechanically supplement the readout of CCDs to achieve this,<sup>4,5</sup> the technology that makes this rate of data capture available without moving parts and using “off the shelf” components has only recently become commonly available.

We have developed a seeing monitor that can measure both spatial and temporal seeing using only parts and a budget readily available to many amateur astronomers. Furthermore, the entire kit excluding telescope optics is sufficiently portable and robust that it can and has been taken on board aircraft as hand luggage. Hence it is well suited to site testing of remote locations and consequent justification of large telescope parameters prior to funding application.

Here we review the device hardware and software and briefly present examples of data taken at the Cambridge Optical Aperture Synthesis Telescope (COAST) located in the United Kingdom.

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## 2. INSTRUMENT OVERVIEW

A system overview is shown in Figure 1. All the components are available commercially and (with the exception of telescope optics) will fit in aircraft hand luggage.

Optically, the system is an ordinary DIMM. A portable telescope with a two-hole aperture mask concentrates slightly defocused starlight onto a CCD within a Starlight Xpress HX516 camera head. This is clocked out by a microcontroller within a Universal Serial Bus (USB) interface, either conventionally or using a customised rapid subframing technique. Digitised data is transmitted via a USB cable to a single board computer, which runs the user program under Linux. The observer interacts with the user program using a notebook computer connected via an ethernet cable and the notebook computer also stores data taken with DIMMWIT.

At the time of writing, the camera and USB controller retailed for about US\$1500 and the single board computer for about US\$900. The custom software is derived entirely from freely distributable components. “Off the shelf” notebook computers and telescopes can be used with DIMMWIT.

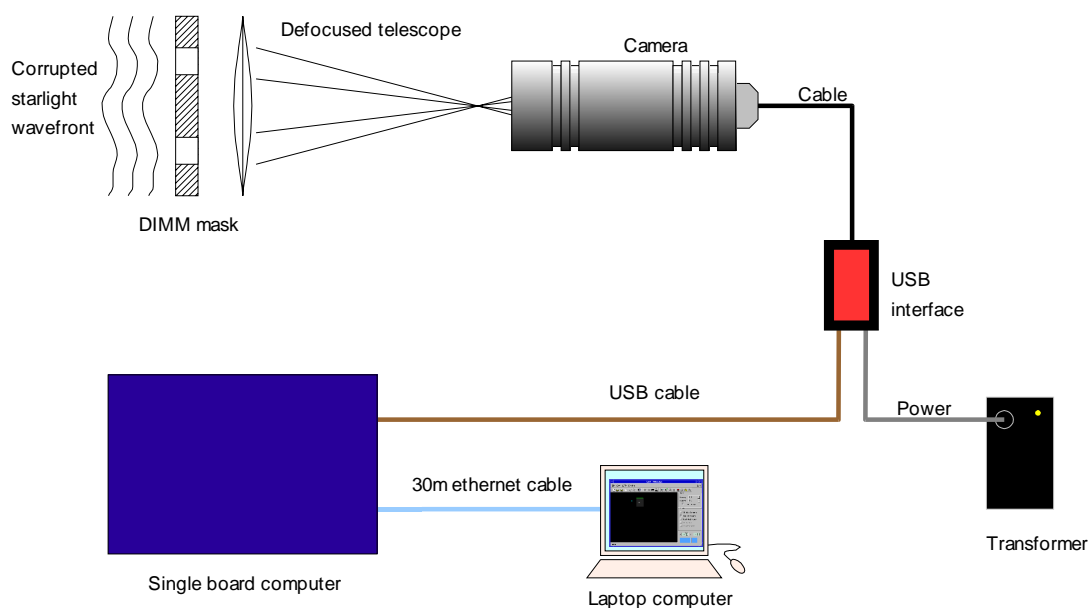


Figure 1. Overview of the DIMMWIT hardware.

## 3. OPTICS

DIMMWIT can be attached to the primary focus of telescopes with apertures of twelve inches or more and focal lengths of several meters. A two-hole aperture mask is also required and some form of autoguiding system is recommended. To date DIMMWIT has been tested with commercially available Celestron 14” and Meade 12” Schmidt-Cassegrain telescopes and the custom telescopes of the COAST array, where it doubles as an acquisition tool.

As starlight passes through the atmosphere en-route to the telescope, atmospheric turbulence will corrupt the plane wavefront such that the angle of arrival varies over the telescope aperture. This wavefront is sampled by the mask, and if the telescope is defocused slightly two separate images will be formed on the camera focal plane and will generate charge on the CCD. As with any other DIMM, analysis of the differences in motion between the two images provides information about the air turbulence while rejecting common-mode effects such as telescope tracking errors.

## 4. IMAGING AND CCD READOUT

The camera is a Starlight Xpress HX516 designed for use by amateur astronomers.<sup>6</sup> The embedded CCD is an interline transfer Sony ICX084AL<sup>7</sup> with microlensed  $7.4\mu\text{m}$  square pixels, a quantum efficiency approaching 50%, antiblooming circuitry, negligible dark current and readout noise of ten to twelve electrons. The spectral response is from 0.4 to  $1.1\mu\text{m}$  and an electronic shutter is incorporated. The camera head also contains a Peltier cooler, amplifier and a 16-bit analogue to digital (A/D) converter (hence a high dynamic range at the cost of digitisation and readout time). The case has a Pentax M42 thread for attachment to common amateur telescopes.

There are two CCD readout modes employed, denoted “ $r_0$  mode” and “ $t_0$  mode”, each of which is designed to meet the acquisition demands of spatial and temporal seeing measurement respectively. The  $r_0$  mode is not strictly required as it is possible to calculate  $r_0$  from data taken in  $t_0$  mode, but is a useful check of such analyses. The  $r_0$  mode is a relatively conventional subframing technique, while the  $t_0$  mode uses the CCD as an analogue storage device, together with binning and subframing, to achieve high frame rates using only unmodified amateur-grade hardware. It is this aspect of the implementation that makes DIMMWIT unusual.

### 4.1. Spatial Seeing Data Acquisition

In  $r_0$  mode, the objective is the measurement of variation in separation of two star images over a long period of time (such as might be encountered during a photographic exposure). A high rate of readout is not required although each frame should have a short exposure time to avoid motion blurring.

The user selects a subframe of the CCD to read out, the amount of binning to be applied and an exposure time. The CCD is exposed for the required period using its electronic shutter and the requested section of the CCD image is then clocked to the readout register in the conventional manner and read out to form a two-dimensional dataset. The remainder of the CCD image is discarded. The cycle repeats for a specified number of frames, which are stacked to form a three-dimensional Flexible Image Transfer System (FITS) file for later analysis.

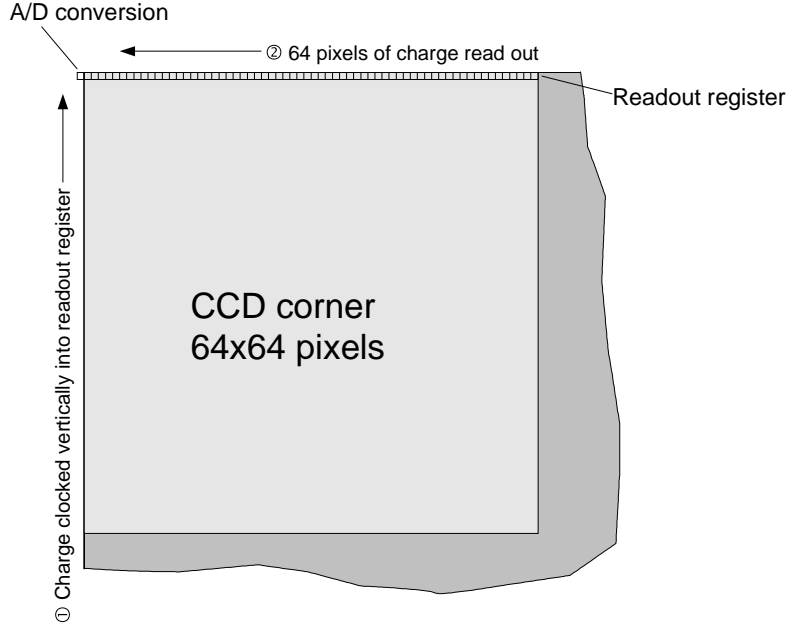
### 4.2. Temporal Seeing Data Acquisition

In  $t_0$  mode, the objective is the measurement of the variation in separation of two stellar images due to short-period atmospheric fluctuations, so DIMMWIT must sample at a sustained and regular rate of several hundred Hertz. However, the entire CCD cannot be clocked out at this rate as the system is constrained by both the digitisation hardware and the rate at which the USB microcontroller can supply clocking signals. Nevertheless, it is possible to read out a small subframe at high speed if:

1. No charge clearing is performed prior to the exposure.
2. The subframe is at the CCD corner closest to the readout register.
3. No clocking is performed after the subframe has been read out.
4. The readout is triggered by a hardware interrupt (the USB 1ms frame signal) rather than an explicit command from the host, thereby rendering the timing independent of operating system and USB latency.

Although only the subframe closest to the CCD corner is explicitly read, the readout clocking signals also move charge generated on other parts of the chip towards the readout register. This side effect can be exploited—an image generated anywhere on the CCD will eventually be digitised, but with a delay of zero or more frame cycles depending on its position. This permits the DIMM images to be conveniently focused in the middle of the chip rather than at its corner. Effectively the CCD is used as a two dimensional analogue “bucket brigade” memory.

There are disadvantages to this readout technique. If there are other images formed elsewhere on the CCD they will be superimposed with the data of interest. A valid readout region is small and telescope autoguiding to within arcseconds is required to keep the images within it. Care must be taken to ensure that the host computer is lightly loaded so that it can keep up with the data stream coming from the USB interface. However, when



**Figure 2.** CCD binning in 1D  $t_0$  mode. Charge is firstly clocked upward 64 times so that the charge in the uppermost 64 CCD lines is summed into the readout register to yield a line of vertically compressed charge. Then the readout register is clocked to the left and digitised 64 times to produce a linear dataset. The cycle then repeats. A side effect of the clocking is that charge elsewhere on the CCD is also moved upward and (when it reaches the readout register) to the left. Hence regions other than the CCD corner can be imaged at high speed provided that the remainder of the CCD is dark.

these precautions are taken the technique does allow a frame rate of up to 500Hz, far in excess of what would normally be expected of the HX516 camera.

There are three  $t_0$  submodes, summarized in Table 1. Each trades off the frame rate with the data per frame in different ways. The 1D mode simply bins the image charge in a  $64 \times 64$  region into a single line, losing all spatial information in one dimension but with high resolution and signal-to-noise in the other (Figure 2). The 2D mode is for fast readout retaining information in both dimensions but with decreased frame rate. The transverse mode has higher vertical resolution for studies into the relative transverse motion of the images. Again, there is a penalty in terms of frame rate.

**Table 1.** Fast readout modes and their cycle times.

$t_0$ submode	Region Size (pixels)	Binning	Cycle Time (ms)
1D	$64 \times 64$	$1 \times 64$	2
2D	$64 \times 32$	$4 \times 4$	3
Transverse	$64 \times 32$	$8 \times 2$	4

The format of data files acquired in  $t_0$  mode depends on the submode selected. In the 1D mode, each image is compressed into a single line of data. These lines are stacked side by side to form a two dimensional FITS file in which the second dimension is time. In the 2D and transverse modes, each two-dimensional frame is stacked into a three-dimensional FITS file with time on the third axis in a procedure similar to that for  $r_0$  mode data.

The CCD is an interline transfer device and is capable of reading out a previous frame while exposing a new one. This allows each frame to be exposed for the entire cycle time and eliminates the need for a mechanical

shutter. As the high frame rate is achieved without mechanical sweeping of the image across the CCD, DIMMWIT requires no moving parts.

## 5. USB INTERFACE

The USB interface ships with the HX516 camera head and directly handles all the low level clocking and readout signals for the camera head via microcontroller input/output lines. The microcontroller in the interface is the Cypress AN2131SC<sup>8</sup> which is an enhanced 8051 microcontroller with USB hardware added. Hence compilers for the 8051 can be used and in this case the tool was `sdcc` ("small device C compiler") for Linux. The code itself is written in a mixture of C and assembler and is based on source code for the HX516 freely made available online.<sup>9</sup>

A very useful property of the microcontroller is that it is reprogrammable via its USB port. This in combination with custom source code yields excellent control over CCD clocking sequences and allows the programming and modification of the fast readout modes described above without changes to the hardware.

## 6. HOST COMPUTER

The host computer is a single board Arcom SBC-GX1 computer and enclosure.<sup>10</sup> The architecture is based on the PC-like Geode processor from AMD running at 300MHz. There are 64MBytes of onboard memory, a 16Mbyte solid state hard drive and the operating system is a subset of Red Hat Linux 7.2 with some modifications as provided by Arcom. A desktop computer running Red Hat Linux 8 is used to develop, cross compile and test software for the SBC-GX1, simplifying the development cycle.

The host computer runs the user program and drivers for the USB interface. The drivers, or modules, are the interface between the USB microcontroller and the user program. They are written in C and are customised versions of source code freely made available online.<sup>9</sup> The compiler is `gcc` under Linux. During compilation a copy of the USB microcontroller code is embedded in the drivers so that this code is downloaded when the microcontroller is plugged in via a USB cable. Hence changes to the microcontroller behaviour can be made very simply by editing and recompiling the driver source code.

The user program itself can be displayed locally or (more commonly) remotely on a user's computer using an ethernet connection and the X Windows display protocol. The user's computer is then also used to store data taken with DIMMWIT using the NFS (Network File System) protocol because storage space on the host computer is limited.

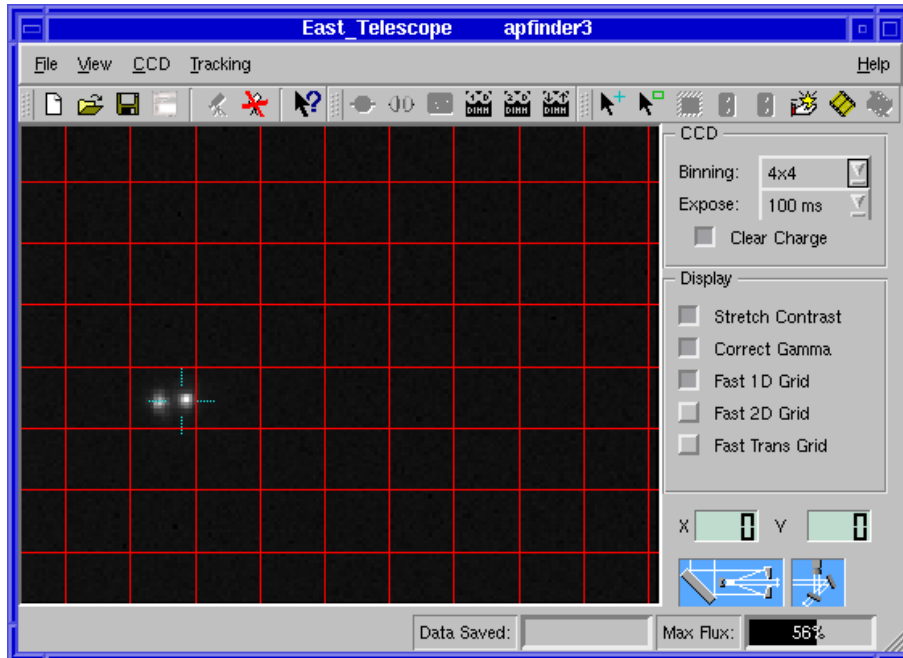
The SBC-GX1 is not strictly necessary as the requirements are only that the host computer runs Linux and X windows and has a USB port. Hence the notebook computer, for example, might act as a suitable host. However, the timing of the  $t_0$  modes is critical if the data is to be used for frequency analysis, and it has been found that interrupts on the host computer due to network activity, disk access and display updates cause delays beyond the limited buffering capacity of the USB interface. To prevent missing data while  $t_0$  files are taken, the user display is not updated and data is saved in memory and dumped to disc at the end of the acquisition. Therefore the maximum data size is limited by available memory and currently is  $2^{17}$  frames or about four and a half minutes of continuous acquisition. The host computer should also be on a relatively quiet network and the user should not move the mouse cursor during acquisition, since this causes network packets containing the mouse location to be sent to DIMMWIT.

If the software had been written for a real-time operating system these precautions would have been unnecessary. As the original source code was written for Linux, RT-Linux was an obvious choice for porting, but at the time of development RT-Linux did not include real-time USB drivers. Fortunately, imposition of the above constraints has proved sufficient to obtain dropout-free performance using ordinary Linux.

One other advantage of an intermediate host is that the ethernet connection allows the user's computer to be up to 30m from the telescope (more if a network hub is used), as opposed to the maximum length of a USB cable (5m).

## 7. USER INTERFACE

The user interface is shown in Figure 3. It is written entirely in-house in C++ using KDevelop<sup>11</sup> and the Qt application programming interface<sup>12</sup> and allows the user to conveniently control DIMMWIT data acquisition. The compiler is gcc running in Linux. The application is static linked as the SBC-GX1 does not natively support the libraries used.



**Figure 3.** The user interface as it appears when the user is preparing to acquire data in 1D  $t_0$  mode. The grid delineates the regions within which all the pixels will be clocked out of the readout register in a single cycle. The ray tracing graphics at the lower right denote the status of the telescope in the COAST array used by DIMMWIT and are only active at COAST.

The default mode is to expose and read out the entire CCD so that a wide field is displayed and the star of interest is easily located. The user can then specify various file parameters, such as the number of frames to acquire per file and the number of such files. Hence if the telescope is sufficiently well guided, a single command can initiate perhaps an hour of unattended data acquisition. By default, file names and headers include the time and date to the millisecond to prevent accidental overwriting of existing files and to simplify sorting (at COAST, several DIMMWITs are allowed to save to the same directory at once and their system clocks are synchronised with Network Time Protocol, or NTP).

After file specification, the data acquisition procedure depends on whether spatial or temporal seeing data is required. If the user wishes to acquire spatial data, they can draw a rectangle around the star pair of interest and tell DIMMWIT to subframe the corresponding CCD region. DIMMWIT will then start reading out subframes as quickly as possible (typically about 10Hz). The user can specify the binning and exposure time on the fly, as well as whether CCD charge is to be cleared prior to each exposure. If charge is not cleared the CCD exposes while it is reading out—this reduces the cycle time but puts a lower bound (the readout time) on the exposure time. A file of thousands of frames can take many minutes to acquire, so the program displays the progress and beeps upon completion.

If temporal data is required, the fast clocking scheme imposes restrictions on where a stellar image pair should be placed if it is to be read out as a single  $t_0$  frame. Such regions are small (the largest is  $64 \times 64$  pixels) so some form of autoguiding is recommended to ensure that the stellar images do not drift during acquisition. The user

can superimpose a grid on the display (Figure 3) as a guide to image placement. When the CCD is put into the required fast readout mode, one subframe in every hundred is displayed to give real-time visual feedback without an excessive screen update rate.

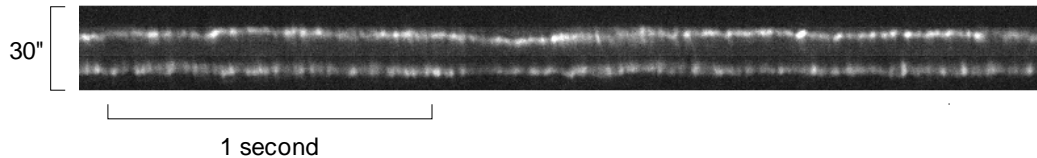
In either of  $r_0$  or  $t_0$  modes, the user initiates data acquisition with a single click of a button. The parameters that were set up previously are then used to determine the file name and other file information. The user can save many files in this way without old files getting accidentally overwritten, as each new file has a unique name based on the current date and time.

## 8. EXAMPLES OF ACQUIRED DATA

We present brief examples of data collected at COAST using DIMMWIT on the night of the 24th of May 2004. The target was Arcturus. These examples are for illustrative purposes—a more in-depth study of DIMMWIT data and analysis methods can be found in Ref. 13 and further examples of reduced data in Ref. 14.

### 8.1. 1D $t_0$ mode

Figure 4 shows a subset from a typical 1D  $t_0$  file. The CCD bins a frame into a single line of charge every 2ms and successive frames from the file are stacked left to right in the picture so that it resembles streak camera output. Features such as scintillation and variation in the separation of the image pair over a range of timescales are visible. In this data  $r_0$  was estimated to be 6–7cm.

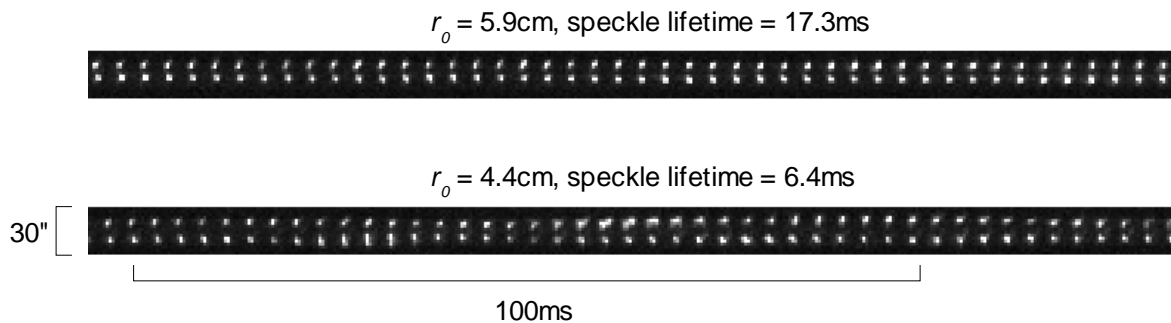


**Figure 4.** Example of 1D  $t_0$  data taken with DIMMWIT at COAST on the night of the 24th of May 2004 at 02:13:40UT.

### 8.2. 2D $t_0$ mode

Figure 5 shows subsets of two 2D  $t_0$  mode files taken forty minutes apart. In each picture, successive frames of the image pair are displayed from left to right and the time between frames is 3ms.

Analysis of the data shows that while  $r_0$  remained relatively stable, the estimated speckle lifetime varied from 17.3ms to 6.4ms, almost a 3-fold decrease. Telescope AO behaviour would certainly have changed in this situation, even though  $r_0$  remained relatively stable.



**Figure 5.** Examples of data taken with DIMMWIT in 2D  $t_0$  mode at COAST on the night of the 24th of May 2004. Top, acquired at 23:24:39UT. Bottom, 00:21:55UT.



## 9. CONCLUSION

We have designed and built a seeing monitor that can collect both spatial and temporal seeing data at frame rates of up to 500Hz using commercially available components. It is portable, robust and accessible to the amateur astronomer or the professional who wishes to do large telescope site testing on a modest budget. Furthermore, DIMMWIT's abilities make it an instrument useful for studying the science of seeing in its own right.

The readout noise of a CCD has traditionally been a function of readout rate, which imposes a tradeoff between frame rate and sensitivity. DIMMWIT works around the problem by subframing and binning, but this substantially reduces the available field of view and telescope autoguiding is necessary to keep the tracking sufficiently precise during  $t_0$  file acquisition. DIMMWIT could be improved through the use of recently developed high bandwidth image technologies such as USB 2.0, FireWire, and network cameras. Furthermore, the advent of the electron multiplying CCD with effectively zero readout noise means that it is now possible to obtain cameras with full frame rates and sensitivities in excess of those available to DIMMWIT.<sup>15</sup> However, such equipment is still very much the domain of the professional astronomer. Furthermore, high frame rate cameras frequently have limited dynamic range or expensive hardware for onboard data storage. Fine control over the hardware can also be difficult if the firmware code is not open sourced. DIMMWIT on the other hand is an open, simple and inexpensive device containing firmware designed specifically for the study of spatial and temporal seeing.

## ACKNOWLEDGMENTS

The authors would particularly like to thank David Schmenk<sup>9</sup> for his original Starlight Xpress code for Linux and assistance with queries concerning its modification, John Young of the Cavendish Laboratory for assistance with data interpretation and Dan KlingleSmith III of the Magdalena Ridge Observatory for many helpful suggestions and diagnostics.

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