*Revista Mexicana de Astronomía y Astrofísica*, **41**, 399–405 (2005)

# FIRST TEST OF THE DRAGON EQUIPMENT

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*Received 2004 December 2; accepted 2005 April 4*

## RESUMEN

El equipo DRAGON constituye un nuevo instrumento astronómico diseñado para llevar a cabo diversas investigaciones relacionadas con óptica adaptativa, óptica activa, astronomía observacional e instrumentación astronómica. En este artículo presentamos los resultados de las primeras pruebas de este instrumento llevadas a cabo en el OAN-Tonantzintla (México).

## ABSTRACT

DRAGON equipment is a new astronomical instrument designed to carry out many types of experimental investigations related to adaptive optics, active optics, observational astronomy and astronomical instrumentation. In this paper we present the results of the first instrument testing at the OAN-Tonantzintla Mexican Observatory.

*Key Words:* **ATMOSPHERIC EFFECTS — INSTRUMENTATION: ADAPTIVE OPTICS — TECHNIQUES: HIGH ANGULAR RESOLUTION — TELESCOPES**

## 1. INTRODUCTION

The quality of astronomical images is one of the key points necessary for successful astronomical observations. However, there are certain factors, both natural and technical ones as well, degrading the image quality: the atmospheric turbulence (Fried 1966; Roddier 1981), the telescope mirror quality, the errors of the telescope guiding, etc. So, in order to reach the best quality of astronomical images one needs to minimize the influence of the factors above. To resolve the problem, one needs to perform many preliminary experiments with a proper equipment. Such an instrument named DRAGON has recently been developed and fabricated with the financial support of CONACyT-México and the TIM project (IA-UNAM).

In this paper we present the description of DRAGON equipment and report the first results of its testing at the Mexican National Observatory (OAN-Tonantzintla). The observations have been carried out in March, 2004 with the 1 m telescope.

## 2. OPTICAL SCHEME

The DRAGON equipment is a new instrument allowing one to carry out many types of experimental investigations related to adaptive optics, active optics, observational astronomy and astronomical instrumentation. The equipment consists of the three independent but temporary-synchronized optical channels that strongly expands the range of possible applications. The complete optical scheme of the equipment is shown in Figure 1.

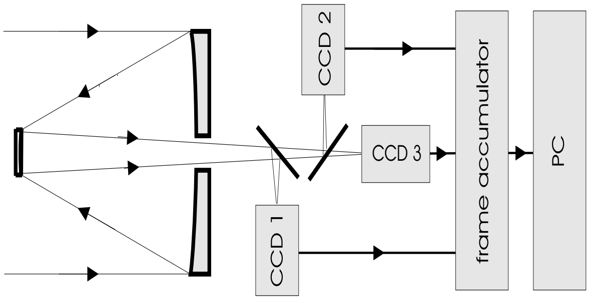

Fig. 1. General scheme of the experimental equipment. There are 3 CCD temporary-synchronized channels.

The light from a star collected by the telescope is divided into three beams by the two beam splitters. Each of the beams is directed to the CCD-camera that grabs the frames, digitalizes them and sends them to the corresponding channel of the frame ac-

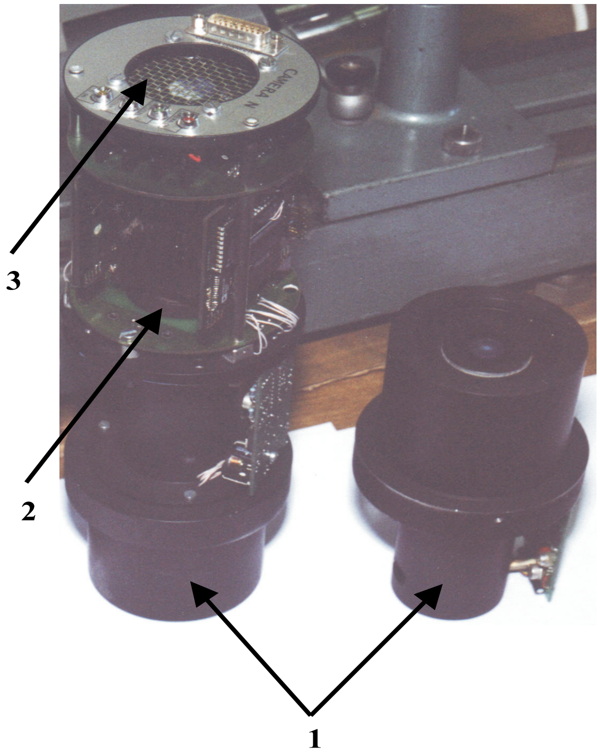

Fig. 2. Single CCD camera. 1-light intensifier, 2-Peltier cooling unit, 3-ventilator.

cumulator. After finishing an experiment, the information collected by the frame accumulator is rewritten from its inner memory to the hard disk of a PC. The PC also controls all the operations performed by the equipment, and allows one to assign all the settings for an experiment and to perform the data reduction.

Fig. 1 shows the complete setup of the equipment when all the three channels are installed. However, depending on the type of experiment performed, it is possible to use more simple experimental configurations with less than three channels. Also the equipment construction allows for the installation of additional optical elements. Some types of DRAGON configurations suitable for certain investigations are discussed below.

## 3. TECHNICAL CHARACTERISTICS OF THE EQUIPMENT

### 3.1. *CCD Cameras*

The equipment includes three equal CCD-cameras. The picture of a single camera is presented in Figure 2.

The main characteristics of the CCD cameras are:

- CCD type: Sony ICX415AL. Progressive scan 8 mm diag.
- CCD size: 584×582 px.
- Pixel: square 8.3×8.3 $\mu$m.
- Two regimes of frame grabbing:

— short-exposure: max. 50 Hz; (20 ms),

— accumulation: up to 10 s, with Peltier cooling.

The two regimes of frame grabbing allow one to extend the range of the equipment applicability. For instance, the fast frame grabbing can be used for investigations related to adaptive optics, while the accumulation regime is more suitable for astronomical applications.

The sensitivity of the CCD cameras can be increased by installing the light intensifiers. The light intensifier allows one to work with weak objects in the short-exposure regime and has the following characteristics.

Type: microchannel plate.

Amplification: computer-regulated, gain up to $10^4$.

Installation type: removable.

In order to reduce the readout noise level the camera is equipped with a Peltier cell cooling unit. The unit can be switched on/off.

All the camera parameters are computer-controlled. Also the computer program allows for the real-time preview of images grabbed by all the three cameras.

### 3.2. *Frame Accumulator*

The frame accumulator provides the real-time accumulation of the frames grabbed by the cameras. In order to provide simultaneous data storage from three cameras, the frame accumulator has three separate channels. Each channel allows the real-time storage of up to 512 Mb of data during a single experiment. After finishing an experiment the data are saved to the external storage device (CD or the hard disk of the PC) and the inner accumulator memory is cleaned up to be ready for the next experiment.

## 4. SOME POSSIBLE EXPERIMENTAL INVESTIGATIONS

DRAGON equipment is designed so as to allow one to use it for many types of experimental investigations related to adaptive optics, active optics, observational astronomy and astronomical instrumentation. A short list of some possible investigations follows:

— adaptive optics wavefront sensing;

— telescope guiding;

— anisoplanatism effects in adaptive optics;

— single-image wavefront curvature sensing and atmospheric tomography;

— influence of atmospheric turbulence on the quality of astronomical images;

— optical testing of telescope mirror quality;

— speckle-interferometry.

In this section we discuss in more details only a few of these investigations which, from our point of view, are more interesting and actual.

### 4.1. *The Experimental Comparison of Adaptive Optics Wavefront Sensors*

The adaptive optics systems are finding more and more applications in astronomical observations. The wavefront sensor is one of the most important parts of an adaptive optics system because the quality of adaptive correction depends strongly on the data coming from the sensor (Noll 1978). The DRAGON equipment allows one to estimate and to compare experimentally the quality of different wavefront sensors (Rigaut, Ellerbroek, & Northcott 1997). One of the possible schemes suitable for such type of investigations is shown in Figure 3.

The light distorted by atmospheric turbulence is collected by the telescope. The beam splitter mounted close to the telescope focal plane divides the incoming focused beam into two beams. The first beam forms the distorted image (in what follows PSF) at the telescope focal plane, which is grabbed by the first CCD-camera (CCD 1). The second beam is directed to the Shack-Hartmann sensor which outputs the Hartmann picture (Shack & Platt 1971). The Hartmann picture is grabbed by the second CCD-camera (CCD 2). Both cameras are synchronized and working in the fast regime and allow one to accumulate the two sets of frames: the first set consists of the PSFs while the second one contains the corresponding Hartmann data. Using the Hartmann data one can reconstruct the phase distortion at the aperture for each frame and then calculate the corresponding PSF. Comparing the calculated PSFs to the measured ones one can estimate the quality of the Shack-Hartmann sensor under investigation (Voitsekhovich et al. 2001).

The quality of other sensor types can be estimated applying a similar approach but adjusted for the particular sensor type. For example, installing three channels one can estimate the quality of the other popular method of wavefront measurements: curvature sensing (Roddier 1988).

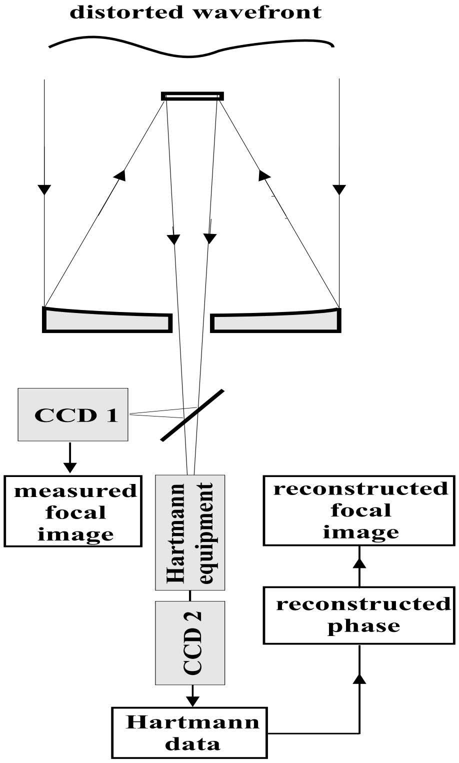

Fig. 3. Scheme for the experimental estimation of the quality of the Shack-Hartmann test.

Finally, analyzing the statistics obtained for different sensor types and sensor schemes it is possible to conclude which one is more suitable for specific applications.

### 4.2. *Quality of Telescope Guiding*

A high quality of telescope guiding is one of the important points for obtaining of high-spatial resolution astronomical data. DRAGON equipment allows one to get the experimental data which, after proper reduction, give us all the necessary information related to the telescope guiding. The experimental setup suitable for such type of investigations is shown in Figure 4.

The light from a star is collected by the telescope and the set of focal images is grabbed by the CCD-camera. During the experiment the digitalized focal images are accumulated by the frame accumulator. The preliminary data reduction consists of the calculation of image centroids for each frame. As a result of the preliminary data reduction we get the data

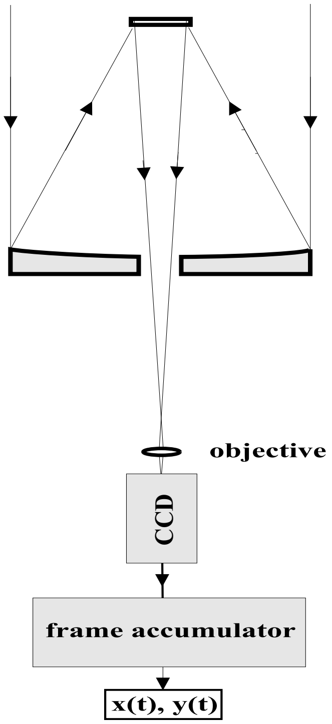

Fig. 4. Experimental setup for investigations of telescope guiding; [x(t), y(t)] are the time-dependent image centroid coordinates.

showing how the image centroid is moving with time [x(t), y(t)]. These movements of the image centroid are mainly due to the three reasons:

— atmospheric turbulence (random, fast movements);

— errors of telescope guiding (slow, more or less harmonic);

— jumps of guiding (slow).

Using suitable methods of analysis (for example, Fourier filtering) one can separate the movements related to atmospheric turbulence from the ones due to telescope guiding. Finally, analyzing the filtered data it is possible to get all the characteristics of the telescope guiding (magnitudes, frequencies, etc.).

The results of some preliminary experiments related to telescope guiding will be discussed later.

### 4.3. *Anisoplanatic Problem in Astronomical Adaptive Systems*

Adaptive optical systems allows one to strongly reduce the influence of the atmospheric turbulence on the quality of astronomical data. However to be

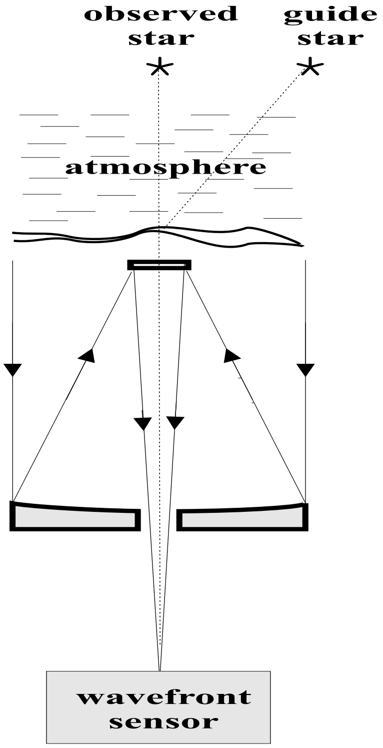

Fig. 5. Adaptive optics wavefront sensing with the use a reference guide star.

able to observe weak stars with the adaptive optics correction, an adaptive optics system has to use a reference star bright enough to perform the real-time wavefront measurements. Such usage of an adaptive optics system is named as the off-axis adaptive optics correction (Orlov et al. 2003; Voitsekhovich & Bara 1999) and it is illustrated schematically in Figure 5.

An adaptive optics system uses a bright reference star to get the wavefront data and then applies the correction obtained to improve the image quality of the observed star. However the light from the two stars passes through different parts of the atmosphere, so the wavefront distortions associated with each star are not equal. As a result, because the difference between the two wavefronts increases with increasing star separation, the bigger the separation is, the worse the correction quality becomes. Moreover, starting from some separation, the adaptive optics correction with a reference star can make the observed image quality even worse than it would be without any correction (Fried 1982). So it is important to estimate experimentally the efficiency of the off-axis adaptive optics correction under real observation conditions. DRAGON equipment allows one to carry out such type of experiments using the setup shown in Figure 6.

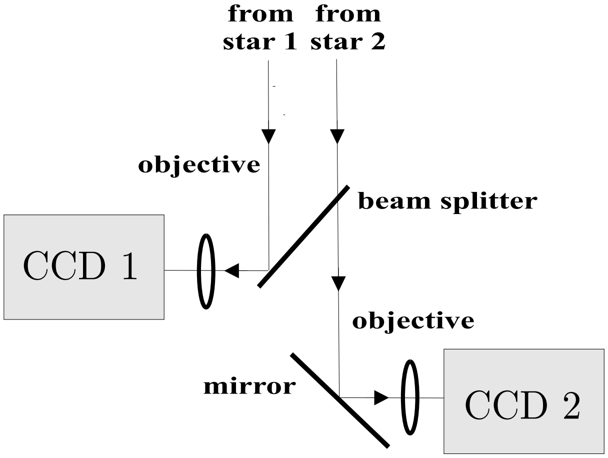

Fig. 6. Experimental setup for anisoplanatic investigations.

The experimental setup consists of the two synchronized CCD-cameras working in the fast regime. The light from the two stars separated by some angular distance passes through the telescope which forms the images distorted by atmospheric turbulence. Each image is enlarged by the objective and grabbed by the corresponding camera. The mirror can be moved in the horizontal direction to provide the proper image positioning on the second CCD. The use of the two cameras along with the objectives allows one to grab the detailed images of the stars with separations of up to the whole field of view of the telescope. Also, the scheme with the two cameras permits one to work with stars of very different magnitudes (choosing a proper amplification for each camera). During the experiment, the two sets of images are accumulated by the frame accumulator. The data reduction consists in the comparison of the images from the two stars. Such a comparison can be done, for example, through the calculation of the image moments. Finally, obtaining the data for different star separations and various turbulence conditions and making use of statistical analysis, one can estimate the efficiency of the off-axis adaptive optics correction.

### 4.4. *Single-Image Wavefront Curvature Sensing and Atmospheric Tomography*

Hickson (Hickson 1994) suggested using only one defocused pupil image to reconstruct the wavefront shape, thus giving also an experimental demonstration of the feasibility of the technique (Hickson & Burley 1994). Indeed, a single defocused star image contains sufficient information to determine the spatial phase fluctuations of the incident wavefront. A CCD sensor which responds to the intensity distribution in the image produces signals proportional to the wavefront curvature within the pupil and the radial slope at the pupil boundary. Nevertheless, unlike Roddier's differential curvature sensing technique, a single-image sensor does not cancel intensity fluctuations due to atmospheric scintillation (Voitsekhovich, Sánchez, & Orlov 2002; Voitsekhovich & Sánchez 2003). Those measurements are affected by scintillation, which is proportional to the wavefront curvature of each perturbing layer weighted by its distance from the telescope pupil. In fact, as suggested by Ribak (Ribak 1995), such dependence can be used to disentangle, to a limited extent, the origin of the wavefront deformation, thus opening the possibility of the so called atmospheric tomography technique. As was proposed in Ragazzoni, Marchetti, & Valente (2000), the brightness distribution on the single defocused pupil is given by a linear combination of the wavefront perturbation contributions for each single layer. We are considering a proper experimental setup of the DRAGON equipment for carrying out atmospheric tomography studies in the near future.

## 5. TESTING RESULTS AT THE OAN-TONANTZINTLA OBSERVATORY

The first observations with DRAGON equipment have been performed in March, 2004 at the OAN-Tonantzintla Observatory (México) with the 1 m telescope. The main goals of the observations have been as follows:

— to check out the viability of the equipment at the observatory conditions;

— to test the limiting sensitivity of CCD-cameras;

— to get some preliminary data for the development of the methods suitable for investigations of telescope guiding;

— to decide what equipment modifications were needed for the investigations related to the anisoplanatic problem in astronomical adaptive systems.

The limiting sensitivity test has been performed in the fast regime of frame grabbing (20 ms exposure time) for the camera with the light intensifier installed. As a test object, the famous Orion Trapezium cluster $\theta^1$ Ori has been chosen. The test results are illustrated in Figure 7 and they show a quite high camera sensitivity despite unfavorable observation conditions (light pollution, clouds, and a high

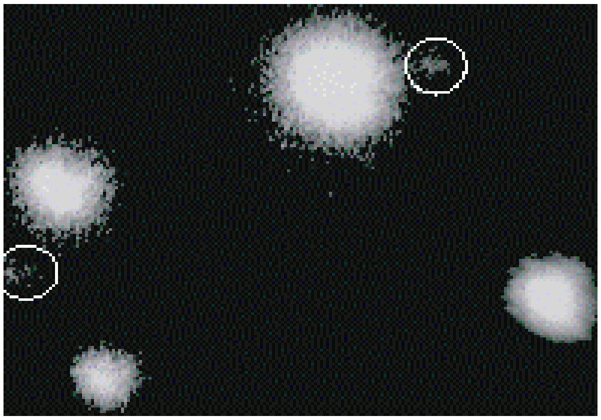

Fig. 7. Limiting sensitivity of CCD-camera. Orion Trapezium cluster $\theta^1$ Ori, 20-ms exposure showing stars up to $11^m$.

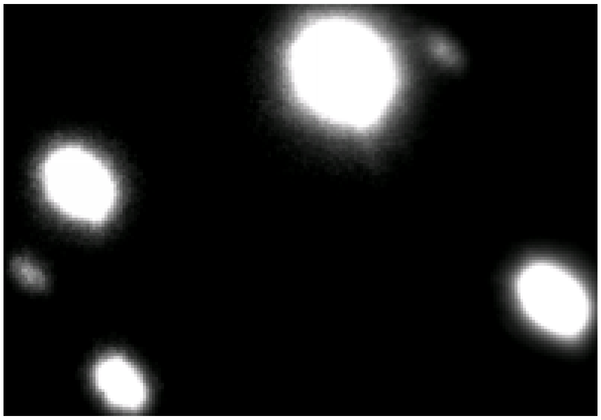

Fig. 8. Telescope guiding data: single frame with 1 sec integration time showing stars separated up to ∼ 19 arcsec.

atmospheric turbulence level), we were able to see starts as faint as $11^{\mathrm{m}}$ .

The preliminary data needed for the development of the methods related to investigations of the telescope guiding have been obtained with the same object: $\theta^1$ Ori. The data consist of a set of frames obtained in the accumulation regime (1 s exposure time). In order to get a suitable spatial image resolution, the observation has been performed in a long effective focus ∼ 100 m). A typical single frame of this data set is shown in Figure 8.

Looking at this frame one can see the elliptic form of the images which is due to the errors of telescope guiding. In order to estimate numerically the magnitude of the guiding errors and their temporal behavior we have calculated the movements of the image centroid which are show in Figure 9.

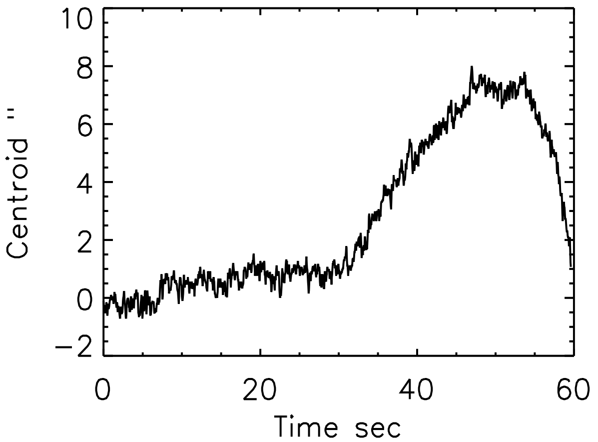

Fig. 9. Telescope guiding data: image centroid displacement in arcsec as function of time.

Analyzing this graph one can separate three type of errors of interest: the linear trend, more or less harmonic oscillations, and the jump. As one can see, the gravest guiding error is the jump: its maximum magnitude reaches ∼ 7 arcsec. The magnitude of the other two errors is smaller (∼ 1 arcsec); however it is big enough to affect the quality of the astronomical images.

The last set of data obtained during the observations is related to the anisoplanatic problem. The data have been obtained in the fast frame grabbing regime and used for the development of the experimental scheme shown in Fig. 6. In order to understand why we have chosen the two-camera scheme instead of the much more simple single-camera one, let us analyze the images shown in Figure 10.

In this figure we present two typical short-exposure frames obtained for two small-separated stars (double star $\gamma$ Leo, HR 4057, and 4058, separation ∼ 5 arcsec).

First let us turn out our attention to the details of the speckle images shown in Fig. 10. One can notice that the images are distorted strongly by atmospheric turbulence. However, despite of a high turbulence level, they are still well correlated. This means that if we want to investigate the limits of the isoplanatic area, the equipment has to allow us to observe stars with a bigger separation (at least, up to ∼ 1 arcmin). On the other hand, to be able to perform a high-quality correlation analysis, each image has to be enlarged to have a size at the CCD entrance of about 100 pixels minimum. Simple calculations show that it is impossible to satisfy these two requirements using a single-camera scheme.

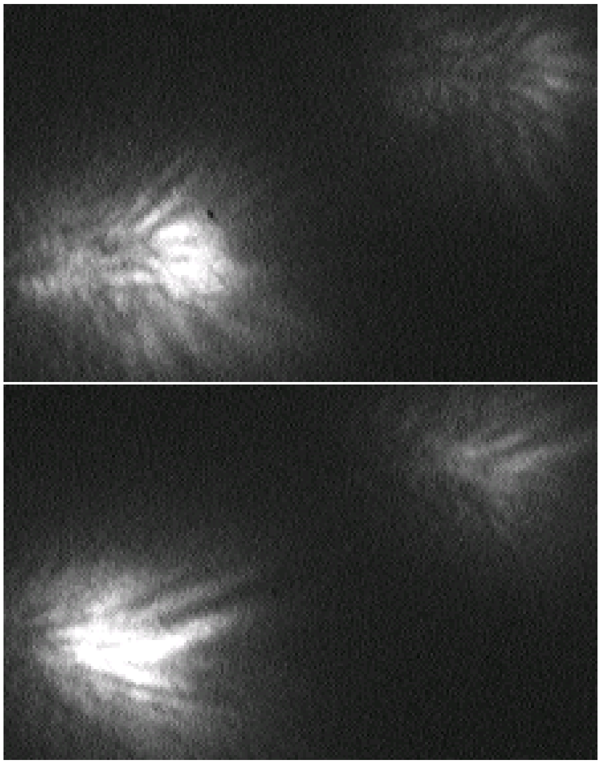

Fig. 10. Turbulence-distorted short exposure stellar images of the double star $\gamma$ Leo (Visual magnitudes 2.6 and 3.8 respectively, angular separation $\sim$ 5 arcsec.)

Now let us compare the intensity of two images. As one can see, their intensities differ ($\sim$ 1.2 magnitudes) and while the left-side one is reducible, the data reduction of the right-side image is very complicated due to its low intensity. However, the usage of the two-camera scheme (Fig. 6) allows one to avoid this problem choosing different amplifications for each camera.

## 6. CONCLUSIONS

The technical characteristics and possible applications of the new DRAGON equipment have been presented. The first test of the instrument at the observatory has shown its viability and high sensitivity.

The experimental data obtained during the testing campaign have allowed us to set up two important problems. The first problem consists on the investigations of the quality of telescope guiding while the second one is related to the study of the isoplanatic area of adaptive optics astronomical systems. Further studies will be carried out with this instrument in all the telescopes of the OAN (México).

This work has been supported by CONACyT (México) grant number 34517-E and by the TIM project (IA-UNAM). We are grateful to the OAN-Tonantzintla staff for their support in observations. We acknowledge an anonymous referee for a valuable suggestion on the possibility of single-image wavefront curvature sensing studies with the DRAGON equipment.

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