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RUCA: A SYSTEM FOR ASTRONOMICAL IMAGING

S. Zazueta, M. Pedrayes, F. Cobos, J. Valdez, J. Bohigas, B. García, A. Córdova, V. García Gradilla, J. L. Ochoa, J. Palomares, V. García, O. Harris, E. Luna, and C. Tejada

Instituto de Astronomía,
Universidad Nacional Autónoma de México

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RESUMEN

Se describe un sistema para obtener imágenes ópticas en el Observatorio Astronómico Nacional en San Pedro Mártir. El sistema incluye una rueda fija con 4 polarizadores, una paleta para reductores focales, una rueda intercambiable de filtros con 8 posiciones y una platina giratoria. Los reductores focales son un par de tripletes optimizados al azul y al rojo, que aumentan 1.6 veces la escala de placa, dando un campo sin viñeta de 14.9′ para el telescopio de 84 cm y 8.4′ para el de 1.5 metros. El control se realiza con una PC dedicada. La tarjeta de interfaz está conectada al puerto IDE de la PC. El programa de control y la interfaz de usuario están escritos en C++. Se desarrollaron dos tipos de interfaz al usuario: una bajo el ambiente WINDOWS y otra que opera como una página escrita en HTML accesible desde cualquier navegador de la red.

ABSTRACT

An optical imaging system for the Observatorio Astronómico Nacional at San Pedro Mártir is described. The system includes a fixed wheel with 4 polarizers, a sliding bench for focal reducers, an interchangeable wheel for up to 8 interference filters and a rotating flange. Focal reducers are a couple of triplets optimized to work in the blue and red ranges, increasing the plate scale 1.6 times, yielding unvigneted fields of view of 14.9′ and 8.4′ for the 84 cm and 1.5 m telescopes, respectively. Control is carried out through an embedded IBM-PC compatible computer. The interface card is connected through the IDE port of the PC. The control and user interface programs are both written in C++. Two user interfaces were developed: one runs under WINDOWS, the other is an HTML page accesible from any web browser.

Key Words: **INSTRUMENTATION**

1. INTRODUCTION

The San Pedro Mártir site of the Observatorio Astronómico Nacional (OAN) has three telescopes: a 2.1 m with three available secondaries (f/30, f/13.5, and f/7.5), a 1.5 m f/13.5 and a 0.84 m f/15. During the past decade a major refurbishing effort has been carried out on these telescopes: new consoles have been provided (Zazueta & Ibarra 1991; Zazueta et al. 1992; Ibarra et al. 1992; Zazueta et al. 1994), guiders were installed (Pedrayes et al. 1993; Gutiérrez et al. 1994; Valdez et al. 1997), baffles were redesigned (Gutiérrez et al. 1996), an active support system for the 2.1 m primary mirror is in operation (Salas et al. 1997), gearboxes were replaced in the declination axis of the 0.84 and 1.5 m telescopes, a new mount was built for the secondary of the 1.5 m telescope (Gutiérrez et al. 2000), etc. The existing instrumentation has also been upgraded: an infrared optical bench (Cruz-González et al. 1994) and a Fabry-Pérot spectrometer (Rosado et al. 1996) were built, several CCD cameras were bought and a mid-IR system is about to be commissioned.

Optical imaging projects occupy $\sim$ 30% of the observing time at the OAN, where a very large collection of filters is available (Bohigas 1990). Thus, a robust and versatile instrument dedicated to optical imaging was required. This system, known as “Rueda Cachanilla” (henceforth RUCA) has been in operation since March 1997 at the 1.5 and 0.84 m telescopes. A preliminary description of the system

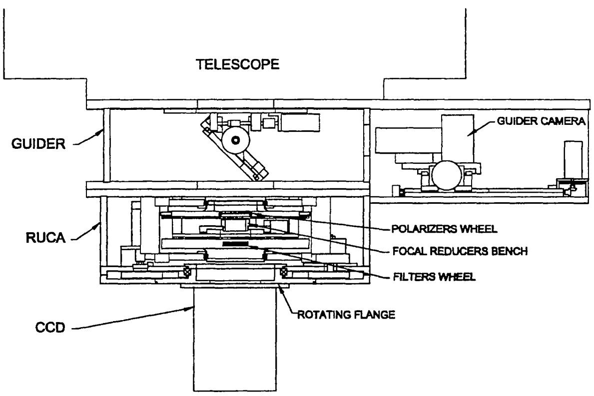

Fig. 1. Sketch of the instrument.

can be found in Pedrayes et al. (1995). The mechanical design and construction was done by Córdova, B. García, Pedrayes, and Valdez; Bohigas, García Gradilla, Ochoa, Palomares, and Zazueta were responsible for the electronics and software development; optical design and construction was carried out by Cobos, V. García, Harris, Luna, and Tejada; finally, Bohigas provided the general astronomical specifications. In this paper we give a full account of the instrument: a general description is given in § 2, important points on the optical design are presented in § 3, the mechanical layout is described in § 4 and the electronic control and user interface are discussed in § 5.

2. GENERAL DESCRIPTION

RUCA was designed to comply with the main capabilities required by astronomical imaging projects: polarimetry, different plate scales, and handling of a large set of filters. This is accomplished with a wheel for polarizers, a sliding bench for focal reducers and an interchangeable wheel for filters. A precise rotating flange was also required to orient the camera at any angle between the EW and NS axes. In Figure 1 we present a sketch of RUCA and its location in the telescope with respect to other instruments. An important demand on the mechanical design was to provide an instrument as compact as possible in order to minimize flexures as well as the optical path to the camera in order to have no problem with the existing guiding systems, which are located between the telescope flange and RUCA.

The polarizer's wheel is fixed and it contains 5 spaces, one of them free. Polarizers are rotated some 45° with respect to each other. The 0° position is approximately aligned with the East-West (or North-South) axis of the telescope. The wheel for polarizers is located at the top of RUCA, i.e., closest to the telescope flange.

The sliding bench for the focal reducers is fixed and has three positions, one of them free. The free position is used for imaging without the focal reducer. The other two positions are occupied by focal reducers with nearly the same reduction factor but each designed for maximum efficiency at either the blue or red wavelength intervals. The focal reducers are installed just above the filter wheel and have a 1:1.6 reduction factor. Most filters at the OAN are designed for an f/7.5 converging beam. With this design the filters with the smallest bandwidth (~ 10 Å) can be used in any telescope at the OAN. Since the guiding systems are located between RUCA and the telescope flange, the guider camera must be moved further away to stay in focus when the focal reducer is in the optical path. In order to minimize the distance that the guider camera must be moved when the focal reducer is in, the sliding bench is installed as close as possible to the imaging camera.

The filter wheel has 8 available spaces, each for a filter inscribed in a 50 × 50 mm square, the maximum size of most filters at the OAN. These filters can be easily changed without dismounting the filter wheel. But the wheel is also interchangeable in order to use predefined sets of filters, such as the *UBVRI* or Strömgren series, or more than one user's filter wheel. Since vigneting is determined by the filter's free diameter, the filter wheel was positioned immediately above the imaging detector. Given the dependence of the filter's central wavelength on the incidence angle, internal flexures are minimal and parallelism is kept to the highest degree. Since the spectral response of interference filters is less sensitive to ambient conditions, no thermal or humidity control was installed. Filters were designed for a 0°C operating temperature. Night temperatures at the OAN typically range from −10 to +10°C. Thus, central wavelength shifts are not larger than ± 2.5 Å, small enough to include any line within the filter's transmission curve.

The user interface was designed as simple as possible to minimize the learning curve. Two versions of the user interface were developed: an ad-hoc program that runs under WINDOWS and an HTML page accessible with any standard web browser. The user can easily move from one interface to the other since their appearence is very similar. Both programs were designed in order to be compatible with

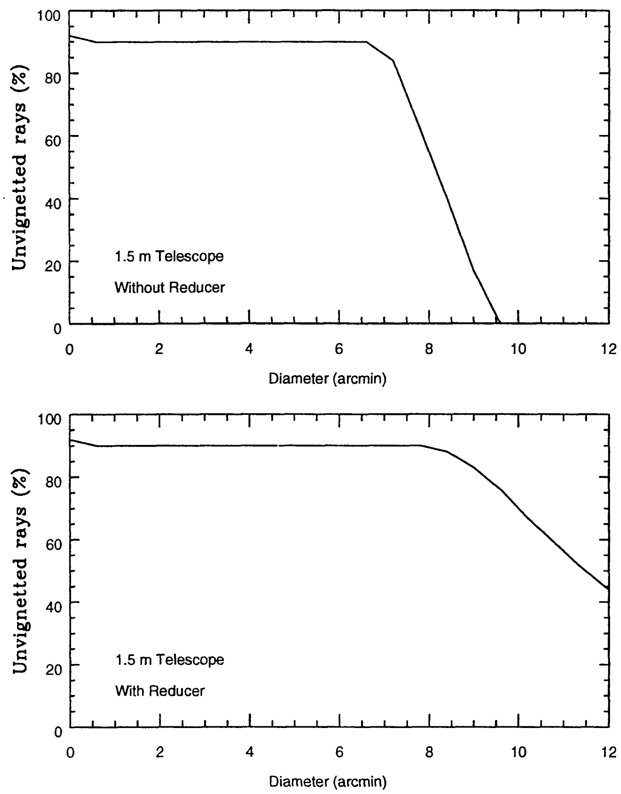

Fig. 2. Vigneting on the 1.5 meter telescope.

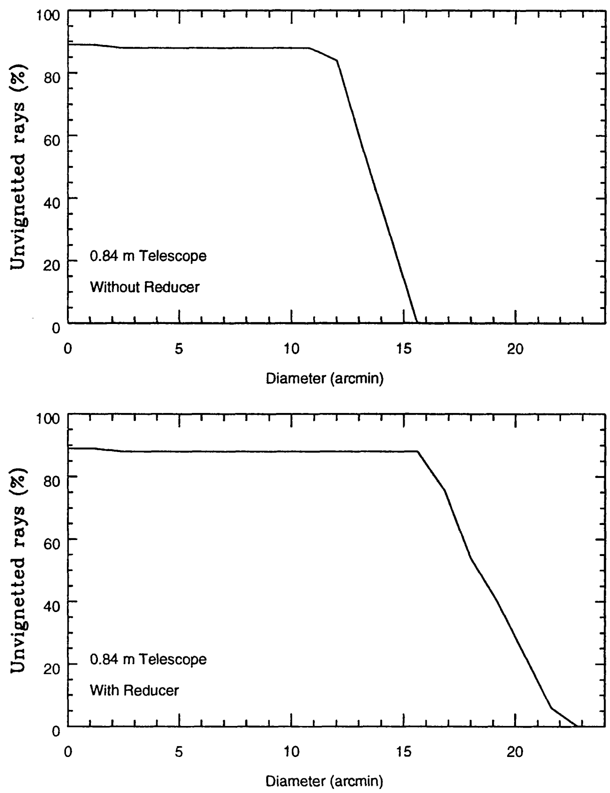

Fig. 3. Vigneting on the 84 cm telescope.

other user interfaces at the OAN (consoles, guiders, CCD's, etc.). The user's computer is connected to the control computer through an RS232 port or through an ethernet adapter card. The control program receives commands from (and sends messages to) either port. The control computer is attached to the instrument, and the electronics main requirement is that the motions of all devices (wheels, sliding bench, and flange) should be fast and repetitible.

Thus, though the instrument is conceptually simple, the requested specifications demanded the highest quality in design and construction.

3. OPTICS

3.1. *Vigneting*

Vigneting is caused by the filter's free diameter, 46 mm for the smallest filters, which are located 70.5 mm above the detector. Vigneting diagrams with and without focal reducer for the 1.5 and 0.84 m telescopes are presented in Figures 2 and 3, respectively. At the 0.84 m telescope the unvigneted field without the focal reducer is 10.5′, 14.9′ with it. These numbers are 6.6′ and 8.4′ at the 1.5 m telescope.

3.2. *Polarizers*

The four polarizing filters are commercial (Prinz). Each is 2 mm thick and has a 62 mm free diameter. According to the manufacturer, their transmittance between 4000 and 11,000 Å is 40%, and is zero elsewhere. The orientation angle in each polarizer is fixed, with increments of $45° \pm 3°$ between each in order to cover the four principal angles. A polarization map of the Crab nebula seen through a 72 Å wide filter centered at 6564 Å is shown in Figure 4. The polarization map overlays an image of the Crab nebula taken with the same filter but with no polarizer. All images were taken at the 1.5 m telescope without the focal reducer, using a Tektronix TK1024AB CCD chip. The field of view is 292 × 292 arcsec. The map was not calibrated, and instrumental polarization can be observed at the edges of the image. Nevertheless, the polarization structure of the Crab is faithfully reproduced (see Conway, 1971 for a comparison).

3.3. *Focal Reducers*

Two focal reducers, both with a 1:1.6 reduction factor, were designed with the ZEMAX development

Fig. 4. Polarization map of the Crab nebula taken with a 72 Å filter centered at 6564 Å. The underlying image is the unpolarized light at this wavelength. Images were taken at the 1.5 m telescope with a Tektronix TK1024AB CCD chip. North is to the top and east is to the right, and the field of view is 292 × 292 arcsec.

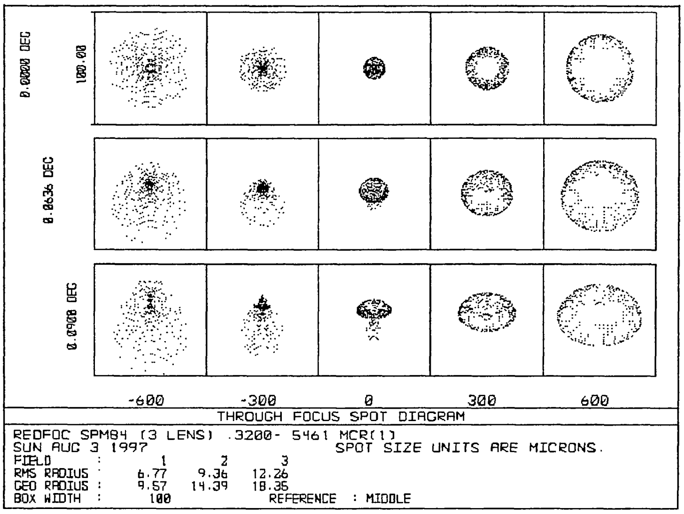

Fig. 5. Spot diagrams for the blue reducer at 4861 Å.

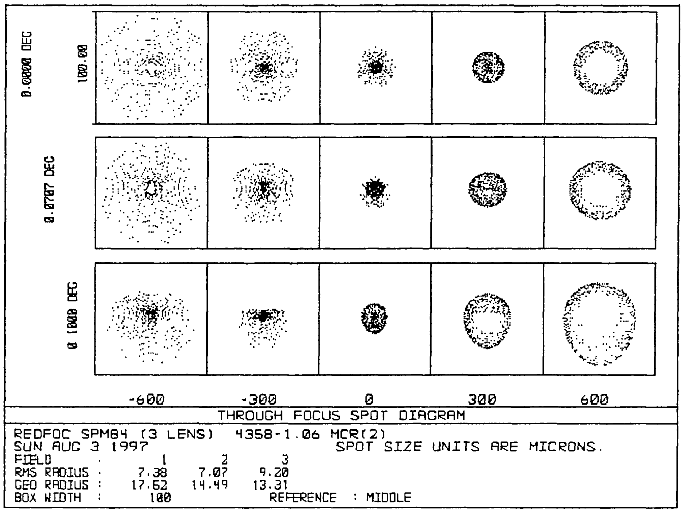

Fig. 6. Spot diagrams for the red reducer at 6563 Å.

package to get the best image quality for the spectral ranges 3200–5470 Å and 4360–10600 Å. Data on the layout for both reducers is presented in Table 1.

Through focus spot diagrams are presented in Figures 5 (blue reducer) and 6 (red reducer), taken at 4861 and 6563 Å, respectively (Hβ and Hα). As can be seen, 5.5$'$ away from the optical axis the focused image is within a 50 μm box, 2–3 pixels in a typical CCD detector.

The optical surfaces were polished at the Centro de Investigación Científica y Estudios Superiores de Ensenada (CICESE) and the optical shop at the Instituto de Astronomía (UNAM). Lenses were coated at the Centro de Ciencias de la Materia Condensada (UNAM, Ensenada B. C., México) and the Centro de Investigaciones en Óptica (León Gto., México). Three coatings were applied to the BaK2 glass of the blue reducer (MgF2, ZnS, and SiO), and four on the SF2 and K7 glass of the red reducer (MgF2, Y2O3, SiO and, again, MgF2). These coatings normally produce transmissions better than 98% over their respective wavelength intervals. NOA 63 optical adhesive was used to cement the lenses. Errors resulting from polishing, centering, and coupling of both triplets are within the design tolerances. Transmisson curves for the assembled lenses are presented

TABLE 1

DESIGN PARAMETERS OF FOCAL REDUCERS

Surface	Glass	Width (mm)	R_c^a (mm)	Type
Blue				
1	BaK2	4.0	300.0	Convex
2	FK5	16.0	68.8	Convex
3	BaK2	4.0	68.8	Concave
4	...	...	204.0	Convex
Red				
1	SF2	4.0	118.5	Convex
2	FK5	4.0	65.1	Convex
3	K7	14.0	41.4	Convex
4	...	...	461.6	Concave

[a] R_c is the radius of curvature.

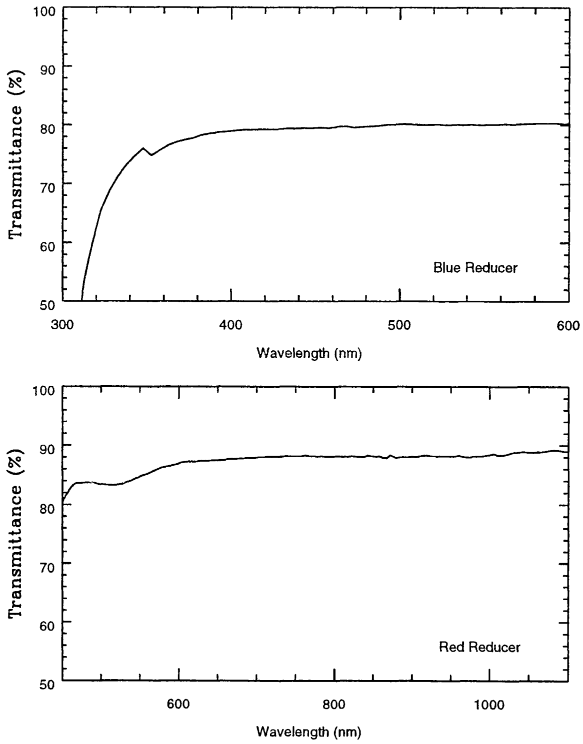

Fig. 7. Transmission curves for the blue and red reducer.

in Figure 7. As can be seen, transmission is quite uniform over the wavelength range. In the blue reducer it drops sharply at $\lambda \leq 3400$ Å, but beyond this point it is fairly constant, increasing no more than 5% towards the red end. Transmission in the red reducer is also very uniform, and is $\sim 5\%$ larger at the longest wavelengths. Bear in mind that the real transmission values are larger, since the incoming beam of light from the instrument used to measure transmission spreads out after crossing the focal reducer. Conservatively, real total transmission values are probably around the 95% level. Images of the Crab nebula with and without focal reducer are presented in Figure 8. These were taken at the 84 cm telescope using a Thuan-Gunn G filter and a Tektronix TK1024AB CCD chip. The field of view with the focal reducer is 692×692 arcsec. It must be pointed out that the lenses of the focal reducer were not cemented when these images were taken. Even so we did not find any evidence of ghosts in the images, as expected since the lenses have antireflection coatings.

4. MECHANICAL LAYOUT

The principal dimensions of RUCA are given in Table 2. Front and lateral layouts of the instrument are shown in Figures 9 and 10, respectively.

The support system and the internal parts were built with aluminum. Acetal delring was used for the polarizer and filter wheel gears. The bench for the optical reducers slides in a couple of linear motion guides. In order to support the CCD camera without introducing any flexure and ware, steel was employed for the rotating flange and gray casting for its gear. From 0° to 60°, the differential displacement along the optical axis is not larger than 96 μm, and is mainly produced by flexure from the circular plates at both ends of the instrument. To stay in focus the secondary would have to move 1/44 and 1/24 times this distance in the 1.5 and 0.84 meter telescopes, i.e., flexures in this direction do not affect the telescope focus. The maximum deflection of the wheel from the optical axis is ~ 30 nanometers (considering it as a cantilever circular beam). These values are only for the structure, and do not include motions between mechanisms and joints. Displacements in the flange should be negligible, since an electromagnetic brake specified for a torque well in excess of the maximum possible value firmly secures the position angle. Tests in the 1.5 meter telescope have shown that deflection from the optical axis, which is due to many other mechanisms besides RUCA, is less than 100 μm (corresponding to $\sim 1''$ in this telescope) for a series of exposures in the same field lasting some

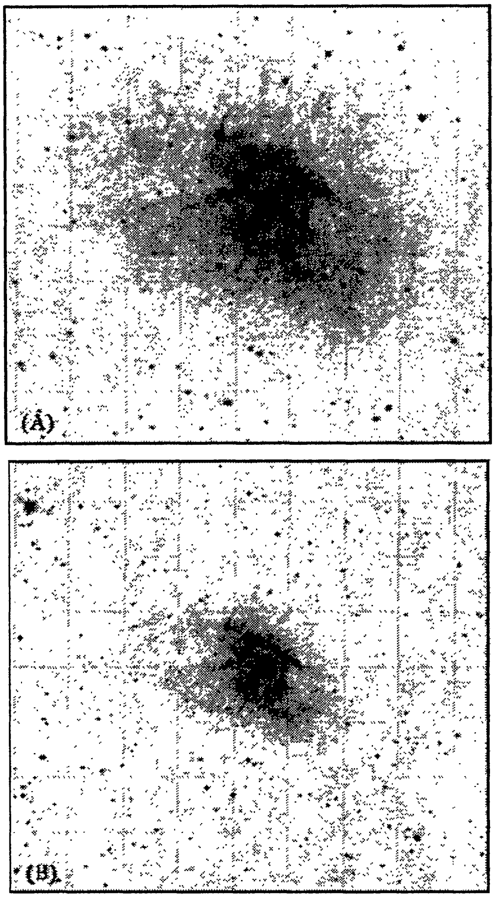

Fig. 8. Image of the Crab nebula taken at the 84 cm telescope using a Thuan-Gunn G filter and a Tektronix TK1024AB CCD chip, with the focal reducer (B) and without it (A). The field of view with the focal reducer is 692 × 692 arcsec. North is to the top and east is to the right.

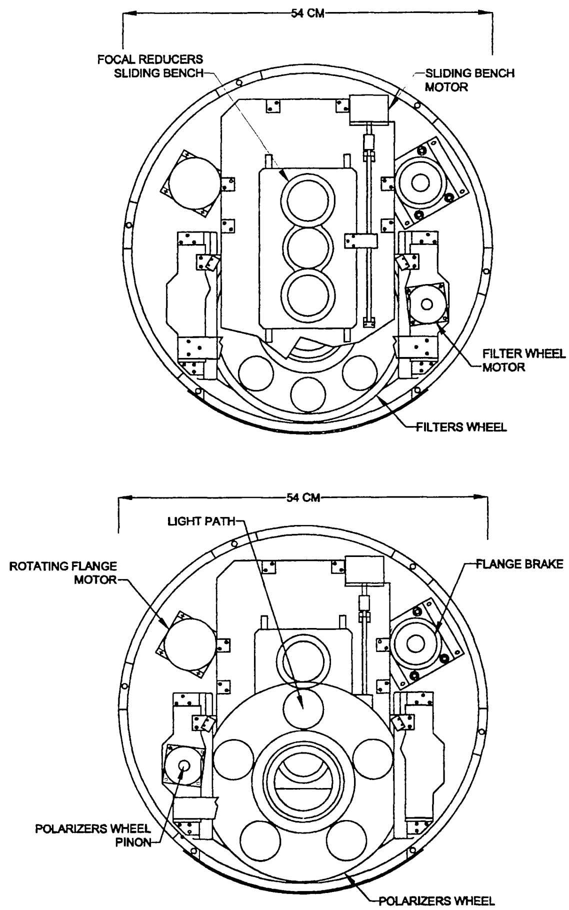

Fig. 9. Front view of the mechanical layout.

4 hours in total. This number is similar to the best image quality in this telescope. Furthermore, since individual exposures usually take less than 20 minutes, it follows that flexures will not produce a significant image distortion. Parallelism is kept within 0.6° for polarizers and filters. For an f/7.5 converging beam, this implies that the central wavelength shift for the interference filters will be smaller than 3.5×10^{-4} CWL, where CWL is the filter's nominal central wavelength.

5. ELECTRONICS, CONTROL PROGRAM AND USER INTERFACE

5.1. *Electronics*

The control electronics consists of an embedded IBM-PC compatible computer and the proper interface to drive the position loops of RUCA. The PC architecture was chosen because of the great support in software packages, many of them readily available in house. The interface card is connected through the secondary IDE port of the PC, which was available since there is no need for a second hard disk drive in this embedded design. Besides price, this port is a very good option because the glue logic required to connect to it is minimal.

The control software, the proper interface card to drive the motors and the user inteface programs were designed and built in house (Zazueta et al. 1997). There are two kinds of motors in RUCA: the filter and polarizer wheels and the focal reducer bench are moved by stepper motors under software control, whereas the rotating flange is moved by means of a direct current (DC) motor. There are two types of stepper motor drivers in RUCA. For the wheels there is an interface driving the motor

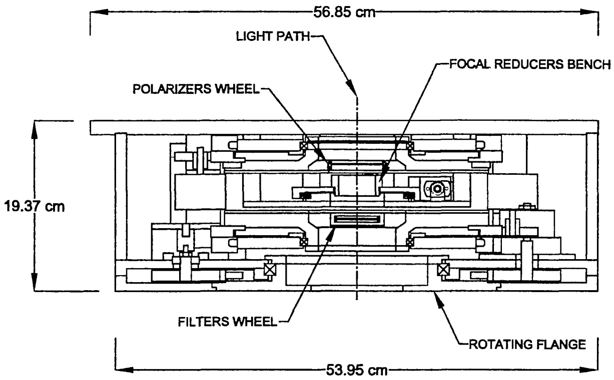

Fig. 10. Lateral view of the mechanical layout.

TABLE 2

PRINCIPAL DIMENSIONS

Weight:	51.8 Kg
Computer's weight:	15.5 Kg
Total diameter:	596.4 mm
Total thickness:	192.1 mm
Upper base to polarizer:	48.9 mm
Polarizer to reducer:	13.0 mm
Reducer to filter:	48.3 mm
Filter to flange:	81.9 mm
Polarizer free diameter:	62 mm
Reducer free diameter:	60 mm
Filter free diameter:	46 mm
Flange hole diameter:	127 mm
Spaces for polarizers:	5
Spaces for reducers:	3
Spaces for filters:	8

phases directly through software. The control program is responsible for the sequence generation to move the motor. The other drive is for the focal reducer bench. It operates through an interface card that accepts pulse and direction. The card generates the sequence that moves the stepper motor. It was designed and implemented in house with a PLD (programable logic device). Power switches in both cases are power transistors.

During power up every motor of RUCA finds its home position or zero. The "in position" signals are generated by microswitches. There are two switches for each of the wheels of filters and polarizers, a "zero position" switch and a filter or polarizer "in position" switch. The repeatability of the switches is very high. However, the maximum position resolution for the filters and polarizers is limited by the stepper motors, which tend to have a preferred position. This limit is 920 μm. Tests have shown that flat fields are accurate at the 5–10% level in the 20×20 mm central region. Distortions due to dust specks were effectively removed. But we found that differences in illumination are significant outside this region. This limitation is being addressed.

The rotating flange required very good precision and high torque. Facing constraints in weight and space, a DC motor with optical encoder feedback was selected. Thanks to a mechanical reduction, the movement resolution is $0.045°$ with a 500 pulses per revolution optical encoder. This motor is controlled by a digital PID filter implemented with an LM628 interface card. The control program contains commands to change the tunning of the PID loop. This is needed to compensate for load changes.

5.2. *Control Program*

The control program was written in C++ with the GNU C++ compiler (version egcs-1.2) running under Linux. It was designed following an object oriented approach. Software drivers for the different types of motors were implemented. The program runs under Linux (kernel 2.0.36). The operating system and the control program are installed in a 4 megabytes IDE-FLASHDISK that occupies the principal IDE port of the control computer.

Commands are indistinctively received from the keyboard, the RS232 port (COM1) of the embedded PC or through the ethernet interface via TCP/IP sockets. Commands are in natural language. For instance, 'FILTRO = 0' will move the filter wheel to position zero. For a complete description of commands see Zazueta et al. (1997).

The program consists of several threads of execution each assigned to a different task. The main tasks are: monitoring the user input and motion control actions. If a valid command is encountered, it is transfered to the command processor which executes the proper function and is immediately ready to receive the next command.

The program is implemented as several threads of execution thanks to Linux multitasking capabilities. The design of the control program follows the object oriented approach, every object in each thread has an "idle" function that is called every 10 milliseconds. There are objects for each motor, for keyboard input, for serial communications input and for the ethernet interface which handles the internet connection. With this approach several motors can be moved simultaneously without interrupting the reception of user commands or state messages from any device.

5.3. *User Interface*

The interface is installed in the user computer at the observing room. As it was mentioned two versions of the user interface program were developed. The first works under WINDOWS, and was developed in C++ using the Symantec V7.2 compiler and the Zinc Application Framework V4.0 graphical design package. User's messages are delivered to and received from the control computer through an RS232 port. There may be an intermediate computer in charge of distributing messages between the user and various devices (RUCA, guider, console, etc.). The user can easily edit and load the names of the filters that have been placed in the wheel. An on-line help is provided, and an extensive description of the user interface can be found in Zazueta & Bohigas (1997).

The second user interface is through an HTML homepage. It can be accessed with any standard web browser with frames capability. Any computer with internet access can view the RUCA homepage but control actions, such as changing filters or rotating the flange, can only come from some computers connected in the OAN network due to security and operational reasons. User actions are transformed in RUCA commands through HTML forms and a CGI (common gateway interface) program running in a web server computer. This computer then routes the user actions via the ethernet connection to the control computer of RUCA. We are using the Apache web server for Linux to handle the internet connections.

Assistance from J. Dávalos (CICESE), J. Nieto and R. Machorro (Centro de Ciencias de la Materia Condensada, UNAM), F. Pérez and S. Monrroy (Instituto de Astronomía, UNAM) is gratefully acknowledged. Several important points were included thanks to perceptive comments by the referee.

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J. Bohigas, A. Córdova, B. García, V. García, V. García Gradilla, O. Harris, E. Luna, J. L. Ochoa, J. Palomares, M. Pedrayes, J. Valdez, and S. Zazueta: Instituto de Astronomía, Observatorio Astronómico Nacional, UNAM, Apartado Postal 877, 22830 Ensenada, B. C., México (chava@astrosen.unam.mx).

F. Cobos and C. Tejada: Instituto de Astronomía, UNAM, Apartado Postal 70-264, 04510 México, D. F., México (cobos@astroscu.unam.mx).