ARNICA: the Arcetri Observatory NICMOS 3 imaging camera

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ABSTRACT

ARNICA (ARcetri Near Infrared CAmera) is the imaging camera for the near infrared bands between 1.0 and 2.5 μm that Arcetri Observatory has designed and built as a general facility for the TIRGO telescope (1.5 m diameter, f/20) located at Gornergrat (Switzerland). The scale is 1″ per pixel, with sky coverage of more than $4' \times 4'$ on the NICMOS 3 (256×256 pixels, 40 μm side) detector array. The optical path is compact enough to be enclosed in a 25.4 cm diameter dewar; the working temperature is 76 K. The camera is remotely controlled by a 486 PC, connected to the array control electronics via a fiber–optics link. A C–language package, running under MS–DOS on the 486 PC, acquires and stores the frames, and controls the timing of the array. We give an estimate of performance, in terms of sensitivity with an assigned observing time, along with some details on the main parameters of the NICMOS 3 detector.

1. INTRODUCTION

Infrared array technology has evolved very rapidly during the last few years. At present, good quality array detectors in formats as large as 256×256 pixels are available for astronomical observations in the spectral range 0.9–2.5 μm (HgTeCd technology). It may be useful to discuss briefly the meaning of the "quality" of an array detector for infrared astronomy. For ground–based astronomy, the overall quality of an infrared array must be established both in term of sensitivity, through a direct comparison to the level of background flux impinging on each pixel and the associated statistical fluctuations, and in terms of photometric accuracy, that is the precision and the repeatability obtained in measurements of the flux of astronomical sources.
Infrared detectors attain the limiting sensitivity when they work at background–limiting performance (BLIP), that is the signal–to–noise ratio of the measurement is limited only by the statistical fluctuation of the background flux. In other words, the physical parameters of the array detector (such as dark current with its associated fluctuations and read–out noise) are not the limiting factors[1]. Another parameter is of outstanding importance for good astronomical work, that is the stability of response over time. This parameter establishes how often a reference frame is required for flat fielding (or, in other words, for calibrating the pixel–to–pixel response). Since most astronomical sources are orders of magnitude fainter than the background, the data reduction process of flat fielding is absolutely necessary[2].
In practice, the flatness of the processed image, regardless of the total exposure time, determines the ultimate sensitivity of the observations. Consequently, the capability of obtaining the detection of very faint astronomical sources with an IR detector is strictly connected to the temporal stability of the pixel–to–pixel response of the array detector itself during the time between two reference exposures.
In contrast, the parameters of interest for photometric accuracy are many and somewhat elusive. We can cite the intrinsic non–linearity of direct read–out in hybrid IR detectors[2], the variation of dark current over time, the differences in colors sensitivity across the array, and imperfect optics, all of which affect the performance of the system.
In Sect. 6, we describe the performance of the ARNICA NICMOS 3 array detector; to date, we have a fairly accurate estimate of the sensitivity limits of the camera, while a similar analysis for photometric accuracy is under way.
The ARNICA project started in 1990, when we decided to design an imaging camera based on the Rockwell HgTeCd array detector NICMOS 2 with a 128×128 pixels format (60 μm pixel size). A short time after, Rockwell announced the 256×256 NICMOS 3 (40 μm pixel size) so that the original opto–mechanical design was modified to house the larger array in the dewar. We decided to adopt the final scale of 1.0 arcsec per pixel, taking into account the

diameter of the seeing disk typically measured at TIRGO and the interest of many Italian astronomers for extra–galactic research. While our main interest was in broad and narrow band imaging of fields as large as 4x4 arcmin, we incorporated into the project the possibility of using the camera as a long slit spectrometer, based on grisms, with low or moderate resolving power.
The project is the result of a collaboration of the Arcetri Observatory with the Department of Astronomy of the University of Florence and the National Research Council of Italy (CNR–CAISMI). The final design was completed at the end of 1990; the first functional and observational tests have been performed at the TIRGO telescope in November and December, 1992.

2. OPTICS AND MECHANICAL DESIGN

2.1 Optics

We conceived the optical design with the following constraints as a guideline:

1. Limited total physical volume, so that the optical train could be lodged in a commercial dewar;
2. Image scale of 1 arcsec per pixel at the TIRGO telescope, giving a corrected field of view of more than 4x4 arcmin;
3. Good quality images in the range 0.9–2.5 μm, by providing also a partial correction for the off–axis aberrations of the telescope, and imposing an overall simplicity of the optical train for maximizing the total throughput;
4. Focal plane inside the dewar in order to house the cold field stop or spectroscopic slit at cryogenic temperatures, to provide good shielding from off–axis sources of light without adding radiating flux from warm surfaces.
5. Provision for a cold, aberration–free image of the entrance pupil of the telescope. The latter helps to further screen out stray light, by simply inserting a cold stop. As a further benefit, it offers a suitable plane for inserting a grism into the optical beam, enabling the operation of the camera as a long slit spectrometer.

We chose to base the optical design entirely on lenses instead of mirrors or a combination of lenses and mirrors. Besides the obvious disadvantage of having to control the chromatic aberrations, lenses are less sensitive to misalignment (a useful property in cryogenic optics) and, most important, they offer a good chance of screening out most of the stray light inside the dewar by means of suitable cold baffles.
The optical scheme of ARNICA is sketched in Fig. 1; it responds fairly well to the requirements we listed above. A set of four lenses accepts the image of the f/20, 1.5 m Cassegrain TIRGO telescope and transfers it onto the detector, while modifying the plate scale and creating an image of the entrance pupil.

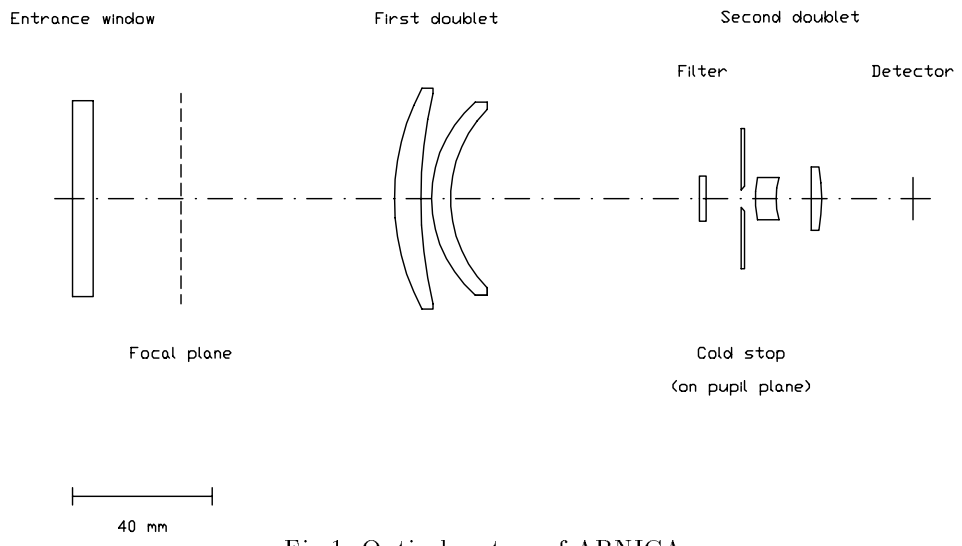

Fig.1. Optical system of ARNICA

After the calcium fluoride entrance window (about 70 mm diameter), the cold stop, mounted onto a three–position slide, defines the field of view at the Cassegrain focus of the telescope. In addition to the field stop, the slide, which is manually operable and in close thermal contact with the radiation shield, holds the slit for spectroscopy and a

shutter which is used to completely blind the detector. The first two lenses, a detached doublet made of fused silica and zinc sulfide for achromatization, create an image of the telescope entrance pupil about 5 mm in diameter. The second lens of the doublet has an aspheric surface, while the other optical surfaces are plane or spherical. The cold pupil stop is placed at the pupil plane where the beam is nearly collimated; just before this plane there is the filter which defines the wavelength range. The last two lenses, a detached doublet made of zinc sulfide plus fused silica, relays the image of the field onto the detector, and modifies the plate scale from 6.8 arcsec/mm to 25.0 arcsec/mm. The total size of the optical train is such that it can be mounted on a cold plate with a diameter of 25 cm. The lenses are coated with an anti–reflection coating which gives a reflectivity less than 2% on each optical surface in the whole wavelength range 0.9–2.5 μm. This allows for an optical efficiency of more than 80% from window and lenses alone, not considering the transmission of filters.
The performance of the optics is such that, with a small refocusing when filters are changed, the total encircled energy is more than 80% on pixels within a circle of 4 arcmin diameter and more than 70% on pixels at the vertices of the field of view.
The filter wheel can hold a total of eight 1–inch filters in the current implementation; besides the standard set of astronomical filters for the J, H, K bands, presently mounted are four narrow–band filters for collecting images in selected spectral lines (FeII, HeI, H_2 and Brγ).
Following a suggestion of E. Oliva[3], after the final optical design, we verified the possibility of inserting a grism into the nearly–collimated beam of the camera. While the full theoretical resolving power is not achievable since the optics are not optimized for this use, a suitable set of grisms makes it possible to reach a resolving power of about 100–150. This should permit the use of ARNICA as a long–slit spectrometer with low resolving power. Particularly attractive is the fact that each J, H, K band could be covered with a single grism. The latter mode of operation will be implemented in the future.

2.2 Mechanics

The mechanical design of ARNICA has been developed taking into account the requirements of the NICMOS 3 array and the associated optics; in particular, while the detector could be cooled down to about 50 K, its low dark current (less than 1 electron per second at 76 K, see Sect. 5) necessitates a very low level of stray light inside the dewar. To this end, the design presents careful positioning of cold baffles and stops. In particular, each doublet is completely enclosed in a light–tight pipe, and the filter wheel is mounted inside a box. The inner surfaces of the pipes and of the filter box are sand–blasted and blackened. The supports of the optics are in close thermal contact with the cold plate.
In order to simplify the mechanics, a standard Infrared Laboratories HD–3(10) dewar was selected. Cooling is provided by means of liquid nitrogen contained in two vessels. The first vessel cools the radiation shield, while the second vessel is in close thermal contact with the optics and the detector support; it can be pumped if needed. The working temperature could be as low as 50 K. A closed–loop control allows for fine tuning of the temperature of the NICMOS 3 detector, through the connection to the cold bath, with a suitable thermal conductance and a heater. The filter wheel is controlled by a stepper motor, mounted outside the dewar and mechanically coupled by means of a vacuum–tight ferrofluidic feedthrough.
A space frame mechanical interface links ARNICA to the TIRGO telescope, allowing an easy alignment with the optical axis of the telescope.

3. ELECTRONICS

Electronics for ARNICA includes a set of subsystems, at the core of which is the IRL System 2, which Infrared Laboratories developed for the specific use of driving NICMOS 3 array detectors. Two different boards, the clock driver and the four preamplifiers for the array analog outputs of the four quadrants, are housed inside the dewar just behind the vacuum shield. External to the dewar, there is the box which contains the main electronics, that is the amplifiers and the A/D converters for the four output signals from the array, the sequence memory which generates the proper timing clocks and a logic for converting the 16–bit parallel data from the array to a serial format. A suitable transceiver sends data to a second electronics box in the control room, through a fiber optics link. The resident firmware, running on the 65C02 microprocessor, supervises and synchronizes the different tasks. The electronics in the dome is completed by the box which contains the power supply, the stepper motor control, and the temperature controller of the array detector.

The last electronics box is in the control room; it contains the logic to decode the serial data protocol, in order to correctly reconstruct the frame coming from the array detector. The fiber optics link is bidirectional, in the sense that it is possible to send instructions to the control microprocessor in the dewar electronics and to control the stepper motor indexer–driver. The output of the electronics consists of 16–bit parallel data, along with some control signals. These data are presented to the custom interface board inside the control PC, which stores one or more full frames in a buffer memory before sending it to the memory of the PC. At the end, each single frame or the stack average of a group of frame are stored on disk. The control computer is a Gateway 2000 PC equipped with a 80486 CPU (33 MHz clock), high–resolution monitor, and a 220 Mb hard disk.

4. SOFTWARE

The control software of ARNICA comprises a full set of procedures that are arranged in several hierarchical layers of differing complexity[4]. The observer has access to the simplest layer, the user interface, which prompts users in order to acquire information about the current measurement (e. g. observer name and source name) and permits the setting of the details of the measurements, such as integration time, number of exposures in a group and so on. All information is printed in the header of the FITS file which stores the image generated at the end of each group of measurements.
The control software allows for the display of acquired images; moreover, a rough data reduction procedure is implemented for the purpose of a quick look at the data. It is also possible to instruct the telescope to move sequentially to a set of different positions after each single group of measurements, by extracting the relative pointing coordinates from a text file. This allows for an automated sequence of measurements, which is very useful both for a rapid acquisition of the source frames and the frames used for flat–fielding, and for producing mosaics of extended sources.

5. NICMOS 3 PERFORMANCE

The main parameters of the NICMOS 3 array detector presently installed on ARNICA are summarized in Table 1. As a general remark, the signal–to–noise ratio of the images taken with broad–band filters is limited by the background fluctuations, when the sky+telescope flux is much lower than the flux from the source.

Table 1. NICMOS 3 array detector performance

Format	256×256
Bad pixel	0.5%
Peak quantum efficiency (2.2 μm)	≈ 0.6
Well capacity	2.0×10^5 e
Dark current (76 K)	0.5 e s^{-1}
Read noise	40 e

Some notes on Table 1 are worthwhile. The count of bad pixels includes, besides the trivial case of hot pixels or zero–response pixels, a few variable pixels which deviate wildly, but sporadically, from neighboring pixels and are thus not usable for accurate measurements.
The peak efficiency of the array detector is just an estimate; we have measured the total efficiency, which comprises atmosphere transmission, telescope mirror efficiency, and other factors external to the camera, from which we derived the above figures, but at present we have no direct measurement of the efficiency of the detector itself.
The well capacity we quote is not determined by the onset of full saturation; instead, we quote in Table 1 the level at which the non–linearity becomes important, that is larger than about 5%.

Dark current was determined by long exposures, with the detector looking at the cold stop on the filter wheel and the field stop on the focal plane of the camera. The same frames were used for estimating the read–out noise, as the shot noise from the background is negligible. It is worthwhile to mention that, without exceptions, we read the array detector twice, first at the very beginning of the integration period, just after resetting the array, and then at the end of the integration time. The stored frame is the result of the subtraction of the former frame from the latter one.

6. SYSTEM PERFORMANCE

Assuming a source (extended or seeing–broadened point–like) with an intrinsic flux level per pixel much lower than the sky flux, the typical observing procedure consists of a group of exposures on the source itself, interleaved by exposures on blank sky. The sky exposures are conveniently shifted relative to the source position, and typically are taken on different non–overlapping positions. In case higher sensitivity is required, more source–sky exposures are repeated in order to obtain the appropriate total integration time on the source. The sky frames are combined with a stack median filter and a clipping algorithm to remove most field stars; this provides a reference frame for flat fielding. The process of read–out using double–sampling obviates the need for explicit subtraction of a bias frame. Also, at present we do not subtract dark current frames; the dark current level is very low and the associated fluctuations are negligible.
In Table 2 we list the parameters representing the performance of the camera ARNICA at TIRGO. We note that most of them are preliminary, in the sense that their values may be modified in the course of the completion of the data reduction process following the next test runs. Note also the variations of the background flux, which is observed on time scale of a few hours in the same night.

Table 2. Typical performance of ARNICA at TIRGO

	J	H	K
Background (e s^{-1}arcsec^{-2})	$0.7 - 1 \times 10^3$	$6 - 10 \times 10^3$	$2.5 - 6 \times 10^3$
Efficiency (e/photons)	0.08	0.20	0.20
Background (mag arcsec^{-2})	15–15.5	12–13	12.5–13.5
Limiting magnitude (arcsec^{-2}, 3σ, 60 s)	20.5–21	19.3–19.6	19.1–19.6
Limiting magnitude ($5''$ apert., 3σ, 60 s)	18.8–19.3	17.6–17.9	17.4–17.9

While most of the entries of Table 2 are self–explanatory, we comment briefly on the definitions of limiting magnitude. The limiting magnitude per square arcsecond assumes that all the flux from the source falls on a single pixel, as in the case of extended sources or the sky. The atmospheric turbulence has the effect of broadening the image of a point–like source, spreading the flux over a number of pixels. In this situation, the limiting magnitude is rescaled to take into account the dimension of the aperture where most of the flux is collected. In Table 2 we chose an aperture of 5 $''$ as representative of the dimension of the seeing disk at TIRGO; obviously, under this assumption, the sensitivity is strictly dependent on the seeing conditions at the moment of the observation.

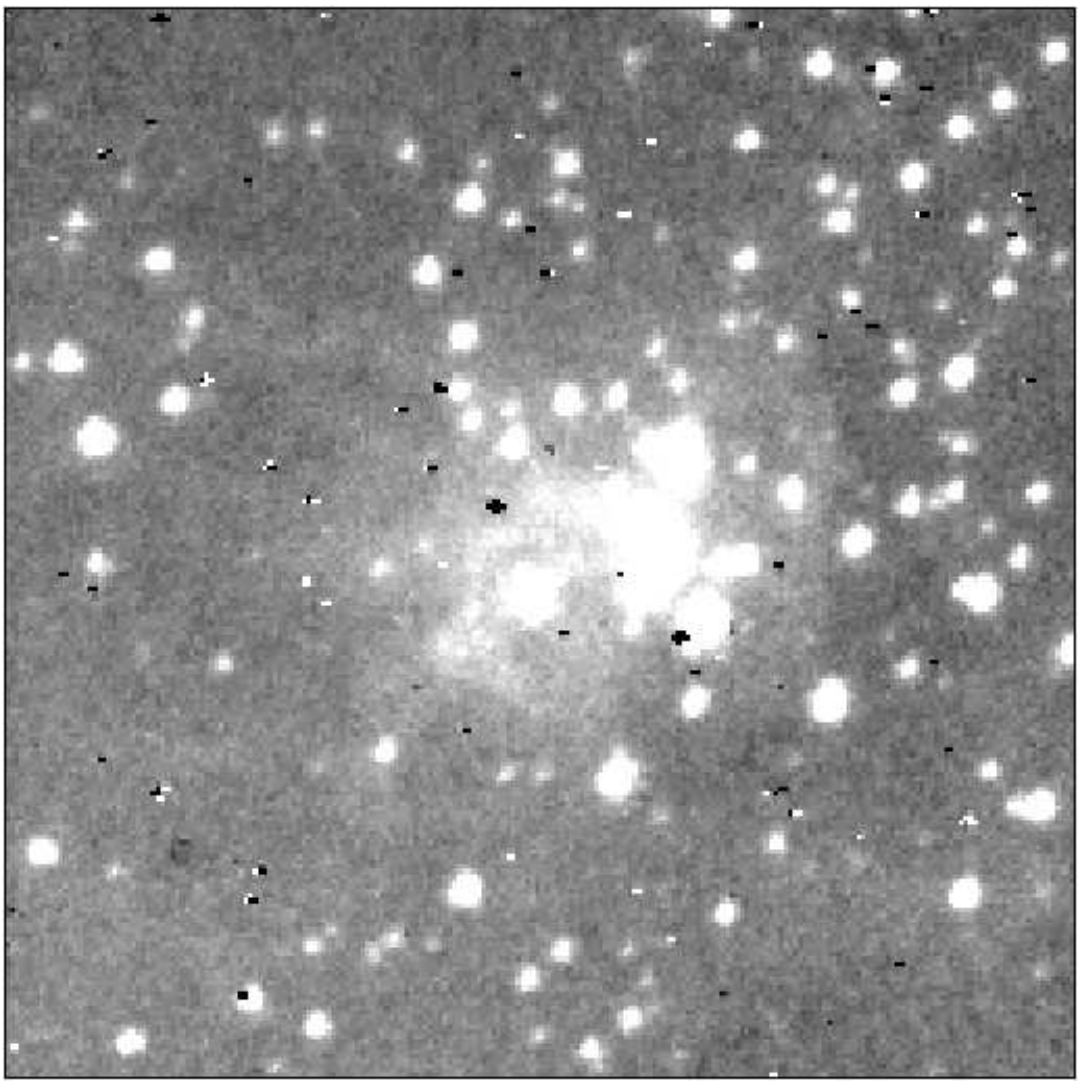

Fig.2. S 155–Cepheus B region (4 × 4 arcmin)

A first analysis of our data suggests that the flat–fielding process can be precise up to a level better than 8 parts in 10^4 with no special precautions. As a consequence, the limiting sensitivity is set by the total integration time also for very weak sources, when a suitable observing technique is used. To show the capability of ARNICA, in Fig. 2 we present the image of a portion of the S 155-Cepheus B region, 4x4 arcmin wide and centered on the IR source,

in the K band. The final image was obtained by coadding twenty frames, for a total integration time of 300 s; the same time was spent integrating on nearby sky.
We are exploring the possibility of obtaining accurate photometry with ARNICA; at present, it is possible to attain photometric measurements with an accuracy of $\approx 10\%$, which is enough for several observational programs. We are confident that it is possible to attain higher photometric precision and are presently addressing the issue.

7. ACKNOWLEDGMENTS

The ARNICA Project is the result of the joint efforts of many people at Arcetri Observatory; we would like to thank them for their collaboration. Moreover, at Infrared Laboratories we found friendly attention toward the particular requests we often made; this helped very much to speed up the completion of the instrument.

8. REFERENCES

1. F. C. Gillett,"Infrared arrays for ground–based astronomy", Infrared Astronomy with Arrays, ed. C. G. Wynn–Williams and E. E. Becklin, pp. 3–12, University of Hawaii at Hilo, 1987.

2. M. J. Mc Coughrean, PhD thesis, University of Edinburgh, 1988.

3. Oliva, E. (1991), Arcetri Observatory Technical Report n. 2/91.

4. Baffa, C. (1991), Arcetri Observatory Technical Report n. 11/91.