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PRECISION LIMITS OF THE TWIN-BEAM MULTIBAND 'URSULA' ADAPTIVE PHOTOMETER

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Abstract

URSULA is a multiband astronomical photoelectric photometer which minimizes the errors introduced by the presence of the atmosphere; it operates with two identical optical channels, one for the star to be measured and the other for a reference star. This renders the signal ratio independent of atmospheric transparency variations, thus eliminating the major source of error, essentially for bright stars. Scintillation error cannot be eliminated, unless the light beams are within the correlation radius of turbulence, so that light variations are in phase. Following this concept, four machines have been constructed for four Italian Astronomical Observatories in late '70s, among which that operating at the Catania Astrophysical Observatory stellar station (1720m asl) has been improved during the past years. The photometer has been used for measuring a wide field of astronomical variable phenomena. After a technical description of the

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present version of the apparatus, we present some measurements of stellar sources of different brightness, and in different atmospheric conditions, by using the 91 cm Cassegrain telescope of the Catania Astrophysical Observatory, to check the photometer accuracy and compare the latter with that of standard photometric techniques.

Introduction

In 1974, an italian technological group (URSA) discussed the possibility of designing a photometer for high accuracy multiband stellar observations.

The idea was of constructing a flexible instrument suitable for observations of a large variety of stellar phenomena without modifying the system hardware. Moreover the instrument was thought for minimizing errors caused by variations of atmospheric transmittance during the measurement times of the star and the reference star, thus eliminating the most important error source of ground based astronomical photoelectric photometry.

With these premises, the URSULA photometer has been designed with two optical channels, one for the star to be measured and the other for the reference star, for eliminating the atmospheric transmittance errors, and integrated to a computer for the control of all the operations. The only parts of the photometer not integrated to the computer were in fact the optical band multiplexers and the detectors with their discriminators and amplifiers.

Four instruments for the Catania, Milano, Napoli and Trieste Observatories were constructed and tested in laboratory through

1975-77, while the first astronomical observations were carried out in 1978. A detailed description of these instruments can be found in De Biase et al. [1978, 1980a,b].

The photometer installed at the Mount Etna stellar station of the Catania Astrophysical Observatory was subsequently improved.

In the following sections we shall describe the concept of this instrument, suggest possible implementations to improve its efficiency and give some example of use.

Astronomical photoelectric photometry error sources

The atmospheric effects are the most serious sources of accuracy lack for ground based astronomical photoelectric photometry [Young 1974]. These effects can be divided into two main classes:

- those deriving from the turbulent nature of the atmosphere which show stationary spectrum, ranging from a few tenths of Hz to a few hundreds Hz, and give rise to the well known phenomenon of stellar scintillation;
- those deriving from large scale inhomogeneities of the atmosphere not averaged by the telescope aperture which show non stationary spectrum, ranging from nearly zero to a few tenths of Hz, and give rise to variations of atmospheric transmittance, so affecting the mean value of the signal during the measurement time.

Besides these two temporal effects, the atmosphere introduces an extra spatial effect called seeing. The effect of seeing on extra atmospheric point sources is to spread the luminous energy over an area much larger than the diffraction pattern. Therefore a larger diaphagram in the center of which the stellar image is formed must be used, so allowing a sizeable fraction of sky background to be collected together with the signal, with the consequence that the signal to noise ratio is lowered. These atmospheric effects are essentially important for bright star measurements, since they alone determine the accuracy that can be achieved in a photometric measurement. For faint stars, photon noise and photomultiplier dark current noise become also important.

The expression for the total relative error of a ground based astronomical photoelectric measurement is thus given by:

$$RE = \left(\sum \varrho^2_{s,b} + \sum \varrho^2_{r,b}\right)^{1/2} + \delta_{s,b} + \delta_{r,b} + \delta_{s,r} \qquad (1)$$

where the suffixes s,r and b refer to the source, reference source and background respectively, ϱ represents statistical photodetection (signal and background) and scintillation errors, and δ the errors caused by atmospheric transmittance variations.

The importance of the above errors depends on the photometric operation mode.

The standard single detector single beam technique is based on separate subsequent measurements of source plus background (S+Bs), source background (Bs), reference source plus background (R+Br), and reference background (Br). In this case all the terms of the expression (1) concurr to RE. This measurement procedure can be classified as 'fully serial mode'.

The optimum operation mode would consist in simultaneous measurements by four detectors of S+Bs, Bs, R+Br, Br. In this case only statistical intrinsic errors given by the ϱ terms in expression (1) are retained (scintillation error can be minimized only if source and reference source are observed within the turbulence correlation radius so as the light fluctuations are in phase); these decrease with the square root of the measurement time. Therefore the optimum photometric mode coincides with the 'fully parallel mode'.

The two detector twin-beam URSULA astronomical photometer uses an operation mode based on the simultaneous measurement of S+Bs and R+Br and a subsequent simultaneous measurement of Bs and Br. In such a way the most important δ error (δs,r) vanishes, because the variations of atmospheric transmittance equally affect both the source and reference source, and, unless measurements are made in dramatic sky conditions, the influence of trasmittance variation on background is a second order effect. Scintillation error can be minimized under the same constraint as before. We define this mode as 'parallel-serial mode'.

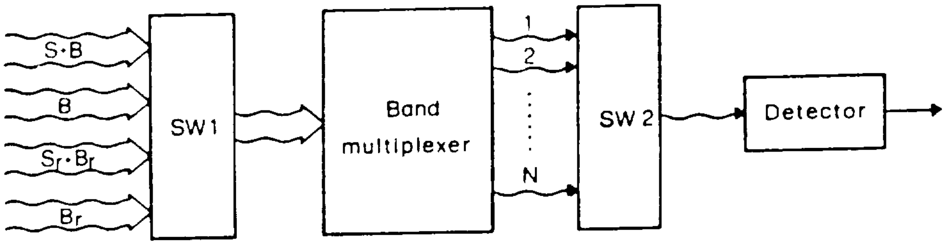

Fig.1 - Operation modes of a multiband photoelectric photometer.

In Fig.1 the general procedure schemes described above are summarized. The switch SW1 defines the operation mode, while the switch SW2 selects the optical bands to be measured. In Fig.2, the relative error is plotted as a function of the visual magnitude m_V (extra atmosphere) of the source for the fully parallel operation mode (curve 1), parallel-serial mode (curves 2,3) and fully serial mode (curves 4,5). All curves refer to a 1m diameter telescope with 2% scintillation, atmospheric transmittance $\tau = 0.8$, 10s measurements time and 0.1 efficiency; a reference source $m_V = 10$ has been used.

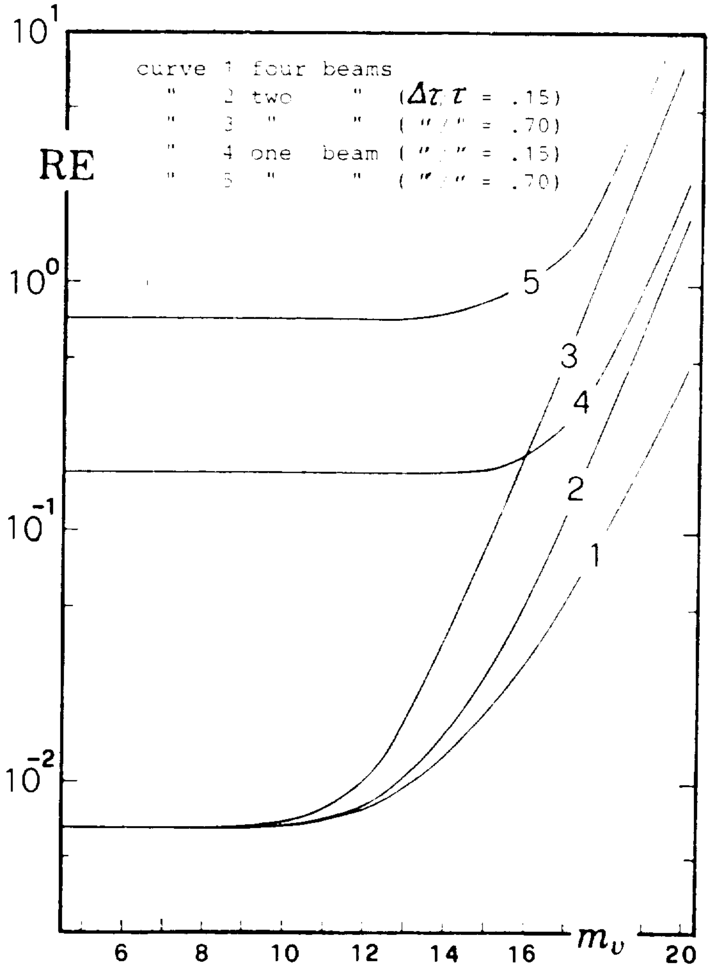

Fig.2. Relative error RE as a function of stellar magnitude for various operation modes and different atmospheric transmittance variations $\Delta\tau/\tau$

For a wide discussion on these curves see De Biase et al. [1978] and Belvedere and Paterno' [1976].

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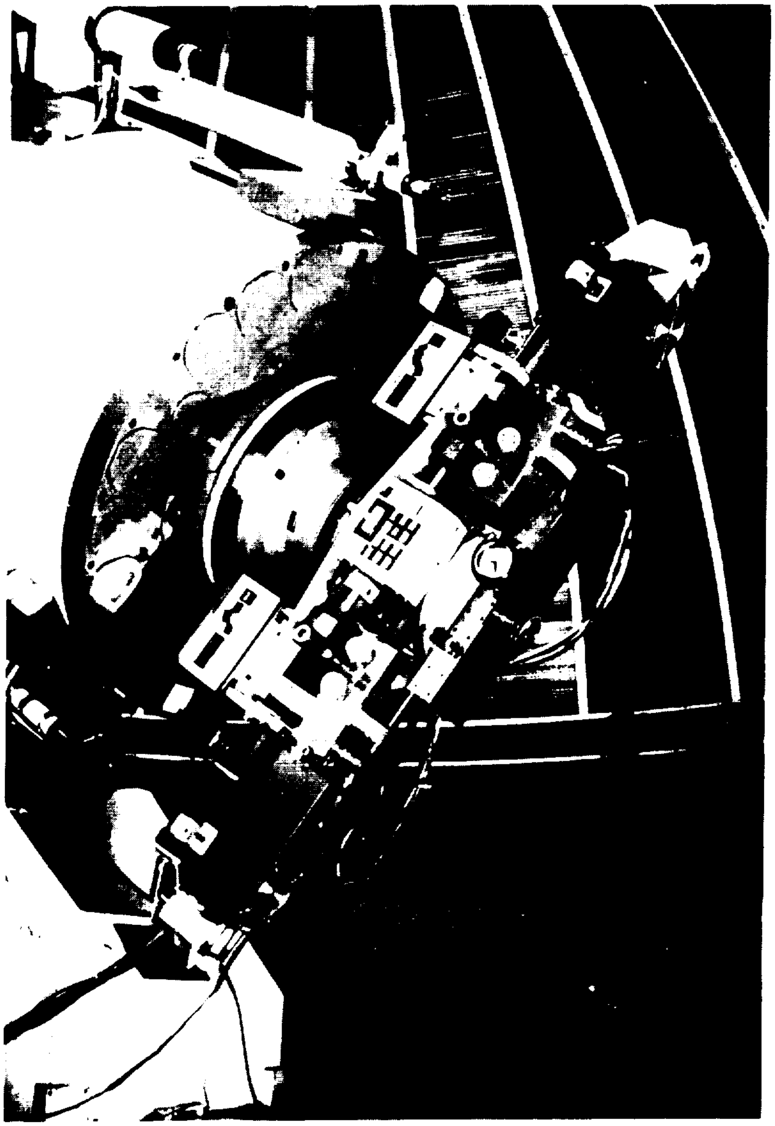

Fig.3. The URSULA photometer of the Catania Astrophysical Observatory working with the Cassegrain 91cm telescope

The Catania Observatory URSULA photometer

At the Mount Etna stellar station (1720m asl) of the Catania Astrophysical Observatory a URSULA two-channel photometer is operative since early '80s. The photometer is assembled on a 91 cm Cassegrain telescope and its overview picture is shown in Fig.3, while the optical and mechanical scheme is outlined in Fig.4. As it has been said, it consists of two identical measure channels (A and B) working by photon counting. On both channels two EMI 9658 R photomultipliers have been set up, cooled at about -20°C through Peltier cells; at this temperature the dark current is of about 8 count/sec.

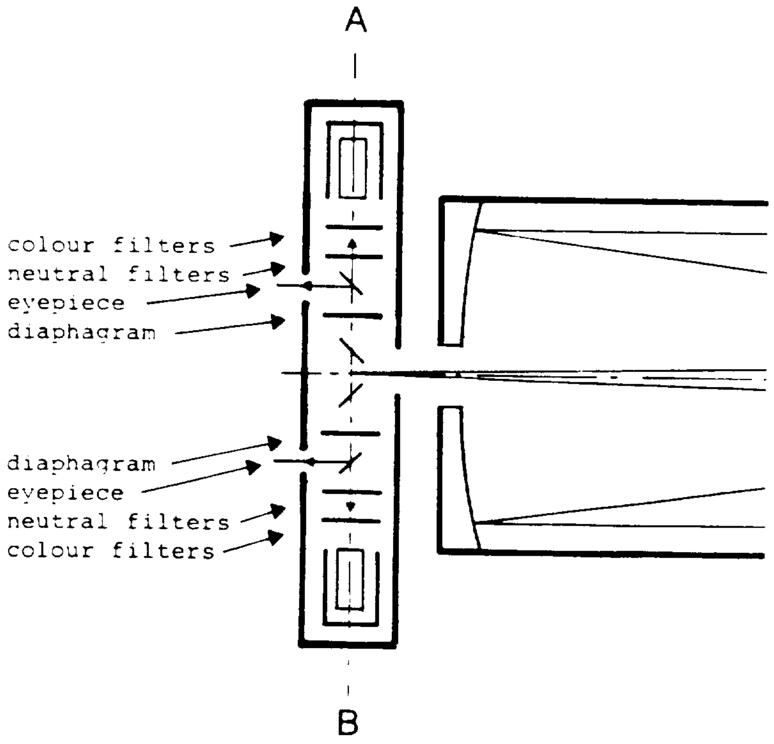

Fig.4. Optical and mechanical diagram of the URSULA photometer

Setting up the photometer occurs manually, utilizing three degrees of

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freedom (in addition to those of the telescope):

1 - rotation of the axis of the photometer (joining the stars to be measured),

2 - shifting of detector A along the axis,

3 - shifting of detector B along the axis.

The useful field of the instrument is 10' with a minimum distance among stars (due to mechanical limitations) of 4'. As can be seen from Fig.4, the instrument allows the introduction of neutral filters (to be used with intense sources) and the choice of a certain number of diaphagrams.

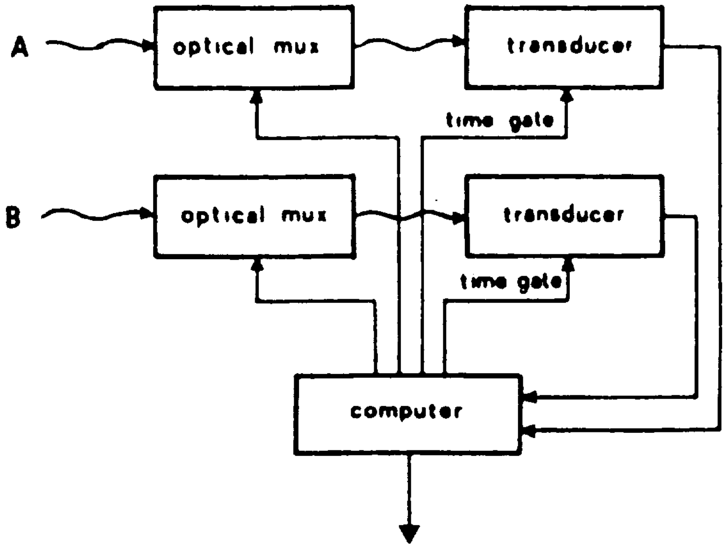

Fig.5. The concept of hardwareless URSULA photometer.
All the electronic parts, except the detectors,
are integrated to the computer

The URSULA photometer is widely integrated with its control computer: as a matter of fact, the only external electronic parts are the photomultipliers with the respective discriminators, as can be seen from Fig.5. The photon pulse counting is carried out by two real time clocks used as counters.

In its first version, the instrument was based on a DEC PDP11/10 computer with 16 KW memory, which conditioned the development of the running software, consisting of a stand-alone program written in assembler language.

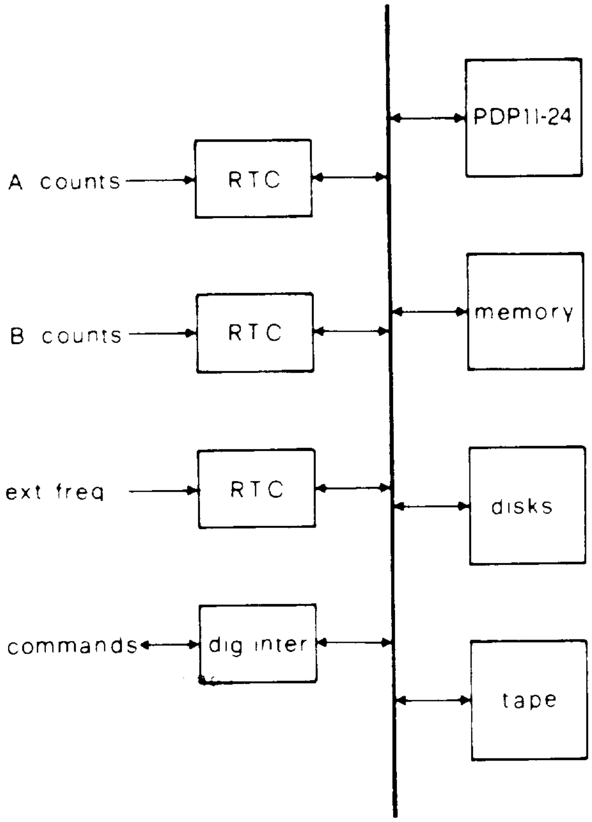

Fig.6. Configuration of the control computer at Mount Etna stellar station

The present structure of the photometer control program is summarized here. Upon starting, one can initialize the time scale, which can be either internal or synchronized with an external one. During the initial dialogue the operator selects the optical bands, the computer asks whether or not a preliminary measurement of the star, reference star, and background is needed, and successively the operator will assign the total measurement time for each band and the ratio between the source and background measurement times. The operator is requested to insert:

- cycle time (elemental measurement time within the complete measurement in all the selected optical bands),
- measurement time (the duration of a complete measurement),
- background repetition rate (the number of complete measurements to be executed on the sources before shifting the telescope to measure the sky background),
- time distribution within the optical bands.

At this point the measurements start and the values of the outputs of the two channels are recorded on magnetic tape (time, star and reference star or respective backgrounds). The system is, furthermore, able to point out some run time errors (for instance, a wrong colour filter displacement).

Differences between the present apparatus and the first installation mainly occur in the addition of the photomultiplier cooling system and in the control computer change into a DEC PDP11/24 system equipped with disks and magnetic tape, as shown by the block diagram of Fig.6.

Examples of use

In the following figures some examples of the photometer performances are shown. One of the first measurements carried out by the URSULA photometer is shown in Fig.7 [Rodono' et al. 1979]. This measurement has revealed a small amplitude long lasting pre-flare activity in YZ CMi. Also in previous observations, using traditional photometers, such a kind of small amplitude activity was suspected, but no firm conclusions could be derived, since such small variations could also be caused by transmittance variations occurring between the star and reference star measurement delay.

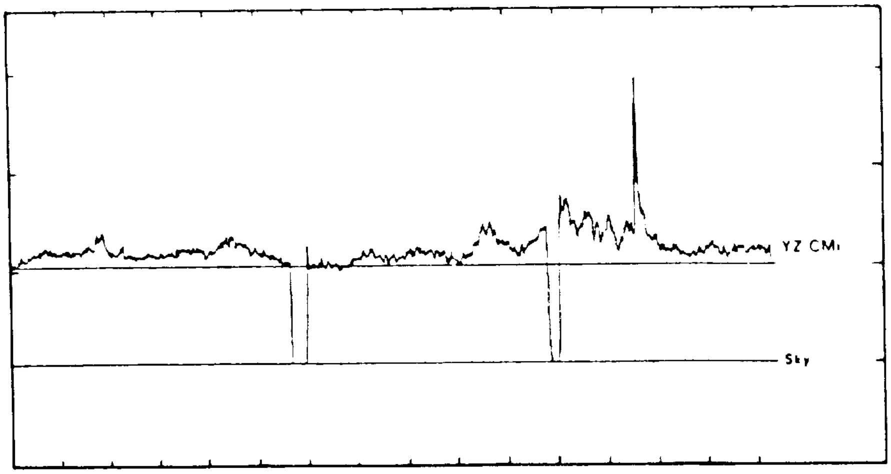

Fig.7. One of the first observations with URSULA photometer carried out in January 1978 shows a pre-flare activity in YZ CMi undetectable with standard techniques.

Observations shown in Figs.8a,b have carried out recently at the stellar station of the Catania Astrophysical Observatory with the new version of the URSULA photometer.

The figures show observing runs of 1500s for the same two stars (m_V = 10, 10.2) in two very different atmospheric transmittance variation conditions. They show the behavior of the signals (counts/s) of the two stars measured in the photometer channels A and B together with their ratio A/B as a function of observing time. In

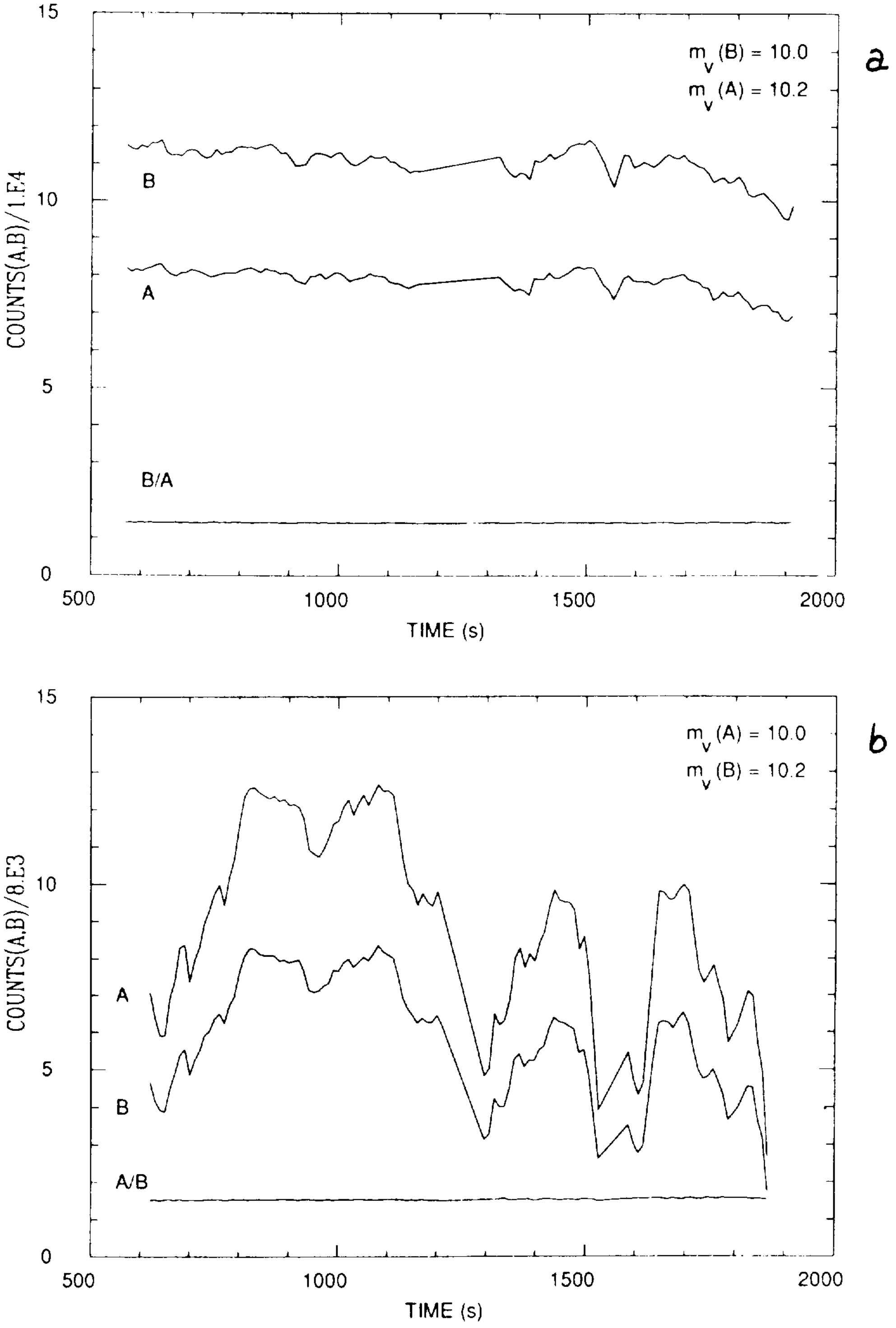

Fig.8. Signals in the channels A and B and their ratio A/B are plotted vs observing time for the same two stars in different transparency conditions: a) $\Delta\tau/\tau \simeq 10\%$, σ (A/B) = 1.2%; b) $\Delta\tau/\tau > 50\%$, σ (A/B) = 3.9%

order to plot all the curves in the same figure, the counts in the channels A and B have been divided by proper factors, while the ratios A/B are in scale.

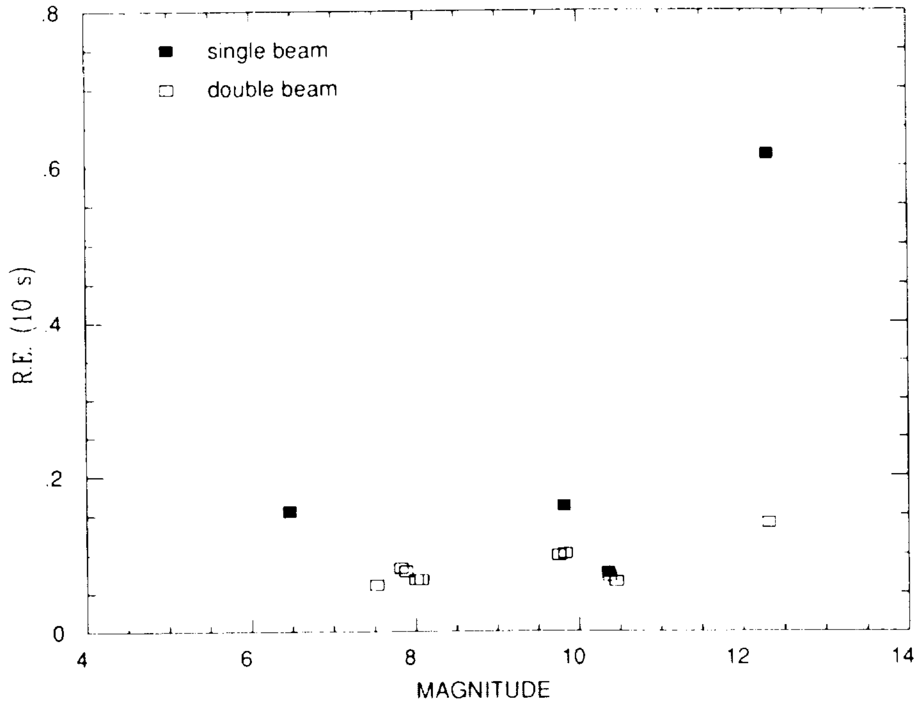

Fig.9. Relative error RE vs. stellar magnitudes for single beam standard photometry (filled squares) and double beam photometry (open squares). The data refer to only three observation nights with different atmospheric conditions.

The different atmospheric transparency conditions are clearly seen from the behavior of signals in the separate channels. In Fig. 8a, transmittance variations not larger than 10% - 15% can easily be estimated, while in Fig. 8b, variations larger than 50% are present during the observation time. In the first case, the accuracy of A/B ratio is within 0.012, while in the second case, in spite of the dramatic variations of transparency, the accuracy is within 0.039 that is not very different from the first case.

Fig.9 summarizes the results of different brightness star observations carried out during three nights in which atmospheric conditions were different. All measurements were taken with the two channels, but in some cases a single channel serial mode measurement has been simulated for comparing accuracies. In the figure the relative error RE, normalized to 10s measurement time, is given as a function of the magnitude of the stars for both single (filled squares) and double (open squares) beam modes. It is possible to see a well definite tendency of double beam points to align along an accuracy level better than single beam points. These latter tend to reach the double beam accuracy level in good photometric nights and greatly diverge from this level in conditions of high transparency variations, as in the case of 12.5 m star.

Outstanding completions

The occurrence that the URSULA photometer practically clashes with its control computer allows a very great flexibility of the apparatus so far not much used, due to the limitation of the system based on PDP11/10. The present control computer (PDP11/24 working under RT11 operating system) allows a greater quickness in the software writing, since, excluding a few command routines, it is being made in FORTRAN language.

Presently, the following developments of the apparatus are being accomplished:

- on-line continuous interpolation or extrapolation of the sky background values through polynomial fitting,

- on-line control of the accuracy of both single measurement and final result,
- on-line removal of wrong measurements (telescope tracking errors, spurious electrical signals, etc.),
- stopping of the measure sequence on achievement of a prefixed precision,
- optimization of distribution of the measurement times on the various bands versus a prefixed precision,
- improvement of the instrument mechanics in order to allow pointing of the stars by optical fibers.

The mechanical improvement is suitable, as the experience in using the instrument has shown that the present mechanical structure makes the pointing of objects difficult and reduces the useful field.

Conclusions

The current use of the URSULA photometer, as well as the already shown examples, have demonstrated the capability of the instrument of measuring with a sufficiently good accuracy in situations of considerable variations of transparency. In particular, by the accomplishment of the above described completions, the instrument will be brought to the maximum efficiency, since its adaptive capabilities will intervene completely [De Biase and Sedmak 1974]. It is to be noted that this photometer is able to make a continuous quality control of the measurements it is carrying out, in the framework of Baade's [1987] considerations.

A noticeable improvement of the whole system could be achieved if one more optical channel is introduced for the continuous measurement of the sky background, which presently is an important cause of lack of precision for faint stars and even for bright ones in the case when variations of sky brightness are high.

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