INFORMATION EFFICIENCIES OF TELESCOPES AND THEIR INSTRUMENTATION

V.S. Rylov
Special Astrophysical Observatory,
Zelenchukskaya, USSR

ABSTRACT: A criterion based upon information content allows one to obtain objective estimates of the efficiencies of astronomical observations for the whole system of light receiving and recording equipment, including the conditions of observation. The proposed method for calculating this information efficiency relies on the analysis of the output observational material and not on the characteristics of optical and electronic components of the instrumentation. The method is quite simple to use for comparison of different astronomical observations and instrumentation (Rylov, 1977, 1979; Karapetian and Oskanian, 1978).

The performance of an astrophysical experiment depends upon the choice of observational means. Experimental data are obtained with the help of a telescope and a light analysing device. The characteristic features of any astronomical observation are:

1. Observed physical phenomena are unique;
2. The light signal is faint;
3. Observational time is limited.

These features should be considered when we choose criteria to estimate the efficiency of an observational system. There is no doubt that the estimation of efficiency is a necessary consideration and various approaches are used nowadays. Usually these are based on an analysis of the characteristics of instrumental components and further prediction of their potential. The parameters most commonly used for this are: (1) The detection limit of a telescope and its instrumentation, and (2) detective quantum efficiency. The detection limit evaluates the threshold sensitivity but says nothing about the reproduction quality of the input signal. The detective quantum efficiency is of more restricted application and is used for different light receivers.

If instead, the evaluation of efficiency is based on the information obtained as a result of the observation, then the task becomes simpler since its solution depends on the output result which is accessible for measurement. The astronomer is interested in the information content of the material obtained (spectrograms, photographs of stars and galaxies,

C. M. Humphries (ed.), Instrumentation for Astronomy with Large Optical Telescopes, 93–98.

speckle-interferograms etc.) i.e. in the volume of information recorded on a carrier (photoemulsion, magnetic tape etc.). Limiting the observation time reduces the ability to obtain information and it is clear, in this case, that the accuracy of reproducing the input information must also be limited; a decrease in information capacity can result, for instance, from a restriction of spatial resolving power, by a signal-to-noise ratio (SNR) decrease, by atmospheric conditions, or by the reliability of astronomical equipment etc. All of these factors should be considered.

Any image can be described in terms of the spatial and spectral distributions of irradiance expressed as a function of position, time, wavelength, and polarization angle. In general, the image can be represented by a distribution over six-dimensional space with arguments x, y, λ, θ, t, ϕ where θ and ϕ are the position angle and the wave phase of the electric field vector. An elementary volume $\Delta\lambda \cdot \Delta x \cdot \Delta y \cdot \Delta\theta \cdot \Delta\phi$ can be characterized by a certain level of radiant energy. According to information theory (Gurevich, 1964) the output information content obtained through any reproduction system, is

$$I = n_\lambda \; n_x \; n_y \; n_\theta \; n_\phi \; n_t \; \log_2(m+1) = n\log_2(m+1) \text{ bits}$$

where

$$n_x = (x_2 - x_1)/\Delta x$$

$$n_y = (y_2 - y_1)/\Delta y$$

$$n_t = (t_2 - t_1)/\Delta t$$

Δx and Δy describe the resolution, Δt is the exposure time for a frame, n_t is the number of frames, and n is the number of elementary volumes in the 6-dimensional space. The energy level of the signal in each elementary volume can be measured with a finite accuracy and this accuracy determines the number (m+1) of distinguishable signal gradations with respect to the zero level. The reproduction system will not be able to transmit the input signal as a function of all 6 arguments simultaneously; any real system inevitably selects only some of these and transforms the information into x, y or t arguments.

Thus, the expression for the amount of information obtained can be reduced to:

$$I = n_x \; n_y \; n_t \; \log_2 (m+1) \text{ bits}$$

The information content, found in this way appears at first sight to be of academic value only since it says nothing about the scientific value of the material obtained and nor does it describe the defects of the recording system. However, although it lacks these important practical considerations, the information content does have the advantage that it can be evaluated from observational material obtained with various telescopes and can be compared in the same units (bits) for different systems.

Consider some specific cases where the information content can be determined:

(a) Spectral observations with slit spectrographs.

$$I = n_x n_y \log_2 (m+1)$$

where n_x, n_y are the number of resolution elements along and across the dispersion direction, respectively. For uniformity in the calculation it is necessary to use values n_x and n_y which are determined at some identical minimum contrast, for instance, 10%. In practice, the resolutions Δx can be derived from a comparison spectrum. The value n_y is used for the case where independent physical events are recorded across the dispersion direction with resolution Δy (as with extended objects). Each $\Delta x \cdot \Delta y$ element has a finite number m of brightness gradations.

For photographic materials m is given by (Gurevich, 1964):

$$m \cong 0.8\ (T_{fog} - T)/\ \sigma_{max}$$

where σ_{max} is the maximum photographic noise of a $\Delta x \cdot \Delta y$ element; T_{fog} is the transmission of the emulsion fog level; and T is the transmission of a $\Delta x \cdot \Delta y$ element of the spectrogram. It is obvious that T can take different values in the spectrum and to simplify the determination of m it is proposed to find an average value of T for all elements of the spectrogram. If continuum radiation is absent or if it is of no interest, then T must be found for the resolution elements corresponding to the spectrogram features which are to be studied. For photon counting systems the value of m is equal to the SNR. In this case the accuracy of measuring m is characterized by 84% reliability; the same value also applies to the calculation of m for photographic emulsions.

(b) Spectral observations with an objective prism or transmission grating in a convergent or collimated beam

Systems consisting of a telescope with an objective prism, or a telescope with a focal reducer and a prism or transmission grating in a collimated beam need a large angular field and a low intensity detection limit. These characteristics produce a large information capacity for the system. The information content depends on the number of $\Delta x \cdot \Delta y$ elements on each slitless spectrogram and on the number of useful spectra on a photographic plate or semiconductor array. The resolution depends on the image size of a star on the photographic plate or array. For this case, we have

$$I = \sum^{N} n_x \cdot n_y \cdot \log_2 (m+1)$$

where N is the number of useful spectra, and m is as defined previously. The number of spectra which are considered to be useful are those which can be identified as being of use for a particular scientific purpose.

(c) Imaging of sky areas.

Two aims are usually pursued here: photographing galaxies and other extended objects, and production of sky atlases. The angular field of the telescope, the plate scale and the image quality are of special importance for producing atlases. The calculation of I requires determination of the real resolution Δx and Δy, which in turn depends on the image quality on the photographic plate. The exposure time is usually set to get images of limiting faint stars and in that case m = 1.

When extended sources are recorded, the object occupies only a part of the total field so that the number of elements $n_x n_y$ must be calculated only for the object area concerned. To simplify the determination of m it is again better to take the average transmission value T. Then

$$I = n_x n_y \log_2 (m+1)$$

The same expression for I applies also to measurements obtained with optical filters or a Fabry-Perot etalon.

(d) Speckle interferometry.

$$I = n_x n_y n_t \log_2 (m+1)$$

where n_t is the number of adequate, processed frames obtained in time $(t_2 - t_1)$. The resolution Δx and Δy can be derived in advance if photographic detection is used. The image of the speckles on the photograph can occupy several resolution elements, hence $n_x n_y$ is the product of the number of speckles and number of resolution elements in one speckle. For a silicon-diode array its resolution is determined by the pixel size, and $n_x n_y$ is equal to the number of recorded events (photoelectrons) per picture.

(e) Electrophotometry and polarimetry.

$$I = \sum_i^N \log_2 (m_i + 1)$$

where m_i is equal to the SNR in each recording channel for the accumulation time $(t_2 - t_1)$, and N is the number of recording channels.

It has already been mentioned that the estimation of efficiency must consider the peculiarities of the astronomical observations and, in particular, the time restriction. The idea developed in this paper is that the information efficiency can be determined from the amount I per unit time for the particular rate at which the signal is recorded. This criterion, when referred to objects of equal brightness, allows for all conditions and peculiarities of the observations and produces efficiency estimates on the basis of certain, concrete observational results for the reproduction system.

To evaluate the information efficiency it is necessary to know the recording time during which the information I is accumulated, and the object brightness. If the brightness is expressed in stellar magnitudes, then the illumination E from the object is

$$E = E_o\, 10^{(M_o - M)/2.5}$$

Thus the signal accumulation time depends on M in the following way:

$$t = t_o\, 10^{(M - M_o)/2.5}$$

This expression is not quite correct for photographic emulsions, but in our case the difference is not important.

If t is the time during which the signal is accumulated, then t_o is the time which would be spent on the observation of an object of magnitude M_o with the same equipment.

$$t_o = t.\, 10^{(M_o - M)/2.5}$$

Hence it follows that t_o may be called an equivalent or reduced observational time for the object of magnitude M.

The reduced time t_o makes it possible to evaluate the information efficiency I_{eff} related to the object of magnitude M_o. Obviously, magnitude M_o must be the same in all calculations. Here $M_o = 10$. Then,

$$I_{eff} = I/t_o$$

It is seen that I_{eff} of one system may be compared to that of another system without referring to the real magnitude and recording time of the object. The efficiency I_{eff} obtained here does not include any detector characteristics or mirror diameters in explicit form. But it is obvious that I_{eff} depends on them, and also on the seeing and transmission of atmosphere, through the observational data.

If necessary, the telescope degree of automation (telescope slewing and setting time, guiding quality), the reliability of equipment in operation (loss of observational time caused by defects), the observer qualification etc., can also be taken into consideration. The conditions enumerated affect the amount of information through the observation time t.

Here is an example of the I_{eff} calculation. During the observations there were obtained 3 spectrograms of stars of the following magnitudes: $M_1 = 15(t_1=1.3^h)$; $M_2 = 13(t_2=0.3^h)$; $M_3 = 14.2(t_3=1^h)$. The time spent to get the telescope setting, to get the image-tube photocamera charged, and for the break-down of the telescope guiding system, was

https://doi.org/10.1017/S0252921100083408 Published online by Cambridge University Press

0.6^h. Hence t_1, t_2, t_3 must be increased by 0.2^h each. The treatment of the spectrograms was made with the microphotometer slit height equal to that of the spectrum. The real photographic resolution was Δx = 0.04mm. It was determined for the double lines of the comparison spectrum with the same film.

The spectrum length was 14.4mm; T_f was 0.74; T was 0.2 (mean along the spectrum). Photographic noise is equal to σ_{max} = 0.006. Then n_y = 1; n_x = 360; m = 72 for each spectrogram. That is

$$I_1 = I_2 = I_3 = 360 \log_2 73 = 2220$$

For the comparison star, magnitude M_o was taken to be 10. Then

$$t_o = 1.5\ 10^{-2} + 0.5\ 10^{-1.2} + 1.2\ 10^{-1.68} = 0.0716^h$$

$$I_{eff} = 3\ I_1/t_o = 9.3\ 10^4 \text{ bit/h}$$

The proposed objective estimation of telescope instrumentation efficiency is quite simple in its application and seems to be useful for quantitative comparison of numerous reproduction systems of astronomical images. In this connection it would be very interesting if data on information efficiency were given in papers concerning different observational results or describing instrumentation of telescopes.

REFERENCES

Gurevich, S.B. 1964, Efficiency and sensitivity of TV-systems (Russian), Energia, USSR.

Karapetian, B.O. and Oskanian, V.S. 1978, Reports of AS Arm SSR, 67, No. 5, pp. 302-308.

Rylov, V.S. 1977, Izvestya SAO AS USSR, 9, pp. 108-110.

Rylov, V.S. 1979, New Techniques in Astronomy, Nauka, USSR, No. 6, p. 52.