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Solar synoptic telescope

Characteristics, possibilities, and limits of design

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Abstract. A rapid evolution of electronics and information technologies makes it possible to use new original designs of synoptic telescopes for solar observations, to increase the demands on their functions, and to fully automate the observation. However, there are hardware and software limits that strongly influence the working capabilities of synoptic telescopes. In this contribution, we analyze relationships between the synoptic telescope's characteristics, the parameters of image digitization, the control, the achievable degree of automation of observations, and the possibilities to implement functions connected with the solar activity monitoring and image archiving. The principles listed above serve as a basis for the design study of the Auxiliary Full-Disc Telescope for the European Solar Telescope (EST), a pan-European project of a large 4-meter solar telescope.

Key words: Sun – telescopes

1. Introduction

Solar synoptic telescopes are used for monitoring and registration of solar activity in several spectral regions. They provide a global detection of active phenomena in different layers of the solar atmosphere and record the activity evolution on the solar disc and in its vicinity. In this paper we focus on general characteristics and functions of ground-based instruments for synoptic observations of the solar photosphere and chromosphere.

2. Functions of the synoptic telescope

2.1. Monitoring of solar activity

In the past, the monitoring of solar activity has mostly been an exclusive job of skilled and experienced observers. Owing to different capabilities of different observers, it has been necessary to homogenize their results in order to compare them. Thanks to contemporary observing and computational techniques, the tedious work of the observer can be automated. The obtained results are free of human factor and they can be utilized efficiently thanks to data processing techniques. The data can be used to check the current state of solar activity or to get information about its history.

2.2. Recording of solar activity

Digital filtergrams or spectra are mostly used for synoptic recording of solar activity. The filtergrams register the actual state of the visible solar hemisphere or its part at a given instant and in a given wavelength band. The wavelength band can be fixed either to a continuum part of the solar spectrum or to the center of a strong spectral line or it can be changed by tuning the filter to scan the line profile in order to obtain additional information about magnetic and Doppler velocity fields. Long-term horizontal motions of sunspots and filaments can be measured from time series of filtergrams. The advantage of filtergrams is the instantaneous imaging of the solar disc or the observed area; the drawback is a relatively poor spectral resolution.

The spectral method is based on successive records of spectra in all points of the solar disc (or its part), *e.g.*, when gradually moving the solar disc across a spectrograph slit. Maps of various physical quantities can be restored from such set of spectra or spectroheliograms (intensity maps in different wavelengths), magnetograms, Dopplergrams, *etc.* The drawback of the spectral method is that the solar disc is not observed all at once but during a certain time interval.

The records produced by a synoptic telescope can be divided into two groups: records of particular fast active phenomena and records of history of the global long-term solar activity.

2.3. Recognition and archiving of fast active phenomena

The correct recognition of fast solar active phenomena (*e.g.*, flares, filament eruptions) should provide information about the beginning, duration, and end of the phenomenon, including a pre-determined period before its onset. The frequency of data storing can vary depending on the magnitude and speed of observed changes that are typical for a given class of phenomena. The recorded data shall describe in detail the evolution of the active phenomenon utilizing the smallest possible storage capacity. It is not necessary to store the full-disc images but only smaller parts of them that contain the active phenomenon.

The method of fast active phenomena recognition and archiving has two steps: (1) the temporary real-time recording of primary data and (2) the primary data processing and archiving of relevant information on the active phenomenon. The second step might require more computational time and it is not necessary to run it in real time.

Temporary recording of primary data:

– digitization of optical information with maximum cadence (5–25 frames per second (fps) per channel);
– selection of best-quality data in a given time period (max. 1 fps per channel);
– temporary storage of selected data (max. 1 fps per channel);
– test of clouds;
– test of the active phenomenon onset/end based on intensity changes;
– test of the active phenomenon onset/end based on area changes;
– test of the active phenomenon onset/end based on positional changes;
– setting of the data storing frequency;
– storage of selected data to the primary data directory (only during the active process, max. 1 fps per channel).

Primary processing and archiving of fast active phenomena:

– image segmentation to separate the active phenomenon;
– selection of a subfield containing the phenomenon;
– calculation of all required physical parameters;
– selection of data suitable for archiving;
– archiving of selected data that describe the evolution of active phenomenon.

2.4. Archiving of the history of long-term solar activity

The long-term history of solar activity (*e.g.*, distribution and evolution of active regions, quiet prominences and filaments) is sampled continuously with a frequency substantially lower than in case of the fast active phenomena (about 2 frames per hour). All relevant full-disc information is stored in a separate archive. The fast active phenomena are strongly undersampled in this archive. For this reason, the long-term activity archive must contain links to particular archives of fast active phenomena.

The temporarily recorded primary data (see sec. 2.3) stored with the maximum frequency of 1 fps serve as an input for the long-term archiving. However, the cadence of archiving is much lower (about 2 frames per hour per channel). Therefore, the archiving routine must be capable in real time of selecting the best frames and align them to compensate image shifts and deformations due to seeing and telescope motions before the frames are stored. It is also possible to store time-averages of aligned images to increase the signal-to-noise ratio.

3. Factors influencing the characteristics of solar synoptic telescopes

In spite of recent advances in electronics and information technologies, synoptic telescopes have certain limitations resulting from the following basic requirements on their functionality:

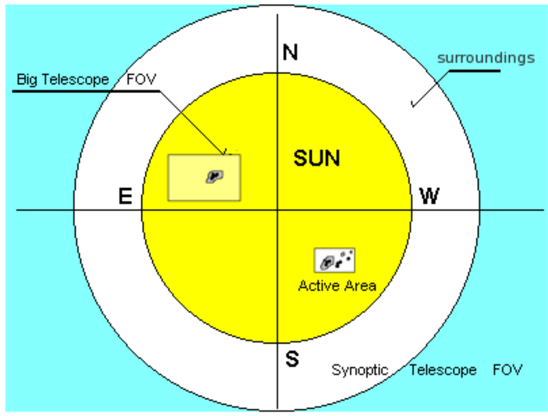

Figure 1. Field of view (FOV) of a synoptic telescope with the solar disc and its surroundings projected to a chip of a digital camera. The area of the chip defines the actual FOV of the telescope. An example of a substantially smaller FOV of a large high-resolution telescope is marked by a rectangle.

– monitoring of activity on the whole solar disc and in its vicinity;
– the necessity to observe active phenomena including the situation before their onset;
– simultaneous monitoring of several active regions;
– automatic operation of synoptic telescopes.

These requirements are met only by full-disc telescopes that collect information coming from the whole visible solar hemisphere. Large high-resolution telescopes with small fields of view (FOV) are not capable of detecting active processes that might appear simultaneously at distant locations.

At present, the number of pixels of a digital camera's chip represents an important limitation for the angular resolution of full-disc telescopes. Let us consider an example of a 48 Mpix (8000×6000 pixels) chip currently available on the market.

To observe off-limb features (*e.g.*, prominences), the diameter of projected solar image must be smaller than the shorter side of the chip but not too small in order not to lose the resolution. A reasonable compromise is shown in Fig. 1. The solar disc diameter is very roughly $2000''$, the diameter of the observed region including the disc and its surroundings is larger by a factor of 1.5, *i.e.*, $3000''$. According to the Nyquist theorem, the sampling frequency must be twice higher than the highest resolvable spatial frequency. The chip with 6000 lines resolves $6000/2 = 3000$ points in the vertical direction. In our case, this corresponds to the angular distance $3000''$. It follows that the resolving power of a full-disc telescope equipped with the chip 8000×6000 pixels cannot be higher than $1''$. We have demonstrated that it is useless to design the optical system of a full-disc telescope with resolution better than $1''$, *i.e.*, the sufficient diameter of the objective is 150 mm.

The requirement of efficient utilization of the chip's resolution imposes also limitations on the design of the control system of the synoptic telescope. The solar disc image projected on the chip must be as large as possible. To obtain the required FOV, the disc cannot move with respect to the chip and the control system must maintain the disc center near the center of the chip. The solution is easy in case of an autonomous telescope, where a standard guiding together with a positional control of the telescope's mount can be used (Klvaňa *et al.*, 2008). If the synoptic telescope is attached to another telescope or located on a common mount, the autonomous positioning must be enabled. The fixed attachment to a telescope with small FOV results in motions of the solar disc on the chip, a necessity of larger FOV and lower resolution power. This alternative is suitable for guiding but not for synoptic observations.

4. Important functional blocks of a synoptic telescope

Automatic evaluation of meteorological conditions
A warning system evaluating relative humidity, clouds, precipitations, and wind speed. In case of unsuitable meteorological conditions the system gives a warning, inhibits to open the telescope or, if necessary, it automatically closes the telescope.

Control of telescope's motion
The control system must maintain the solar disc center at a minimum distance from the optical axis of the telescope.

Automatic focusing
If required by the optical system design, the automatic focusing of all optical channels is essential. It is a precondition of the full automation of the telescope.

Wavelength ranges
Solar synoptic telescopes usually observe in the spectral lines Hα, Ca II H or K, and in continuum. Tunable filters or capability of spectral observations strongly extend the potential of the telescope.

Image detection
Each spectral channel has its own digital camera. All cameras are synchronized and their exposure times are adjustable. The control of exposure time is important to avoid saturation in brightness and to measure intensity changes in strong flares.

Image quality evaluation
Each digital image is evaluated for quality (contrast, sharpness) and an index

of quality together with an index of perturbation by clouds is assigned to the image. These indices will serve for selection of the best frame in a defined time period.

Tip-tilt

A mechanical tip-tilt mirror is not necessary, because the position of the solar disc on the chip is not critical (unlike the disc position on the spectrograph slit). An electronic version of tip-tilt can be used that calculates in real time the displacement of the solar disc center from the origin of the coordinate system (*e.g.*, the chip center). These displacements may be used for the positional correction of the telescope and the compensation of different refraction in different spectral channels. Since the telescope's aperture is small ($\leq 150\,\mathrm{mm}$) and the FOV is large, the use of adaptive optics has no sense.

Recognition of active phenomena

The onset of active phenomena is checked using brightness and structural changes in digitized images. The determination of the frequency of image storage and the cameras' exposure times are also parts of this functional block.

Quality of archived images

The quality enhancement using image restoration methods (speckle, multi-frame blind deconvolution) has no sense due to a small aperture and large FOV. The frame-selection method shall be used to obtain the best frames during a predefined time interval. Only the best images shall be stored with a frequency depending on solar activity changes to minimize the required storage space. Time-averaged images can also be stored in addition to the best ones.

Coordinate system

The origin of coordinate system is in the center of the imaging chip. The chip center is defined by the intersection of the optical axis with the chip plane. The Cartesian axes have directions of the rows and columns of the chip. The direction of chip's rows coincides with that of the daily motion. An accurate alignment of the optical system and cameras is necessary to reach that. Such coordinate system is independent of the solar disc position that may be different in different spectral channels due to refraction.

Automatic mode of work

The work a of synoptic telescope with characteristics described above can be fully robotized. All functions can be automated, without any intervention of an observer. The user will only watch the current solar activity on the monitor(s) or work with images stored in archives of fast active phenomena and the long-term activity archive.

Data storage

The data should be stored in a searchable form, so that the users can easily access the data of interest. The use of the data management services makes it possible to split the observations into the data segment stored on the filesystems and a set of tags/keywords (*e.g.*, date and time, spectral channel, observation quality *etc.*), which is stored in the database. A database query (possibly using some graphic or web-based interface) allows the users to export the data exactly matching their requirements.

5. Summary

A modern solar synoptic telescope should be capable of performing the following tasks:

- visualization of the current solar activity on the disc and in its surroundings;
- recognition and archiving of fast active phenomena;
- archiving of long-term history of solar activity.

These tasks can be fully automated. The observer becomes now a user who utilizes the synoptic telescope as a source of information without the necessity to operate it. To reach this goal, it is necessary to take into account the limitations due to resolution power of present digital camera chips:

- The telescope's control system must maintain the solar disc at the chip center.
- The resolution limit of a full-disc telescope equipped with a 8000×6000 pixel chip cannot be finer than $1''$.
- The optimum aperture of the synoptic telescope equipped with the above mentioned camera is 150 mm. A larger aperture does not bring any new information.

The principles described above have been accepted as a basis for the conceptual design of the Auxiliary Full-Disc Telescope (Sobotka *et al.*, 2010) for EST – a project of the four-meter aperture European Solar Telescope (Collados *et al.*, 2010) developed by nine European countries.

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