



Solar magnetograph for space weather prediction

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Received 14 October 2023

ABSTRACT

Space weather prediction is a necessary element of the technological safety system for ground- and space-based objects. At present, the most promising approach is the development of a ground-based observation network. Such a network should include solar magnetographs providing observation of large-scale solar magnetic fields. Magnetographic observation data allow estimating parameters of recurrent solar wind streams. The paper presents a project of a solar magnetograph to ensure space weather prediction.

Key words: Sun, solar observations, magnetic field, solar telescopes

1 Introduction

One of the most relevant tasks in studying the Sun and solar-terrestrial relations is the investigation and prediction of space weather (SW), whose state is determined by solar activity. Various SW manifestations can affect many technological systems on Earth, in airspace, and in space. Solar flares can produce powerful X-ray radiation that disturbs the ionosphere. High-energy solar particles (energetic protons) are able to penetrate satellite onboard electronics, leading to spacecraft failures. Geomagnetic storms can alter radio navigation system signals (GLONASS, GPS, GNSS), reducing geopositioning accuracy. Geomagnetic storms also cause auroras.

The strategic kind of observations that takes the central place in operational SW forecasting and predicting solar effects is solar magnetic field detections. These data allow one to simulate the corona structure that depends on these fields and the associated electromagnetic radiation in a wide wavelength range from radio to X-rays. In the USA, the main source of magnetic field data for SW prediction is the Global Oscillations Network Group (GONG) observational network. It consists of six identical monitoring stations distributed around the world. These stations ensure nearly continuous solar observations, including magnetograms of the visible solar disk and images of the chromosphere in the $H\alpha$ line during the passage of the Sun over each station. Thus, the global distribution of GONG observatories provides almost continuous 24-hour monitoring of the full solar disk magnetic field state with a characteristic measurement time of 60 seconds. Over 18 years of observations (2002–2019) analyzed by [Jain et al. \(2021\)](#), the GONG network, consisting of six observational sites, achieves an average duty cycle coverage of 88.3%, with a median value of 92.0%.

Nevertheless, to make a prediction of non-explosive phenomena, there is no need to conduct observations so frequently. Coronal holes near the central meridian can generate high-speed streams and solar wind compression regions that regularly modulate geomagnetic activity. The characteristic lifetime of the sources of disturbance is ~ 27 days or one solar rotation. Unlike flares and coronal mass ejections (CMEs) caused by rapidly developing active regions, recurrent streams are associated with relatively stable coronal structures whose lifetime can be several months. This makes it possible to use solar observations far east of the central meridian to forecast the solar wind at Earth's orbit days or weeks later. Therefore, to forecast recurrent solar wind streams, it is sufficient to obtain several magnetograms during a day. This can be achieved by installing three observation stations separated by longitude across the country's territory.

Thus, to predict SW, it is necessary to conduct regular observations of the magnetic field over the entire solar disk. Currently, only two countries, the USA and Russia, have magnetographs allowing such measurements. Regular observations of large-scale magnetic fields at the Kislovodsk Mountain Astronomical Station have been carried out since 2014 with the STOP telescope-magnetograph ([Peshcherov et al., 2013](#); [Tlatov et al., 2016](#)) developed at ISTP SB RAS by order of Roshydromet within the federal target program “Geophysics” based on deep modernization of the previous version of STOP operating at the Sayan Solar Observatory.

The magnetograph observation results are used to predict solar wind parameters ([Tlatov, Berezin, 2023](#)). For a number of parameters, simulation based on STOP data provides better agreement between the solar wind speed forecast and observations compared to GONG and SDO/HMI magnetographs ([Berezin, Tlatov, 2020](#)). The telescope has a spatial resolu-

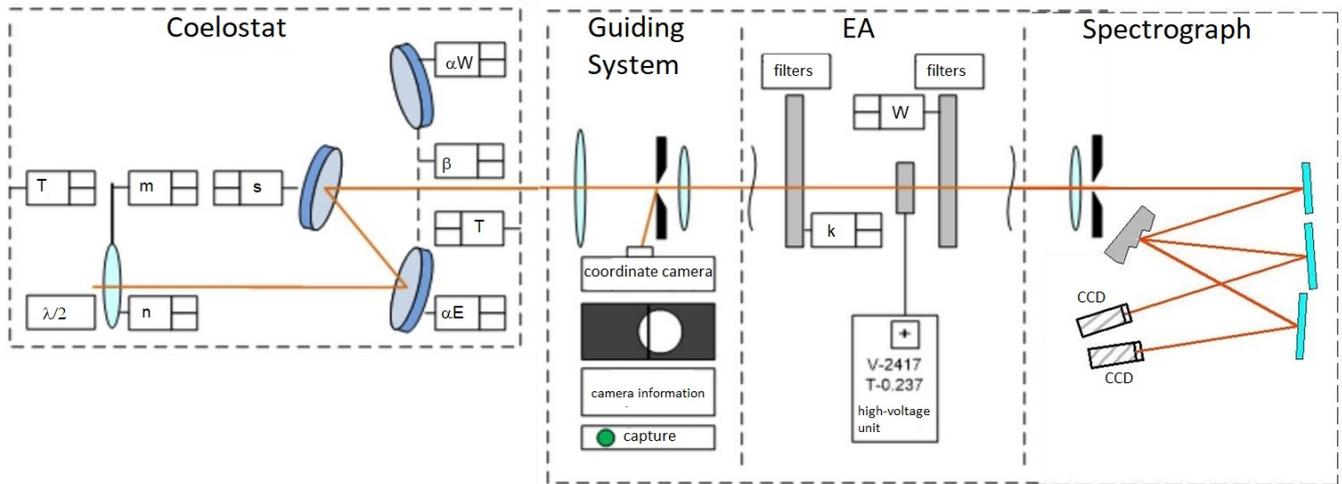


Fig. 1. Scheme of the SolMagPro solar magnetograph.

tion of 33×6 arcseconds and sensitivity of ~ 0.3 G, which is sufficient for successful prediction of SW parameters. At the same time, the telescope's resource is limited. Significant efforts are being made to carry out continuous observations. Currently, modernization of the STOP telescope and creation of a new magnetograph are required.

2 New full-disk solar magnetograph project

Based on the experience of operating the STOP magnetograph, we propose a new magnetograph project. The conventional name of the new telescope is the Solar Magnetograph for Space Weather Prediction (SolMagPro). Despite the best parameters in its class, the STOP magnetograph has several disadvantages. These include insufficient spatial resolution, significant artifacts in the recorded spectrum, long scanning time, etc. The telescope uses the main objective with a small aperture of 5 cm and focal length of 0.5 m. Consequently, the number of steps along the spectrograph slit when scanning the full solar disk is limited (~ 60). The time for magnetic field reconstruction from one solar disk scan data is ~ 20 minutes. These parameters limit the telescope's use, for example, in analyzing active regions and forecasting solar flares.

In the new magnetograph, we plan to increase the spatial resolution to 2–3 arcseconds while maintaining sensitivity of ~ 0.1 G. The telescope's structure and composition are chosen based on its purpose, the nature of measured signals, physical properties of the large-scale magnetic field, radial velocity field, rational observation time, and ensuring a modern level of measurement automation. The measurements are based on theoretical models of absorption line formation in the solar atmosphere and the physical Zeeman and Doppler effects, as well as the following measurement methods: photoelectric, differential, polarization, and in the visible wavelength range.

SolMagPro consists of a horizontal-type telescope equipped with an optically aligned high-dispersion spectrograph with a reflective diffraction grating. The telescope is

designed as a Stokesmeter, which allows recording the distribution of Stokes parameters in selected spectral lines. The scheme of the SolMagPro telescope is shown in Fig. 1. The telescope is illuminated by sunlight via a coelostat system. The coelostat mirrors are equipped with drives that ensure construction (together with the telescope objective) of a fixed and non-rotating solar image at the recorder's entrance window with specified heliographic coordinates in the instrumental coordinate reference system. The objective builds a solar image in the plane of the spectrograph entrance slit.

Behind the slit, between two relay objectives, elements of an electro-optical analyzer (EA) and blocking polarization filters are installed. The diverging light beams behind the slit are converted into parallel ones to ensure normal EA operation. Light reflected from the spectrograph slit's mirror at an angle of $\sim 15^\circ$ to the optical axis is used to build the solar image on the guiding system's CCD matrix. To ensure polarization measurements, the instrument is equipped with various polarization equipment and relay optics. The electro-optical analyzer is a circular polarization analyzer (Stokes V-parameter), which allows alternately extinguishing different components of circularly polarized light and consists of an electro-optical crystal and a Glan prism located behind it. Crystal control is carried out by a high-voltage alternating power source. Using a mechanical modulator installed before the coelostat mirrors, the sign of the Stokes V-parameter is alternately reversed. In this case, instrumental distortions remain unchanged, providing the ability to account for instrumental measurement errors.

All optical-mechanical telescope units that require movement during observations, calibration, or fine adjustment are equipped with electromechanical drives based on stepper motors with matched reducers. The telescope is mounted on a single foundation (~ 4.5 m long) and equipped with a pavilion with a wind-protective dome (Fig. 2). The pavilion is divided into two parts: heated (operator room) and unheated (telescope).

The main differences of the new SolMagPro magnetograph from the STOP magnetograph are the modified spec-

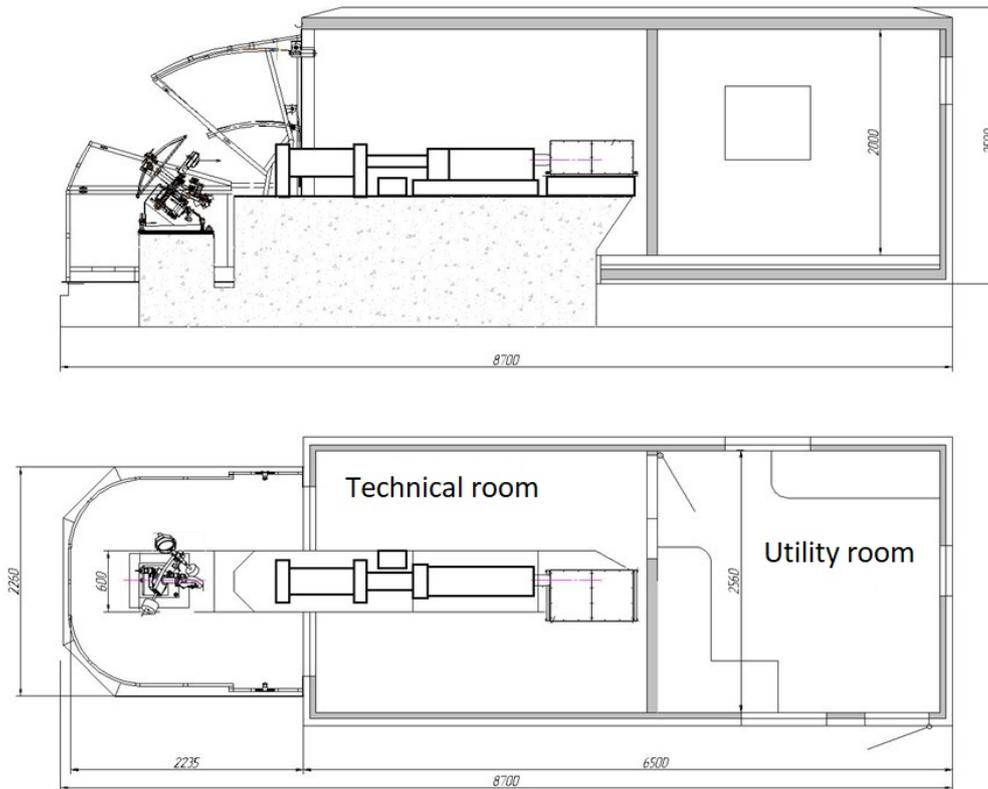


Fig. 2. Scheme of the telescope.

troglyph scheme, increased aperture, and focal length of the main objective. The increase in spatial resolution will lead to a significant increase in the volume of obtained information, more than an order of magnitude compared to the STOP magnetograph. The standard procedure for magnetic field reconstruction with the STOP telescope takes about 20 minutes. With an increase in the volume of obtained data, the processing time with the standard procedure becomes unacceptably long. To solve this problem, we plan to use our developed fast algorithms for processing spectra of magnetically sensitive spectral lines (Tlatov, Berezin, 2023). To significantly speed up the processing procedure, one can apply the fast approximate methods of Guo (2011) and FAS (Al-Nahhal et al., 2019), which allow approximating data with a Gaussian function in just one iteration. The use of approximations noticeably reduces the noise level and allows determining the center position of the magnetically sensitive line in measured spectra as the center of the approximating Gaussian. Intensity reconstruction occurs by directly measuring the distance between the centers of the left and right circular polarization Gaussians. By determining these distances, we can reconstruct maps of the longitudinal component of the large-scale photospheric magnetic field.

3 Conclusions

To predict SW, systematic observations of the full solar disk magnetic fields with high sensitivity are required. Only one

magnetograph conducting regular observations currently exists in our country. The STOP magnetograph is installed at the Kislovodsk Mountain Astronomical Station of SAO RAS. Based on the experience of operating the STOP telescope, this work proposes a project of a new magnetograph intended for SW prediction. Its important feature is the presence of a half-wave phase plate installed before the coelostat mount and designed to eliminate the effect of instrumental polarization. Measurements are carried out in two modes without the plate and with the introduced plate. This allows calculating and excluding instrumental polarization and achieving high measurement accuracy (~ 0.1 Gauss), which is necessary when observing weak large-scale fields.

To measure magnetic fields from spectral observation data, it is proposed to use new methods for reconstructing the complete profile of spectral lines. Such methods allow one to reduce instrumental noise and significantly reduce processing time.

Acknowledgments. This work was supported by the Ministry of Science and Higher Education of the Russian Federation under the state assignment No. 075-03-2025-420/4.

References

- Al-Nahhal I., Dobre O.A., Basar E., Moloney C., Ikki S., 2019. *IEEE Signal Processing Magazine*, vol. 36, no. 6, pp. 157–163.

- Berezin I.A., Tlatov A.G., 2020. [Geomagnetism and Aeronomy](#), vol. 60, no. 7, pp. 872–875.
- Guo H., 2011. [IEEE Signal Processing Magazine](#), vol. 28, no. 5, pp. 134–137.
- Jain K., Tripathy S., Hill F., Pevtsov A., 2021. [Pub. Astron. Soc. Pacific](#), vol. 133, no. 1028, id. 105001.
- Peshcherov V.S., Grigor'ev V.M., Svidskii P.M., et al., 2013. [Avtometriya](#), vol. 49, no. 6, pp. 62–69. (In Russ.)
- Tlatov A.G., Pashchenko M.P., Ponyavin D.I., et al., 2016. [Geomagnetism and Aeronomy](#), vol. 56, no. 8, pp. 1095–1103.
- Tlatov A.G., Berezin I.A., 2023. [Geomagnetism and Aeronomy](#), vol. 63, no. 8, pp. 70–74.