SAMM-E: the enhanced version of the Solar Activity Magnetic Monitor for the SAMM-NET Space Weather network

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ABSTRACT

In June 2022, the first prototype of the SAMM (Solar Activity Magnetic Monitor) telescope was installed on the roof of the INAF-Monte Mario Astronomical Observatory in Rome, Italy, to test its capabilities for space weather observations. SAMM was designed to measure magnetic fields and Doppler velocities along the line of sight in the solar atmosphere at high cadence and two different heights, determined by the formation layers of the solar absorption lines corresponding to the resonance lines of the chemical elements used in the MOF (Magneto-Optical Filters). The use of potassium (K) and sodium (Na) in the MOF filters positions the sensitive layers at approximately 300 km in height (solar photosphere) and 600 km in height (solar chromosphere), respectively. This capability to measure the monitored quantities at different heights enables, for the first time, the 3D reconstruction of their fields, providing additional parameters to feed into forecast models. Building on the experience with the first prototype, an enhanced version of the SAMM telescope, SAMM-E, has been designed and built to overcome the limitations of its predecessor and provide a stable, reliable, and calibrated data source for space weather models. In particular its capability to acquire real time solar magnetic field and Doppler velocity maps at high cadence makes it a unique instrument to identify precursors of solar CMEs and flares and so to provide valuable data for forecasting the energetics events starting on the Sun. Here, we present the characteristics of the new instrument, its first-light images and discuss its planned use in the SAMM-NET network, a network of three coordinated nodes, co-funded by the Italian Ministry of Defence.

Keywords: SAMM-E, SAMM-NET, MOF, space weather, solar magnetic field, telescopes network

1. INTRODUCTION

In recent years, space weather has become a widely recognized term, and its bulletins are now broadly available to both the scientific community and the media. Space weather forecasting has gained increasing attention from agencies and governments worldwide since it has become evident that the most intense space weather events can affect critical infrastructures, particularly power grids and communication networks.

Within this context, SAMM (Solar Activity Magnetic Monitor) was conceived to provide a new source of real-time space weather data, offering unique capabilities at lower cost thanks to its ground-based nature and relatively simple infrastructure[1,2]. The instrument concept derives from previous work on magneto-optical filters carried out at the Rome Astronomical Observatory during the last decades of the twentieth century [3,4], as well as from the experience gained with the VAMOS instrument at the Capodimonte Astronomical Observatory [5]. SAMM telescopes measure line-of-sight magnetic fields and plasma velocities at different heights in the solar atmosphere. These observations enable, for the first time, a three-dimensional reconstruction of magnetic field structures, with the goal of promptly identifying regions likely to produce CME eruptions and solar flares through magnetic reconnection.

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The first SAMM prototype was funded by the Italian Ministry for Economic Development through a loan granted to Avalon Instruments Srl. The project aimed to develop an innovative solar instrument for space weather observations in collaboration with INAF–Rome Astronomical Observatory. This initiative led to the installation of the first SAMM prototype on the roof of the Monte Mario Astronomical Observatory (Rome, Italy) in June 2022. The site was selected for its long-standing record of favorable solar observing conditions, owing to a stable atmosphere, particularly during the early morning hours. The prototype, together with the site's excellent observing conditions, enabled a complete commissioning phase, with major efforts focused on data calibration.

After some months of observing activity, the team acquired a thorough understanding of the instrument and its limitations. In particular, it became clear that the most significant obstacle to its full scientific exploitation was the lengthy calibration procedure. Although technically feasible, calibrations proved impractical in routine operations, as their duration exceeded the typical stability timescale of the solar features on which they rely.

These findings, together with the instrument's clear potential, motivated the design and construction of an upgraded version named SAMM-Enhanced (SAMM-E). This paper reports the details of this development, presents the first-light observations, and outlines the future implementation of a network of instruments known as SAMM-NET.

2. WORKING PRINCIPLES

Measuring magnetograms on the Sun is not a new capability. What is different about SAMM and SAMM-E with respect to the current competitors (SolarOrbiter, SDO, GONG, etc.) is the used technique. Instead of passing through spectroscopic scan and analysis, SAMM-E uses very narrow band filter imaging. This allows simpler instrumentation design, less demanding optical bench stabilization and definitely faster operations and cheaper implementation.

The observable quantities are the wavelength shift of absorption lines in the solar spectra produced by K (potassium) and Na (sodium) and generated at specific heights in the solar atmosphere. Zeeman effect separates each absorption line into two components of opposite circular polarization by an amount proportional to the local magnetic field, while Doppler effect moves both components of the same amount depending on their velocity with respect to the observer, including convective motion in the solar atmosphere.

SAMM-E uses atomic filters known as MOFs (Magneto-Optical Filters) to match exactly the same wavelengths emitted on the Sun. Each filter is composed of a glass cell containing metallic K or Na, a heater and a constant uniform magnetic field generated by the neodymium magnets inside the holder. The heater evaporates the metal creating a cloud in the middle of the cell where that same cloud is subject to the stationary magnetic field (Figure 1).

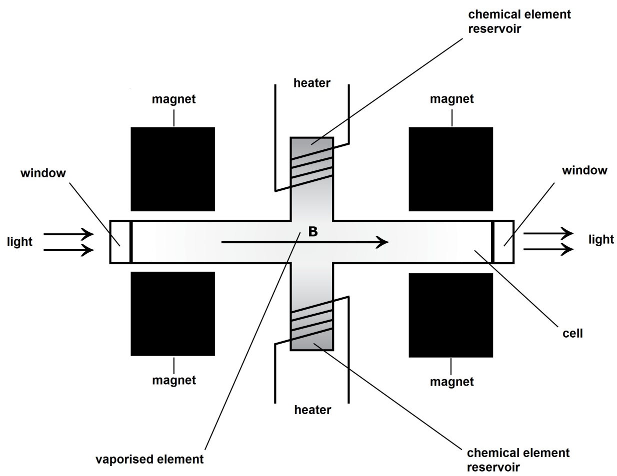

Figure 1: MOF cell schematic

Properly tuning the working temperatures and the magnetic fields allows each cell to alter the passing light to create the desired filter transmission curve. Temperatures from 100 to 250 Celsius and magnetic fields in the interval from 1000 to 4000 G are used in SAMM-E MOFs to obtain filters having only about 0.005 nm of FWHM or about 10 times smaller than the width of the corresponding solar line.

A first stage composed of a ¼ wavelength retarder and a linear polarizer selects and converts one of the two Zeeman lines coming from the telescope to a linearly polarized beam of light. A second stage containing a MOF, a linear polarizer, another ¼ wavelength retarder and one more MOF, filters the light coming from the first stage at two wavelengths placed slightly before (λ_b) and after (λ_r) the central wavelength (λ_0) defined by the chemical element filling the cell (Figure 2). The atomic effects allowing this filtering are the Zeeman effect, the Faraday effect and the Macaluso-Corbino effect. Finally a fast shutter camera takes the images at high cadence (~ 1 ms) to freeze the air turbulence.

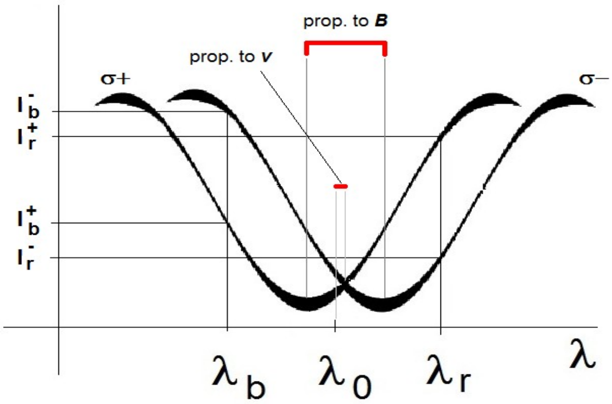

Figure 2: The two solar absorption lines split by Zeeman effect and shifted by Doppler are sampled through MOF filters at two wavelengths called λ_b and λ_r so that the result intensities I_b^-, I_b^+, I_r^- and I_r^+ could be used to retrieve the magnetic and velocity fields that exist in the solar atmosphere.

To completely define the solar absorption lines position it is necessary to get images in four polarimetric configurations corresponding to the possible combinations of the two retarders in their ± 45° positions. The first selects which Zeeman line is imaged (clockwise or counterclockwise polarizations) while the second one is able to place the filter band at fixed positions on the blue (slightly before) or red (slightly after) edge of the central wavelength of the atomic line of the element inside MOF. For each line the ratio of intensities measured on the blue and red edges gives the wavelength offset with respect to its rest/no magnetic field position: equal values mean perfectly centered line. A linear combination of the four intensities is then able to return both Doppler and Zeeman shifts.

3. SAMM LEGACY

The SAMM prototype (opposed to the current version called SAMM-E) demonstrated its potential during its early observing period, but also showed a number of limitations. Namely the main limitations were low sensitivity and suboptimal polarization handling due to bend optical design and reflections.

The limitation about sensitivity was partly due to a too complex optical design and some suboptimal components and partly due to a too high spatial resolution. These circumstances led to quite long exposures to obtain a suitable SNR. In particular, since images need to be exposed just for a few milliseconds to freeze seeing turbulence, each field imaging would require hundreds of images to properly handle dithering, statistics and the four polarimetric configurations. As a result a few minutes were required for each field and since the field of view was rather small (about 10 arcmin) and mosaicing was required with a suited overlapping, tens of minutes were required to cross the full solar disk.

One of the consequences of this situation was an extremely difficult calibration procedure. Since magnetograms' calibration requires to match the Doppler profile measured along the full solar equator with its expected behavior, a mosaic of at least 4 or 5 fields is needed. The problem here is not only the long time required to perform the full data acquisition but, since some fields are completely contained within the solar disk with no border visible, the presence of features to properly position the mosaic tiles. In the absence of sun spots the only possible candidates are photospheric details such as granulation and super-granulation. But solar granulation coherence time is on the scale of minutes and images taken at much larger time separation could not be easily matched.

In this scenario the Alt-Az mount of SAMM and the absence of a field rotator worsened the situation. In specific observing configuration this made more fields required to image the solar equator and slower performances. Moreover, since the two channels were connected on the two sides of the declination axis without being interconnected, whether a copointing device with micrometric regulations was implemented, the two were not pointing to the same exact field except in the specific conditions they were regulated. Changes in telescope aiming and ambient temperature resulted in cross-eyed vision with several problems in operations management.

Over all of this, the SAMM prototype was based on LCVR devices (liquid crystal variable retarders) that operate more reliably at controlled temperature: a not so easy condition to meet in a small instrument and anyway not implemented in the prototype.

All these inefficiencies made the design and construction of a completely new instrument absolutely unavoidable.

4. SAMM-E DESCRIPTION

SAMM-E is the direct descendant of the first SAMM prototype. SAMM-E consists of two independent channels, one based on sodium (Na) cells and the other on potassium (K) cells just like in the original SAMM. Each channel is configured as a linear assembly comprising a Schmidt–Cassegrain telescope, a polarimetric unit, and a fast-shuttering camera. The two channels are mounted and mechanically aligned within a rigid binocular frame, taking advantage of the dual-tube configuration of the Avalon M3 equatorial mount (Figure 3).

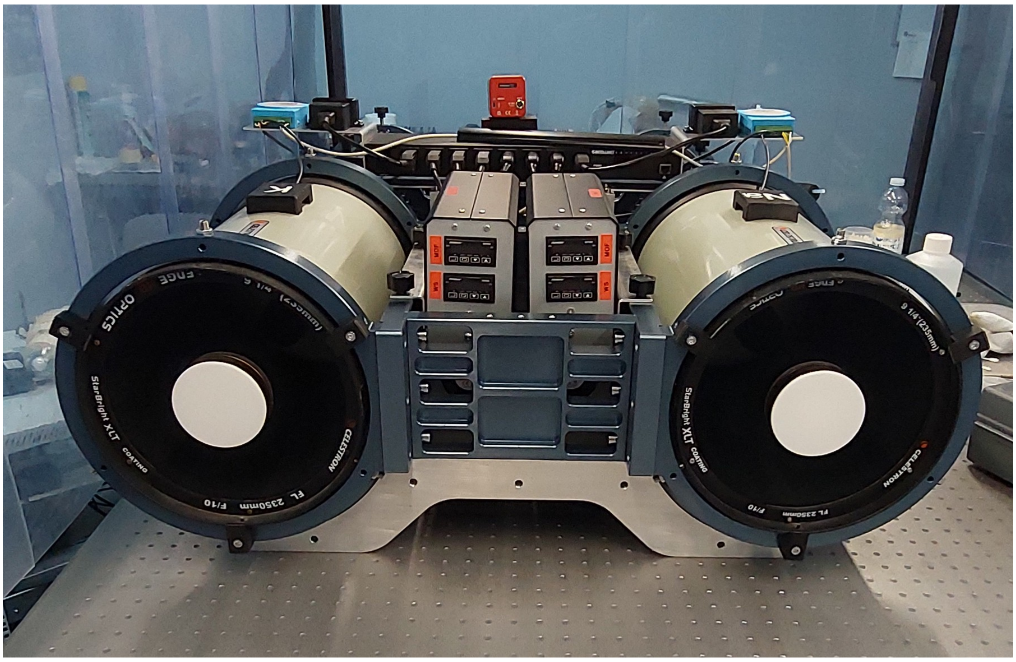

Figure 3: The SAMM-E optomechanics assembly fully integrated on the optical bench prior to Sun screen installation.

The complete binocular assembly, including two electrical panels, two industrial PCs and a finder telescope, weights approximately 100 kg and requires no additional counterweights on the mount. The remaining control and computing infrastructure is housed at ground level in a 19-inch rack containing the central control unit, a NAS with approximately 100 TB of storage, a 64-core data-processing server, as well as UPS unit and PDUs.

The white screen mounted in front of the binocular assembly is thermally insulated from the structure and shields all onboard devices and mechanical components from direct sunlight. This also prevents differential thermal expansion of the structure, which could otherwise introduce pointing misalignment between the two channels. An external water chiller regulates the temperature inside the polarimetric units and removes heat generated by the cameras.

Within this architecture, the two channels are logically independent and can operate separately, sharing only the ground infrastructure and the cooling system.

The entire instrument is housed within a custom enclosure developed by Avalon Instruments, measuring approximately 2 m on each side and 2.5 m in height. The enclosure provides full-sky access and, once opened, allows pointing anywhere in the sky without moving parts. The instrument can observe down to about 8° elevation toward the east and west, while the southern limit is approximately 15°. This configuration was designed to ensure full operational capability throughout the year at mid-latitude sites (Figure 4).

Figure 4: SAMM-E as seen through partially open enclosure (left) and with completely open enclosure (right) at the Avalon Instruments testing facility.

Inside each polarimetric unit, a reflection-free linear optical design accommodates two MOF filters operating on the same chemical element, interleaved with polarizers and retarders. Compared to the original SAMM prototype, liquid-crystal variable retarders (LCVRs) have been replaced by conventional optical retarders, providing more predictable behavior. In addition, the adjustment of the crossing of the two linear polarizers is now performed through a manual micrometric rotation stage rather than a motorized mechanism providing more reliable and accurate positioning. Both modifications improve repeatability and reduce sensitivity to operating temperature while maintaining essentially unchanged operating speed. A potential drawback could be a reduction in long-term reliability due to wear of the mechanical components associated with the retarding plates.

This solution is more efficient with respect to the SAMM prototype and should deliver 2.0x to 2.5x the optical flux and a larger field of view at the expense of resolution with 3.0x more flux. SAMM-E is then going to produce up to 7.5x shorter exposures and a time per field of about 30 seconds while maintaining the same SNR of its ancestor. The field of view of about 17 arcmin allows the full equator to be acquired with just two pointings in about one minute allowing much easier calibration.

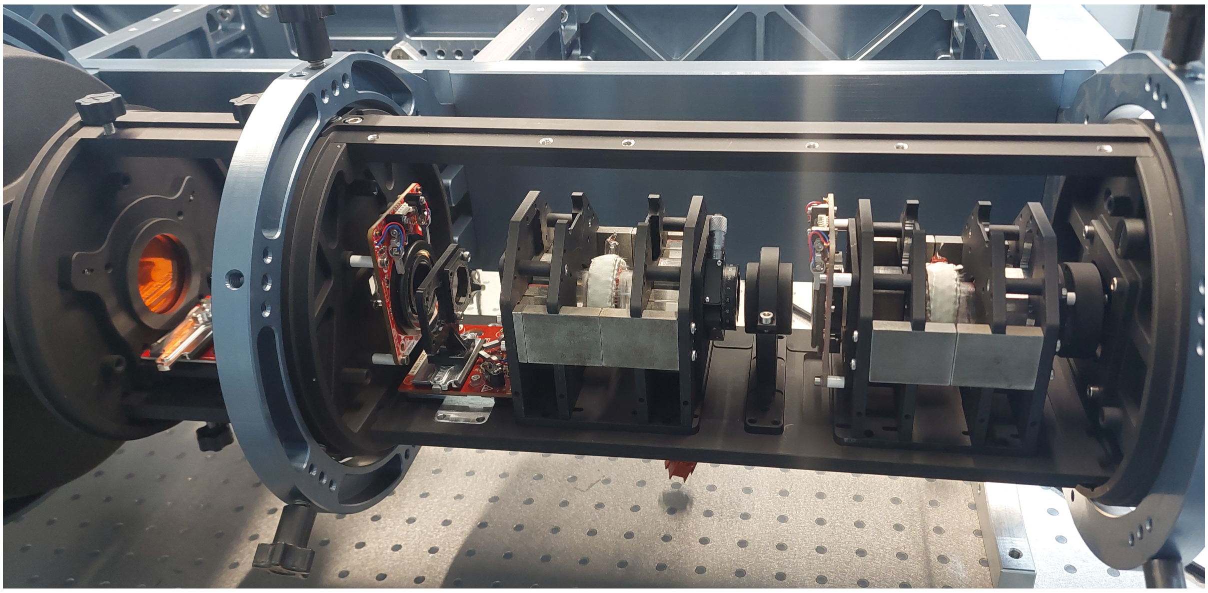

Figure 5: One of the two SAMM-E channels skeleton during testing at the integration lab at the Avalon Instruments Srl.

The main characteristics of the instrument are summarized below (Table 1):

Channel	Na (sodium)	K (potassium)
Solar absorption line	Na-D1	K-D1
Line wavelength	589.6 nm	769.9 nm
Photospheric altitude	~600 km	~ 300 km
SAMM filter FWHM	~ 0.005 nm	
Telescope mount	Equatorial (Avalon M-tre)	
Declination accessibility	±27°	
Minimum elevation	+8°	
Telescope optics	Schmidt-Cassegrain (Celestron 9.25)	
Telescope aperture	23.5 cm	
Camera	SCOMS (Andor Zyla 5.5)	
Field of view	17 x 14 arcmin	
Resolution	0.4 arcsec/px	
Typical exposure time	1-5 ms	
Sequence acquisition time	~25 s	
Co-pointing error	< 1 arcmin	
Optical assembly binocular	~100 kg	

Table 1: SAMM-E characteristics summary.

5. FIRST LIGHT

Following several years of development, the SAMM-E telescope achieved first light on June 16th 2026 at the Avalon Instruments facility near Rome, Italy, and is currently entering its science verification phase. This initial technical first-light, aimed at validating functionality, reliability, and thermal management under summer operating conditions, will be followed by more detailed testing at an astronomical site focused on optimizing sensitivity and calibration procedures. Nevertheless, the preliminary results indicate that the instrument is on track to deliver its full design capabilities, enabling, for the first time, high-cadence measurements of solar magnetic fields and plasma velocities at multiple heights in the solar atmosphere.

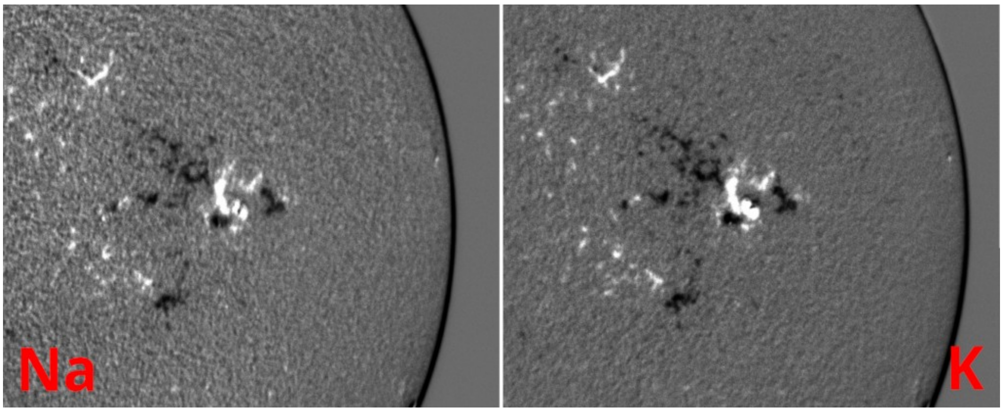

Figure 6: Magnetograms from the very first technical first-light obtained from the two channels with 0.12 s cumulative exposure for each polarimetric configuration.

The two images (Figure 6) have been obtained simultaneously from the two channels and present about the same SNR as those obtained from the SAMM prototype in about 7x less time and with the solar disk center and limb imaged in the same field. These characteristics, the excellent image cleaning and the good copointing of the two channels demonstrates the design improvements studied for SAMM-E have delivered the expected results and should soon give positive results also in data calibration.

6. SAMM-NET

A space weather facility should provide a continuous real-time stream of calibrated data; SAMM-E, even if fully successful, cannot achieve this objective on its own. As a ground-based instrument, it requires a global network of SAMM-E nodes distributed across different longitudes to enhance temporal coverage and mitigate the impact of local weather conditions, thereby ensuring uninterrupted 24/7 observations.

SAMM-NET is a project aimed at deploying three SAMM-E units as a prototype of a future global monitoring network. The initiative has already been approved and co-funded by the Italian Ministry of Defence and INAF, with the collaboration of Avalon Instruments Srl. The first phase of SAMM-NET was completed at the end of 2025, followed by the integration of a prototype node during the first half of 2026.

The deployment of the full SAMM-NET network is planned for 2028, subject to the successful completion and validation of all network nodes.

7. CONCLUSIONS

SAMM-E is currently fulfilling all the expectations and will be fine-tuned and optimized in the next months. All the issues limiting the SAMM prototype have been successfully addressed and the scientific commissioning will certificate.

A mini network composed of three nodes on a limited geographic area is already approved. It is foreseen that it will be operative in a couple of years, paving the way to a global network of SAMM-E devices that will supply 24/7 two layers real-time magnetic data of the solar atmosphere for space weather forecasts support.

ACKNOWLEDGEMENTS

SAMM-NET work is co-funded by the Italian Ministry of Defence to implement national space weather capabilities.

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