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Original article

Cosmic rays detection in Saudi Arabia: Review of the facilities and preliminarily results

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ABSTRACT

Solar activity modulates cosmic ray (CR) particles with different magnitudes on different time scales. CR modulations have been studied using ground-based detectors, primarily neutron monitors, distributed around the world. In 2002, CR research began in Saudi Arabia with the installation of the first CR detector at the King Abdulaziz City for Science and Technology (KACST) in Riyadh (lat. 24 43; long. 46 40; Rc ~ 14.4 Gv), the capital of Saudi Arabia. The facility is located in the central Arabian Peninsula. Because of its high cutoff rigidity, the site is ideal for monitoring CR variations and is of great significance to the research community.

Different CR detectors employing various measuring techniques have been developed and installed, at this site, to record the intensity of cosmic rays on different time scales and assess their correlation with atmospheric and climatic parameters. They include scintillator detectors, single-channel and rotatable telescopes, multi-wire detectors, CARPET detectors, small mobile detector, and mini-neutron monitors. In this paper, we briefly describe these detectors and offer observations on their use in CR research.

1. Introduction

Cosmic rays (CR) are high-energy particles (primarily protons and alpha particles) traveling close to the speed of light. CRs originate in extraterrestrial sources and are continually bombarding Earth's atmosphere. Cosmic ray studies, particularly those focusing on their time variations, are essential to many scientific disciplines. These include climate change (Christ et al., 2004; Usoskin and Kovaltsov, 2008; Svensmark et al., 2009; Singh and Singh, 2010; Maghrabi and Kudela, 2019; Maghrabi et al., 2021), the effect of CRs on microelectronic devices (Manabe et al., 2018), cosmic ray as an imaging tool for geophysical applications, (Yamashina et al., 2010; Saracino and Carloganu, 2012;) and, recently, the relationship between CRs and human health (e.g., Maghrabi and Maghrabi, 2020).

CRs are modulated by solar variability on different timescales, either periodic (e.g., Bonino et al., 2001; Kudela et al., 2002; Kane, 2006; Maghrabi et al., 2021) or transient (e.g., Cane, 2000).

Since their discovery, CRs have been measured from space and on the ground by various instruments that were sensitive to multiple CR characteristics; those instruments are operated at different sites around the world (Stoker, 2009; Maghrabi et al., 2012, and references therein). The exact type of detector used in a particular experiment depends entirely on the project goals and the investigation's size and complexity. Most of the studies on CR variations have been conducted using ground-based monitors; primarily neutron monitors (NM). There are more than 50 NM currently networked and distributed in different regions and, particularly, in the low cutoff rigidity regions (http://www.nmdb.eu/nest). Measurements of CRs at different cutoff rigidities are especially crucial for understanding their properties and variations (e.g., Stoker, 2009).

In Saudi Arabia, optical astronomy is the primary field of research that led to development of several astronomical observatories around the Kingdom. Given the importance of CR research and the unique geomagnetic location of Saudi Arabia, CR research in Saudi Arabia was initiated by Dr. Abdullarahman Maghrabi in 2000 (Maghrabi et al., 2010, 2013). The first cosmic ray detector in the country was installed in 2002 at the King Abdulaziz City for Science and Technology (KACST) in Riyadh, Saudi Arabia. The

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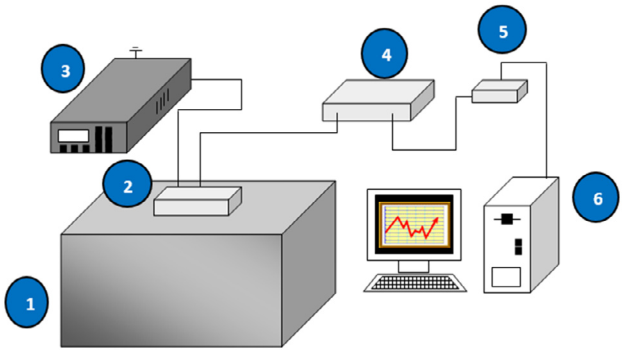

1	Muon Box	4	Amplifier
2	PMT Base and Preamp	5	ADC
3	HV Power Supplier	6	Data Acquisition Board

Fig. 1. Schematic diagram showing the main components of the KACST 1 m^2 CR scintilltor-based detector.

detector was designed and constructed under international collaboration with the University of Adelaide, Australia (Maghrabi et al, 2012; Maghrabi et al., 2010; Clay et al., 2000). The detector has been in operation since that time. Several publications and research activities, including student projects and training programs, have been conducted using available data from the muon detector (e.g., Maghrabi et al., 2012, 2013; Maghrabi and Al Mutairi, 2018; Maghrabi, 2015).

Between 2014 and 2019, and under the supervision of Dr. Maghrabi, four additional types of CR detectors which employ various techniques were designed and installed. These detectors were developed by KACST-based researchers or in collaboration with international institutes. The main goals of these detectors are: (1) complement the existing muon detector, (2) investigate the modulations of several types of CR particles having different energies, and (3) provide research comunity with CR data beyond the energy ranges of extant cosmic ray detectors to explore the CR variations

In addition to the existed muon detector, the developed detectors include the rotatable muon telescope, multi-wire detector, mini-neutron monitor, CARPET detector, and the small mobile detector. The basic properties and some of the results obtained by these detectors will be presented and discussed in this paper.

2. Scintillator detectors

Scintillator-based detectors are one of the most common types of particle detectors used for CR observations. They have several advantages compared to other types of detectors (e.g., gas-discharge detectors). Those advantages include low dead-time, reliability, and unlimited working periods with a high counting rate. Using scintillator materials, detectors of practically any size and geometry can be designed (e.g., Dorman et al, 2005; Yamashinaet al., 2010; Saracino and Carloganu, 2012).

Two CR detectors (a single-channel detector and a rotatable telescope) have been developed using plastic scintillators.

The single-channel detector is a 1,000 mm × 1,000 mm × 50 mm plastic scintillator contained in a light-tight enclosure and viewed using a 120 mm photomultiplier tube (PMT) placed in the middle of the box (Fig. 1). The signals from the PMT are amplified and discriminated against the background noise using locally-designed circuits. The signals are digitized using the homemade A/D converter and then linked to a PC card, which records and stores the data. The first version of this detector was installed in July 2002 and was in continuous operation until late 2012 (Maghrabi et al.,2012). Several upgrades were made to the data acquisition system, software, and some of the detection system electronics.

Since its installation in 2002, the detector has recorded nearly a complete solar cycle and several solar transient and atmospheric events. Fig. 2.a shows the mean monthly data for the CR muons observed by the scintillator detector and the smoothed sunspot number (SSN) from 2002 to 2018. The data recorded by the detector presented the expected behavior during the low and high solar activity periods. The relationship between the two variables shows significant anti-correlation ($p < 0.05$) and correlations coefficient of 0.46. During the solar maximum, the CR flux was reduced because

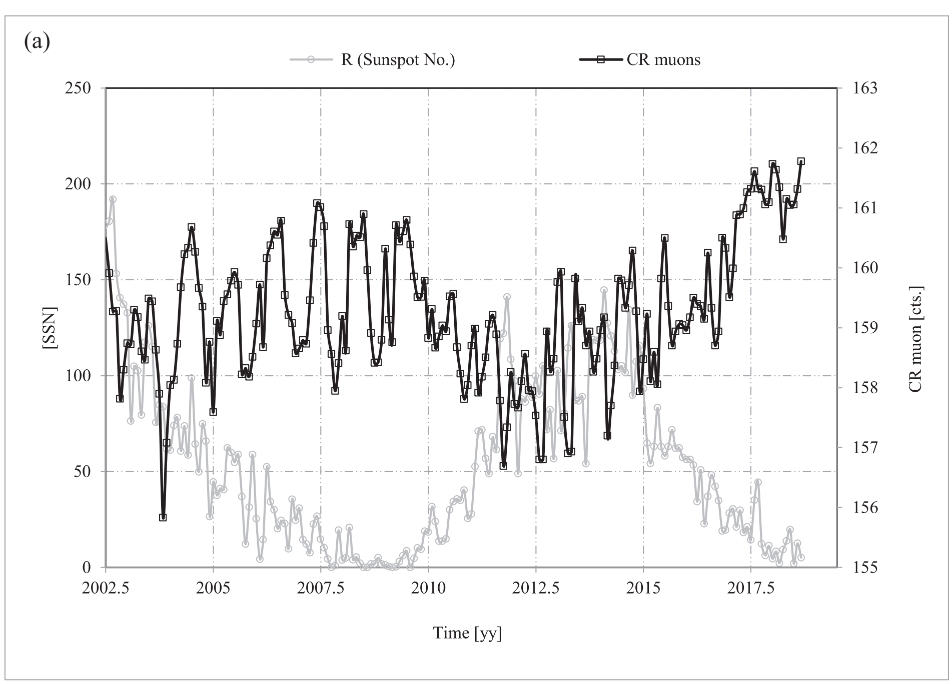

Fig. 2a. Monthly mean sunspot numbers (SSN) and cosmic ray variations observed by the KACST single-channel muon detector from July 2002 to November 2018.

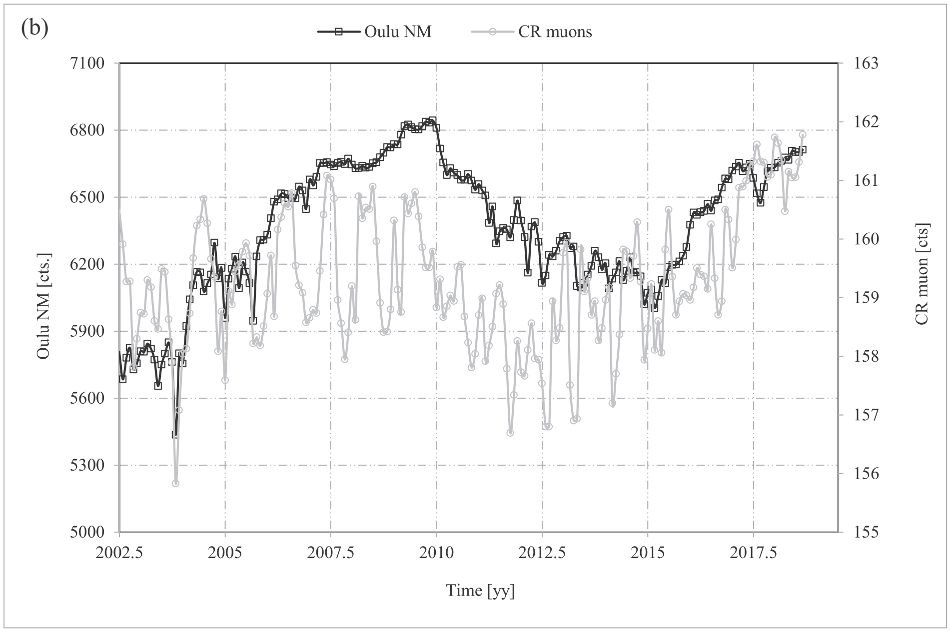

Fig. 2b. Time series of the monthly means of cosmic rays observed by the KACST muon detector and the Oulu NM data for July 2002 to November 2018.

of increased solar magnetic fields, which prevented the CRs from reaching Earth. The opposite occurred during the period of solar minimum.

Fig. 2.b shows the behavior of the CR data recorded by the KACST muon detector compared to the CR neutrons obtained from the Oulu NM (http://cosmicrays.oulu.fi/) for the period 2002 to 2018. The trend during the solar cycles was consistent for the two detectors (correlation coefficient between the two variables was 0.45). The maximum CR count rates during the very quiet year 2009, the minimum during the active year 2015, and the significant Forbush decreases in 2003 and 2005 are all evident in both detectors. However, the seasonal variations in the muon data are more prominent than the NM monitor data due to the atmospheric effects of the CR muons (e.g., Ganeva, et al., 2013; Maghrabi and Al Mutairi, 2018).

Another detection system using a plastic scintillator as the single-channel detector was developed. However,the system consists of two identical scintillator detectors arranged one above the other to form a telescope. Each detector consists of a 50 cm × 50 cm × 10 cm plastic scintillator with the same electronic components as the single detector (Alghamdi et al., 2014). Signals from the two detectors fed to the Data Acquisition Unit (DAU), which was built with two arrays running simultaneously. This telescope can rotate in both the zenith and azimuthal directions. This configuration allows us to study the variations in CR flux at different zenith angles and obtain useful information about the zenith angle variations of the CRs in the atmosphere. When this detector is positioned in a vertical direction, it performs as a single channel detector. However, CR particles with higher energies are recorded because it operates in coincidence mode.

3. Multi-wire proportional chamber detector

A multi-wire proportional chamber (MWPC) is a gaseous detector known for its position resolution and high counting rate capabilities (Charpak et al., 1968; Sauli, 2001).

The designed detector presented here consists of three layers of 40 × 40 cm^2 MWPCs stacked together (Fig. 3). Each layer consists of an array of 16 anodes and 16 field wires. The detector is filled with a gas mixture of Argon: CO2 at a ratio of 80:20 and powered by a high-voltage supplier. The detector chamber's signals are discriminated from the background noise and amplified using a custom-made electronic circuit. The amplified signals are received by a data acquisition board every second, which sends them to a RaspberryPi computer card (Varga et al., 2013; Maghrabi et al., 2017a, 2017b). To prevent the low-energy particles from being detected, the detector was designed to operate in a coincidence mode. The DAC records a particle that simultaneously triggers the three layers. The detector's electronic components were provided by the Wigner Research Centre for Physics, Hungary, as part of a collaborative project (Varga et al., 2013). The detector was constructed, calibrated, and operated at the KACST laboratory.

While these types of detectors are typically used for short-term high-energy experiments, in our case the developed detector has been utilized for long-term CR particle observations since August of 2016. However, due to technical factors or power failures, there were several downtime periods during the operating period.

The MWPC detector, the CARPET detector, and the mini NM (discussed below) were installed during a quiet period of solar

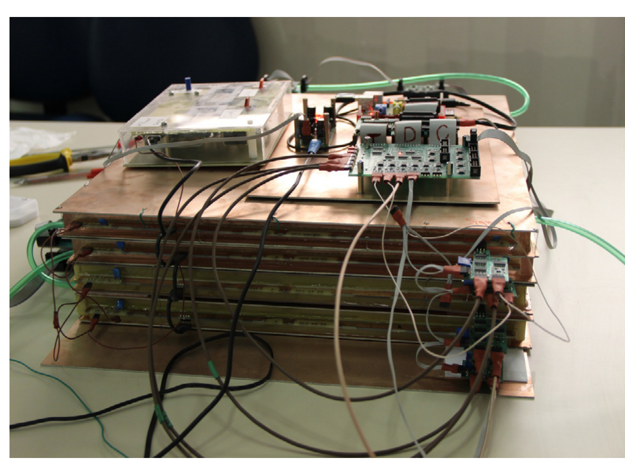

Fig. 3. Photograph shows the KACST developed 40 × 40 cm^2 MWPC.

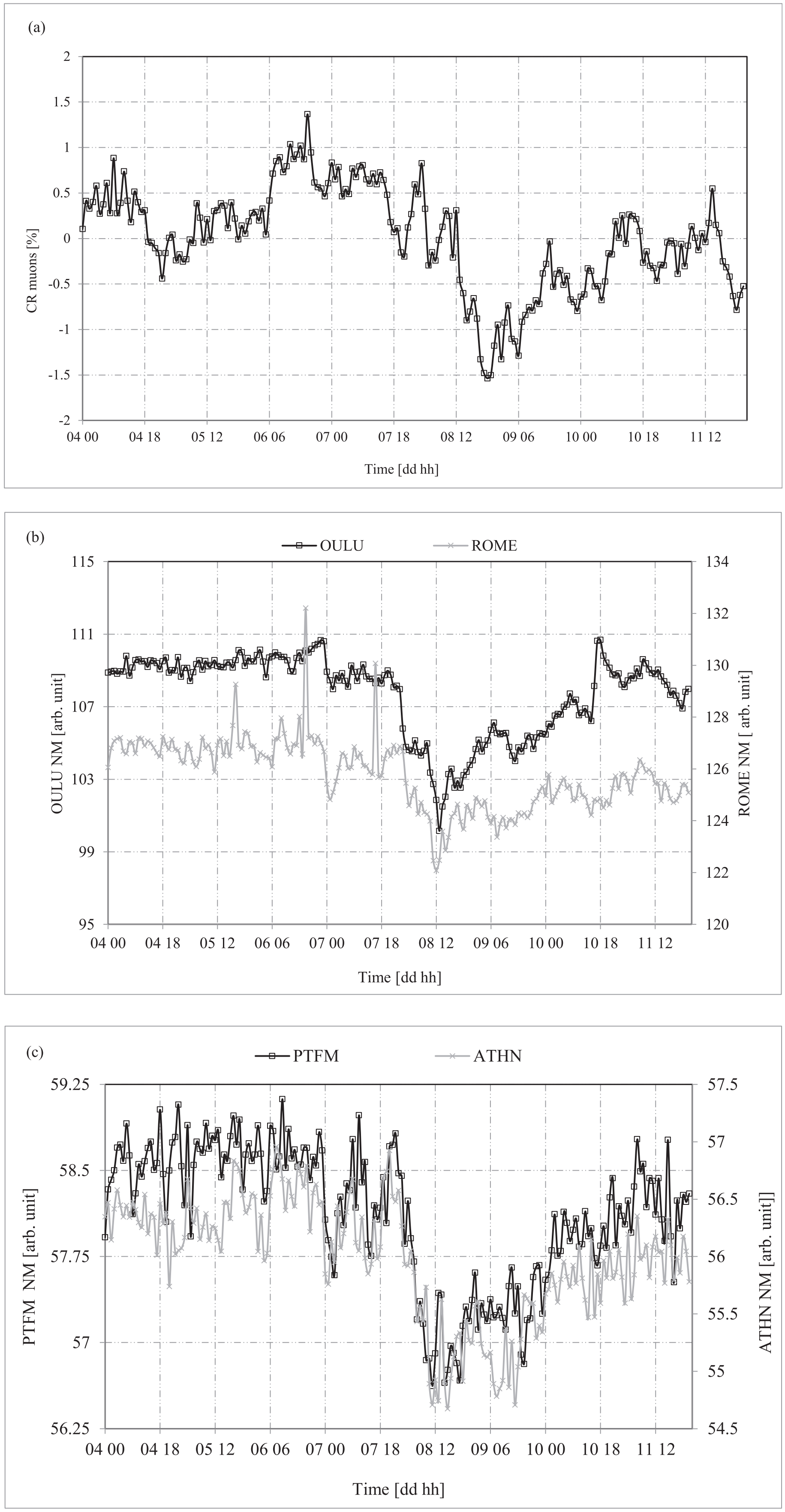

Fig. 4. shows the hourly variations of the pressure-corrected cosmic ray (a) muons observed by the KACST MWPC detector, (b) neutron observed by Oulu NM [Rc ~ 0.81 GV] and ROME NM [Rc ~ 6.27 GV], and (c) PTFM NM [Rc ~ 6.98GV] and ATHN NM [Rc ~ 8.53 GV]; for the period between 4 and 11 September 2017.

(a)

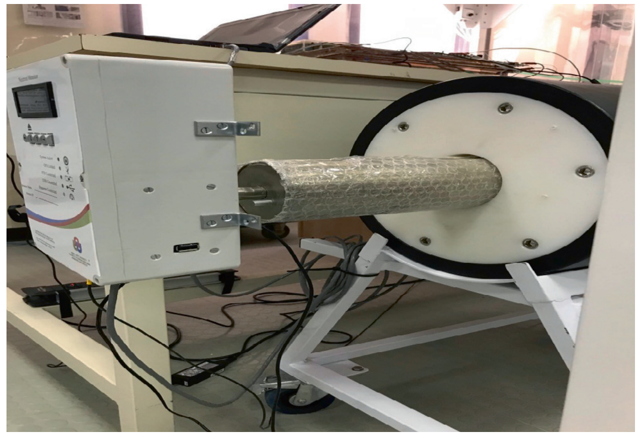

Fig. 5a. photograph shows the mini neutron monitor installed at the KACST station.

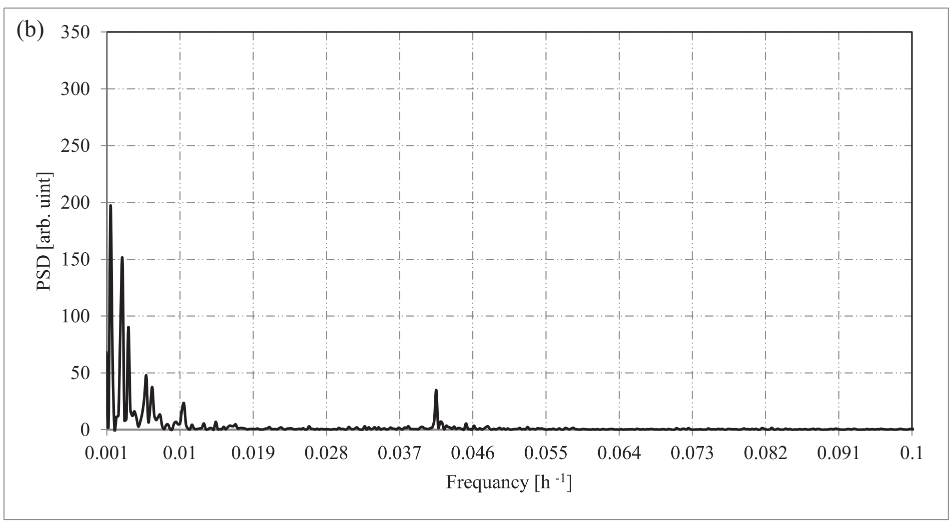

Fig. 5b. Power spectrum density (PSD) of hourly time series of the KACST mini neutron monitor for time period between November 2019 and July 2020. PSD computed by FFT method.

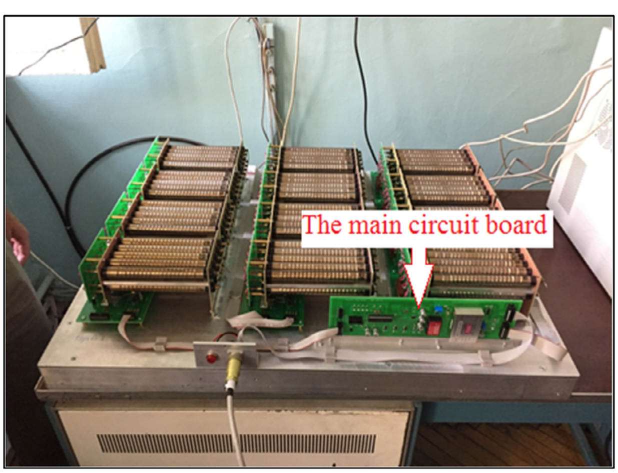

Fig. 6. view of the CARPET detection unit.

activity. As a result, the CR variations since the installation have been at low solar activity levels and shown to be stable and comparable in performance with existing CR detectors in different locations worldwide. However, other properties of the detected CRs can be inferred from the data collected to date.

During its operation, the MWPC detector was able to record the Forbush decrease occurred on September 9, 2017. This event resulted from an X9.3 solar flare on September 6, originating in the Region AR2673. Fig. 4 shows the data recorded by the MWPC detector, as well as four neutron monitors at different locations.

As a result of this solar event, we observed that the KACST MWPC detector recorded a ~2.6% decrease in its count rate. Athena NM records decreased by about 5%, Rome decreased by about 6%; Oulu decreased by about 10%; and PTFM station decreased by about 5.9%. Some of the features of this event recorded by NM stations were visible on our detector. These results demonstrated that the detector could record such transient events with accuracy comparable to other detectors around the world.

4. A mini neutron monitor

Neutron monitors (NM) are typically used to detect the lower energy part of the CR spectrum (>10 GeV). Since the first NM invented by Simpson in 1953 (Simpson et al., 1953), several NMs using Simpson's concept have been developed and deployed worldwide. The main drawback of NMs is their large size (Simpson 2000). However, the detector used here is of the mini size, developed by the University of South Hampton in South Africa

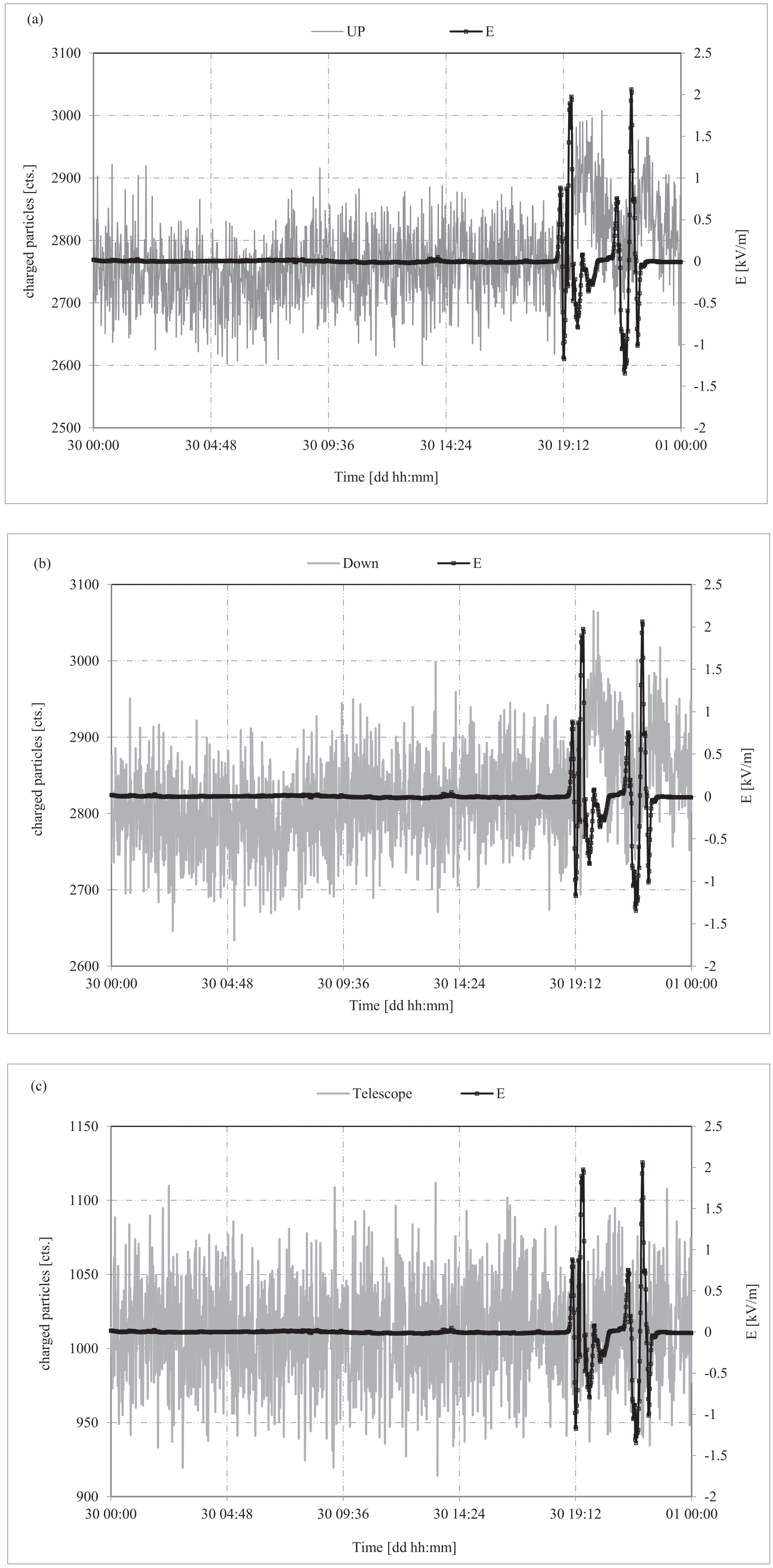

Fig. 7. The pressure corrected 1 min averaged charged particles counts obtained by CARPET (a) up channel, (b) Down channel, and (c) Telescope channel, during the dust storm event that occurred on April 30, 2018. The electric field data are also presented.

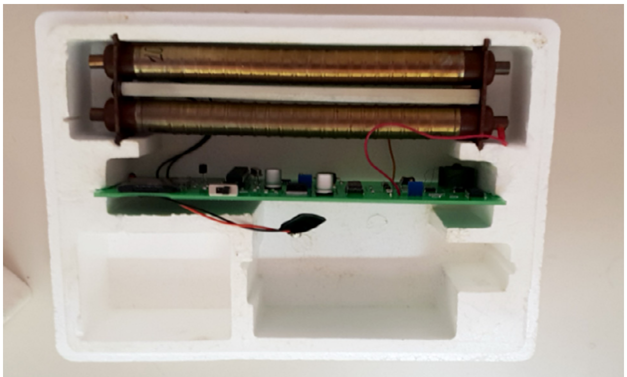

Fig. 8. Single charged particle detector based on two Geiger counters.

(Krüger et al., 2003; Heber, et al., 2014; Poluianov, et al., 2015; Toit et al., 2020).

The detector (Fig. 5.a) is about 1/3 the size of a typical neutron monitor, yet its actual count rate is the same as the standard NM detector. The detector consists of an outer paraffin wax reflector (9.5 cm) surrounded by a lead producer. The inner, two cm-thick, paraffin wax moderator was also surrounded by a neutron producer made of lead. The multiplied and decelerated neutrons reach the 63 cm-long LND2043 counter, filled with BF3 gas at a pressure of 933 hPa. An interface unit was developed for logging and storing the data at a resolution of 1 ms. The detector has been in operation since November 2019.

The data obtained from the mini NM during operation period have been used to investigate short term periodicities in the CR neutrons using the power spectral analyses technique. Fig. 5.b shows the power spectral density demonstrating the significant peak of different amplitudes and strengths over all frequencies of the neutron monitor. The neutron monitor has several significant peaks, such as 27 days, 13 days, 9.7 days, 7.1 days, and 5.6 days, and 1 day. These periodicities are consistent with those observed by several investigators (Kudela, et al. 2002, El Borie and Al Thoyaib, 2002).

5. The CARPET detector

The CARPET detector is designed to detect different types of charged particles with different energies from CR sources and atmospheric phenomena (Maghrabi et al., 2020). The detection unit consists of 120 Geiger counters (type STS-6) located on a platform of ~1.5 × 1.5 m (Fig. 6). The 120 counters were divided into groups of 60 upper and 60 lower, separated by an aluminum absorber with a thickness of 7 mm. The detector operation is controlled by an interface unit that contains all the components required to operate the detector. The detector records data from three channels with a time resolution of 1 ms, (Up, Down, and Telescope or Tel). The three channels are sensitive to particles with differing energies. The Up and Down channels record particle numbers that cross 60 upper counters or 60 lower counters. The telescope channel registers the total number of particles that simultaneously cross the Up and Down layers of the counters.

Since its installation in late 2017, the CARPET has detected a number of events with significant variations (primarily increases) in the count rates detected by the Up and Down channels.

Fig. 7 illustrates an example of this event. It presents simultaneous measurements at an average count rate of 1 min measured by the Up, Down, and Telescope channels of the CARPET, in addition to 1 min averages of the electrical field during a dust storm event. We observed that the charged particle count rates increased in both Up and Down channels simultaneously with the extreme values of the electrical field. On the other hand, no significant variations were observed in the Telescope channel during the event because that channel records particles with higher energies than the other two channels.

6. Single-channel charged particle detector

The single-channel charged particle detector was developed for mobile studies to measure the intensity of charged particles from different sources. The detector consists of two Geiger counters that record data from one of the lower or upper counters (Fig. 8). It also records the particles that cross the two counters at the same time (Makhmutov et al., 2014).

The detector has been used in several pilot studies to assess the charged particles from power and telecommunications towers. Moreover, the detector was used to study the variations in charged particles at different altitudes by placing it in civilian aircraft on several domestic flights.

Fig. 9 displays the data from one of those flights, showing the flight path between Riyadh and Medina on January 29, 2020. The data was collected at a rate of one minute. The flight reached a cruising altitude of about 8500 m. Flight information was obtained from the Flightradar24 flight-tracking website (https://www.flightradar24.com).

The data show that the detected particles increased as the altitude increased until the plane reached cruising altitude. At the cruising altitude, the number of the detected particles remained stable, with slight variations due to the atmospheric conditions.

7. Conclusions

The subject of CR studies, particularly their time variations, is significant to many scientific disciplines. CR research activities in Saudi Arabia began in 2002 with the installation of the first cosmic ray muon detector at the KACST, Riyadh, Saudi Arabia. The data collected from that detector covered nearly a complete solar cycle. The long-term data from that detector have shown a clear anticorrelation with the solar cycle represented by the number of sunspots. Moreover, several short-term transient events (several Forbush decreases) have been recorded by this detector. Between 2014 and 2019, four additional types of CR and charged particle detectors were designed and installed. Those detectors were developed by the KACST-based researchers or through collaboration with international institutes. The detectors employ several techniques to investigate further the properties and time variations of several types of CR particles with different energies. These detectors included the rotatable muon telescope, multi-wire detector, mini neutron monitor, CARPET detector, and single channel mobile detector.

While the newly-developed detectors were installed during a period of quiet solar activity, the CR variations since installation have been at low levels. However, other properties of the detected CRs have been obtained from the collected data. Data collected from these detectors during the coming solar cycles will be of great importance to the scientific community because of the variety of their techniques, their sensitivity to various energies of the detected particles, and the unique location in which they operate.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

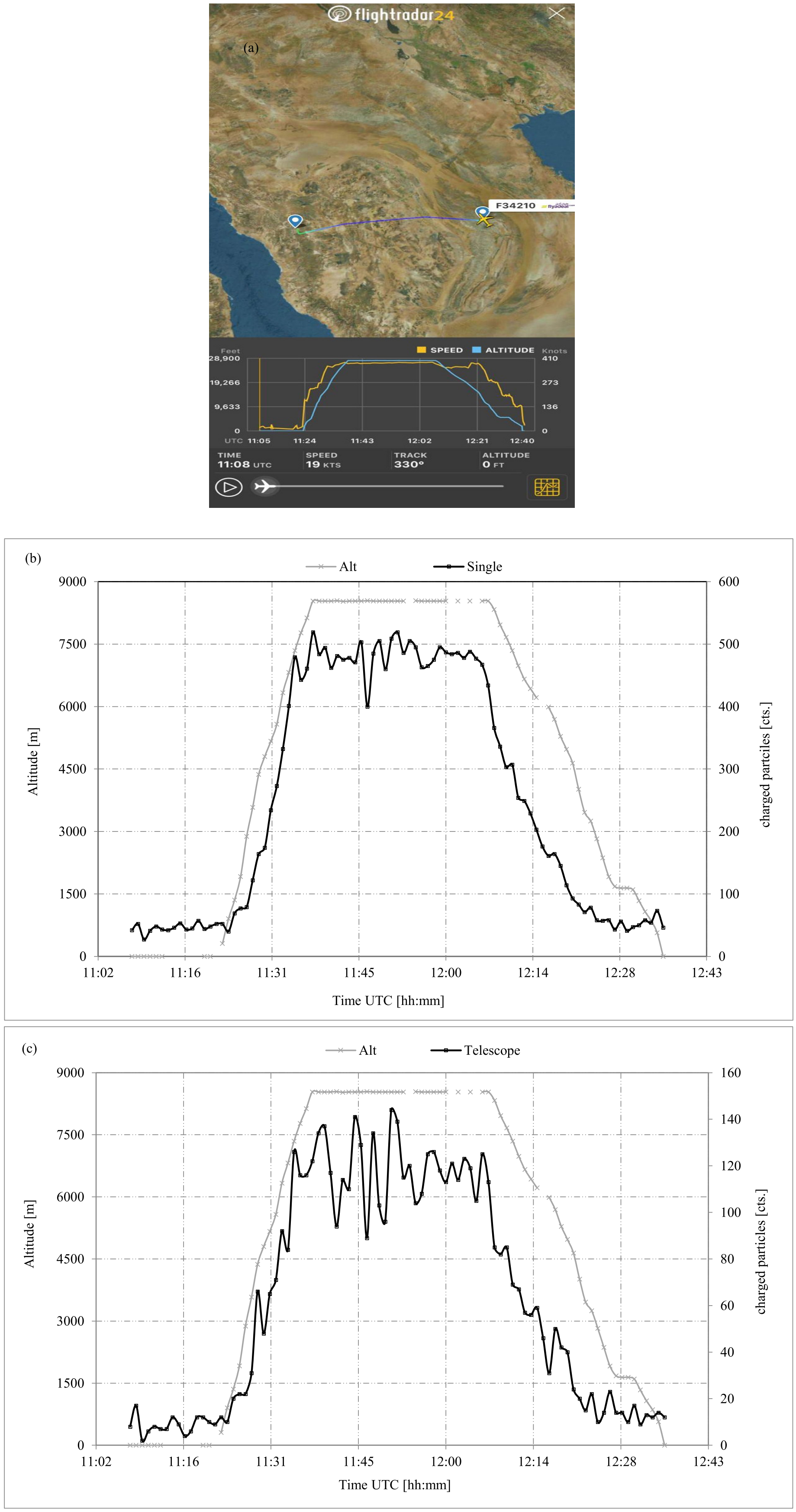

Fig. 9. (a) Flight route on January 29, 2020 from Riyadh to Medina (https://www.flightradar24.com) (b) 1 min charged particles recorded by the single-counter, and (c) by the telescope channel. The altitudes of the flight are indicated.

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