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Neutron Monitor Data as Input to European Projects

SWESNET and PECASUS

Norma Bock Crosby [1], Mark Dierckxsens, Erwin De Donder

1 Royal Belgian Institute for Space Aeronomy, Brussels, Belgium, norma.crosby@aeronomie.be

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Abstract
Various space weather services, like those for spacecraft operations and aviation, rely on neutron monitor data. In this paper, two major European projects are discussed, respectively the ESA Space Safety Program Space Weather Service Network (SWESNET) project and the Pan-European Consortium for Aviation Space Weather User Services (PECASUS) project. Neutron monitor data is used by several products in the SWESNET Space Radiation Expert Service Centre product portfolio (e.g., ANeMoS products, AVIDOS, COMESEP, RadSEP, and UTU-SEP products). PECASUS relies on neutron monitor data to estimate the radiation exposure at flight level, a key input for compiling ICAO radiation advisories. Maintaining these and other products that depend on neutron monitor real-time data will require further extensions and support of the current neutron monitor network with new or updated stations.

1. Introduction

The approximate 11-year solar cycle alternates between solar minimum, when the sunspot number is at its lowest, and solar maximum, when it is at its highest. During the latter, the interplanetary magnetic field strength increases, resulting in enhanced shielding of the heliosphere against penetrating Galactic Cosmic Ray (GCR) particles. In contrast, during solar minimum, GCRs have easier access entering the heliosphere, subsequently arriving in the inner Solar System and interacting with Earth's atmosphere. When primary GCRs collide with nuclei in Earth's atmosphere secondary particles (e.g., protons, neutrons, pions, muons from pion decays, photons, electrons) are created resulting in what is known as cosmic ray air showers. The approximate constant GCR background, highest at solar minimum and lowest at solar maximum, is monitored by ground-based detectors such as neutron monitors that record variations in the nucleon component of GCRs (Similä et al., 2021; Simpson, 1957, 2000).

Strong Solar Energetic Particle (SEP) events, most often associated with solar maximum, are also known to occur when solar activity is close to its minimum (Bütikofer et al. 2009). SEP events with space-

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based proton flux energies exceeding about 500 MeV may in some instances reach the upper layers of the atmosphere and produce air showers. This elevated radiation can often be observed as an increase in ground-based neutron monitor observations of the GCR background in what is called Ground Level Enhancement (GLE) event (Mavromichalaki et al. 2022; Souvatzoglou et al. 2014). This increase in particle radiation poses a hazard to avionics (e.g., single event effects in micro-electronic devices). The risk for negative health effects due to the cumulative radiation dose received by aircrew and frequent flyers over time, especially at high latitudes and altitudes, cannot be excluded and is the reason why monitoring programs exist (Meier et al. 2020, Hands et al. 2022). The impact of GLEs on the radiation environment is generally negligible, but SEP events have been found in cosmogenic isotope data suggesting the possibility that much stronger events could occur in the future (Usoskin et al. 2023 and discussion therein). In addition, indirect medical radiation effects associated with air travel can impact people's health, namely through malfunctions of medical devices (e.g., pacemakers, epilepsy neurostimulators) caused by single event effects in microelectronics (Dong et al. 2016, Meier et al. 2020). Therefore, it is important that ground-based observations such as those provided by neutron monitors are available to monitor the GCR background and provide timely notifications of GLE events which can last for several hours (Anashin et al. 2009, Mavromichalaki et al. 2007, Souvatzoglou et al. 2014).

This paper presents two European projects that rely on neutron monitor data for providing space weather services, respectively the ESA Space Safety Program Space Weather Service Network (SWESNET) project and the Pan-European Consortium for Aviation Space Weather User Services (PECASUS) project. The paper concludes by highlighting several new neutron monitors and by providing recommendations for maintaining the neutron monitor network.

2. ESA SWE Service Network & SWESNET

The ESA Space Safety Program Space Weather Service Network (https://swe.ssa.esa.int/, last accessed 2026 Jan 22) monitors and helps in mitigating hazards from space due to space weather. The SWESNET project (https://swe.ssa.esa.int/swesnet-project, last accessed 2026 Jan 22) is a Consortium of more than 50 groups bringing together 1.) the pre-operational activities of five Expert Service Centres (ESCs) covering Solar Weather, Heliospheric Weather, Space Radiation, Ionospheric Weather, and Geomagnetic Conditions, 2.) the SSA Space Weather Coordination Centre, and 3.) developments to improve service capability and network maturity, and to stimulate the end-user engagement. Several Space Radiation ESC products use neutron monitor data and are presented below.

2.1 ANeMoS products

Built and provided by the National and Kapodistrian University of Athens Cosmic Ray Group the ANeMoS product group consists of two products that rely on neutron monitor data, respectively ›GLE Alert++‹ and ›Multi Station Neutron Monitor Data‹.

Every minute the GLE Alert++ service produces an individual neutron station alert graph for each station participating in the neutron monitor network and a General GLE Alert Graph (Mavromichalaki et al. 2022). GLE Alert++ issues an alert when at least three neutron monitor stations are in alert mode. Archived GLEs can be accessed via the GLE Alert system and as an example GLE72 is shown in Figure 1.

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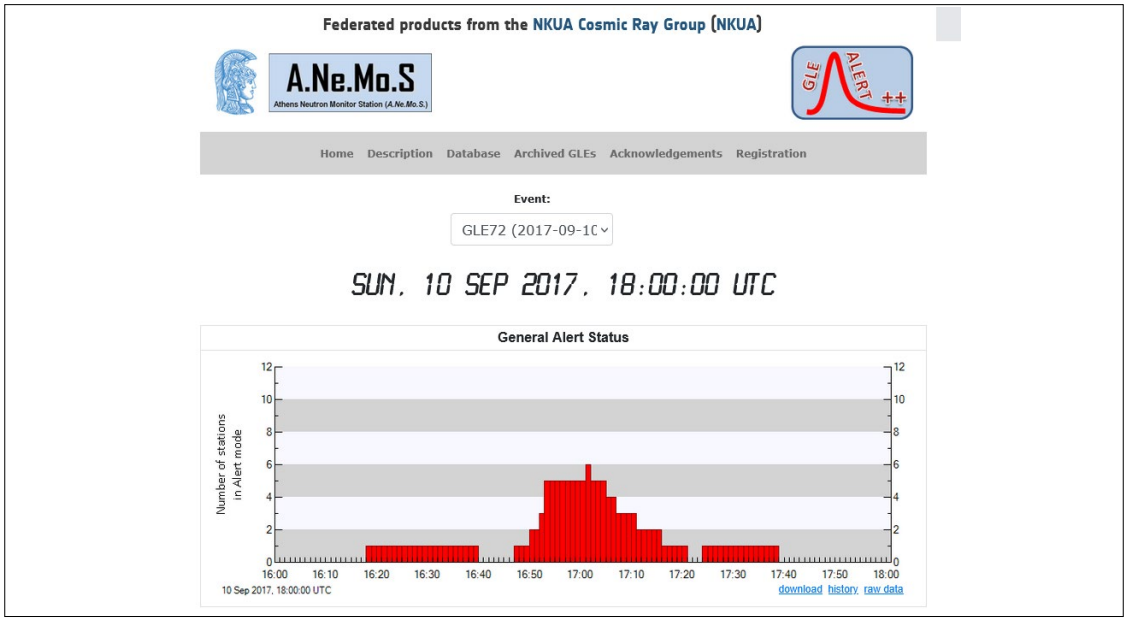

Fig. 1: GLE72 event occurring on 2017 Sep 10 as presented on the ›Archived GLEs‹ page (https://swe.ssa.esa.int/anemos-federated).

Three neutron monitor stations are seen to be simultaneously in alert mode at 16:53 on 2017 Sep 10 triggering GLE Alert++ to issue an alert (Mavromichalaki et al. 2018).

The Multi Station Neutron Monitor Data is a copy (slave server) of the Neutron Monitor DataBase (NMDB, https://www.nmdb.eu/, last accessed 2026 Jan 22). Its web interface to the NMDB allows the user to access GCR and SEP measurements from neutron monitors located around the world for user selected time intervals (see Figure 2). In addition, the user can select various output formats (plot, ascii, file) of the selected data.

2.2 AVIDOS

AVIDOS (AVIation DOSimetry), a product available on the ESA Space Weather Portal (https://swe.ssa.esa.int/avidos-federated, last accessed 2026 Jan 22), is an informational and educational software built and provided by Seibersdorf Laboratories that estimates cosmic radiation dose at civil flight altitudes to passengers and aircrew. Figure 3 is a screenshot of the main page and shows the three AVIDOS modes that are available. Public mode is the simplest one and for calculations requires only departure, destination, and the date of the flight. In aircrew mode one can perform an advanced analysis by using a detailed flight route, and science mode allows for radiation dose estimation for GLEs.

The contribution of GCRs to effective dose levels at flight altitudes is described in Latocha et al. (2009). For GCR calculations, AVIDOS employs a multi-parameter model built upon Monte Carlo simulations of cosmic radiation transport in the atmosphere and appropriate fluence-to-dose conversion coefficients. AVIDOS uses near real-time count rates from the neutron monitor station in Oulu, Finland, to assess the impact of GLEs (Latocha and Beck, 2016). Based on obtained neutron monitor count rates, AVIDOS constructs two estimates for the primary solar proton energy spectrum (soft and hard version) that are then folded with results of Monte Carlo simulations. Calculations are possible for many different altitu-

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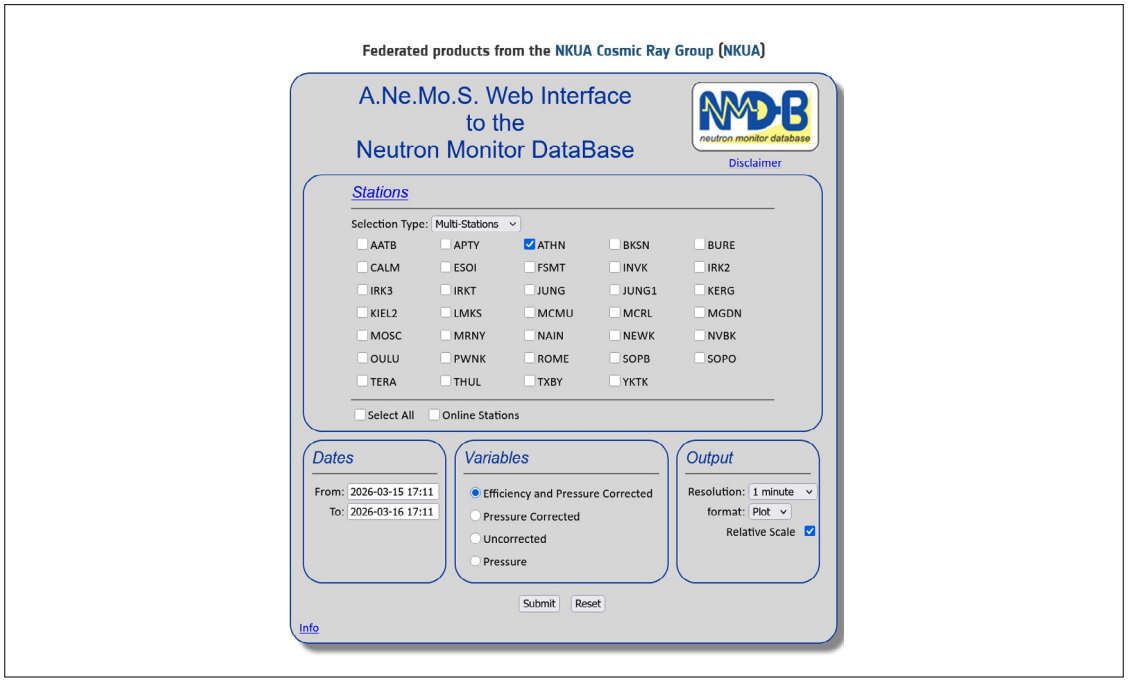

Fig. 2: Screenshot of the Multi Station Neutron Monitor Data (https://swe.ssa.esa.int/anemos-federated).

Fig. 3: Screenshot of the AVIDOS main page (https://swe.ssa.esa.int/avidos-federated).

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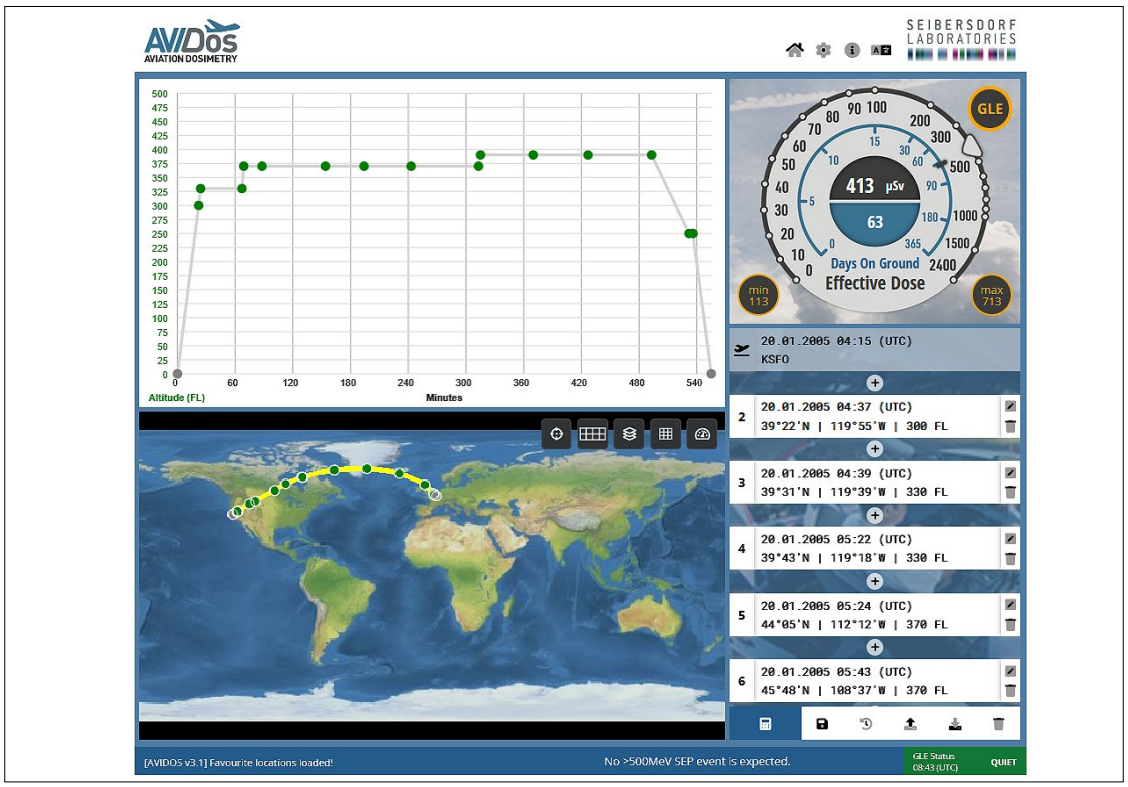

Fig. 4: Advanced analysis of a detailed flight route using multiple waypoints during the GLE69 event of 20 of Jan. 2005 while in aircrew mode (https://swe.ssa.esa.int/avidos-federated).

des up to about 15 km of altitude, all geographical positions, and all phases of solar activity. Currently, preloaded spectra for three GLEs (GLE42 on 1989 Sep 29, GLE69 on 2005 Jan 20, and GLE72 on 2017 Sep 10) are implemented in the AVIDOS system for an assessment of associated effective doses. However, the science mode allows for estimation of effective dose for any GLE and any flight when the solar proton spectrum and flight route are both provided by the user as input data. Figure 4 has been produced in aircrew mode and is an example of real-time estimation of the effective dose for a flight departing from San Francisco, USA, and arriving at Charles de Gaulle Airport, France during the 2005 Jan 20 GLE69 event. By clicking on the relevant icons, the user can upload an own flight profile using a defined format, download the results, and store the data in a personal account on the AVIDOS server.

2.3 COMESEP

The COMESEP Alert System was built and is provided by the Royal Belgian Institute for Space Aeronomy. It contains a tool that provides SEP (proton) storm alerts for energies greater than 10 MeV and 60 MeV in the form of a risk level, combining the probability and expected impact intensity for every observed Earth directed solar flare with a magnitude of at least M1 (Crosby et al. 2012). Figure 5 shows the SEP proton storm alerts for the two energies that were issued by the SEPForecast tool during the period 2013 Nov 5–6.

The SEPForecast tool in the COMESEP system provides predictions based on solar flare intensity and longitude location, as well as the CME speed and width, if an observed CME can be associated with the

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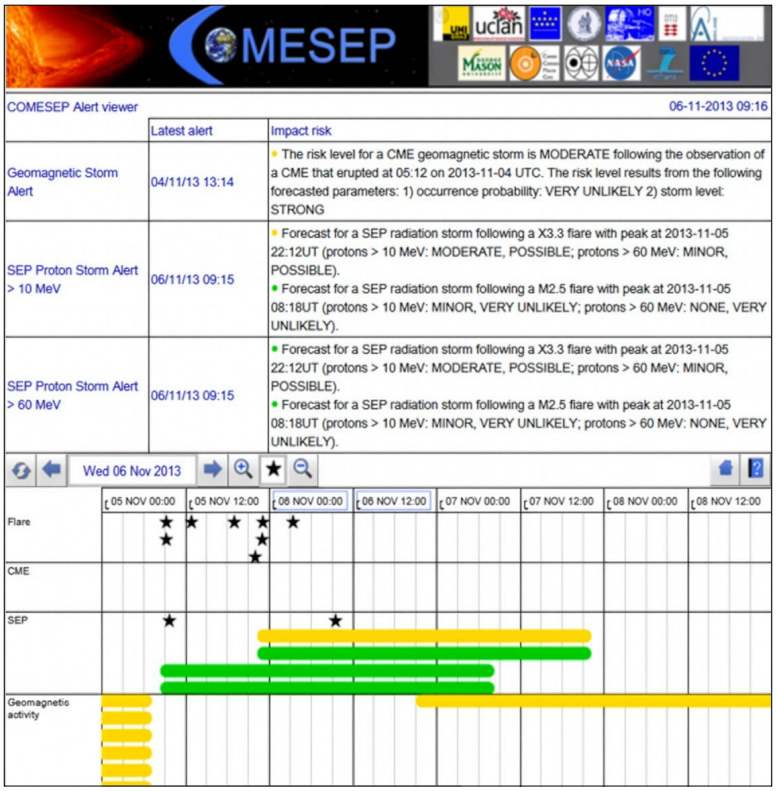

Fig 5: Snapshot of COMESEP SEP (proton) storm alerts for (E > 10 MeV and E > 60 MeV) issued on 5 and 6 Nov 2013 (https://swe.ssa.esa.int/bira-comesep-federated).

flare, and if an alert is issued by GLE Alert++. When a solar flare of M- or X-class alert is received within the COMESEP Alert System, an SEP alert is issued using the information available at that time. Subsequent updates are provided if more information becomes available. Predictions are based on a statistical analysis of SEP events and their parent solar activity during Solar Cycle 23 (Dierckxsens et al. 2015). Additionally, SEPForecast produces predicted time profiles of SEP intensity at 1 AU from the Sun obtained with the SPARX tool which consults a previously generated database of test particle model simulation outputs (Marsh et al. 2015).

Currently, the interactive features of the COMESEP Alert page are disabled due to security issues linked to the outdated underlying technology. The SEPForecast tool has been re-implemented as a stand-alone tool and is expected to replace the COMESEP Alert page in Q2/2026 on the ESA Space Weather Service Portal.

2.4 RadSEP

The Department of Radiation Biology of the DLR Institute of Aerospace Medicine provides the RadSEP product which is a post-event analysis of SEP events for avation radiation exposure. Two GLEs, i.e., GLE69 (Matthiä et al. 2009a) and GLE70 (Matthiä et al. 2009b) have been analyzed and dose rates for generic flight profiles calculated. For each analysed GLE, the user can select from a list of flights and for each flight the departure time with respect to the event onset. Figure 6 is a post-event analysis output example for the selected flight route ›Frankfurt–Tokyo‹ during GLE69 which occurred on 2005 Jan 20.

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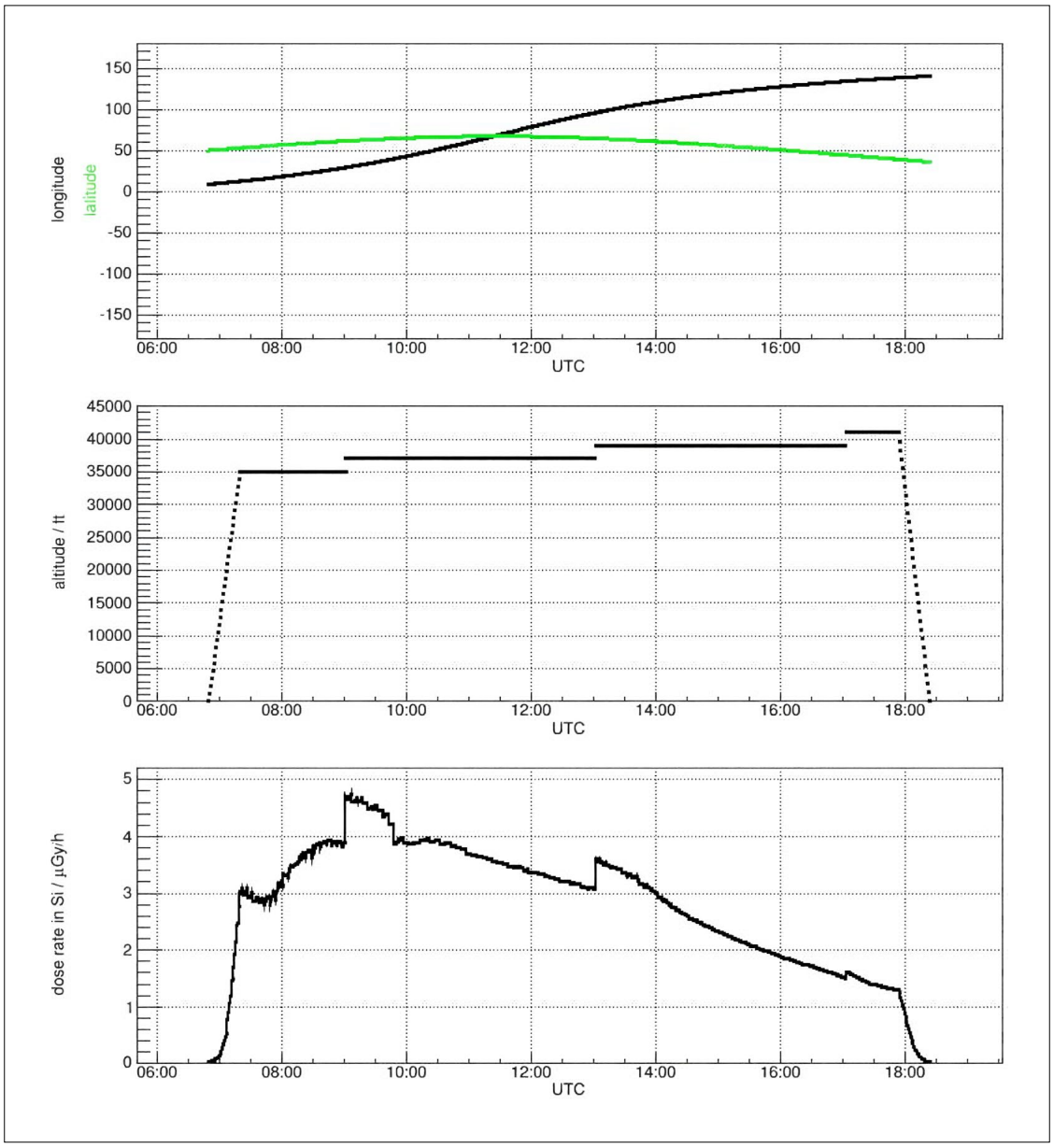

Fig. 6: Output example of the flight route Frankfurt to Tokyo during GLE 69. Upper panel: Flight latitude and longitude as a function of time, Middle panel: Flight altitude as a function of time, Lower panel: Dose rate as a function of time (https://swe.ssa.esa.int/dlr-iam2-federated).

2.5 UTU-SEP products

The University of Turku provides two UTU-SEP group products that use neutron monitor data. The UTU-SEP ›Very high-energy Solar Energetic Particle environment mission specification: Proton fluence‹ consists of a calculator to evaluate the cumulative and worst-case event fluences for very high-energy (10-1000 MeV) protons for space mission durations between 0.5 and 7 years in GEO and near-Earth orbits. The model is based on an analysis of GLEs and sub-GLEs between April 1976 and December 2017, where sub-GLEs refer to SEP events with proton energies above 300 MeV that are registered only by high-alti-

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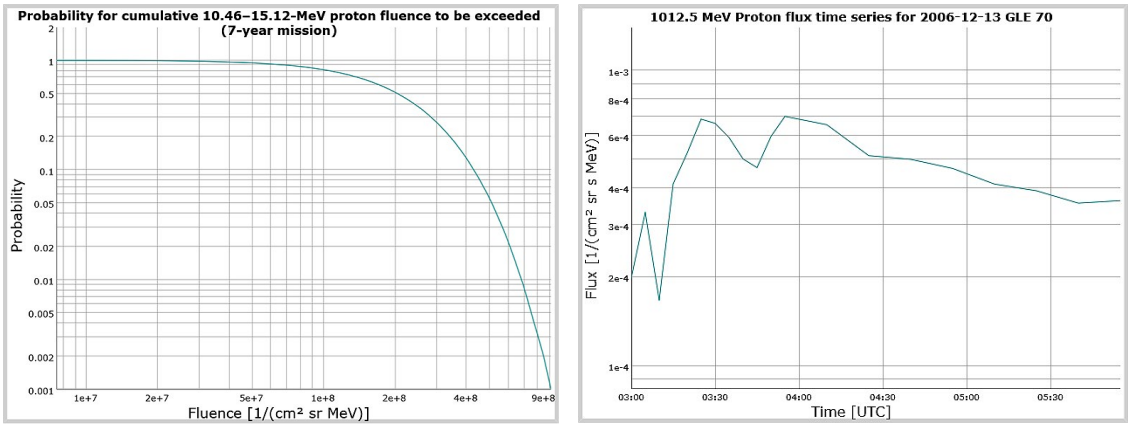

Fig 7: Left panel: Output example of the probability for cumulative 10.46-15.12 MeV proton fluence to be exceeded for a seven year space mission. Right panel: Output example of the 1012.5 MeV proton flux time series for the GLE 70 event on 2006 Dec 13 (https://swe.ssa.esa.int/utu-srl-federated).

tude polar neutron monitors. Figure 7 (left panel) is an example of the probability for a cumulative 10.46-15.12 MeV proton fluence to be exceeded for a seven-year space mission.

The UTU-SEP ›Very high-energy solar proton event database‹ consists of very high-energy (>300 MeV) solar proton events and covers solar cycles 22-24, i.e., between September 1986 and December 2019. Specifically, the database includes 33 ground level events, which have been detected with neutron monitors (GLEs 40-72) and 35 events which have been detected with space-borne detectors above 300 MeV but have not produced sufficient fluxes at high energies to be detected with ground-level neutron monitors near sea level. The database includes differential fluence and peak flux spectra for all events. In addition, flux spectra at 5 min. resolution around the high-energy peak of the event are provided for six of the well-observed GLEs based on the inversion method described in Mishev et al. (2014). In Figure 7 (right panel), the 1012.5 MeV proton flux time series for the GLE 70 event ocuring on 2006 Dec 13 is shown.

3. PECASUS

The Pan-European Consortium for Aviation Space Weather User Services PECASUS project (https://pecasus.eu/, last accessed 2026 Jan 22), led by the Finnish Meteorological Institute is one of the four International Civil Aviation Organization (ICAO) Global Space Weather Service Centres (Kauristie et al. 2021). As a service provider, it delivers ›Moderate/Severe‹ advisories for High Frequency Communication (HF COMM), Global Navigation Satellite Systems (GNSS) and RADIATION. ICAO Radiation thresholds are:

- Moderate: 30 < effective dose rate (microSievert/h) ≤ 80
- Severe: 80 < effective dose rate (microSievert/h)

An example of the PECASUS Radiation Dashboard is shown in Figure 8 based on the space environmental conditions on 11 May 2024.

PECASUS relies on neutron monitor data to estimate the radiation exposure at flight level, a key input for compiling ICAO radiation advisories. Three sources that rely on neutron monitor data are used as inputs:

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RADIATION DASHBOARD on 2024-05-11 02:10 UTC				
AVIDOS FL>460	AVIDOS FL≤460	GOES Proton	GLE Alert	COMESEP
Current status:	Current status:	Current status:	Current status:	Current status:
2024-05-11 02:10	2024-05-11 02:10	2024-05-11 02:10	2024-05-11 02:10	2024-05-11 02:10
QUIET	QUIET	ONGOING	GLE ALERT	SEP ALERT
Past 3-hour status:	Past 3-hour status:	Past 3-hour status:	Past 3-hour status:	Past 3-hour status:
QUIET	QUIET	ONGOING	GLE ALERT	SEP ALERT

Fig. 8: Example of the PECASUS Radiation Dashboard on 11 May 2024 (copyright: Solar-Terrestrial Centre of Excellence).

- AVIDOS (Oulu neutron monitor station data) is used to construct a world map with nowcast effective dose rate for a wide range of flight levels.
- GLE Alert++ (27 stations) is used as input to the PECASUS radiation alert table and verification for increased radiation dose at flight level.
- Neutron monitor world map provides visualization/position of the stations and their modus (alert/watch/warning or quiet), based on the ANeMoS database.

4. Looking Forward

Maintaining products and services that rely on neutron monitor data such as those provided by the SWESNET and PECASUS project will require the continued operation of neutron monitor stations. Ground-based neutron monitors have been shown to provide very useful data for the assessment of cosmic radiation dose rates for the aviation industry. In addition, advancing our current understanding of cosmic ray events, specifically those that result in GLEs can be pursued by combining ground-based data with space environment data (Crosby et al. 2024).

Further extensions and support of the current neutron monitor network with new or updated stations and services in terms of reliable real-time data is also vital. Recent initiatives in this area show a positive trend in expanding and improving the network. For example, a new 9-counter neutron monitor was installed at the RMI Geophysical Centre in Dourbes, Belgium in January 2019 and is in full operational mode complementing the already existing Doubes neutron monitor (http://neutronmonitor.meteo.be/, last accessed 2026 Jan 22). Since mid-August 2023 the Budapest Neutron Monitor Station has been operating in Hungary (https://www.nmdb.eu/station/buda/, last accessed 2026 Jan 22). Filling a critical observational gap between the existing Mexico City Cosmic Ray Observatory in Mexico and Princess Sirindhorn Neutron Monitor station in Thailand, the Haleakalā Neutron Monitor Station (HLEA) and Thailand-Hawai'i Monitor (THIMON), located at the summit of Haleakalā, Maui, USA have been operational since December 2024 (Bindi et al. 2024). Recently, under the U.K. Space Weather Innovation, Modelling, Measurement and Risk (SWIMMR) programme a new compact neutron monitor design (the NM-2023) has been underway and includes two new ground-based neutron monitor stations for UK operation (Aspinall et al. 2024). The newly installed neutron monitor is located at the Met Office site in Cornwall and a smaller monitor will soon be based at Lancaster University.

Not only will the future of the neutron monitor network require maintaining and upgrading existing stations, as well as investing in new stations, but also sustaining robust data open access repositories and fostering international collaboration will be essential. More importantly, the future of the neutron monitor network community calls for a new generation of scientists and engineers. Not only should they

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be scientific experts, but their expertise should also cover the handling of instrumentation and related technical issues, data quality, and data cleaning methods. In addition, understanding the user needs when defining new products and services, as well as pursuing novel approaches to secure funding will be critical. Ensuring a bright future for the neutron monitor community will be a challenging endeavour, but one that can be achieved if recommendations such as these are embraced.

Acknowledgements

The authors acknowledge the continued commitment of the neutron monitor community in operating their stations so that products and services that rely on neutron monitor data can be maintained. In addition, the authors acknowledge the ESA Space Safety Programme and the product providers (Athens Neutron Monitor Station of National and Kapodistrian University of Athens, Seibersdorf Labor GmbH, COMESEP Consortium (https://comesep.eu/, last accessed 2026 Jan 22), Department of Radiation Biology of the DLR Institute of Aerospace Medicine, and University of Turku) for the use of the data obtained from the ESA SWE Portal.

References

Anashin, V., Belov, A., Eroshenko, E., Krjakunova, O., Mavromichalaki, H., Ishutin, I., et al. 2009, The ALERT signal of ground level enhancements of solar cosmic rays: Physics basis, the ways of realization and development. In: Giller, M, Szabelski, J (eds.), Proceedings of the 31st International Cosmic Ray Conference. Łódź, http://cr0.izmiran.ru/GLE-AlertAndProfilesPrognosing/Publication/icrc1104_The%20ALERT%20signal%20of%20ground%20level%20enhancements%20of%20solar%20cosmic....pdf (last accessed 2026 Jan 22).

Aspinall, M. D., Alton, T. L., Binnersley, C. L., et al. 2024, A new ground level neutron monitor for space weather assessment. Scientific Reports 14, 7174, https://doi.org/10.1038/s41598-024-57583-0.

Bindi, V., Consolandi, C., Corti, C., Nikonov, N., Wang, S., Ryan, J., Nuntiyakul, W. 2024, Haleakala Neutron Monitor Redeployment. Proceedings of 38th International Cosmic Ray Conference 444, 1299, https://doi.org/10.22323/1.444.1299.

Bütikofer R., Flückiger, E. O., Desorgher, L., Moser, M. R., Pirard, B. 2009, The solar cosmic ray ground-level enhancements on 20 January 2005 and 13 December 2006. Advances in Space Research 43(4), 499–503, https://doi.org/10.1016/j.asr.2008.08.001.

Crosby, N. B., Veronig, A., Robbrecht, E., Vrsnak, B., Vennerstrom, S., Malandraki, O., Dalla, S., Rodriguez, L., Srivastava, N., Hesse, M., Odstrcil, D., COMESEP Consortium. 2012, Forecasting the space weather impact: The COMESEP project. In: Hu, Q., Li, G., Zank, G.P., Ao, X., Verkhoglyadova, O., Adams, J. H. (eds.), Space Weather: The Space Radiation Environment: 11th Annual International Astrophysics Conference, Palm Springs, CA, USA: American Institute of Physics, 159–164, https://doi.org/10.1063/1.4768760.

Crosby, N., Mavromichalaki, H., Malandraki, O., Gerontidou, M., Karavolos, M., Lingri, D., et al. 2024, Very high energy solar energetic particle events and ground level enhancement events: Forecasting and alerts. Space Weather 22, e2023SW003839. https://doi.org/10.1029/2023SW003839.

Dierckxsens, M., Tziotziou, K., Dalla, S., et al. 2015, Relationship between Solar Energetic Particles and Properties of Flares and CMEs: Statistical Analysis of Solar Cycle 23 Events. Solar Physics 290, 841–874, https://doi.org/10.1007/s11207-014-0641-4.

Dong, A. X., Gwinn, R. P., Warner, N. M., Caylor, L. M., Doherty, M. J. 2016, Mitigating bit flips or single event upsets in epilepsy y neurostimulators, Epilepsy & Behavior Case Reports 5, 72–74, https://doi.org/10.1016/j.ebcr.2016.04.002.

Hands, A. D. P., Lei, F., Davis, C. S., Clewer, B. J., Dyer, C. S., Ryden, K. A. 2022, A new model for nowcasting the aviation radiation environment with comparisons to in situ measurements during GLEs. Space Weather 20, e2022SW003155, https://doi.org/10.1029/2022SW003155.

Kauristie, K., Andries, J., Beck, P., Berdermann, J., Berghmans, D., Cesaroni, C., De Donder, E., de Patoul, J., Dierckxsens, M., Doornbos, E., et al. 2021, Space Weather Services for Civil Aviation – Challenges and Solutions. Remote Sensing 13, 3685, https://doi.org/10.3390/rs13183685.

Latocha, M., Beck, P., Rollet, S. 2009, AVIDOS – A software package for European accredited aviation dosimetry. Radiation Protection Dosimetry 136, 286–290, https://doi.org/10.1093/rpd/ncp126.

Latocha, M., Beck, P. 2016, Cosmic radiation assessment at ESA's space weather portal with AVIDOS. In: Proceedings of the 2016 16th European Conference on Radiation and Its Effects on Components

and Systems (RADECS), Bremen, Germany 2016, 1–4, https://doi.org/10.1109/RADECS.2016.8093138.

Marsh, M. S., Dalla, S., Dierckxsens, M., Laitinen, T., Crosby, N. B. 2015, SPARX: A modeling system for Solar Energetic Particle Radiation Space Weather forecasting. Space Weather 13, 386–394, https://doi.org/10.1002/2014SW001120.

Matthiä, D., Heber, B., Reitz, G., Meier, M., Sihver, L., Berger, T., Herbst, K. 2009a, Temporal and spatial evolution of the solar energetic particle event on 20 January 2005 and resulting radiation doses in aviation. Journal of Geophysical Research: Space Physics 114(A08104), https://doi.org/10.1029/2009ja014125.

Matthiä, D., Heber, B., Reitz, G., Sihver, L., Berger, T., Meier, M. 2009b, The Ground Level Event 70 on December 13th, 2006 and Related Effective Doses at Aviation Altitudes. Radiation Protection Dosimetry 136(4), 304–310, https://doi.org/10.1093/Rpd/Ncp141.

Mavromichalaki, H., Paouris, E., Karalidi, T. 2007, Cosmic-ray modulation: An Empirical relation with solar and heliospheric parameters. Solar Physics, 245(2), 369–390. https://doi.org/10.1007/s11207-007-9043-1.

Mavromichalaki, H., Gerontidou, M., Paschalis, P., Paouris, E., Tezari, A., Sgouropoulos, C., et al. 2018, Real-time detection of the ground level enhancement on 10 September 2017 by A.Ne.Mo.S.: System report. Space Weather 16, 1797–1805, https://doi.org/10.1029/2018SW001992.

Mavromichalaki, H., Paschalis, P., Gerontidou, M., Papailiou, M.-C., Paouris, E., Tezari, A., et al. 2022, The updated version of the A.Ne.Mo.S. GLE alert system: The case of the ground-level enhancement GLE73 on 28 October 2021. Universe 8(7), 378. https://doi.org/10.3390/universe8070378.

Meier, M. M., Copeland, K., Klöble, K. E. J., Matthiä, D., Plettenberg, M. C., Schennetten, K., Wirtz, M., Hellweg, C. E. 2020, Radiation in the Atmosphere – A Hazard to Aviation Safety? Atmosphere 11, 1358, https://doi.org/10.3390/atmos11121358.

Mishev, A., L., Kocharov, G., Usoskin, I. G. 2014, Analysis of the ground level enhancement on 17 May 2012 using data from the global neutron monitor network. Journal of Geophysical Research: Space Physics 119(2), https://doi.org/10.1002/2013JA019253.

Similä, M., Usoskin, I., Poluianov, S., Mishev, A., Kovaltsov, G. A., Strauss, D. T. 2021, High-altitude polar NM with the new DAQ system as a tool to study details of the cosmic-ray induced nucleonic cascade. Journal of Geophysical Research: Space Physics, 126(4), e2020JA028959, https://doi.org/10.1029/2020JA028959.

Simpson, J. A. 1957, Cosmic-radiation neutron intensity monitor. Annals of the International Geophysical Year 4, 351–373, https://doi.org/10.1016/B978-1-4832-1304-0.50020-8.

Simpson, J. A. 2000, The cosmic ray nucleonic component: The invention and scientific uses of neutron monitor. Space Science Reviews 93, 1–20. https://doi.org/10.1023/A:1026567706183.

Souvatzoglou, G., Papaioannou, A., Mavromichalaki, H., Dimitroulakos, J., Sarlanis, C. 2014, Optimizing the real-time ground level enhancement alert system based on neutron monitor measurements: Introducing GLE Alert Plus. Space Weather 12(11), 633–649, https://doi.org/10.1002/2014SW001102.

Usoskin, I., Miyake, F., Baroni, M., Brehm, N., Dalla, S., Hayakawa, H., et al. 2023, Extreme solar events: Setting up a paradigm. Space Science Reviews 219(8), 73. https://doi.org/10.1007/s11214-023-01018-1.

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