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Solar Cosmic Ray Dose Rate Assessments During GLE 72 Using MIRA and PANDOCA

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Key Points:

- GLE 72 caused concern among aircrew members and reached S 3 on the NOAA scale, but at and below 12.2 km the solar *D* index remained at zero
- Solar cosmic ray effective dose rates calculated using MIRA and PANDOCA during GLE 72 agreed well where vertical cutoff rigidity was low
- In addition to GOES data, solar radiation alert system models for aircrews can benefit from neutron monitor or other data

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Abstract Ground level enhancement (GLE) 72, which occurred 10 September 2017, is the most recent of two solar particle-induced enhancements in ground level measurements of cosmic radiation secondary neutrons in solar cycle 24. GLEs have been unusually rare in this solar cycle. GLEs can significantly increase ionizing radiation dose rates at aviation altitudes for hours to days, leading to concern among crewmembers. Real-time monitoring and preliminary evaluation of solar proton events, including GLEs, in regard to effective dose rates at aviation altitudes has been ongoing since the U.S. Federal Aviation Administration began operating its Solar Radiation Alert System (SRAS) in 2002. Since then, SRAS has been revised multiple times. In this report, model calculations of dose rates during GLE 72 from Maps of Ionizing Radiation in the Atmosphere (MIRA), the latest SRAS software based on CARI-7A, are compared with those from the model Professional Aviation Dose Calculator (PANDOCA) developed by the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt). At very low cutoff rigidities model calculations agree within 40% and indicate no significant increase in radiation exposures at commercial aviation altitudes. The larger than expected differences at very low cutoff rigidities indicate Geostationary Orbiting Environmental Satellite particle flux data alone that are insufficient to produce consistent solar particle dose estimates.

1. Introduction

Very large solar proton events (SPEs) are a form of space weather that can result in increased counting rates at neutron monitor stations on Earth. Usually, most of the count rate in such monitors is from galactic cosmic radiation (GCR) secondary neutrons, so this kind of event is called a ground level enhancement (GLE).

GLEs can significantly increase ionizing radiation dose rates at aviation altitudes for hours to days, particularly at high latitudes and altitudes, where Earth's atmosphere and magnetic field provide the least protection. The impacts of SPEs without GLEs on this radiation field were studied by Kataoka et al. (2015) using several historic events. It could be shown that corresponding dose rates would not have exceeded 5 μSv/hr at conventional flight altitudes of 12.2 km (40,000 ft) during the largest SPE without GLE that was investigated.

Increased dose rates are a long-term health concern for crewmembers, who can theoretically incur over 100 mSv of exposure to GCRs over the course of a lengthy career in aviation (estimated average 3 mSv/year; United Nations Scientific Committee on the Effects of Atomic Radiation, 2000). While extremely high flight doses have not been measured yet during large SPEs (they are very rare events), model calculations indicate the possibility of the dose to the conceptus exceeding the widely accepted recommended limit of 1 mSv during a single flight at altitudes used by commercial carriers (e.g., Copeland et al., 2008; Dyer et al., 2003).

The University of Oulu maintains an archive of GLEs (University of Oulu, 2018). In the previous five solar cycles, the average rate of occurrence was slightly more than 1 per year, with at least 10 in each cycle. So far, only two GLEs have occurred during this solar cycle (cycle 24). The most recent of these was GLE 72 (Figure 1; Space Weather Prediction Center, 2018), which occurred 10 September 2017. During this event, the greatest shift in count rate relative to pre-event rates was observed at the high-altitude Antarctic Dome A and B monitors, with a maximum of 16% observed at the Dome-B monitor. These were the only monitors to record a count rate increase greater than 10% during this event. There was no obvious event at any monitor with a cutoff rigidity above ~4 GV. Thus, it was relatively weak when compared with other GLEs.

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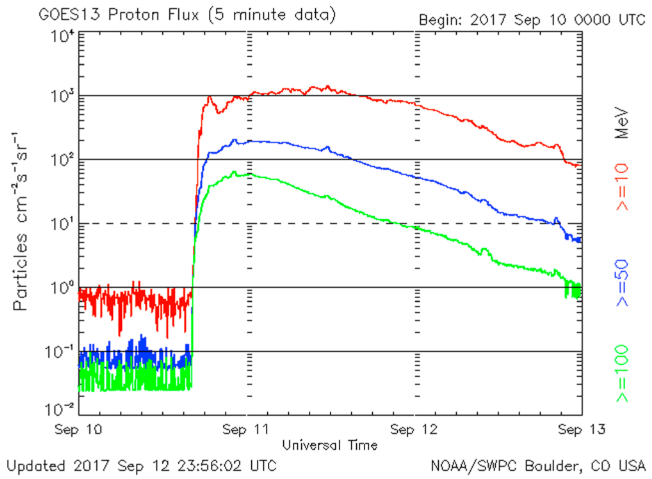

Figure 1. Integral proton flux during and just prior to the onset of GLE 72 as measured on GOES-13 (Space Weather Prediction Center, 2018). GLE = ground level enhancement; GOES = Geostationary Orbiting Environmental Satellite; NOAA = National Oceanic and Atmospheric Administration.

The U.S. Federal Aviation Administration (FAA) began operating its Solar Radiation Alert System (SRAS) in 2002 (Copeland et al., 2005), providing near-real-time (lag of 5–10 min) calculations of dose rates in the atmosphere during SPEs through the U.S. National Oceanic and Atmospheric Administration's Weather Wire Service (NWWS), which is publically accessible (Figure 2). Issued SRAS messages are searchable at the Iowa State University Mesonet archives under the ALTPAV header (Iowa State University, 2018). The SRAS has been updated multiple times (Copeland, 2016, 2018; Copeland et al., 2009). In addition to the advisory information from SRAS, FAA regulations require those operating flights at high latitudes (except flight contained entirely within the Alaska region) to have a plan of action in place in the event of extreme space weather, such as a large SPE (U.S. Government Printing Office, 2018).

The German Aerospace Center (DLR, Deutsches Zentrum für Luft- und Raumfahrt) began the development of its Professional Aviation Dose Calculator (PANDOCA) for the operational dose assessment of aircrew in Germany in 2005. Although its regular application is the assessment of the GCR component, the PANDOCA radiation transport model can also be used to assess solar particle contributions to the radiation field at aviation altitudes using a correspondingly adapted energy spectrum of the impinging particles and to inform aircrew correspondingly (Matthiä et al., 2018, to be published in this issue). The German Aerospace Center was contacted about the impact of GLE 72 on aviation by concerned aircrew members shortly after the event. The corresponding assessment of the radiation field and information provided for aircrew in Germany was based on PANDOCA model calculations.

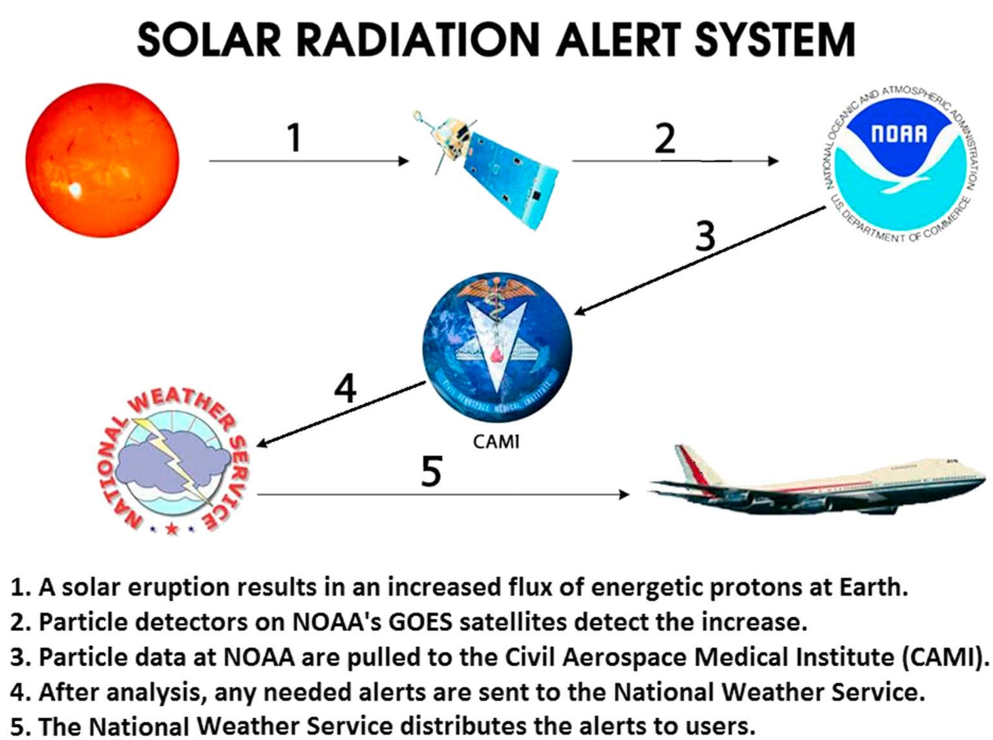

Figure 2. The U.S. Federal Aviation Administration's solar radiation alert system. NOAA = National Oceanic and Atmospheric Administration; GOES = Geostationary Orbiting Environmental Satellite.

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Table 1
Average Effective Dose Rates From Galactic and Solar Cosmic Rays During GLE 72 on 10–12 September 2017, as Calculated by MIRA and PANDOCA

Vertical cutoff rigidity (GV)	Altitude (km [ft × 1,000])	MIRA (μSv/hr)		PANDOCA (μSv/hr)		GCR percent difference[a] (%)
		GCR	SEP	GCR	SEP	
0.01	10.7 (35)	6.32	0.79	5.39	0.47	−14.79
	12.2 (40)	8.25	1.25	7.21	0.94	−12.58
	15.2 (50)	12.72	3.75	10.60	3.04	−16.54
	21.3 (70)	24.01	18.16	—	16.80	
1	10.7 (35)	6.24	0.22	5.38	0.18	−13.80
	12.2 (40)	8.15	0.33	7.20	0.32	−11.64
	15.2 (50)	12.54	0.77	10.56	0.94	−15.52
	21.3 (70)	23.50	2.69	—	3.23	
2	10.7 (35)	5.88	0.06	5.13	0.02	−12.76
	12.2 (40)	7.61	0.09	6.75	0.04	−11.26
	15.2 (50)	11.45	0.15	9.50	0.06	−17.38
	21.3 (70)	20.54	0.24	—	0.08	
3	10.7 (35)	5.29	0.02	4.57	0.00	−13.69
	12.2 (40)	6.78	0.02	5.91	0.01	−12.86
	15.2 (50)	9.85	0.04	8.03	0.01	−18.48
	21.3 (70)	16.35	0.05	—	0.01	
4	10.7 (35)	4.72	0.01	3.99	0.00	−15.40
	12.2 (40)	5.98	0.01	5.10	0.00	−14.77
	15.2 (50)	8.43	0.01	6.75	0.00	−19.95
	21.3 (70)	13.17	0.02	—	0.00	

Note. Average is for the 48 hr starting 1600 UT on 10 September 2017. GLE = ground level enhancement; MIRA= Maps of Ionizing Radiation in the Atmosphere; PANDOCA = Professional Aviation Dose Calculator.
[a]PANDOCA relative to MIRA.

In this report, model calculations of dose rates during GLE 72 from the latest SRAS software, based on CARI-7A (Copeland, 2017), are compared with those calculated with the PANDOCA model from the German Aerospace Center (DLR).

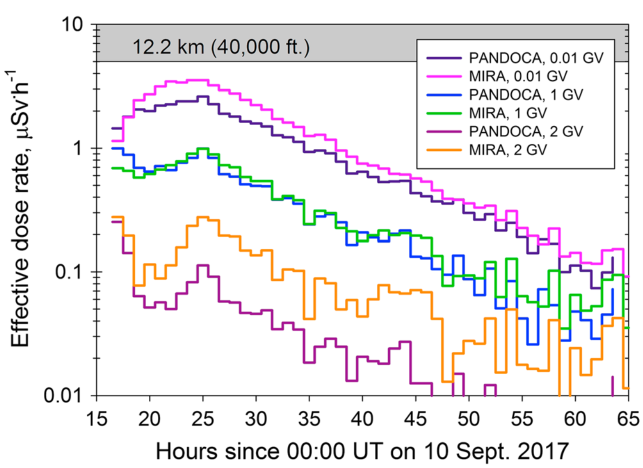

Figure 3. One-hour average SEP dose rates from 1630 UT 10 September 2017 to 1629 UT 12 September 2017 at an altitude of 12.2 km (40,000 ft, FL 400) with R_{cut} = 0.01, 1, and 2 MV, as calculated by MIRA and PANDOCA. Shading indicates the solar radiation *D* index (shaded for *D* = 1, clear for *D* = 0). MIRA= Maps of Ionizing Radiation in the Atmosphere; PANDOCA = Professional Aviation Dose Calculator.

2. Methods

2.1. Maps of Ionizing Radiation in the Atmosphere

The most recent update to the U.S. FAA's SRAS is called Maps of Ionizing Radiation in the Atmosphere (MIRA) and is described in an FAA Office of Aviation Medicine Technical report DOT/FAA/AM-18/6 (Copeland, 2018). It generates world grids of the current cosmic radiation effective dose rates (based on 2007 recommendations in International Commission on Radiological Protection Publication 103 and following International Commission on Radiological Protection (ICRP), 2007, 2010, 2013) in the atmosphere at altitudes ranging from 20,000 to 70,000 ft using effective dose rate calculations of CARI-7A (Copeland, 2017). World grids of solar and GCR effective dose rates are calculated at locations with vertical cutoff rigidities from 0 to 15 GV, using the local interstellar GCR spectrum from the International Standards Organization model ISO 15390:2004 (International Standards Organization, 2004) modulated by the CARI-6 heliocentric potential (O'Brien et al., 2003) for the previous month (adjusted upward internally by 150 MV). GCR are uncorrected for Forbush effects and short-term drift in solar modulation, since these effects are unknown at the time of the event. The solar spectrum generation method was unchanged from previous versions of SRAS based upon 5-min averaged particle sensor data from the National Oceanic and Atmospheric Administration's (NOAA) Geostationary

Table 2

Maximum 1-Hr Average Effective Dose Rates and D Indices From Solar Cosmic Radiation During GLE 72 on 10–12 September 2017, as Calculated by MIRA and PANDOCA

Vertical cutoff rigidity (GV)	Altitude (km [ft × 1,000])	MIRA (μSv/hr)	PANDOCA (μSv/hr)	Percent difference[a]	Solar *D* index[b]
0.01	10.7 (35)	2.23	1.33	−40.16	0
	12.2 (40)	3.54	2.62	−26.06	0
	15.2 (50)	10.52	8.28	−21.28	2
	21.3 (70)	51.66	44.44	−13.97	4
1	10.7 (35)	0.66	0.58	−13.03	0
	12.2 (40)	0.99	1.00	0.71	0
	15.2 (50)	2.27	2.85	25.43	0
	21.3 (70)	7.73	9.68	25.12	1
2	10.7 (35)	0.20	0.17	−11.74	0
	12.2 (40)	0.28	0.25	−8.63	0
	15.2 (50)	0.47	0.41	−14.05	0
	21.3 (70)	0.76	0.59	−22.49	0
3	10.7 (35)	0.08	0.05	−35.56	0
	12.2 (40)	0.11	0.07	−36.07	0
	15.2 (50)	0.17	0.10	−41.59	0
	21.3 (70)	0.24	0.13	−47.64	0
4	10.7 (35)	0.03	0.02	−35.81	0
	12.2 (40)	0.04	0.03	−36.73	0
	15.2 (50)	0.06	0.03	−41.70	0
	21.3 (70)	0.08	0.04	−46.70	0

Note. GLE = ground level enhancement; MIRA= Maps of Ionizing Radiation in the Atmosphere; PANDOCA = Professional Aviation Dose Calculator.
[a]PANDOCA relative to MIRA. [b]Considers both MIRA and PANDOCA results.

Orbiting Environmental Satellite (GOES). GOES data are available to the public from the NOAA Space Weather Prediction Center (SWPC) archives (SWPC, 2018). In brief, GOES differential proton flux channel data for channels P4-P7 (EPEAD), P10 (HEPAD), and P11 (HEPAD) are used to create several single-index power law spectra in rigidity. The process converts the P11 channel back to an integral flux channel, but the uppermost energy is unknown. The spectral index of the uppermost (P11) spectra is first estimated using the P10 and P11 data. If using this index allows all the P11 flux to be accounted for within an upper rigidity of 33 GV, it is assumed to be correct. If this does not account for all the measured flux, the index is altered until all the flux occurs below 33 GV. In a comparison with a more involved method, which used neutron monitor data to correct the spectral index and which also included solar alpha particle fluxes in the dose rates, differences in globally averaged dose rates during seven of the largest SPEs at polar latitudes were generally small: mean = −5.1%, median = −5.4%, standard deviation = 20% (Copeland et al., 2008, 2009). It was noted the method could lead to overestimates for smaller events.

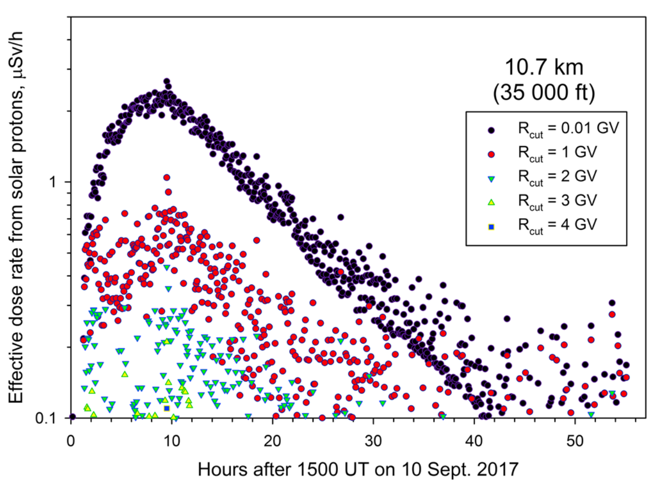

Figure 4. Effective dose rates at 10.7 km (35,000 ft, FL 350) calculated from 5-min averaged GOES-13 proton flux data by MIRA for the period from just before (1500 UT on 10 September) to a few days after the start of GLE 72 at vertical cutoff rigidities from 0.01 to 4 GV. GOES = Geostationary Orbiting Environmental Satellite; MIRA= Maps of Ionizing Radiation in the Atmosphere; GLE = ground level enhancement.

The process for global issuance of solar radiation alert messages to NWWS is unchanged from prior versions of SRAS (Figure 2; Copeland et al., 2009). In addition to the NWWS text output of SRAS, text files needed to build custom map layers, including D indices (Meier & Matthiä, 2014, 2018) for solar and combined solar and galactic cosmic radiation effective dose rates, are constructed from the *CARI-7A* results.

The event was monitored and evaluated in near real time by FAA, but MIRA was undergoing testing and was not providing data to NWWS. Results were recorded for some periods of the event but only from

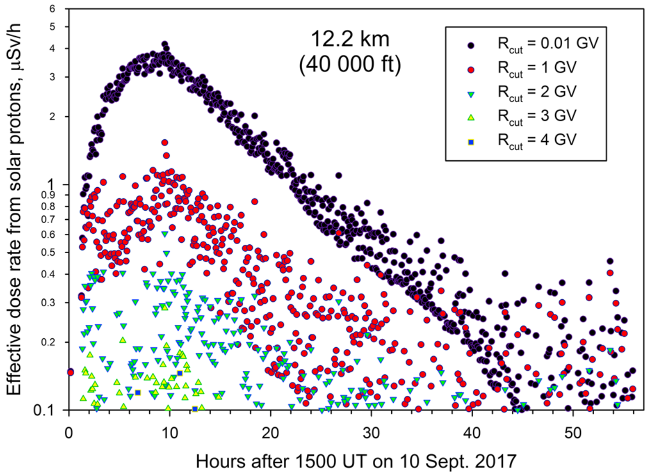

Figure 5. Effective dose rates at 12.2 km (40,000 ft, FL 400) calculated from 5-min averaged GOES-13 proton flux data by MIRA for the period from just before (1500 UT on 10 September) to a few days after the start of GLE 72 at vertical cutoff rigidities from 0.01 to 4 GV. GOES = Geostationary Orbiting Environmental Satellite; MIRA= Maps of Ionizing Radiation in the Atmosphere; GLE = ground level enhancement.

11 September and later. Thus, for this study, rather than using data calculated from the live system, the MIRA solar cosmic ray dose rates were calculated using the daily particle data files at 5-min resolution from the GOES ftp archives of GOES-Primary (GOES-13 for this event) data. These doses rates were found to be identical to those calculated during the live testing that occurred while the event was ongoing. One-hour average dose rates from MIRA were calculated by averaging the 5-min dose rates. Results based on GOES-Secondary (GOES-15 for this event) data were also examined for comparison.

2.2. Professional Aviation Dose Calculator

The PANDOCA model (Matthiä et al., 2014) for the calculation of radiation exposure at aviation altitudes has been developed at DLR and is based on transport calculations performed with GEANT4 (Agostinelli et al., 2003; Allison et al., 2006, 2016) in which the description of the atmosphere and the magnetosphere was provided by the PLANETOCOSMICS toolkit. The model is based on transport calculations of primary protons and alpha particles with energies between 50 MeV and 1 TeV through the atmosphere. The limitation of PANDOCA to primary protons and alpha particles means that at altitudes where heavier GCR ions gain importance, the model tends to underestimate the true value. However, this effect is small at altitudes below 15.2 km (50,000 ft) (Copeland, 2015). As solar energetic particles are mainly protons, the related radiation exposure is not affected by this limitation at higher altitudes either.

For the calculation of the exposure from galactic cosmic radiation PANDOCA comprises the implementation of a model of the primary radiation (Matthiä et al., 2013). PANDOCA is authorized for the assessment of the occupational radiation exposure of aircrew from GCR by the Federal Aviation Office in Germany.

PANDOCA can also be used with arbitrary input spectra and is capable of calculating particle fluxes and a number of dosimetric quantities, for instance, absorbed dose rate in water and silicon, ambient dose equivalent rate, and effective dose rate after ICRP 60 (ICRP, 1991) and ICRP 103 (ICRP, 2007), at arbitrary positions in the atmosphere. In this work, we present results for the effective dose rate using recommendations for the radiation weighting factors of ICRP 103.

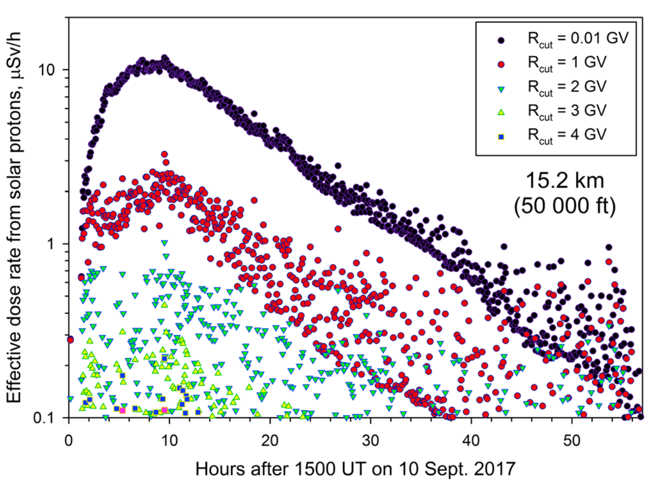

Figure 6. Effective dose rates at 15.2 km (50,000 ft, FL 500) calculated from 5-min averaged GOES-13 proton flux data by MIRA for the period from just before (1500 UT on 10 September) to a few days after the start of GLE 72 at vertical cutoff rigidities from 0.01 to 4 GV. GOES = Geostationary Orbiting Environmental Satellite; MIRA= Maps of Ionizing Radiation in the Atmosphere; GLE = ground level enhancement.

The primary proton spectra used for the calculation of the exposure related to solar energetic particles were derived by fitting of 1-hr averages of GOES-13 and GOES-15 measurements (more details on the procedure can be found in Matthiä et al., 2018). The GOES EPEAD (above 10 MeV) and HEPAD proton measurements were fitted with a power law and a double power law in rigidity. The derived primary spectra are very similar in the energy region that is relevant for the radiation exposure at aviation altitudes, that is, above a few hundred megaelectron volts, and differences show mostly at lower energies, simply because the transition from the first power law to the second power law is at lower energies. Here the results from the double power law fit are presented. To derive the proton spectra, the GOES data were used with the recalibrated energy channels from Bruno (2017) as further elaborated in Matthiä et al. (2018). In this recalibration, the highest energy channels of the HEPAD instruments have mean energies of 1002.4 MeV (GOES-13) and 1094.7 MeV (GOES-15). As even higher energies may contribute to the radiation exposure at aviation altitudes for certain events, the energy spectra were extrapolated to 20 GeV using the fitted power law in rigidity. In order to validate this extrapolation, the expected response of neutron monitor stations to the fitted primary spectrum was calculated using neutron monitor yield functions (Matthiä et al., 2009) and qualitatively compared to the measured increases of

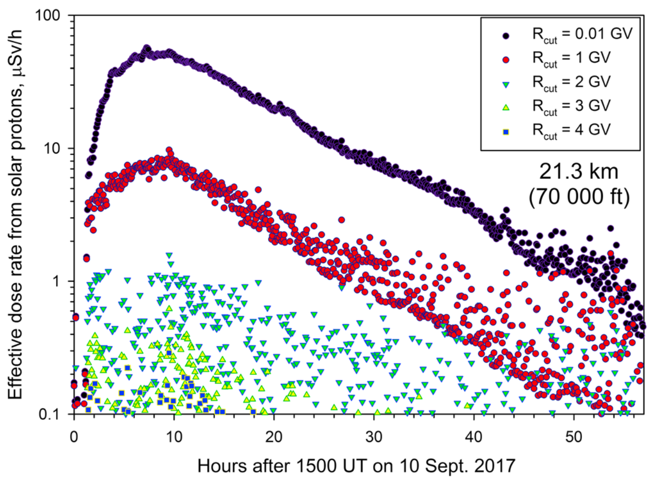

Figure 7. Effective dose rates at 21.3 km (70,000 ft, FL 700) calculated from 5-min averaged GOES-13 proton flux data by MIRA for the period from just before (1500 UT on 10 September) to a few days after the start of GLE 72 at vertical cutoff rigidities from 0.01 to 4 GV. GOES = Geostationary Orbiting Environmental Satellite; MIRA= Maps of Ionizing Radiation in the Atmosphere; GLE = ground level enhancement.

different stations. In section 3 of this paper it will become clear that protons with rigidities above 2 GV and corresponding kinetic energies of more than 1.3 GeV did not contribute significantly to the radiation exposure at aviation altitudes during this event.

3. Results

Dose rates calculated for galactic cosmic radiation (GCR) during the event are provided in Table 1, along with event average SEP dose rates based on the first 48 hr. In Figure 3, hourly average effective dose rates from solar cosmic radiation are shown for an altitude of 12.2 km (40,000 ft). Dose rates are for the 48 hr from 16:30 UT on the 10 (just after onset) to 2 days after the onset at vertical cutoff rigidities (R_{cut}) of 0.01 and 1 GV, based on GOES-13 proton flux data. Shading indicates the D index (clear for $D = 0$, shaded for $D = 1$) (The D index was developed for ionizing radiation dose at aviation altitudes: $D = 1$ corresponds to and effective dose rate between 5 and 10 µSv/hr, $D = 2$ is 10 to 20 µSv/hr, etc. It is more appropriate than the current NOAA scales for evaluating the biological harm of exposure for aircrews and passengers; Meier & Matthiä, 2014). For the conditions shown, a D index of 1 is consistently indicated by both MIRA and PANDOCA for GCR and combined solar + GCR ionizing radiation. Peak hourly average (centered on the hour, i.e., 16:30 to 17:29 UT) solar cosmic radiation dose rates and D indices are provided in Table 2. At altitudes of 12.2 km and below the D index did not exceed $D = 0$. Even at the higher business jet altitudes, the only cases of $D > 0$ were at $R_{cut} = 0.01$ GV. At the high business jet altitude of 15.2 km (50,000 ft), solar dose rates peaked at values near GCR dose rates, equivalent to close to the $D = 2$ threshold. At the highest altitude (21.3 km, 70,000 ft), the realm of surveillance aircraft and stratospheric balloonists, solar dose rates peaked at $D = 4$ at 0.01 GV and $D = 1$ at 1 GV. With the exception of 0.01 GV at 21.3 km, GCR dose rates were consistently higher than solar particle dose rates throughout the evolution of GLE 72. Also as expected, solar cosmic radiation dose rates were much more sensitive to cutoff rigidity: dose rates for solar cosmic radiation from $R_{cut} = 0.01$ GV to $R_{cut} = 1$ GV were significantly reduced, while GCR remained almost unaffected. At $R_{cut} = 2$ GV and higher cutoff rigidities, solar doses did not exceed 10% of the GCR dose rate. At $R_{cut} = 4$ GV and higher cutoff rigidities the solar contributions become negligible compared to the GCR component due to the comparatively soft spectrum of this SPE.

Table 3
Ratios of Effective Doses as Calculated by MIRA and PANDOCA Using Input Data From GOES-13 and GOES-15

Vertical cutoff rigidity (GV)	Altitude (km [ft × 1,000])	MIRA[a] $E_{GOES-13}/E_{GOES-15}$	PANDOCA $E_{GOES-13}/E_{GOES-15}$
0.01	10.7 (35)	0.97	0.82
	12.2 (40)	0.98	0.85
	15.2 (50)	1.02	0.90
	21.3 (70)	1.06	0.96
1	10.7 (35)	0.72	0.56
	12.2 (40)	0.73	0.56
	15.2 (50)	0.78	0.61
	21.3 (70)	0.89	0.71
2	10.7 (35)	0.50	0.45
	12.2 (40)	0.50	0.45
	15.2 (50)	0.50	0.46
	21.3 (70)	0.51	0.47
3	10.7 (35)	0.45	0.37
	12.2 (40)	0.45	0.37
	15.2 (50)	0.46	0.37
	21.3 (70)	0.46	0.38
4	10.7 (35)	0.43	0.32
	12.2 (40)	0.45	0.32
	15.2 (50)	0.44	0.32
	21.3 (70)	0.44	0.33

Note. GOES = Geostationary Orbiting Environmental Satellite; MIRA= Maps of Ionizing Radiation in the Atmosphere; PANDOCA = Professional Aviation Dose Calculator.
[a]For the 4-hr period starting on 10 September 2017 at 2100 UT.

Effective dose rates from solar cosmic radiation calculated by MIRA using the 5-min average solar proton flux data archived at SWPC from just before to a few days after the start of GLE 72 at R_{cut} values from 0.01 to 4 GV are shown in Figures 4–7. Calculations indicate a rapid rise in dose rate at low cutoff rigidity beginning between 16:15 and 16:20 UT on 10 September. Dose rates follow the trend of >100 MeV integral proton flux, with those at $R_{cut} = 0.01$ GV at 21.3 km (70,000 ft, FL 700) following the trend most closely.

The results depended strongly on the source of the input data for model calculations, that is, the detector systems used and the location of the data source during SPEs. This can be demonstrated using data of both GOES satellites (GOES-13 and GOES-15) as input for the same radiation transport model. Table 3 shows the comparison of the results calculated with MIRA and with PANDOCA. For PANDOCA the observed differences for GLE 72 at aviation altitudes (FL400) range from about 15% without geomagnetic shielding ($R_{cut} = 0.01$ GV) up to a factor of 3 at a geomagnetic shielding corresponding to $R_{cut} = 4$ GV. For MIRA, the data in Table 3 are restricted

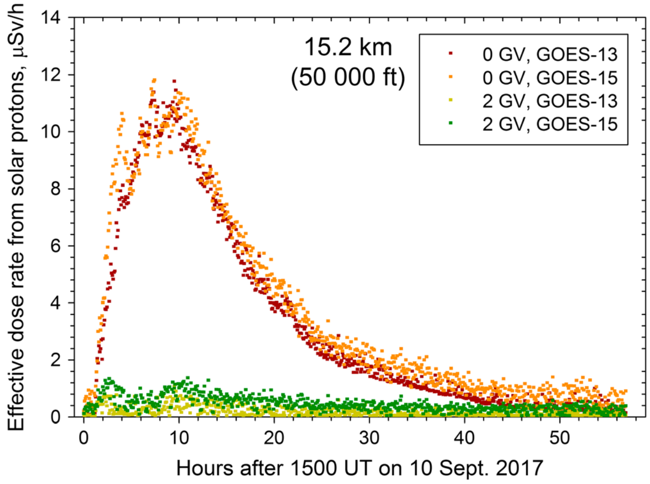

Figure 8. Five-minute average effective dose rates from solar protons beginning at 1500 UT on 10 September 2017 at an altitude of 15.2 km (50,000 ft, FL 500) calculated with MIRA using on GOES-13 and GOES-15 proton flux data. MIRA= Maps of Ionizing Radiation in the Atmosphere; GOES = Geostationary Orbiting Environmental Satellite.

to only four of the most intense hours of the event at 0.01 GV, that is, starting at 2100 UT on 10 September. The comparison produces a very similar pattern, but MIRA results are less sensitive at all R_{cut} values. Figure 8 shows MIRA results using data from the two sources at a high business jet altitude of 15.2 km (50,000 ft, FL500), at R_{cut} values of 0.01 and 2 GV. Dose rates calculated from GOES-15 data have a noticeable early peak between 1800 and 1900 UT and eventually fall more slowly. While the maximum dose rates were similar at R_{cut} = 0.01 GV, they were consistently lower at higher R_{cut} when calculated from GOES-13 data, indicating differences in SPE spectra at high energies.

For GCR, the model results were very similar at all rigidities and altitudes: PANDOCA dose rates range from 11% to 20% below MIRA.

4. Discussion and Conclusions

Commercial and business aviation are currently limited to altitudes of 15.5 km (51,000 ft, FL 510). Model calculations for these aviation altitudes agree well at R_{cut} = at 0.1 and 1 GV, ranging from −40% to +25% (e.g., the International Commission on Radiation Measurements and Units considers GCR calculations accurate enough for general use when calculations are consistently within 30% of their reference data set; 2010). This is in spite of differences in methods used to define solar proton flux spectra. Relative to GCR background rate during GLE 72 at such altitudes, both calculation methods revealed only minor increases: less than double local GCR for 0.01 GV at 15.2 km, up to about an added third of local GCR for 0.01 GV at 10.7 km, and much less for locations with higher cutoff rigidities.

The impact of SPEs on the radiation field at flight altitudes can be classified and communicated to aircrew and to the interested public using the Space Weather D-scale with the corresponding radiation dose index (*D* index; Meier & Matthiä, 2014). The investigation of GLE 72 with MIRA and PANDOCA has shown that the *D* index did not exceed the threshold D = 0 for quiet space weather conditions at 12.2 km and below anywhere in the Earth's atmosphere (Meier & Matthiä, 2018). While neither system accounts for anisotropy, globally GLE 72 can be considered insignificant in terms of radiation exposure at commercial flight altitudes, although this event reached the S 3 level on NOAA's Space Weather S-scale, which is used as an action level in some countries.

Neutron monitor data indicate that GLEs with significant flux above about 5 GeV, such as GLE 42, are rare and that GLE 72 was not such an event (University of Oulu, 2018). Information needed to model the cosmic ray proton spectrum at energies above 1 GeV traditionally comes from the global set of ground-based neutron monitors, many of which do not make their data available for immediate use. Alert systems such as MIRA and PANDOCA require reliable real-time data streams. While the data stream from NOAA is very reliable, GOES satellites provide a very limited picture of the >1 GeV proton spectrum. Real-time systems based on GOES that do not also incorporate neutron monitor data cannot account for anisotropy to estimate local dose rates and must extrapolate the shape of the proton spectrum above 1 GeV. Thus, it is not surprising that MIRA estimates diverge from PANDOCA estimates at higher cutoffs. Despite the differences and lack of inclusion of neutron monitor data, both MIRA and PANDOCA agree that there was little solar proton flux with rigidities above 2 GV during this event.

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