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LIULIN-AA SPECTROMETER MEASUREMENTS OF THE RADIATION DOSE DURING THE TRAVEL FROM BULGARIAN ANTARCTIC BASE ON LIVINGSTON ISLAND TO LONGYEARBYEN TOWN, SVALBARD ARCHIPELAGO, NORWAY AND BACK TO SOFIA

Tsvetan Dachev[1], Petar Sapundjiev[2], Borislav Tomov[1], Yuriy Matviichuk[1], Mityo Mitev[1], Malina Yordanova[1]

[1]Space Research and Technology Institute - Bulgarian Academy of Sciences
[2]National Institute of Geophysics, Geodesy and Geography, Bulgarian Academy of Sciences
e-mail: tdachev59@gmail.com

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Abstract: *The battery-operated spectrometer-dosimeter "Liulin-AA" performed radiation dose and flux measurements in wide range of geographic latitudes from 62°S latitude in the Bulgarian Antarctic Base on Livingston Island to 81.2°N latitude at Longyearbyen town, Norwegian Svalbard archipelago. This happened during two trips of our colleague Peter Sapundjiev. The first one was from 24 of February until March 9, while the second from June 27 until July 26, 2024. Different radiation and environment conditions were observed. The first trip starts with few days' measurements in the Bulgarian Antarctic Base and includes four trips by car, one by ship, four aircraft flights, one of which crossing the magnetic equator, one bus travel and two stays in hotels in Punta Arenas town, Chile and Buenos Aires, Argentina. The second trip starts with three aircraft flights from Sofia to Munich, Oslo and Tromso in Norway. It continues with a long travel by ship in Arctic sea. The maximal northern latitude reached was 81.2° N. This trip finished by other three aircraft flights from Longyearbyen to Oslo, Munich and Sofia.*

The lowest dose rates were observed during the car and ship trips. The dose rates during the ship travel were smaller than the dose rates on the ground. The dose rates registered in a bricks building in Sofia were higher than the ground based dose rates. As expected, the highest dose rates were registered during the aircraft flights. This paper describes and analyzes different dose rates and spectra.

ИЗМЕРВАНИЯ НА РАДИАЦИОННАТА ДОЗА СЪС СПЕКТРОМЕТЪР ЛЮЛИН-АА ПО ВРЕМЕ НА ПЪТУВАНЕ ОТ БЪЛГАРСКАТА АНТАРКТИЧЕСКА БАЗА НА ОСТРОВ ЛИВИНГСТЪН ДО ГРАД ЛОНГИЪРБИЕН, АРХИПЕЛАГ СВАЛБАРД, НОРВЕГИЯ И ОБРАТНО ДО СОФИЯ

Цветан Дачев[1], Петър Сапунджиев[2], Борислав Томов[1], Юрий Матвийчук[1], Митьо Митев[1], Малина Йорданова[1]

[1]Институт за космически изследвания и технологии - Българска академия на науките
[2]Национален институт по геофизика, геодезия и география - Българска академия на науките
e-mail: tdachev59@gmail.com

Ключови думи: *Спектрометри-дозиметри „Люлин", доза радиация на повърхността на земята и при пътуване с кораб и самолет, галактически космически лъчи*

Резюме: *Батерийният спектрометър-дозиметър Люлин-АА проведе измервания на радиационната доза и поток в широк диапазон от географски ширини от 62° южна ширина в Българската антарктическа база на остров Ливингстън до 81,2° северна ширина в град Лонгиърбиен, архипелаг Свалбард, Норвегия. Това се случи по време на две пътувания на нашия колега Петър Сапунджиев, първото между 24 февруари и 9 март и второто между 27 юни и 26 юли 2024 г. Първото пътуване започна с няколкодневни измервания в Българската антарктическа база и включва: четири пътувания с кола, едно пътуване с кораб, четири полета със самолет, един от които пресича магнитния екватор, едно пътуване с автобус и два престоя в хотели в градовете Пунта Аренас, Чили и Буенос Айрес, Аржентина. Второто пътуване започва с три самолетни полета от София до Мюнхен, Осло и град Трьомсо в Норвегия. Продължава с дълго пътуване с кораб в Арктическо море.*

Достигната е максималната северна ширина 81,2°. Това пътуване завърши с други три самолетни полета от град Лонгиърбиен на норвежкия архипелаг Свалбард до Осло, Мюнхен и София.

Най-малките мощности на дозите са наблюдавани по време на пътуванията с кораб и кола. Мощностите на дозите по време на пътуването на кораби са по-малки от мощностите на дозите на повърхността на земята. Регистрираните мощности на дозите в тухлена сграда в София са по-високи от мощностите на дозите на повърхността на земята. Както се очакваше, най-високите дози са наблюдавани по време на полетите на самолети.

Различните мощности на дозата и спектрите са описани и анализирани в тази статия.

The dominant radiation component in near the Earth space environment are the galactic cosmic rays (GCR), modulated by the solar activity. The GCR are charged particles that originate from sources beyond our solar system. These particles are accelerated by high energetic sources like neutron star, black holes and supernovae within our Galaxy. GCR are the most penetrating of all major types of ionizing radiation. The energies of GCR particles range from several tens up to 10^{12} MeV nucleon^{-1}.

The air radiation field arises because of the interaction of primary GCR particles with the Earth's atmosphere. An additional flux of albedo secondary GCR is observed at altitudes below 3 km, which contributes to the forming of the flux minimum around 1.6 km altitude [1]. The intensity of the atmospheric radiations composed of GCR primary and secondary particles and their energy distribution vary with altitude, location in the geomagnetic field, and the time in the sun's magnetic activity (solar) cycle [2]. The atmosphere provides shielding, which depends on the overhead atmospheric depth. The geomagnetic field provides a different kind of shielding, by deflecting low-momentum charged particles back to space. Because of the orientation of the geomagnetic field, which is predominately dipolar in nature, the Polar Regions are susceptible to penetrating GCR particles. At each geographic location, the minimum momentum per unit charge (magnetic rigidity) a vertically incident particle can have and still reach a given 3 location above the earth is called the geomagnetic vertical cutoff rigidity [3]. The local flux of incident GCR at a given time varies widely with geomagnetic location and the solar modulation level. When the solar activity is high, the GCR flux is low, and vice versa. The dynamic balance between the outward convective flux of solar wind and the inward diffusive flux of GCR is responsible for the anti-correlation between the incident GCR and the level of solar activity [2].

Instrument description

The design of the portable dosimeter-spectrometer Liulin-AA is not a new one. Since 1989, Space Research and Technology Institute (SRTI-BAS), in an international cooperation with scientists from Russia, Germany, Japan, Czech Republic, Italy, Norway, Switzerland, Belgium, USA and India, etc., worked at mountain peaks, flew in space and on stratospheric balloons, rockets and aircraft with more than 35 similar devices [4, 5], (http://www.space.bas.bg/SollarTerrestialPhysics/files/Poster-IKIT-BAN-2019%20SZF.pdf)).

The latest application of Liulin device is the flight of the first commercial mission into suborbital space with the SpaceShipTwo spacecraft of Virgin Galactic Company (Virgin Galactic launches first commercial spaceflight (spacedaily.com). The flight took place on June 29th, 2023 at 08:00 a.m. MT or 03:00 p.m. GMT from Spaceport America in New Mexico, USA.

Liulin-AA spectrometer contains one silicon-PIN diode of Hamamatsu S2744-08 type (2 cm^2 area and 0.3 mm thickness, Fig. 1), one ultra-low noise charge-sensitive preamplifier of AMPTEK A225F type, and 2 microcontrollers.

The doses (deposited energies in the detector) are determined by a pulse height analysis technique then passed to a discriminator. According to AMPTEK A225 specifications, the pulse amplitudes A [V] are proportional by a factor of 240 mV/MeV to the energy loss in the detector and respectively to the dose. This is the key feature of the AMPTEK A225 preamplifier, which directly transfers the pulse amplitude, measured in volts by the spectrometer to dose and dose rate.

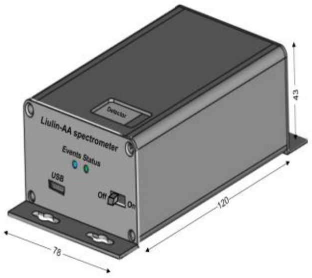

Fig. 1. Draft of Liulin-AA spectrometer

The amplitudes of all signals from the income particles and quanta are transformed into digital signals by ADC converter and are sorted into 256 channels by a multichannel analyzer. For every exposure interval, a single 256 energy deposited spectrum is collected.

Two microcontrollers, through specially developed firmware, manage the unit. Liulin-AA communicates with a personal computer by a universal serial bus (USB) signal.

The following method for calculations of the dose is used [6]. The dose D [Gy] by definition is one Joule of energy deposited in 1 kg of a mater or:

(1) $D = K.Sum(EL_i{*}i)_{ET}/MD$,

where MD is the mass of the detector in [kg] and EL_i is the energy loss in Joules in channel i. Energy loss in channel i is proportional to the number of events A_i in it multiplied by i. K is a coefficient.

During the construction of the Liulin-AA, actions have been taken to reduce the microphone effect at the detector. As a result, when Liulin-AA is transported by water, land and air under general conditions, shock and jolt disturbances are not registered anywhere. A new power supply circuit for the detector [7] has been constructed and used. As a result the EMI, noises were also reduced. The device has been calibrated by applying a new methodology [8], which leads to an increase in the accuracy and convergence of the registered data.

Scientific results

The paths of the two trips are presented in Fig. 2. The first trip is presented with yellow arrows, while the second one from Sofia, Bulgaria to Longyearbyen town and back is presented with magenta arrows for the aircraft flights and with sky blue arrows for the ship travels. All pats are presented over a fragment of a 3D map of the estimated ambient dose equivalent rate at 11.887 km, according to the right side color bar as calculated by Makrantoni et al. [13].

The white labels next to the flight from Buenos Aires to Rome are the measured in this points equivalent dose rates by Liulin-AA spectrometer. Good coincidence is observed.

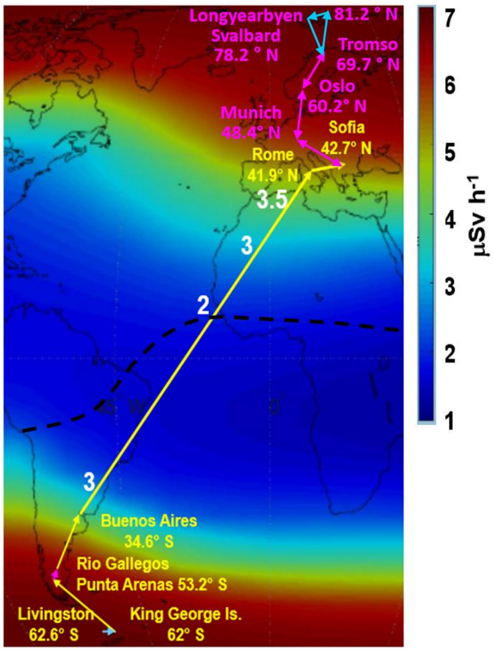

Fig. 2. The path from Livingstone Island to Sofia, Bulgaria during the first trip is presented with yellow arrows, while the trip from Sofia, Bulgaria to Longyearbyen town and back is presented with magenta arrows for the aircraft flights and with sky blue arrows for the ship travels. All pats are presented over a fragment of a 3D map of the estimated ambient dose equivalent rate at 11.887 km, according to the right side color bar as calculated by Makrantoni et al. [13].

Environmental radiation and commercial aviation flights dosimetry during the travel from Bulgarian Antarctic Base on Livingston Island to Sofia

Fig. 3 contains two panels. In the upper panel on the left y-axes are plotted: a) with red line and markers the dose rate and the 10 per moving average of dose rate with black line; b) with blue line the 10 per moving average of flux; c) the dose to flux ratio with green line and markers.

On the right y-axes of the upper panel are plotted two Neutron Monitor (NM) data: the Oulu NM https://cosmicrays.oulu.fi/ counts (per min. divided by 100000) with a black line and the South Pole NM (SOPO) https://neutronm.bartol.udel.edu/realtime/southpole.html counts divided by 4470 with a magenta line. No significant dependence of the dose rate from the neutron monitors values is observed.

The lower panel of Fig. 3 presents a 3D color-coded graphic, showing the first 32 channels' counts in the spectra population. The right side color bar provides information for the counts.

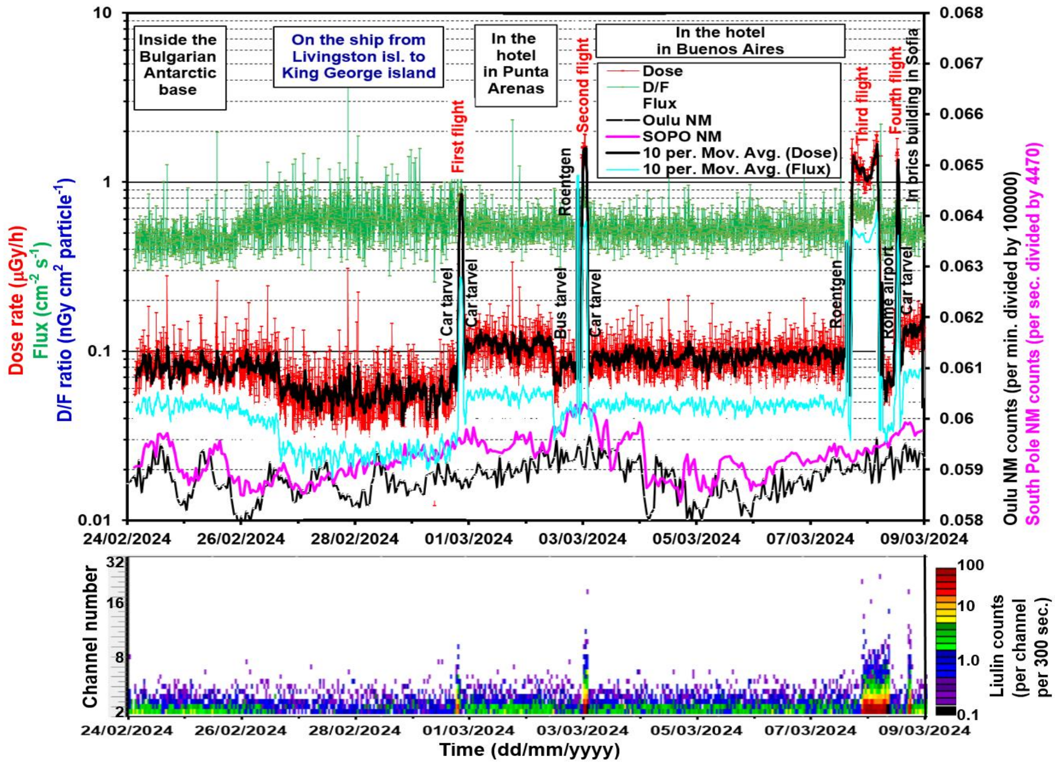

Fig. 3. Environmental radiation and commercial aviation flights dosimetry during a travel from Bulgarian Antarctic Base on Livingston Island to Sofia, Bulgaria

Table 1 contains the averaged values of the absorbed dose rate, equivalent dose rate, flux, dose to flux ratio for some points of interest of the trip back to Bulgaria.

The ambient equivalent dose rates in Table 1, were calculated using the method developed by Spurny and Dachev, 2002 [9].

As seen in the first row of the Table 1, the measurements began "Inside Bulgarian Antarctic Base" on 24 of February 2024 and ended on 25 of February at 21:29 (Sofia time (UT+ 3 hours)) "Inside bricks building in Sofia (last row).

The measured dose rate inside the Bulgarian Antarctic Base of 0.087 µGy h^{-1} are very similar to the published in [10] doses, obtained at the Argentine Antarctica base in Marambio (Antarctica, 64.24° S, 56.63° W, 196 m a.s.l., vertical cutoff rigidity Rc=2.35 GV). In Table 1, (therein) the measured dose rate is 75.7 ± 3.3 µGy h^{-1} in January-May 2013 and 74.6 ± 2.8 in March-October 2015.

The lowest dose rates of 0.056 µGy h^{-1} and 0.0963 µSv h^{-1} were observed during the travel on the ship between Livingston Island and King George Island (Fig. 1). The value in µSv h^{-1} is very close to the average dose rate of 0.091 ± 0.010 µSv h^{-1} recorded by the use of a Geiger-Müller Gamma-Scout during the non-stop sailing on the yacht Katharsis II from Cape Town, South Africa to Hobart, Australia around the Antarctic continent between 23rd December 2017 and 5th April 2018 [11].

The car travel and the bus travel doses are at low levels between 0.0423 µGy h^{-1} during the car trip between Sofia airport and Sofia town and 0.078 µGy h^{-1} during the bus trip between the hotel in Punta Arenas to the airport in Rio Gallegos town.

The doses in different buildings during the trip vary between 0.133 µGy h^{-1} inside the brick building in Sofia and 0.092 µGy h^{-1} inside the hotel in Punta Arenas. The high doses in the buildings are understandable. According to Shahbazi-Gahrouei et al. [12], Table 1 therein the radioactivity concentration in (Bq/kg) in brick is the highest with 37±1.5 from ^{226}Ra, 12.2±0.7 from ^{232}Th and 851.4±15 from ^{40}K. The cement, which is the major contributor in the concrete, is on the second place.

Table 1. List of the parameters, measured at different locations during first trip from Bulgarian Antarctic Base on Livingston Island to Sofia, Bulgaria

Location and Time	Average measured abs./ amb. eq. dose rate (μGy/h)/(μSv/h)	Average measured Flux (cm^{-2} s^{-1})	Calculated Dose to flux ratio (nGy cm^2 part.$^{-1}$)	Elevation above the see level (m)
Inside the Bulgarian Antarctic base at Livingston Island, 62.5999° S 60.4999° W, Rc=2.79 GV. **From** 24/02/2024 03:09:00 **Until** 25/02/2024 21:09:00	0.087/1.391	0,047	0.472	12-15
On the ship from Livingston island to King George Island, 61.9882° S, 58.0196° W, Rc=2.84 GV. **From** 26/02/2024 16:49:00 **Until** 29/02/2024 15:49:00	0.056/0.0963	0.025	0.622	0.00
First Car travel to King George airport **From** 29/02/2024 18:04:00 **Until** 29/02/2024 18:34:00	0.0532/0.0915	0.26	0.568	
First aircraft flight from King George Island to Punta Arenas, Chile, 53.1634° S, 70.9078° W, Rc= 4.54 GV. **From** 29/02/2024 19:19:00 **Until** 29/02/2024 21:14:00	0.808/1.779	0.268	0.862	~9,000
Second Car travel to Punta Arenas hotel **From** 29/02/2024 21:34:00 **Until** 29/02/2024 22:04:00	0.0757/0.130	0.041	0.519	0.516
Inside the Hotel in Punta Arenas, 53.1634° S, 70.9078° W **From** 29/02/2024 22:34:00 **Until** 01/03/2024 20:44:00	0.110/0.189	0.055	0.556	
Bus travel from the hotel in Punta Arenas to the airport in Rio Gallegos **From** 02/03/2024 11:09:00 **Until** 02/03/2024 18:14:00	0.078/0.134	0.0393	0.554	
First Roentgen security check at airport in Rio Gallegos **From** 02/03/2024 21:39:00 **Until** 02/03/2024 21:39:00	8.319	10.551	0.219	
Second aircraft flight from Rio Gallegos to Buenos Aires, Argentina 34.6037° S, 58.3816° W, Rc= 8.44 GV. From 29/02/2024 19:19:00 Until 29/02/2024 21:14:00	1.543/3.696	0.561	0.766	~12,000
Third Car travel from Buenos Aires airport to the hotel **From** 03/03/2024 05:34:00, **Until** 03/03/2024 06:14:00	0.060/0.1032	0.034	0.599	
Inside the hotel in Buenos Aires 34.6037° S, 58.3816° W **From** 03/03/2024 03:04:00 **Until** 07/03/2024 13:54:00	0.092/1.582	0.0478	0.535	25
Second Roentgen security check at Buenos Aires airport **From** 07/03/2024 15:09:00 **Until** 07/03/2024 15:09:00	3.542	4.102	0.239	
Third aircraft flight Buenos Aires to Rome, Italy 41.8967° N, 12.4822° E, Rc= 6.2 GV. **From** 07/03/2024 17:24:00 **Until** 08/03/2024 04:09:00	1.16/3.076	0.432	0.670	~12,000
Fourth aircraft flight from Rome to Sofia, Bulgaria 42.6977° N, 23.3219° E, Rc= 5.9 GV. **From** 08/03/2024 12:19:00 **Until** 08/03/2024 12:54:00	1.496/3.935	0.533	0.780	~12,000
Fourth Car travel from the airport in Sofia **From** 08/03/2024 13:14:00, **Until** 08/03/2024 13:34:00	0.0423/0.0727	0.0213	0.563	
Inside the bricks building in Sofia **From** 08/03/2024 14:24:00 **Until** 09/03/2024 11:09:00	0.133/0.228	0.729	0.509	

The highest dose rates were observed during the four commercial aircraft flights, depicted on Fig. 4. The maps with the ground projection of the aircraft paths (red lines) are visible in the background of the four figures. In addition, the variations of the ambient equivalent dose rate in μSv h^{-1} (blue lines), the absorbed dose rate in μGy h^{-1} (black lines) and the dose to flux ratio in nGy cm^2 $particle^{-1}$ (magenta lines) are shown.

The variations of the mentioned above two dose rate parameters during first flight from King George Island (61.9882° S, 58.0196° W, Vertical cut-off rigidity (Rc) 2.84 GV) to Punta Arenas in Chile, (1,241 km distance) are seen in Fig. 4. The measured absorbed and equivalent dose rate during this flight are the smallest in comparison with the other three flights. The reason is that this flight was performed with aircraft type BAE146, which cruise altitude is at about 9 km. The highest average dose to flux value of 0.862 nGy cm^2 $particle^{-1}$ in comparison with other three flights gives information that in the spectra exist particles depositing energy in higher energy channels. This is expected due to the relative high latitudes of the flight.

The high dose rates seen in the second and fourth flights are very similar because of the similar latitudinal and altitudinal conditions. This is also expected because the cruise altitude of flights 2 and 4 is around 12 km.

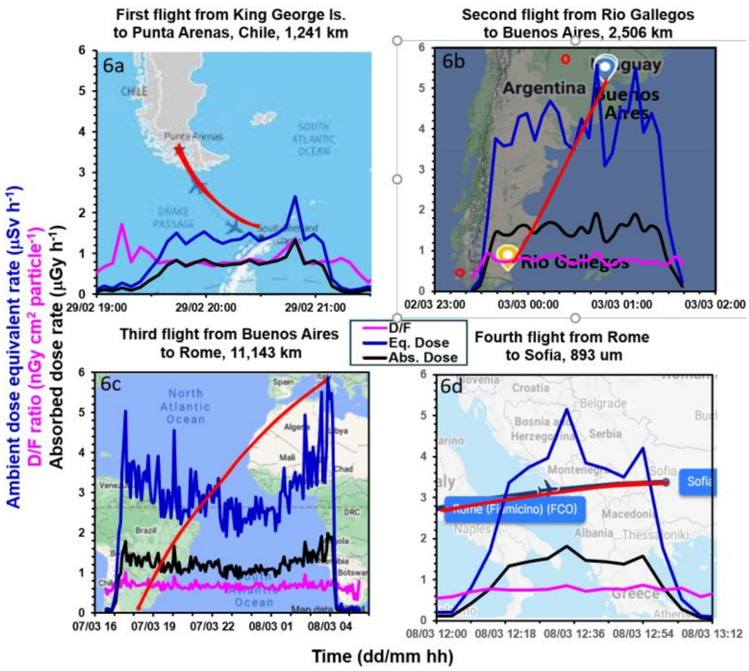

Fig. 4. Environmental radiation and commercial aviation flights dosimetry during a travel from Bulgarian Antarctic Base on Livingston Island to Sofia, Bulgaria

The most interesting, is the third flight being the longest and crossings the geomagnetic equator (please look at the dashed black line, Fig. 1) somewhere on the west coast of Africa. Both sides of the path in both hemispheres are from -35° to 42° geographic latitudes and Rc=6.2 GV and Rc=5.9 GV. Close after the take-off from the Buenos Aires airport and before the landing in Rome, the predicted ambient dose equivalent [13] is about 4-6 μSv h^{-1}. The latter is in a good coincidence with the values in the blue line (Fig. 4). With the decrease of the latitude toward the magnetic equator (black dashed line, Fig. 1), the doses also decrease down to values of 2–2.5 μSv h^{-1}.

Environmental radiation and commercial aviation flights dosimetry during a travel from Sofia, Bulgaria to Longyearbyen town, Svalbard, Norway and back

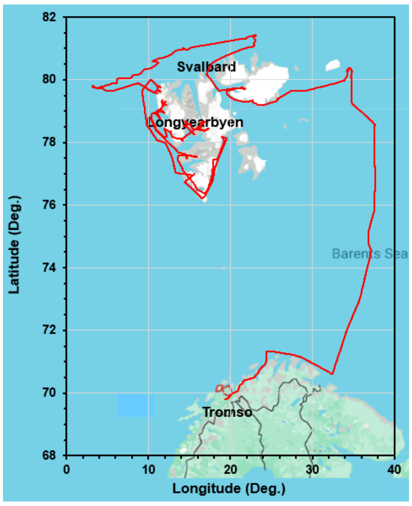

Fig. 5. The ship trip from Tromso to Longyearbyen town, Svalbard, Norway is presented with red line

The travel from Sofia to Longyearbyen town, Svalbard, Norway begins on 27th of June 2024 with a flight from Sofia to Munich, Germany. There are no data from this flight. Liulin-AA was switched ON at the airport of Munich and worked during the next two flights from Munich to Oslo, Norway and from Oslo to Tromso, Norway. There is 5–10 min. travel by car from the Tromso airport to the Tromso seaport.

Between 27th and 30th of June 2024, Liulin-AA spectrometer was inside of the ship. On 30th of June Liulin-AA together with a GPS logger, inside of plastic suitcase, was moved to the forward deck of the ship (Please see Fig. 6). The travel on the ship begins on June 30 and ended at the seaport of

Longyearbyen on 24th of July 2024. Liulin-AA was transported from Longyearbyen town to Sofia in three aircraft flights to Oslo, Munich and Sofia.

Fig. 6. The position of the plastic suitcase at the forward deck of the ship

Fig. 7 contains all dose rate data (red markers and lines), obtained during the second trip. Data are plotted against the red vertical scale. The sky blue line, against the sky blue scale, on the left shows the variations of the calculated per 24 hours average values of the hourly measurements. The averages are calculated using 288 single 5 minutes measurements (12 per hour multiplied by 24 hours equal to 288). The green line presents the variations of the geographic latitude as measured with the GPS logger during the trip with the ship. As expected, there is a relatively good correlation between the green and sky blue lines. The increase of the geographic latitude and accordingly the geomagnetic latitude decreases the vertical geomagnetic cutoff rigidities [3] of the GCR particles and they penetrate easier in the atmosphere, increasing the dose rate.

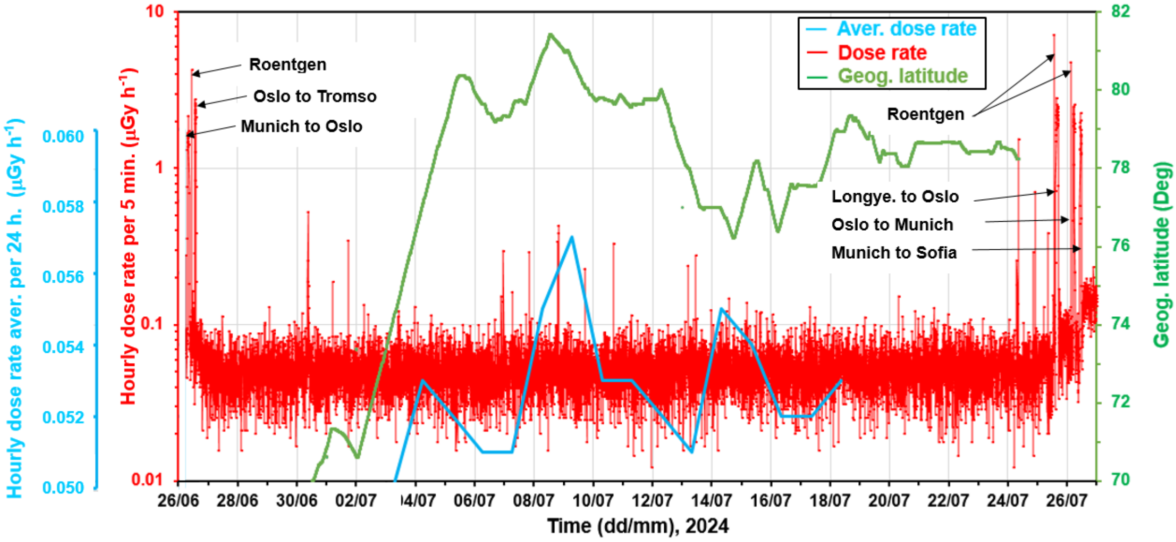

Fig. 7. Environmental radiation and commercial aviation flights dosimetry during a travel from Sofia, Bulgaria to Longyearbyen town, Svalbard, Norway and back

Fig. 8 illustrates the first three days of the trip with a better time resolution. The measurements began with an average dose rate data on Munich, Oslo and Tromso airports that are similar to the data, observed in Punta Arenas town during the first trip.

The measurements continue with higher aircraft dose rate data during the flight from Munich to Oslo. The average dose rate during the flight is 1.63 μGy h^{-1}, which is similar to the second aircraft flight from Rio Gallegos to Buenos Aires, Argentina during the first trip because of the similar geomagnetic conditions. The Roentgen security check average dose rate at the Oslo airport is much higher than the two analogical security checks during the first trip. It reaches 4.27 μGy h^{-1}. The average absorbed dose rate during the flight from Oslo to Tromso is the highest observed dose rate and reach 2.24 μGy h^{-1}. This is realistic because the geographic latitudes of this flight between 60.2°N

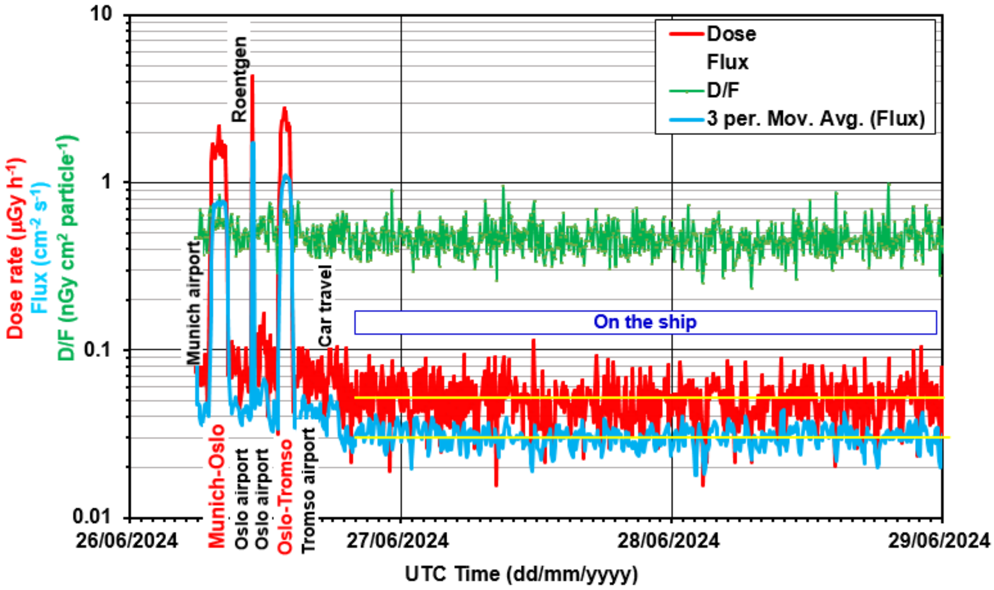

Fig. 8. Environmental radiation and commercial aviation flights dosimetry on the route from Munich airport (26 June 2024) to the ship (29 June 2024)

and 69.7°N is the highest observed until now. The same considerations for the vertical geomagnetic cutoff rigidities as in the previous paragraph are valid in this case.

The average absorbed dose rate on the ship between 27 and 29 June 2024 is 0.52 µGy h^{-1}. It is very similar to the observed dose rates in the ocean in the Southern hemisphere during the first trip that is 0.56 µGy h^{-1}.

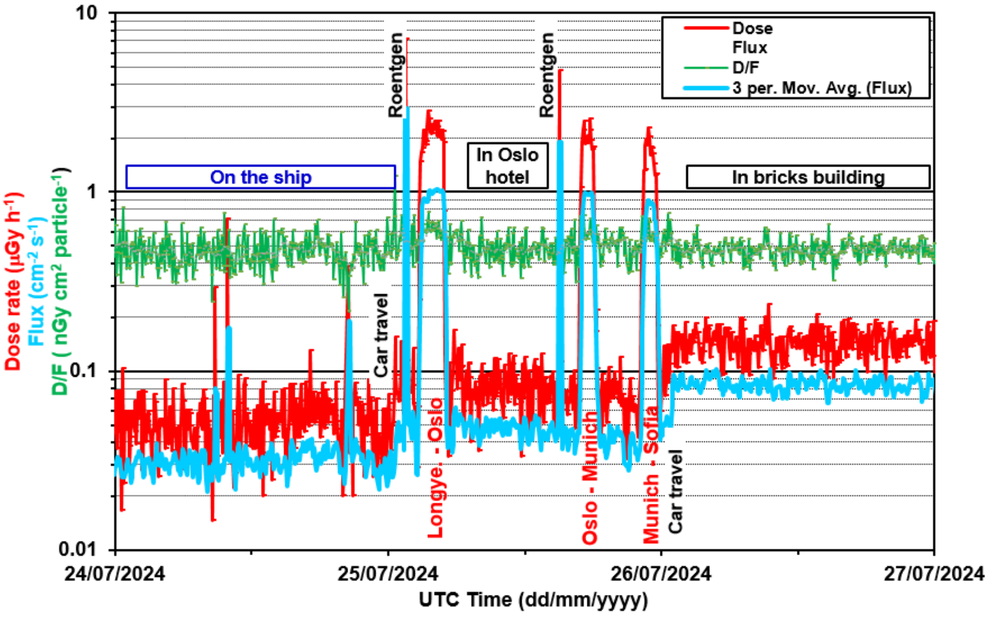

Fig. 9. Environmental radiation and commercial aviation flights dosimetry during a travel from Longyearbyen town, Svalbard, Norway to Sofia, Bulgaria

Fig. 9 shows the dose rate variations in the last 3 days of the second trip, 24–27 July 2024, with a better time resolution. The three high dose rate bursts on 24th of July are generated most probably by microphone effect of the detector. The two Roentgen security checks and the two car travels seen in Fig. 9 are very similar to those that are already observed. The three consecutive flights from Longyearbyen town, Svalbard, Norway to Sofia, Bulgaria in a good way show the decreasing GCR induced dose rates due to the increase of the vertical cut off rigidity [3]. The relative high dose rates in the bricks building on 26th of July are also nothing new.

Conclusions

The most important achievement of the paper is the discovery and the proof of the existence of stable measurements of Liulin-AA instrument in different ground and aircraft conditions and different natural radiation surroundings.

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