Unmanned Radiation-Monitoring System

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Abstract—The absence of online radiation-monitoring systems (RMSs) has been observed in the case of the Fukushima nuclear accident. As the tsunami destroyed 23 of the 24 status-monitoring points, almost no relevant radiation dose measurement data were available. Rapid deployment of a mobile radiological unit that can quickly determine the activity and direction of the radioactive cloud spread on the ground or in the air can prevent unnecessary deaths and related financial losses. Although the design of the current generation of nuclear power plants (NPPs) incorporates features that minimize the risk of large radioactive releases outside the reactor, it is still important to focus on the development of systems that can mitigate the consequences of such events. In situations when the level of radiation does not permit the personnel to perform the required measurements, online unmanned RMSs may come into play. For such a purpose, the RMS-00x RMS could be used, which is a modular system covering the functionality of dose rate measurement, air sampling, and radiation map creation without requiring human personnel to be present at the measurement site. The main purpose of the RMS-00x RMS is the rapid deployment of unmanned monitoring devices to reduce the radiation burden on workers and on public. The system can be applied in the vicinity of an NPP or at any location, where the source of ionizing radiation could be present. Before this system is used in real conditions, its components must be thoroughly calibrated, based on certified measurement equipment and the state-of-art simulation tools. This article deals with the description of the RMS-00x sensor modules and demonstrates their functionality in combination with unmanned aerial vehicles (UAVs). In addition, the use of the developed technology was demonstrated as part of the regular emergency planning and preparedness exercise of Jaslovské Bohunice NPP (EBO NPP) on October 26, 2017.

Index Terms—Accident, demonstration, radiation monitoring, radiation-monitoring system (RMS), unmanned aerial vehicle (UAV).

I. INTRODUCTION

The absence of online radiation-monitoring systems (RMSs) has been observed in the case of the Fukushima nuclear accident. As the tsunami destroyed 23 of the 24 status-monitoring points, almost no relevant radiation dose measurement data were available. The serious situation resulting from the accident led to the decision to evacuate the populations. This was made on the basis of the parameters computed from the simulation models. The associated stress resulted from the invisible threat and the evacuation process caused significant socio-economic consequences and a death toll. The real radiological measurement proved that the effective radiation dose had not exceeded the daily limits in some areas and showed the needlessness of evacuations. More information with the monitoring results can be found in [1]. Rapid deployment of a mobile radiological unit that can quickly determine the activity and direction of the radioactive cloud spreading on the ground or in the air can prevent unnecessary deaths and related financial losses.

For the last couple of years, national or international organizations responsible for radiation detection and protection have been developing various types of mobile radiation surveillance equipment. These units are typically mounted on a car or other ground-based platform, on a helicopter or on airplane. Regardless of the carrier type, well-trained crew are necessary to operate these systems [2]. Otherwise, unmanned aerial systems (UASs) operating in semiautomatic mode are capable of effectively measuring larger areas, while the ground personnel can be at a safe distance, and far, hard-to-reach locations can be explored. UAS sensors used for the monitoring of the radiation situation and the escape routes help to assess the seriousness of the situation and provide the basis for the most appropriate decision making.

UAS can also serve as a complement to periodic preventive dosimetry measurements around nuclear power plants (NPPs). The currently used dosimetry-monitoring stations are static, so they cannot dynamically respond to fast measurement requests in different locations. Illustrative is the example of the Sellafield NPP in the U.K., where the static monitoring station reported radiation leakage, which ultimately led to NPP shutdown. Subsequently, an investigation revealed that the increased levels of the measured quantities had been caused by a natural radioactive source, located outside the NPP area, raised by the wind. In such a situation, a mobile detection unit located on an unmanned device would have effectively identified the source of the radiation [3].

Following the accident at the Fukushima Daiichi NPP (FDNPP) initial measurements of radiation intensity, dose and distribution were performed using manned military and civilian aircraft at high altitudes. Afterward, in the case of assessing contamination and following remediation efforts, UAS found its application [4]. During the last few years, the UAS has been integrated to the contamination-monitoring systems all over the world. The use of UAS is demonstrated in the case of the Cornwall open-pit mines in England, where the
radiological characterization of single legacy mining site has been carried out [5].

II. RMS

The main purpose of the RMS is to create a UAS by combining radiation sensors with an unmanned aerial vehicle (UAV). Rapid deployment of the UAS in the case of a radiation event, which is its key feature, shall reduce the radiation burden on workers and on the public. The system can be applied in the vicinity of an NPP or at any location, where the source of ionizing radiation could be present. Individual modules of RMS have been designed to operate with UAV without influencing the functionality of each component, to provide sufficient information for the dosimetry staff, and to achieve a high standard of reliability. The key features of the RMS are the modularity, the custom independent in-house control software, the possibility to hibernate and subsequently activate the system upon specific incentives, the easy-to-wipe anticontamination layer of sensors and the compatibility with various UAV carriers. The originality of the RMS lies in optimized compatibility with UAVs and modularity, enabling implementation of various radiation sensors. At the same time, the overall concept of RMS should follow low-cost principles, making it affordable for practical applications.

The proposed solution involves the parallel operation of several UAVs, their efficient cooperation with the ground station and the deployment of modular sensor nodes, which can be linked to a chain. The proposed management of multiple nodes ensures greater flexibility for fast deployment and more efficient mapping of large territories, compared to a single node system. A system of measuring nodes, optimized for minimal power consumption, distributed by the UAVs in the area of interest, can provide information on the local radiation situation for even several weeks. The deployment of this system is foreseen in situations and at locations where the risk of radiation exposure on personnel responsible for radiation measurements is expected. The modularity of this system also makes it possible to be used in the research and development field. The biggest advantage of the system is the low weight of the modules and long operation time, which, in the case of energy-saving mode, can achieve one month or more.

Recent developments in microcontrollers capable of covering radiation detection and data management make it possible to combine them with aviation technology, making the exploitation of UAVs in different environmental applications possible. The main constraint could be the availability of low-cost commercial instrumentation to detect ionizing radiation, which can be used attached to a UAV. In this article, we introduce a concept of a cheap, modular, and flexible system capable of detecting radiation in the environment and collecting samples from air using a small-size UAV as a platform.

III. Detailed Description of the RMS Modules

RMS is a modular system still in development; therefore, in this article, the RMS_v2017 version is presented. This version consists of the RMS-000 communication and control module, the RMS-WASP communication software and three sensor modules (RMS-001, RMS-002 and RMS-003). RMS-001 is the radiation measurement module, RMS-002 the air-sampling module and RMS-003 the telemetry module. The schematic view of the system is shown in Fig. 1.

A. RMS-000 Communication and Control Module

One of the essential parts of the RMS is the RMS-000 communication and control module. It serves to support the operation of the measurement modules and acts as a gateway between the ground station and the sensors. It makes efficient use of the programmable microcontroller and uses it as its brain. Considering that in the case of a nuclear accident or other radiological threat the mobile networks might not be available, the emphasis in the design of the RMS-000 module was placed on securing independent communication and electricity supply channels. To achieve the maximum communication range and good penetration, 866-MHz industrial, scientific and medical (ISM) band and sequential communication mode were selected. The communication antenna, connected via the universal serial bus (USB) port of the computer, is used to receive the signal from the RMS-000 node. Both modules provide two-way encrypted communication. The signal transmission is routed in regular time intervals, defined by the user. The RMS-000 module also provides device positioning with global positioning system (GPS) coordinates and is transmitted to the ground station within a single message that includes also the measured parameters from the RMS-001 or RMS-002 modules. The main parameters of the RMS-000 module are listed in Table I.

B. RMS-001 Radiation Sensor Module

The RMS-001 radiation sensor module serves for the online measurement of effective dose rate of gamma and beta radiation. The major parts of the module are the radiation sensor

| Table I: Main Parameters of the RMS-000 Module [6] |
|-----------------------------------------------|
| **Application** | **Modularization** |
| Communication | Primary – Radio in 866 MHz EU ISM band |
| Range | Up to 20 km for 1 node |
| Positioning | External GPS, precision < 1m |
| Connectivity | RMS-001, RMS-002, RMS-003 |
| Supply | Independent Li-Po batteries |
board and the J305\(\beta\) Geiger–Müller (GM) detector. The sensor board, the RMS-000 and the battery are placed in a protective casing made of carbon fiber material. The casing is equipped by the connectors necessary for the communication of the RMS-000 module with ground station. The GM detector and the carbon fiber casing are placed in the outer casing, which provides IP56 protection against dust and humidity. The current configuration, selected for the purpose of demonstration, allows measurement from the natural background level to 277 \(\mu\text{Sv/h}\) (up to 100 \(\mu\text{Sv/h}\) without significant impact of dead-time). For real operation, the replacement of the GM tube is possible for any GM tube meeting the dimensional and supply conditions. The main parameters of the RMS-001 module are presented in Table II.

### C. RMS-002 Air-Sampling Module

The RMS-002 air-sampling module serves to demonstrate the air-sampling capability through a removable aerosol filter which could be used to capture radioactive particles carried by aerosols in the case of a nuclear accident. The filters can be subsequently used for spectral analysis to identify key radioisotopes. The module consists of a sensor board, removable filter, special LiPo battery, blower and flowmeter. The electronic parts (sensors and RMS-000) and the suction nozzle are located in a casing made of carbon fiber material. Currently, the device is able to perform air sampling at the speed of human respiration rate or more. The main parameters of the RMS-002 module are listed in Table III.

### D. RMS-WASP Control Software

The RMS-WASP control software has been developed to ensure the communication between nodes and to provide the user with a simple user-friendly environment, which, however, summarizes all the required parameters right on the screen, see Fig. 2. The software was developed in the ECLIPSE environment in C++ language using wxWidgets multiplatform libraries to create the graphical user interface (GUI) of the program. The communication between the measuring nodes is secured by configuring the receiving module, which requires a serial port configuration using the RMS-WASP software. The control message is encrypted using the “CRC MODBUS-16” cipher. The measurement data are treated in real time, and the results can be visualized in the form of radiation maps. The results are processed to the specific “kml” file that can be directly visualized using QGIS – Open Street Map, Google Earth or other mapping software. This functionality involves the creation of a contoured radiation map directly plotted into real geographic coordinates, indicating also the trajectory of the UAV flight. In the software version v5.3, the radiation data are transformed to effective dose rate, based on the count rate and the calibration constant of the used GM detector. The program interface also enables switching the signal processing on/off, which is an important feature in case of fast transport of the UAV between the measuring points.

### E. Currently Used UAV System

Although RMS is compatible with almost every UAV that meets the required payload capacity, our reference UAV type is the DJI MATRICE – 600, owned and operated by UAVONIC Ltd. This UAV was used in the case of all testing and demonstration activities performed so far. The main parameters can be found in [7] and the UAV can be seen in Fig. 3. The position of the RMS-001 module was selected in the bottom part of UAV to have GM tube oriented to the ground. The RMS-002 module was placed on the top of the UAV control unit, as can be seen in Fig. 3, for better air circulation around the module and to minimize air turbulence.

### IV. Laboratory Testing and Calibration

In the development phase, the sensor modules and the RMS-WASP control software were intensively tested. Since
the SMS_v2017 configuration was designed for demonstration purposes and uses only a simple and cheap J305/β GM detector, it is not foreseen to achieve precision comparable with state-of-the-art detectors. The J305/β GM detector was calibrated by its manufacturer, and guaranteed its precision for $^{137}$Cs and $^{60}$Co sources and for the energy range between 0.1 and 1.1 MeV. However, we consider important to partially verify the gamma conversion factor declared by the manufacturer using a certified detector. For this purpose, the Thermo Scientific ESM FH 40G-L10 [8] handheld multipurpose digital survey meter was used. It is a wide range digital proportional channel suitable for nearly all measurement tasks arising in radiation protection. It is a gas-filled detector that measures $H^*(10)$ ambient dose equivalent. In order to provide stabilized results, the detector uses time integration constants that are functions of the measured dose rate.

A. Measurement Setup

For the experiments, three sources of gamma radiation were used: $^{137}$Cs, $^{60}$Co, and $^{57}$Co. The first two sources are commonly used in calibration sources. $^{57}$Co was used in order to evaluate the effectiveness of the sensor module for a source, for which the manufacturer does not guarantee its precision. The measurements were performed at the experimental workspace developed for laboratory exercises, mainly measurement of dose rate and exposure rate, at Institute of Nuclear and Physical Engineering (INPE), Faculty of Electrical Engineering and Information Technology (FEI), Slovak University of Technology (STU). The experimental setup (see Fig. 4) consists of a sliding bench, an adjustable holder, lead shielding blocks and the detection position. The gamma sources were placed at exactly the same height in every case and five positions (10–50 cm) from the detector were investigated. The results of the FH 40G-L10 certified detector were read directly from the display and evaluated in regular time intervals, according to the recommendations of the manufacturer. The results of the RMS-001 module were stored in a text file on the measurement laptop.

B. Overview of the SCALE6 Calculations

For the purpose of verification of the results obtained by measurement, the experimental setup was modeled and simulated also in the SCALE6 [9] system. The model is shown in Fig. 5. For the calculations, the Monaco with Automated Variance Reduction Using Importance Calculations (MAVRIC) sequence with the Monaco transport solver was used in forward mode, without taking advantage of variance reduction techniques, and with the “v7-27n19g” cross section library (the effect of fine vs. broad group structure is negligible for this application). The library consists of incident neutron and gamma cross sections prepared based on ENDF/B-VII.1 [10] evaluated data, in 27 neutron and 19 photon groups. The geometry of the measurement workspace was created in the interactive GeeWiz environment. The created 3-D geometric ensures the necessary level of details for the calculation. The simulations were performed for the same geometry conditions and distances between the source and the detector, as it was in the experiment. The definition of the gamma source was provided as volume source of real dimensions and composition. The ICRU-57 “9510 Effective dose” response in
TABLE IV
BRANCHING RATIOS OF $^{137}$CS MODELED IN MONACO

| Energy [keV] | Number of particles per 100 disintegrations | Type of particle |
|-------------|---------------------------------------------|------------------|
| 36.379      | 1.055E+00                                   | X-ray            |
| 37.312      | 2.660E-01                                   | X-ray            |
| 283.500     | 5.800E-04                                   | Gamma            |
| 661.657     | 8.499E-01                                   | Gamma            |

TABLE V
BRANCHING RATIOS OF $^{60}$Co MODELED IN MONACO

| Energy [keV] | Number of particles per 100 disintegrations | Type of particle |
|-------------|---------------------------------------------|------------------|
| 347.140     | 7.500E-03                                   | Gamma            |
| 826.100     | 7.600E-03                                   | Gamma            |
| 1173.228    | 9.985E-01                                   | Gamma            |
| 1332.492    | 9.998E-01                                   | Gamma            |
| 2158.570    | 1.200E-03                                   | Gamma            |
| 2505.692    | 2.000E-06                                   | Gamma            |

TABLE VI
BRANCHING RATIOS OF $^{57}$Co MODELED IN MONACO

| Energy [keV] | Number of particles per 100 disintegrations | Type of particle |
|-------------|---------------------------------------------|------------------|
| 122.061     | 8.549E-01                                   | Gamma            |
| 136.474     | 1.071E+01                                   | Gamma            |
| 250.270     | 4.000E-04                                   | Gamma            |
| 339.670     | 3.800E-03                                   | Gamma            |
| 352.340     | 3.200E-03                                   | Gamma            |
| 366.740     | 1.300E-03                                   | Gamma            |
| 369.940     | 1.500E-02                                   | Gamma            |
| 692.01      | 1.590E-01                                   | Gamma            |
| 706.415     | 5.000E-03                                   | Gamma            |

TABLE VII
ACTIVITY AND STRENGTH OF SOURCES

| Source | Radioactivity [Bq] | Gamma source strength [par/s] | Beta source strength [par/s] |
|--------|--------------------|-------------------------------|----------------------------|
| $^{137}$Cs | 3.083E+07          | 2.661E-07                     | 3.659E+07                  |
| $^{60}$Co  | 1.282E+05          | 2.563E-05                     | 1.281E+05                  |
| $^{57}$Co  | 3.332E+06          | 3.211E-06                     | 2.406E+05                  |

The calculations were performed using identical conditions, 500 batches with 50 000 histories per batch.

C. Definition of the Emission Spectra for Simulations

The emission spectra of the radioactive sources were modeled based on the decay schemes and the branching ratios (presented as the number of particles per 100 disintegrations) of the sources [11]. Due to the declared energy range of FH 40G-L10, only photons and X-rays above 36 keV [8] were modeled. The branching ratios of the sources are presented in Tables IV–VI and the strength of sources used for simulation is presented in Table VII.

D. Dead-Time Correction

The RMS results showed considerable discrepancy between simulated and measured values caused by detection dead time. According to our previous measurements, the RMS detection system is characterized by nonparalyzable dead time. In the case of such behavior, an event happening during the dead time is simply lost, so that with an increasing event rate the detector will reach a saturation rate but will not lead to the decrease of count rate due to dead time. In order to take this phenomenon into account in the evaluation of results, dead-time correction was performed by the method of double sources. The dead-time $\tau$ can be determined by the two radiation sources that give approximately the same number of pulses per unit of time. In our case, two $^{137}$Cs sources were used and the dead-time $\tau$ was calculated based on (1), where $N_1$, $N_2$, and $N_{12}$ are the count rates from the first, second and both sources together. The dead-time corrected count rate $N_{cor}$ was calculated using (2), where $N_{det}$ is the measured uncorrected count rate from the detector. Using the presented formulae, the dead-time of the RMS-001 detection unit was calculated to 1.898 ms $\pm$ 0.353 ms.

$$\tau = \frac{N_1 + N_2 - N_{12}}{2N_1N_2}$$

$$N_{cor} = \frac{N_{det}}{1 - N_{det} \cdot \tau}.$$  

E. Correction of Beta Radiation

In addition to photons and x-rays presented in the previous tables, the sources in the detectable range of RMS-001 produce a continuous spectrum of beta radiation with strength comparable with the gamma source. In addition, the lead shielding elements and the concrete wall could also produce secondary radiation that might be detected by RMS. However, neither the FH 40G-L10 detector nor the SCALE6 system is able to treat beta radiation. In order to measure and simulate comparable quantities, two options are possible, i.e., shielding of beta particles with extra material or correction of the results measured by RMS based on coupled electron–photon transport calculation. In this article, both options are presented. The correction of beta radiation was performed for all three sources in MCNP5 [12], where the same geometry and material model was created with a combined photon (discrete energies with respect to Tables IV–VI) and beta (continuous energy spectrum) sources. The correction was performed based on the calculated responses of F4:e and F4:p tallies (track length estimation of the particle flux) multiplied by flux-to-dose conversion factors defined by ICRP-116 [13] and the strength of source presented in Table VII.

The calculations were performed for each source and position from the source (10–50 cm) and based on the acquired results the $f_{cor}^\beta$ correction function was defined. The $f_{cor}^\beta$ correction function can be calculated by (3), where $R_{\text{MCNP}}^\beta$
and \( R_{MCNP}^\beta \) are the calculated gamma and beta responses, respectively

\[
f_{\text{corr}}^\beta(x) = \frac{R_{MCNP}^\gamma(x)}{R_{MCNP}^\gamma(x) + R_{MCNP}^\beta(x)}. \tag{3}
\]

The corrected RMS responses \( R_{\text{corr}}^\text{RMS}(x) \) were calculated using (4), where \( R_{\text{mes+DT}}^\text{RMS} \) is the dead-time corrected measured response of RMS

\[
R_{\text{corr}}^\text{RMS}(x) = f_{\text{corr}}^\beta(x) \cdot R_{\text{mes+DT}}^\text{RMS}(x). \tag{4}
\]

The shielding of beta radiation was demonstrated in the case of \(^{60}\text{Co} \) gamma source. The measurement geometry was modified so as a 100 mm \( \times \) 200 mm \( \times \) 4 mm plate of carbon fiber (RMS casing material) was placed in front of the detector. In order to evaluate, whether the 4-mm-thin layer is able to sufficiently filter beta radiation and does not cause significant increase of gamma radiation (due to Bremsstrahlung), a simple MCNP5 coupled electron–photon transport calculation was performed. In the simplified geometry, only the \(^{60}\text{Co} \) source, the shielding plate and the detector were modeled. The results are shown in Fig. 6.

The results clearly show that the casing of RMS-001 has appropriate electron shielding properties without producing significant amount of gamma particles due to bremsstrahlung. Therefore, it is justified to use the measurement results for the case with extra beta shielding for comparison with SCALE6 simulation.

F. Results and Discussion

The comparison of measured and simulated results is shown in Figs. 7–9 and the relative uncertainty between RMS and the reference ESM FH 40G-L 10 detector as well as between RMS and the SCALE6 calculation are shown in Figs. 10–12. In the graphs, the results are presented with the corresponding 3\( \sigma \) uncertainty coming from the statistical nature of measurements and simulations. In the case of the RMS, the combined uncertainty includes also uncertainties coming from the dead-time and the beta corrections. In addition, the uncertainty of the ESM FH 40G-L 10 reference detector includes uncertainty of the integration constant [8].

The results presented in the graphs show an agreement between the measured and calculated quantities at the level of uncertainties. However, due to the large uncertainty of the RMS results, this agreement is not satisfactory, therefore, several corrective measures are planned for the RMS_v2020 update. The RMS-001 module will be equipped with multiple detection tubes, to minimize the statistical fluc-
tuation of results. Also optimization of their position will be carried out.

The relative uncertainty between RMS and the reference ESM FH 40G-L 10 detector could have been also caused by several reasons. First of all, discrepancy might have been caused by the measurement of different quantities, i.e., ESM FH 40G-L 10 measures ambient dose equivalent, RMS measures effective dose. Additionally, the error could have been caused by the reflection of photons and the production of secondary radiation due to lead shielding elements and the concrete wall. In the following period, the RMS_v2020 will be reverified using a new experimental workspace that minimizes errors resulting from secondary radiation. Another source of discrepancy could have been the calibration constant of RMS-001 for which the manufacturer gives guarantee only for $^{137}$Cs and $^{60}$Co sources.

Possible errors between measurement and simulation could have been caused by the older ICR-57 conversion factors implemented in the SCALE6 system, simulation of low energies that might have not been efficiently detected and deficient modeling of the workspace, since the exact distance of the effective center of the detection tube of ESM FH 40G-L 10 and the source is difficult to measure. Despite the identified errors and uncertainties, the verification of the RMS-001 module has met our expectations and help to aim the research of the RMS system in the next period.

V. DEMONSTRATION OF RMS AND UAV SYSTEM

Demonstration of the use of the developed technology was carried out as part of the regular emergency planning and preparedness exercise of Jáslovské Bohunice NPP (EBO NPP) on 26th October 2017. The scenario of the demonstration consisted of two flights, where the capabilities of two measurement modules, the control unit and the RMS-WASP software were demonstrated. The aim of the first flight was to demonstrate real-time creation of radiation map, based on online measurement performed by the RMS-001 module. 13 measurement points were defined in the selected area, spaced apart approx. 150–200 m. The UAV equipped by the RMS-001 module flew between the measurement points and carried out 25 s stationary measurement at each point. Data collected during transportation between the measurement points, which took approx. 5–10 s, were omitted. The demo flight took approximately 20 min. The UAV flew 30 m above the ground and covered 18 000 m$^2$ total land area. The aim of the second flight was to demonstrate air sampling on demand by the RMS-002 module. The UAV equipped by RMS-002 performed an autonomous flight to the selected location of demonstration. After the UAV reached the measurement location, the air sampling was initiated from the ground station through RMS-WASP control software. Then the UAV carried out a short flight in selected perimeter while changing its height and speed. On the way back, air sampling was terminated.

The radiation map created from the measurements during the exercise is shown in Fig. 13. Since no artificial radioactive
TABLE VIII

|           | RMS-001 | SHMI [14] | EBO NPP [14] |
|-----------|---------|-----------|---------------|
| RMS       | 247.36±61.34 | 124.19±7.41 | 82.25±2.94    |

scales were present, only natural background was measured during demonstration. The specification of the locality, where the demonstration was carried out, was close to the dosimetry stations of Slovak Hydrometeorological Institute (SHMI) and the EBO NPP. The mean value of the dose rate measured during demonstration was thus compared with the values of SHMI and EBO NPP from periodical monitoring of the locality in Table VIII.

Although all three results meet the 99.9% (3σ) confidential interval of RMS, there is 99.18–200.74% relative change between the measured data. This discrepancy is mainly caused by three facts. They are the short integration constant of RMS (25 s), the low number of measurement points (13) and the calibration constant of the GM tube (123.15 cpm/μSv/h).

Though the operational range of the J305β GM tube that starts from 50 nSv/h, this GM tube was not designed for precise background measurement. In the case of the average 247.36 nSv/h, the GM tube accounted for only 0.45 counts per second, thus the increase of measured counts by only a few per minute, may cause significant deviation in the results. However, for background measurements, the J305β GM tube can be simply replaced, without requiring the RMS electronic and software parts to be modified. It should be noted that data of SHMI and EBO NPP are the mean values of monthly measurements with integration constant 10 min and 24 h, respectively, while the RMS value is the average of 325 s. Therefore, these values can also hide day to day fluctuations as another source of obtained deviation.

VI. CONCLUSION

Although the design of the current generation of NPPs incorporates features that minimize the risk of large radioactive releases outside the reactor, it is still important to focus on the development of systems that can mitigate the consequences of such events. In situations when the level of radiation does not permit the personnel to perform the required measurements, unmanned RMSs may come to the play. Such a system has been developed in the cooperation of the B&J NUCLEAR Ltd., and UAVONIC Ltd., companies. It is the RMS-00x technology and its main features are modularity, affordable price, long operation time, high level of reliability and operation with an UAV system. Currently, the system consists of the RMS-000 communication module, three measuring modules RMS-001, RMS-002, and RMS-003 and the control software RMS-WASP. The RMS_v2017, designed for demonstration purposes, makes possible to measure the effective dose of gamma and beta radiation up to the level of 277 μSv/h, air sampling at a speed twice the human respiration rate, collection of the parameters of the measurement environment and the creation of online radiation maps. The RMS-001 module was tested and calibrated using various radioactive sources and certified measurement instruments at INPE FEI STU. Later the testing was performed in environmental conditions. The obtained results showed that the precision of the RMS-001 radiation measurement module is comparable with the certified detector, however, the dead-time of the detection tube and the high statistical uncertainty play an important role.

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