MEASURING REGENER-PFOTZER MAXIMUM USING DIFFERENT TYPES OF IONIZING RADIATION DETECTORS AND A NEW TELEMETRY SYSTEM TF-ATMON

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Exact location of the Regener-Pfotzer maximum depends on many parameters such as atmospheric conditions, geographical locations, solar activity, and also the type of detected particles. To investigate cosmic radiation at high altitudes and to test new detectors for cosmic radiation measurements, stratospheric balloons are useful. Due to necessary data processing of data measured by instruments, the balloon gondola needs to carry, together with radiation detectors, a number of additional supplementary sensors measuring humidity, temperature, location and orientation, altitude, atmospheric pressure, acceleration etc. This was the reason why a new universal system TF-ATMON was developed. The system is based on using already existing tools of the PX4 open-source project that makes it possible, apart from data recording and monitoring, to solve other related issues - the possibility to trace the balloon gondola after the flight. The application will be demonstrated on stratospheric balloon flight FIK 6. This flight was unique because three different types of radiation detectors were used at one flight. It enables us to compare the altitude of the Regener-Pfotzer maximum measured with a different type of sensor sensitive to a different type of secondary cosmic radiation generated in the atmosphere.

INTRODUCTION

Particles of primary cosmic radiation with sufficient energy interact in the upper part of the atmosphere and generate showers of secondary cosmic radiation. With increasing depth of the atmosphere the intensity of primary radiation decreases whereas the secondary component increases. At an altitude of about 20 km the intensity of secondary cosmic radiation reaches its maximum, called the Pfotzer-Regener maximum [10], [1]. The maximum varies with geomagnetic vertical cutoff rigidity and with solar cycle and it is generally located at 15-27 km [3]. In the past, several experiments were done with the aim to measure vertical profile of ionization in the atmosphere at various locations in the word, mainly using radiosondes consisting of Geiger tubes [3], [8],[9], [6], [7], or to characterize instruments' response used for space-based missions [2] [4] [5]. To investigate cosmic radiation at high altitudes (around and above Regener-Pfotzer maximum region) and to test new detectors for cosmic radiation measurements, stratospheric balloons are very useful. However, the radiation measurement instruments need to be supplemented also by other sensors measuring temperature, pressure, humidity, altitude, acceleration, etc. All these sensors should be continuously monitored during the launch and the flight of the balloon to verify their proper function and theirthe values have to be recorded for further processing of all obtained data. Platform developed for experiments at different altitudes consisting of a balloon tracking system and different measuring instruments will be presented. The universal system TF-ATMON, based on the use of existing tools of the open-source project PX4 and supplemented with an telemetry transmitter, enables it to monitor and record data during the flight and to trace the balloon. The application is demonstrated on stratospheric balloon flight FIK-6 Fig. 2. Various radiation detectors - Geiger-Mueller tubes, Si-diode based detector SPACEDOS, and scintillation detectors AIRDOS-C with inorganic scintillation crystals - were used to measure the vertical profile of cosmic radiation in the atmosphere.

MATERIALS AND METHODS

Since 2015 we launched several stratospheric balloons, the overview of flights is summarized in Table 1. During the first measurements, the construction of balloon gondola was always designed for the use of specific detectors. Balloon avionics was therefore built around the chosen detectors. This concept led to a situation when every new flight meant a significant amount of work despite the fact that a number of components was recycled every year and used the next one. The reason was the need to adapt the avionics to the innovated version of detectors.

Due to a relatively high value of payload it was necessary to ensure the return of the gondola every flight. The main construction criteria were as follows:

- Reliable transmission of information about the geographical location of the gondola
- Good resistance to impact
- Ensuring the function in temperatures far below zero

Due to the fact that since the first flight there were various partial shortcomings and despite the generally successful nature of all fights and the fact that the gondola was always found, we tried different technologies to eliminate the complications, which have emerged. During the last experimental flights these included the way the data is recorded.

For this reason, the originally used telemetry system was made significantly more robust and an IoT LoRa transmitter was added to the system, making it possible to transmit the data necessary for tracing the gondola to the TheThingsNetwork. In this way, a high reliability of finding the gondola and recording the data is ensured. In case of active detectors, it is also necessary that the flight trajectory is recorded synchronously with the supplementary quantities.

An overall overview of the success of the used technologies is summarized in the table 1.

Apart from technologies used in gondolas a number of supplementary tools have undergone intensive development. For example, in order to find the balloon it was necessary to have an accurate real-time map of its position together with a prediction of the subsequent flight and the site of impact. In the case of the last two flights, FIK-5 and FIK-6, the problem is solved by [16]. As can be seen from the table, during the last flights the avionics was implemented using an UAV technology. It uses the Pixhawk autopilot with PX4 firmware. Telemetry is implemented by a very reliable combination of LoRa modem and SiK modem. Power is provided by Li-ion 18650 batteries that also have a reliable flight history.

Universal avionics

Based on our experience we have used a universal concept of avionics called TF-ATMON that makes it possible to connect different types of payloads and carry out various atmospheric measurements. Furthermore, it provides the detectors with basic services such as power supply, time, position and orientation information. Basic quantities that affect many types of measurements are also recorded. Such quantities are temperature, pressure, humidity, magnetic field and acceleration. Flight computer provide a possibility to record data from carried experiments in a common log file. Therefore it is extremely useful for testing high-altitude cosmic radiation detectors and dosimeters. And it reduces the number of modifications in experiments (dosimeters) required for balloon flight.

The schematic diagram of the new avionics is summarized in the figure 1.

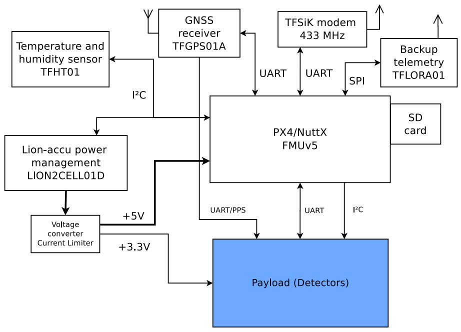

Figure 1. The schematic diagram of the new avionics

Transition to the concept, where the balloon specific parts of avionics are completely separate from the system of detectors, simplified the realization of next balloon flights. It reduced the complexity of connecting different types of detectors and at the same time it improved the integrity of supplementary data measurements. Overall, the new features can be summarized as follows:

- Easy implementation of different payloads
- Redundant telemetry links
- Gondola orientation and spatial position tracking and logging
- Reliable IMU sensor processing and calibration
- Possible use of relative high-power consumption payloads
- Pre-flight continuous charging as an option
- Power monitoring and maximum uptime calculation relevant to actual temperature
- Real-time pre-flight payload diagnostic

The documentation of used blocks could be found in the following sources TFGPS01 [17], TFSIK01 [18], TFHT01 [19], TFLORA01 [20], [21].

Payload

The payload of FIK-6 flight contained TF-ATMON and three different types of ionizing radiation detectors. The payload was not fully optimized for this use yet. All the detectors thus have their own SD cards for data recording and some even have their own power supply, therefore the payload weight was higher than theoretically required and some lift was wasted. This situation originates in conservative flight plan, which required successful log and function of payload even in failure of the new TF-ATMON system. Results from flight FIK-6 will be presented.

Table 1. Table summarising success of used technologies, with colours representing a degree of reliability: Failure Partial failure Perfect function .

Flight	FIK-1	FIK-2	FIK-3	FIK-4	FIK-5	FIK-6
Location (year)	CZ (2015)	CZ (2017)	CZ (2018)	SE (2019)	CZ (2019)	CZ (2020)
Payload	Candy detector, Web camera	Candy detector, Web camera	AIRDOS, 360 deg camera	AIRDOS-C CRY19, SPACEDOS, G-M, Socrat-R	AIRDOS-C CRY19,SPACEDOS, G-M, 360 deg camera	AIRDOS-C NaI(Tl), SPACEDOS, G-M, Ionmeter, 360 deg camera
Landing site	vineyard Austria	rapeseed field	Poland	swamp (Finland)	forest	railway corridor
Power source	Li-ion 18650 accu	Li-ion 18650 and li-pol accu	Lithium primary cells and li-pol accu	Lithium primary cells	Lithium primary cells	Li-ion 18650 accu
Telemetry system	GSM	GSM, 868 MHz Proprietary Modem	SigFox, 868 MHz Proprietary Modem	Outsourced	LoRa, SigFox, SiK 433 MHz	2x LoRa, SiK 433 MHz
Rescue beacon	433 MHz CW	433 MHz CW	433 MHz CW	Outsourced	433 MHz CW	433 MHz CW
Flight control computer	Odroid-U2	Odroid-U2	Not used	Not used/outsourced	PX4, FMU v5	PX4, FMU v5

Detectors

The payload of FIK-6 flight contains three different types of ionizing radiation detectors. There were deployed SPACEDOS with silicon PIN diode sensor (namely SPACEDOS02A), AIRDOS-C with scintillation crystal and silicon photomultiplier and a G-M tube. The total payload mass was 2 kg.

SPACEDOS is a lightweight dosimeter intended for space applications for measurements on board spacecraft. The detector has been described in [12]. The detector is a silicon PIN diode with a volume 300 µm $\times$10 mm $\times$20 mm $=$ 0.06 cm^3. The energy range of this detector is from 0.2 MeV to 9 MeV.

AIRDOS-C is a scintillation detector with a small crystal. The detector has been described in [13]. This detector enhauses NaI(Tl) crystal with a volume $\varnothing 10mm \times 20mm$ $=$ 1.6 cm^3 and SiPM (Silicon Photomultiplier) with a sensitive surface 6 mm $\times$6 mm. The energy range of this detector is from 0.2 MeV to 18 MeV.

The G-M tube STS-5 was used in the Geiger–Müller counter. The volume of the tube is $\varnothing$10 mm$\times$76 mm $=$ 6 cm^3. This detector is capable of registering only the flux. All detectors, together with other sensors and TF-ATMON system were put inside a polystyrene box.

RESULTS

The flight FIK-6 took place on December 18th, 2020 and lasted 1 hour and 40 minutes 3. The system TF-ATMON recorded temperature, air pressure, humidity and radiation characteristics as histograms of deposited energy of radiation events from all three radiation sensors in the gondola: gamma spectrometer AIRDOS-C with a scintillation crystal NaI(Tl), Spacedos with a PIN diode detector, and Geiger-Müller counter (see Figure 4. The barometric altitude was calculated using the International Standard Atmosphere model 1976 [14].

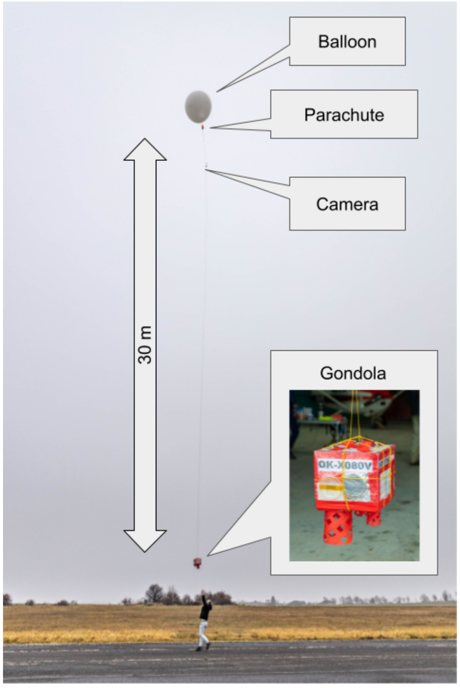

Figure 2. FIK-6 experiment setup using the Hwoyee Weather Balloon 1600.

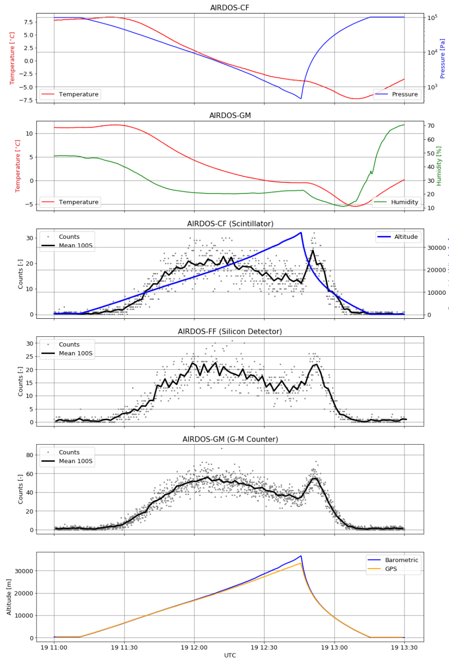

Figure 4. Raw data measured during the whole flight. From top to bottom: temperature near scintillation crystal, air pressure inside the box of crystal, temperature inside the gondola, relative humidity inside the gondola, counts of radiation events per 10 seconds counted by scintillator, silicon detector, and G-M counter, barometric altitude, and altitude from GNSS.

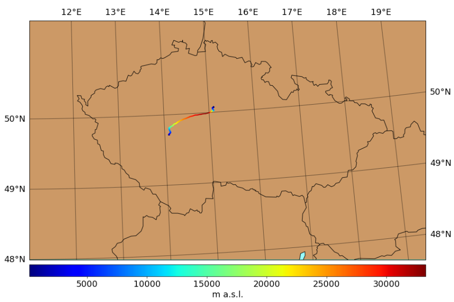

Figure 3. FIK-6 flight path

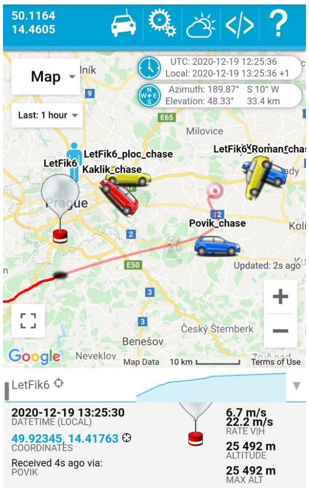

Figure 5. Chasing cars with telemetry receivers at the landing site.

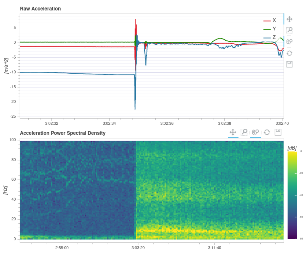

Figure 6. FIK-6 balloon burst

The graphs show that the maximum reached altitude was approximately 33km above sea level. The length of the flight trajectory in this case was approximately 100km. During the flight the balloon passed the Regener-Pfotzer maximum twice. The rescue team follows the balloon along the whole flight trajectory. The precision of tracking allows some participants of the rescue team to actually see the gondola touchdown visually. Therefore the gondola was successfully rescued within few minutes after touchdown.

By processing the data a graph of detected altitude Figure 7 can be obtained. It shows that the measured altitude of the Regener-Pfotzer maximum was for all detector types around 19km above sea level.

Pro urceni R-P maxima jsme pouzili Log-norm distribution fit na namerena data normovany na maximalni pocet castic pro dany detektor.

$$A\frac{1}{x\sigma\sqrt{2\pi}}\ \exp\left(-\frac{(\ln x-\mu)^2}{2\sigma^2}\right) \tag{1}$$

Parametry prokladu A, μ, σ a vypoctene polohy R-P maxima jsou uvedeny ve Figure. Pro fit byl vybran rozsah barometrickych vysek 7000 m az 29000 m. Spodni hranice byla zvolena tak, aby nebyl prubeh funkce ovlivnen terestrialnim zarenim a radon progenies v atmosfere. Horni hranice byla urcena ze simulace, protoze ve vetsich vyskach neni podle simulace tok ionizujicich castic klesajici rovnomerne.

Povsimnete si, ze absolutni pocty merenych castic odpovidaji aktivnimu objemu pouziteho detektoru. Cim vetsi objem, tim vice castic. Zaroven kazdy detektor zmeril odlisnou polohu R-P maxima. Nejnize zmeril maximum detektor s nejvetsi hustotou (NaI(Tl), $\rho = 3.67$ g/cm^3), potm kremikovy detektor (Si, ρ = 2.33 g/cm^3) a nakonec nejvyse zmerila polohu maxima G-M trubice (thin metallic tube filled with low pressure gas).

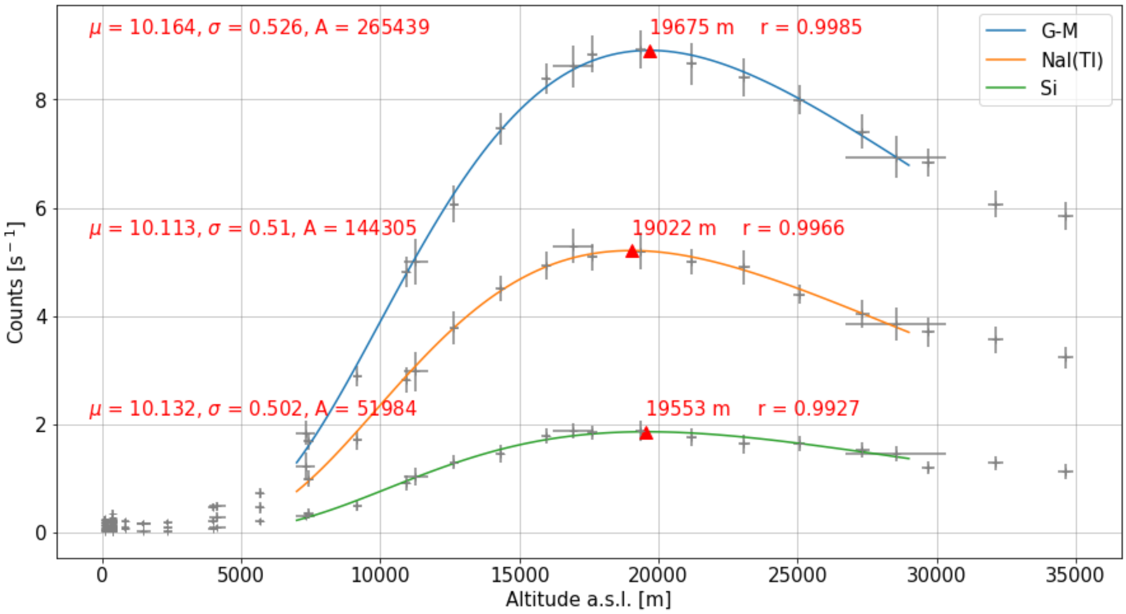

Figure 7. Log-norm fit of ionising radiation measured data with calculated Regener-Pfotzer maxima for different detectors (G-M tube, NaI(Tl) scintillator and silicon PIN diode). Measured data are depicted with gray color as mean from 5 minutes of measurement with 2σ standard errors.

DISCUSSION

Z naměřených dat je patrné, že během letu je velmi znatelný rozdíl mezi počtem bodů kvalitou měřených dat ve směru vzhůru a při klesání. Tento rozdíl je dán kromě odlišných tepelných podmínek hlavně rozdílnou hodnotou vertikální rychlosti. Tuto záležitost se v následujících balonových letech chystáme vyřešit kontrolovaným sestupem, kde by bylo možné rychlost klesání v některých fázích letu snížit. Tak aby byla více srovnatelná s rychlostí výstupu.

Zaroven je videt, ze behem klesani dochazi ke značným vibracim, skokovym zmenam zrychlení a také dochází k rotaci gondoly. Vsechny tyto parametry mohou mit vliv na mereni atmosferickych velicin a pro nektere druhy pristroju musi byt kompenzovany. Zaroven je videt pri klesani narust vlhkosti, ktera muze v urcitych castech letu i namrzat na přístroje.

Further plans

As can be seen from the table, the last unsolved problem with the balloon flights is the landing site. Therefore, in the future flights we are planning to use the autopilot for a controlled descent as well. The descent will be carried out using an unmanned autogyro carrying a payload. The purpose of this solution is in using the autogyro's rotor instead of the original parachute as it has the advantage of good controllability. Thus it would be possible to choose the landing site and reduce the possible risk of creating dangerous situations. And at the same time it is able to control the descent rate.

CONCLUSION

Flight FIK-6 was unique due to radiation measurements of the Regener-Pfotzer maximum using three different types of radiation detectors. Altitude of the Regener-Pfotzer maximum was about 19 km and slightly differ based on the detector type: GM counter measured the highest value (19270 m), silicon PIN diode measured lower value (18802 m), and scintillation detectors the lowest value (18668 m).

A telemetric system TF-ATMON has been developed. It enables data recording, pre-flight instruments control and their monitoring during flight. Thanks to the availability of different communication interfaces on the basic avionics, the use of various alternative detectors is simplified. The technology at the same time improves the possibilities of a quick location of a balloon gondola after its landing. It is therefore possible to carry out even experiments requiring a very short period till recovering the balloon after the flight. The system was successfully tested during FIK-6 flight.

ACKNOWLEDGEMENT

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