A Study for an Unmanned Aerial Vehicle carrying a radiation spectrometer networked to the new Athens Center active in Space Weather Events forecasting

E.G. Stassinopoulos, H. Mavromichalaki, C. Sarlanis, G. Souvatzoglou and S. Tsitomeneas

Abstract — **A proposal is presented for flying a light Unmanned Aerial Vehicle (UAV) carrying a Linear-Energy-Transfer (LET) radiation spectrometer and networked to the Athens Neutron Monitor Data Processing Center (ANMODAP), active in Space Weather Events (SWE) forecasting. The ANMODAP receives data from a large number of remote neutron monitor (NM) stations, provided in real time over the Internet, together with satellite data. Through this project, the ANMODAP forecasting capability will be increased with the collection of data at high atmospheric altitudes over Greece by the LET radiation spectrometer, carried on the specially designed UAV. The advantages of this spectrometer are its very small dimensions, light weight, and low power consumption. The UAV, powered from photovoltaic generators, flying at high altitudes with propellers on small electrical motors, and carrying simple networking equipment, will achieve long range telecommunication links with a terrestrial footprint larger than the area of Greece.**

Index Terms— **Cosmic rays, spectrometer, Unmanned Aerial Vehicle, Neutron Monitor network, forecasting, Linear-Energy-Transfer, Space weather**

I. INTRODUCTION

Solar relativistic particles measured at Earth have an essential property of bringing information on solar and interplanetary conditions much earlier than low and mid energy solar particles. The early detection of an Earth-directed solar proton event by NMs offers an opportunity of preventive prognosis of dangerous particle fluxes and can provide an alert with a very low probability of a false alarm [1]. A data collection system, with the capability of getting data from a large number of widely dispersed NM stations, has been developed at the Athens cosmic ray station. The system provides reliable data, using independent programs for simultaneous data collection from different stations in a periodic scheme with a specific time period determined automatically or even manually. A feasible and statistically proven method, using total counts from several stations in real time, could be used for this purpose. Up to now twenty three stations are accessible online, together with GOES and ACE satellites data.

A long-range effort to study the complex dynamics of the atmospheric radiation field on a global scale has been initiated by [2]. For this purpose a comprehensive database is being generated, using aircraft measurements made by a Low-Let Radiation Spectrometer (LoLRS), to enable a multivariable global mapping of doses and Linear-Energy Transfer spectra at aviation altitudes. As described by [2], this data base will be used to generate a detailed description of the cosmic ray induced particle environment and determine the effects from long- and short-term variations.

In 1990, the International Commission on Radiological Protection (ICRP) recommended that the radiation exposure due to cosmic rays at high altitudes be taken into account, where appropriate, as part of occupational exposure to radiation. Results of experimental studies of air crew exposure regularly compared with the results of transport codes, permit the estimation of the level of exposure due to the galactic cosmic ray component [3]. From the spring of 2000, such measurements were obtained with an energy deposition spectrometer based on a Si semiconductor, MDU-Liulin [4]. It allows the estimation of low (electrons, high-energy protons, mesons etc) and high (neutrons mostly) LET components of onboard aircraft radiation fields and the total exposure level. Recently, in [5] reported that in a series of long term measurements performed with this equipment

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onboard of Chech Airlines aircraft during the year 2001, they were able to register the solar cosmic ray event GLE60 on April 15, as well as the Forbush Decreases (FD) on April 12 and November 06, 2001.

Based on the above, the use of a small and light UAV, flying at high altitudes and carrying on board a detector for monitoring radiation levels and additionally telecommunication transceivers, can open new measurement structures at some important altitude levels, over an extensive geographical area, offering complimentary services to the appropriate terrestrial, aircraft, and satellite probes [2]. The main advantages of having the LET spectrometers on the UAV are their favorable physical attributes (very small dimensions, light weight, very low power consumption), the opportunity their measurements will provide to determine the impact of GLEs on the atmospheric radiation environment, and the possibility to obtain a quantitative assessment of the induced changes.

The main benefit of the high altitude flights (inside and/or above the tropopause) is that the meteorological phenomena will be limited and that a radio-link, having as node an UAV, can be very effective, almost as it happens from a satellite, according to the International Telecommunication Union (ITU) [6], [7]. These flights can offer a wide range of telecommunication capability [8] and the UAV, acting as High Altitude Platform (HAP), may cover a footprint that will be extended in a diameter up to 1000Km.

The references on the technological structure of the already tested UAV prototypes show continuous development in automation and improvements in the power consumption, with the solar cell use as the new attractive powered technology, already established in the satellite transponders and in small terrestrial telecommunication stations [6]. Some of the research and development reports of UAVs include the on-board power generation with the transformation of microwave or solar radiation. Specifically, regarding the solar cell power supply, so far only some prototypes UAV have been developed and tested (all in the USA). Figure 1 shows the PATHFINDER, one of the earlier successful solar powered UAVs, on a test flight over the Hawaiian islands in the summer of 1997, where it reached a record altitude of 21.8 km (71500 ft) [Courtesy : NASA – AeroVironment].

II. MEASUREMENT AND PROCESSING ABILITY

The "Low-LET Radiation Spectrometer" (LoLRS) is a basic instrument that is designed to measure the energy deposited by particles with low LET values from approximately 0.6 to about 14 keV/μm (electrons, protons, neutrons). The heart of the instrument is a silicon-lithium drifted diode 1 mm thick, with a sensitive area of 1 cm^2 [9]. Test results show that the LoLRS can be used to monitor the radiation threat to personnel on spacecraft and aircraft, and also to generate a comprehensive data base from aviation and satellite measurements that would make it possible to study slow or fast spatial and temporal variabilities and evaluate their impact on the atmospheric radiation environment. Moreover, a "High-LET Radiation Spectrometer" (HiLRS) has been developed that measures energy deposited by heavy ions in microelectronic devices [10], causing Single Event Effects (SEEs). It operates on pulse height analysis principles and is designed for space and aviation applications.

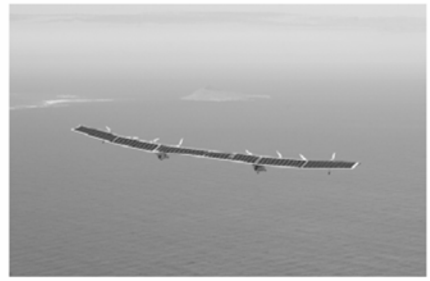

Fig. 1: Flight of "Pathfinder" UAV
(http://www.aerovironment.com/news/news-archive/PMRF.html)

On the other hand, it is known that Neutron Monitor detectors provide continuous ground based recording of the nucleonic component in the heliospheric secondary radiation that is related to primary cosmic rays. The worldwide network of neutron monitors is a powerful tool to allow measurements of the cosmic ray spectrum down to low primary energies using the Earth's magnetic field as a spectrometer. The neutron monitor energy range is complementary to the upper range of energies measured by cosmic ray detectors flown in space, Figure 2 [11]. With their high counting rates due to large detecting area that can only be accommodated at ground based stations, neutron monitors excel at measuring the small variations that occur in the galactic cosmic ray intensity at these high energies, especially when these variations are anisotropic [12]. The use of these large area detectors on the ground is also vital for measuring the low fluxes of high energy particles accelerated in the vicinity of the Sun due to solar flares and coronal mass ejections. The high energy particles from the most severe solar events which can cause damage, arrive at Earth about a half hour earlier than the abundant 'killer' medium energy particles, thus providing an opportunity to establish an early warning system to alert interested parties about the potential hazard to satellites, the space station, space personnel, and aircraft flights scheduled over the poles.

Taking into account that only few of the great number of solar flares and coronal mass ejections (CMEs) produce dangerous ion fluxes, it is not only critical to alert clients about the arrival of the most severe radiation storms, but also to minimize the number of false alarms against events which

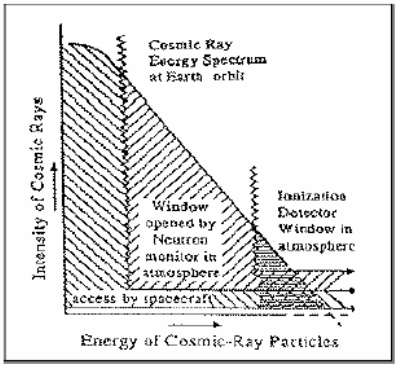

Fig. 2: Power spectrum of cosmic rays

are not severe enough to cause damage. So, the use of detectors at different altitudes and low and mid latitudes, detecting secondary fluxes generated by the few high energy ions as they enter the Earth's atmosphere, can help to make unambiguous forecasts and estimate the energy spectra of the upcoming dangerous fluxes. Figure 3. shows the effects from the interaction of the cosmic rays with the constituents of the Earth's atmosphere, producing a cascade of secondary particles, mostly energetic neutrons and protons [13]. The detection of at least two or three cosmic ray components at different latitudes and altitudes make it possible not only to reconstruct the solar ion flux outside the Earth's atmosphere, but also to estimate the energy spectra of upcoming solar particle fluxes.

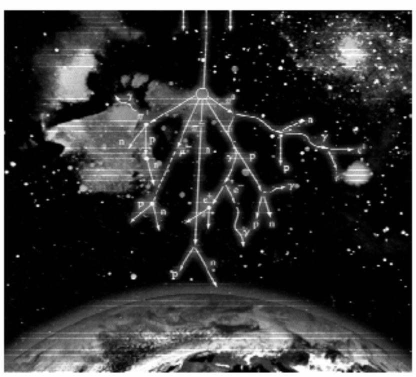

Fig. 3: Cosmic ray progeny in the Earth's atmosphere

In order to accomplish this purpose, a fully functional data analysis Center in real time is in operation at the Athens Neutron Monitor Station (ANMODAP Center) for research applications (http://cosray.phys.uoa.gr), Figure 4. It has a vertical cut off rigidity of 8.53 GV. The system consists of six BF3 gas proportional counters with the enriched isotope B^{10} type BP28 Chalk River Canada.

To perform a detailed study of potential cosmic ray variations and space weather conditions, it is necessary to compare good quality data from a number of high rigidity stations.

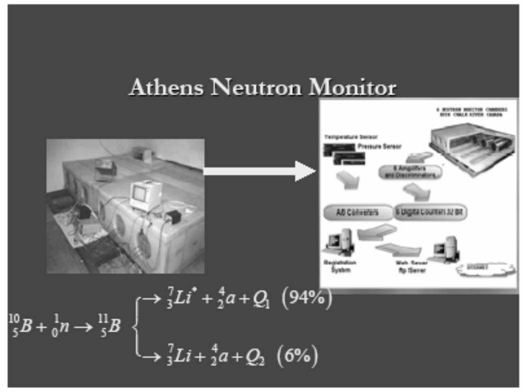

Fig. 4: Athens Neutron Monitor data collection system

A multi-sided use of neutron monitors consisting of twenty three stations, operating in real-time, provides crucial information on space weather phenomena [14], [1]. In particular, the ANMODAP Center can give alert for the onset of ground level enhancements (GLEs) of solar cosmic rays which can be registered much earlier than the main part of the lower energy particles, that can be dangerous for causing damages on space-born and ground based electronic systems. Moreover, the monitoring of the precursors of cosmic rays gives an advanced estimate on what kind of solar-terrestrial events should be expected, on geomagnetic storms and/or on Forbush Decreases. In other words, the network of Neutron Monitors is a unified multidirectional spectrograph/detector characterized by considerable accuracy, providing a significant tool of forecasting the arrival of interplanetary disturbances at the Earth, Figure 5. An example of a characteristic sequence of events is depicted in Figure 6, which shows data from seven different neutron monitor stations. At the point "A", a CME occurred on the Sun. At "B", the CME arrives at Earth and cosmic rays decrease suddenly, generating a FD. At "C", a second CME occurred on the Sun. This one accelerated high energy particles that reached the Earth minutes later, causing a GLE, that is, the sudden increase (spike) in neutrons received by the neutron monitors. At "D", the second CME arrives at Earth and cosmic rays decrease again: another FD.

III. Data from the UAV study

The obvious advantages of the radiation measurements at different altitudes led us to the study and development of a

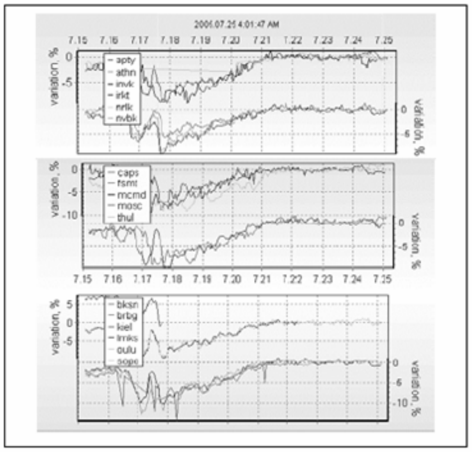

Fig. 5: NM plots from ANMODAP Center in July 2005

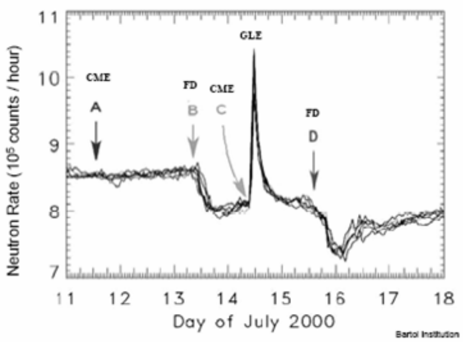

Fig. 6: Cosmic rays during high solar activity

small UAV, powered by solar cells, carrying the appropriate radiation detectors, and at least a transceiver as the network terminal, in order to achieve the direct communication to the ANMODAP. The maximum distance D_{tr} (in Km) between the UAV's transceiver and the remote point that the radio-wave reaches on the curved surface of the Earth, depends on the UAV's altitude "h_{tr}" (in Km) and on the refraction coefficient "k" ($k \cong 1.25$ in UHF telecommunication bands) of the radio waves. Supposing "a" is the average Earth radius (in Km), then:

$$D_{tr} = \sqrt{2K\, a h_{tr}} \cong \sqrt{h_{tr}}\ 4.12\ Km \qquad (1)$$

Hence, the D_{tr} of the transceiver, being at an altitude of 21 Km, will be 597.5Km corresponding to a footprint radius of 597.1 Km, covering the whole Greece, if the UAV flies over the Athens area. The UAV will be launched as a small dirigible balloon from its base. Reaching the height of $21Km \le h_{tr} \le 23Km$, the air-chamber either will be released as consumable, or it will empty and will be gathered in the UAV, while the electromotor propellers will continue to move and bring the UAV to the desired place with a speed of $6\ Km/h \le u \le 60\ Km/h$. The return and the landing will be achieved with the progressive UAV's descent as a glider. The autonomy imposes the need to control the flight with automation, utilizing the existing radio-navigation or GPS facilities. If the UAV's wings have a total surface of $1.5m^2 \le A_s \le 12m^2$ and an inclination to the horizontal level of $\theta \le 12°$, then the main forces in the centre of mass will be the weight $20Kp \le B \le 136Kp$, the aerodynamic uplift A (in units of Kp), the aerodynamic resistance T (in units of Kp) and the atmospheric drag E (in units of Kp), Figure 7.

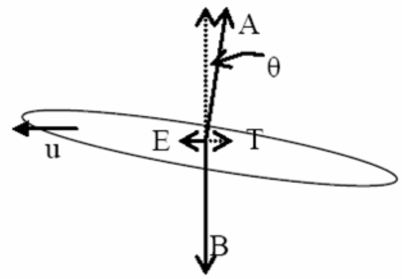

Fig. 7: The forces to the wings

Consequently, the motors should have the capability to develop power P_k (in Watt) which will be:

$$70W \le P_k = uE = uB \tan\theta \le 4726\,W \qquad (2)$$

If ρ is the atmospheric density (in Kg/m^3) and the lift and aerodynamic resistance coefficients are "c_a" and "c_{ar}", then during the descent of the UAV as a glider the following will apply:

$$A = c_\alpha \frac{\rho u^2}{2} A_S$$

$$T = c_{ar} \frac{\rho u^2}{2} A_S \qquad (3)$$

In a horizontal flight of the UAV, the electric power will depend on the roughness of its surface, the cross-section, the total mass (weight) and the 4-6 engines type (DC or AC). From the relation (2) it is estimated that with $20Kp \le B \le 136Kp$ the average motive power will be 16~125W and it will be re-defined after the tests in the laboratory and the experimental flights having as a basic criterion that the photovoltaics should have been adapted to the given wings surface of $A_s \le 12m^2$ and must cover all the daytime and night-time power needs. When the UAV supports transceivers with a circular or mixed polarisation directional antenna, having gain between 10-20db, it will require an equivalent isotropic radiated power (erp) of 0-3dbW in each radio-link, in order to achieve communication during the 95% of time. Therefore, each radio-link will consume 25-200 Wh. Therefore the power budget indicates that the UAV will be sufficiently powered by a typical (efficiency 10%) photovoltaic generator with surface of 1.32 up to 10.56 m^2, producing power of 175 up to 1400 Wp. The power management of the UAV needs special automation that ensures the undisturbed operation of all the equipment and systems and for the maximized transformation of the solar radiation [15], in combination with the storage of the produced electric energy in deep discharge batteries, Pb.

The telecommunication (and flight automation) systems of the UAV will require 125~1000Wh per 24-hour period (factor of losses 0.3), while the electric motors will consume 375~3000 Wh per 24-hour period (factor of losses 0.1). Consequently, the photovoltaic generator with surface 1.32-10.56 m2 and efficiency of 10% should produce power of 175-1400 Wp and at least 0.379 KWh/m^2 daily. The batteries weight Pb (factors 100~150 W/Kg and 35~40 Wh/Kg) should be 10~76 Kg. Even if experimental measurements with special tests are required, for the adaptation in the practice of the above theoretical estimations, it seems that the energy balance is realistic.

IV. CONCLUSIONS

The collection of radiation data at different altitudes will be very important for estimation of the exposure level during extreme events of solar activity. Previous results from many researchers demonstrate quantitative and qualitative influence of cosmic events on the radiation situation close to the Earth's surface. Measurements on board of aircraft by a Low-Let Radiation Spectrometer can contribute to the analysis of the characteristics of corresponding solar events. The flight of an unmanned vehicle at aviation altitudes carrying such equipment will generate the comprehensive database of the unified ANMODAP CENTER. This Center, based on the activities of the Athens and IZMIRAN cosmic ray groups, provides a real time monitoring of cosmic ray variations. The preliminary study for the UAV indicates that a photovoltaic generator of up to $12m^2$ would supply with electric power the radiation spectrometer(s) and both the flight and the radio systems (radio-links etc) in order to cover the whole area of Greece. Therefore the joint complex analysis of the relevant information from space borne and ground based detectors will be completed with the on flight measurements. A real time prediction of space weather phenomena will minimize the false alarms and will maximize the reliability and the timely forecasting of the arrival of dangerous fluxes from space.

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