Cosmic Rays and Space Situational Awareness in Europe

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***Abstract.* In this paper European space weather activities are sketched and the contribution of cosmic ray research and technology to the European space situational awareness programme is described. Especially the cosmic ray muon detection technique is studied – on ground and in future space based -, because it is considered to be very useful for coronal mass ejection forecast in the next solar maximum between 2011 and 2012.**

1. INTRODUCTION

APPLICATIONS of cosmic ray research will play a dominant role in the Space Situational Awareness (SSA) programme in Europe. The ESA Ministerial Council decided in November 2008 to fund M€ 55 for SSA activities between 2009 and 2011. These activities include projects related to space weather and space debris, radar applications as well as space weather pilot data centres [1].

SSA is the current highlight of ten years space weather activities in Europe. Starting in 1998, ESA organized annually a space weather workshop and conference or a space weather week with increasing contributions from cosmic ray community [2]. Already in 2000, Kudela et al. reviewed the importance of cosmic ray records for space weather research [3]. It was shown that some cosmic rays indices are reliable tools for space weather forecasts. A main step forward to a European space weather programme was the ESA space weather feasibility studies carried out by the ALCATEL Space and RAL consortia between 1999 – 2001 [4]. For example Jansen (2001) proposed within the ALCATEL space consortium a European space weather telescope based on cosmic ray muon measurements [5]. This, first European space weather telescope - so-called MuSTAnG telescope - was constructed between 2004 – 2006 at Greifswald University in Germany [6]. The MuSTAnG telescope and the associated service of a global muon detector network (GMDN with NST – Nagoya Scintillator Telescope / Japan, HST – Hobart Scintillator Telescope / Australia, SMST - Sao Martinho Scintillator Telescope / Brazil, KPC – Kuwait Proportional Counter / Kuwait), are described below in the chapters 2 and 3. It could be shown that the observational results from several cosmic ray muon telescopes are a very sensitive space weather prediction tool with the capability to generate warnings of CME (Coronal Mass Ejection) arrivals at Earth up to 24 hours in advance. This is considered to be very useful for SSA related supports in aviation, radio communication [7], security [8] and ground based effects on power lines and pipelines [9]. For more space weather effects see in [10].

On the political side, the European Commission (EC) developed a Green Paper of the European Space Policy (ESP). However the Green Paper not yet contained hints to space weather. During the Berlin workshop in April 2003 the scientific community was asked by EC and ESA about the space science in ESP. Therefore space weather science was proposed by the author (F.J.) of this actual paper. According to further panel discussions the White Paper of the European Space Policy included for the first time the important and specific statement „….to ensure that Europe has the capacity to supply to the different users critical information on solar flares, near Earth objects, space debris („space weather prediction")…" [11]. The implementation of ESP by SSA is based on two statements: 1) the peaceful use of outer space and 2) that the space has a security dimension and correspondingly that security has a space dimension. Consequently global monitoring, early warning and space surveillance, as an example, is needed. The actual ESA proposed SSA programme underlines the definition and scope of a European SSA system. It supports the safeguarding of space infrastructures and the protection of critical terrestrial infrastructures in Europe because the infrastructures are a key element for economic development and protection of population. Worst case scenarios were discussed under the US National Research Council auspices [12]. Insurances like Swiss Reinsurance [13] studied already space weather business cases and Allianz [14] the disaster management in Germany. Consequently SSA covers space weather, but also space debris, asteroids and near Earth objects (NEO) impacts.

To support SSA activities on a national German level, the DLR Institute for Space Systems in Bremen is currently studying a space-based AsteroidFinder mission. The main objective of this satellite is to find asteroids between Earth orbit and the Sun (IEOs - Interior to Earth's Orbit). Especially important are those asteroids, which may cross Earth`s orbit.

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So far, only 11 IEOs have been detected by ground based observatories out of an assumed overall population of about 1000 down to a size of 100 m. Therefore AsteroidFinder will provide a considerable contribution to SSA / NEO research.

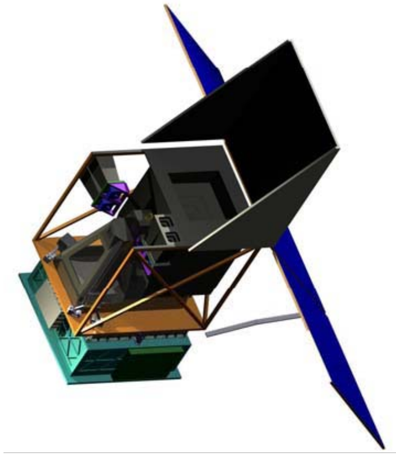


Fig. 1 Sketch of the DLR AsteroidFinder satellite [15].

The next chapters will contain descriptions and data of GMDN (chapters 2 and 3), the conclusions and future perspectives for SSA purposes (chapter 4).

2. THE GLOBAL MUON DETECTOR NETWORK (GMDN)

Why is GMDN important for space weather storm forecast? Space based coronagraphs on SOHO and STEREO observe CMEs by means of UV photons and the images and movies are available in data centres at Earth in near real time (about 30 minutes after the onset of the event at Sun). LASCO coronagraph on SOHO observes CMEs up to 30 solar radii – or about only to 1/3 of Mercury orbit [16]. If so-called halo CMEs were observed, SOHO data are useful to predict CME arrival time at Earth. STEREO spacecrafts are able clearly to identify earthward oriented CME [17]. In 2007, May 21 STEREO coronagraphs measured the propagation of a CME from Sun towards Venus.

However direct observations of interplanetary CME propagation between Venus and Earth orbits are an accessible interplanetary space for the ground based cosmic ray muon telescope network in real time without any delays due to technical reasons of data transfers from orbiting spacecraft to ground based receivers. Another benefit of ground based cosmic ray muon telescopes are that they are not affected in operation by space environment conditions like space based UV coronagraphs during space weather storms.

In 2007 Kudela already reviewed the advantages of cosmic ray muon and neutron measurements for space weather storm predictions [18]. In general: cosmic ray particles have due to their relatively large gyroradius and their long mean free path λ_p in interplanetary space (~ 1 … 2 AU) as well as due to their high velocity (~ c = 300 000 km/s) in comparison with CME propagation speed (v ~ 1000 … 2000 km/s) a high relevance in forecasting SSA related disturbances nearby or on Earth.

Cosmic ray muon space weather telescopes open a complete new window for space weather observations compared to UV telescopes – or detection by charged particle versus electromagnetic radiation by UV photons.

Ground level cosmic ray muon telescopes scan various directions on the sky (including to the Sun) as Earth rotates with them. The daily variations in counting rates of secondary produced muons on ground reflect the anisotropic flux distribution of primary, galactic cosmic ray in space. In addition the telescopes observe a reduced flux of primary cosmic ray particles moving away from the interplanetary shock in the front of the CME. The cosmic rays leaving the depleted region behind the shock with small pitch angles. A cosmic ray flux deficit or increase in the order of 1% to 5% - so-called precursor anisotropy decreases (PAD) or precursor anisotropy increase (PAI) were already measured in the early 1990s [19]. For the October 29, 2003 CME the PAD increased up to 11 % [20]. A first detection of the CME shock is in principle possible at a distance of

$$r \sim 0.1 \ \lambda_p \cos \beta \qquad (1)$$

(λ_p scattering mean free path of cosmic rays, β angle between Sun – Earth line and the mean interplanetary magnetic field at Earth). For example λ_p is about 1 AU for 10 GeV cosmic ray neutrons. Insofar CME arrivals are detectable by neutron monitors on ground about 5 hours before arrival at Earth. The muon telescopes of GMDN measure at about 50 GeV, with a much longer λ_p. Depending on the situation during CME propagation λ_p is in the interplanetary space between Sun and Earth in the order of 2 AU [21]. Therefore by means of a single muon telescopes or an entire network it is calculated to observe the cosmic ray anisotropy between 10 – 24 hours before shock / CME arrival at Earth – up to the Venus orbit (about 50 Million km distance). The actual cosmic ray muon anisotropy depends on CME geometry, magnetic field, speed, direction of propagation and IMF inhomogenities and discontinuities in interplanetary space.

Cosmic ray muon telescopes have two different detection principles: measurements by proportional counter (PC) and plastic scintillator (PS). PC telescopes are installed for instance at Australian Mawson station in Antartica (detection area: underground 2 x (2.5 x 1.8 sqm), ground 3 x (2.4 x 2.5 sqm)), Mt. Norikura in Japan (5 x 5 sqm) and the Kuweit PC with a detection area of 3 x 3 sqm. The Armenian muon telescope is a combination of PC and PS telescopes with a detection area of 3 x 2 sqm. Different details about these space weather telescopes are published in 2005 by Chilingarian [22] and about GMDN by Jansen [23] and Okazaki et al. in 2008 [24]. Cosmic ray muon telescope URAGAN at MEPhi Moscow is also in operation in integral and hodoscopic modes [25].

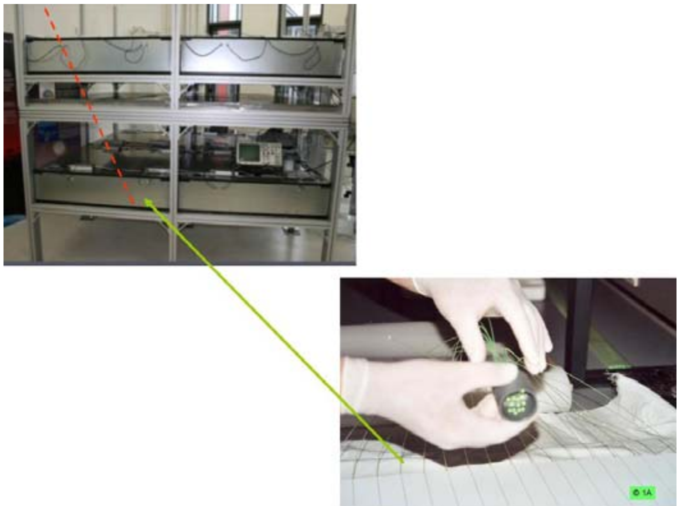
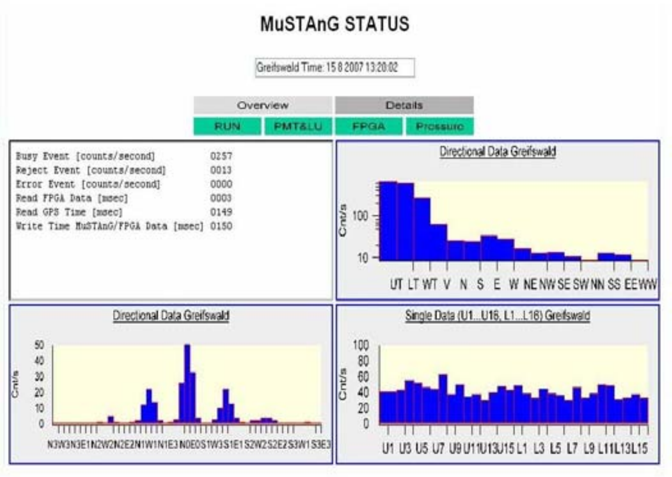


Fig. 2 Secondary cosmic ray muons (red line) passing trough two layers of MuSTAnG telescope (metal boxes). A lead layer is placed between the two layers. MuSTAnG plastic scintillator (PS) detectors (within the metal boxes) couple wavelength shifter (WLS) fibre optics to the PMTs (Photomultipier Tubes). White painted PS with green emission of WLS fibres are on the top of the PS. The grey PMT socket is also seen.

MuSTAnG has 4 PMTs per sqm to obtain a high angular resolution. The optical coupling between PS and PMTs is done by the WLS, according to L3+C detector technology at CERN [26]. This enables MuSTAnG telescope to receive a maximum efficiency. The UV light produced the cosmic ray muon in the PS will be shifted into green light, in which the selected PMTs of MuSTAnG have the maximum response. MuSTAnG has 49 viewing directions. The electronic component consists of the following parts:

1) local units for each of 32 PMTs, which contains preamplifer, high voltage supply and a signal conditioner with pulse shaper and
2) a recording system [27] as a coincidence unit based on advanced logical circuit using Field Programmable Gate Array (FPGA) and VHDIS Hardware Description Language (VHDL).

The local units are new developed electronic components. The recording system is also used in the GMDN telescopes NST, HST, SMST and KPC for successful inter-calibration of data sets into the network.



```
Busy Event [counts/second]             0257
Reject Event [counts/second]           0013
Error Event [counts/second]            0000
Read FPGA Data [msec]                  0003
Read GPS Time [msec]                   0149
Write Time MuSTAnG/FPGA Data [msec]    0150
```

Fig. 3 MuSTAnG operator display: the status of the telescope operation shows in three windows the count rates as a function of incoming directions - combined into V – Vertical, N – North, NE – North-East, S – South, E – East, W – west etc. and all 49 directions (for instance N0 to N3 – lowest northward direction etc.) and for all 32 PMTs the count rates (U1 – upper layer PMT1 to L16 lower layer PMT16).

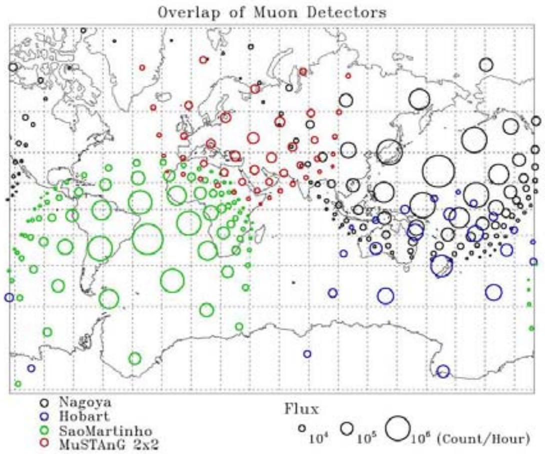


Fig. 4 The figure shows the overlapping of asymptotic viewing angle of four telescopes. MuSTAnG detects northwards up to Svalbard, eastwards behind Ural mountain, westwards up to the middle of the Northern Atlantic ocean and southwards just above the equator.

NST, HST and SMST telescopes have the self-evident pyramid like box structure. On the top of each pyramid is one PMT, which measure the UV light from the cosmic ray muons.

Fig. 3 Left: HST in Tasmania. Right: SMST in Brazil. In both images the lead layer between the pyramid like box with a quadratic box on top for the PMT are visible.

Fig. 4 Mt. Norikura muon telescope in Japan. In background: the proportional counter tubes. In foreground on the left side is the electronic box. Identical items are also used in MuSTAnG, NST, HST, SMST and KPC.

The GMDN member MuSTAnG has currently two layers of 2 x 2 sqm PS, NST two PS layers of 6 x 6 sqm, HST currently two PS layers of 3 x 3 sqm, SMST two PS layers of 7 x 4 sqm and KPC a detection area of 3 x 3 sqm.

3. GMDN DATA

The cosmic ray muon counts of the GMDN ground based telescopes must be converted into cosmic ray anisotropy in interplanetary space in real time. According to Fujimoto et al. [28] the numerical calculation is based on equation (2)

$$
\begin{aligned}
I_{i,j}^{cal}(t) = {} & c_{0i,j}^{0} I^{0}(t) + \xi_{x}^{GEO}(t)\left(c_{li,j}^{l}\cos\omega t_i - s_{li,j}^{l}\sin\omega t_i\right)\\
& + \xi_{y}^{GEO}(t)\left(s_{li,j}^{l}\cos\omega t_i + c_{li,j}^{l}\sin\omega t_i\right)\\
& + \xi_{z}^{GEO}(t)c_{li,j}^{0}
\end{aligned}
$$

$$
I^{0}(t), \xi_{x}^{GEO}(t), \xi_{y}^{GEO}(t), \xi_{z}^{GEO}(t)
$$

$$
\omega = 2\pi/24 \qquad (2)
$$

In the GMDN the function $I_{i,j}^{cal}(t)$ is fit to the measured pressure-corrected hourly count rates $I_{i,j}^{obs}(t)$ of secondary cosmic ray muons at universal time t in the j-th directional channel in the i-th muon detector (t_i – local time at the i-th telescope). Therefore we receive the best fit density of primary cosmic rays ($I^0(t)$ – the omni-directional component of intensity), the three components of first order anisotropy in the geographic coordinate system ζ_x^{GEO}, ζ_y^{GEO}, ζ_z^{GEO} and the so-called "coupling coefficients" connect the observed muon count rates to the primary cosmic ray intensity in the interplanetary space.

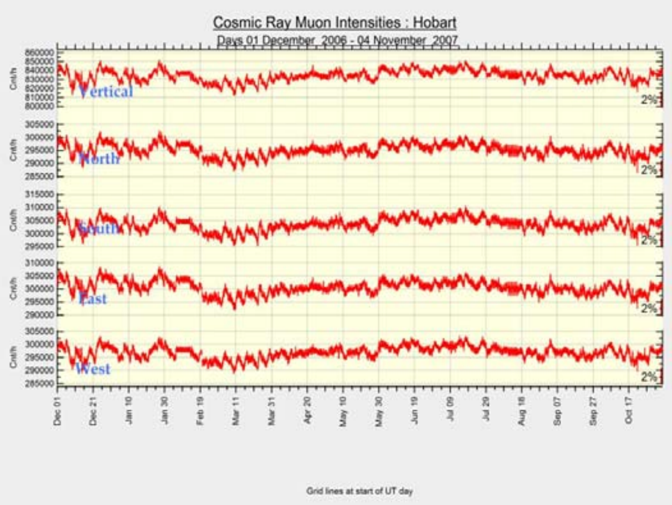


Fig. 5 Approximately two years of HST data: atmospheric pressure corrected count rates from vertical and all N, S, E and W directions.

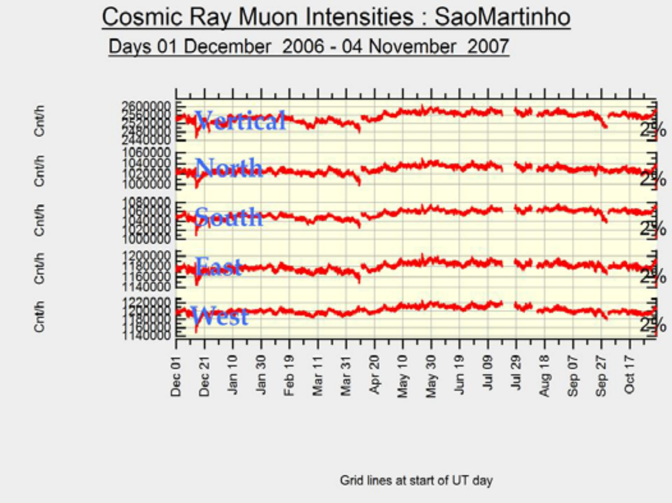


Fig. 6 Nearly two years of SMST data: atmospheric pressure corrected count rates from vertical and all N, S, E and W directions.

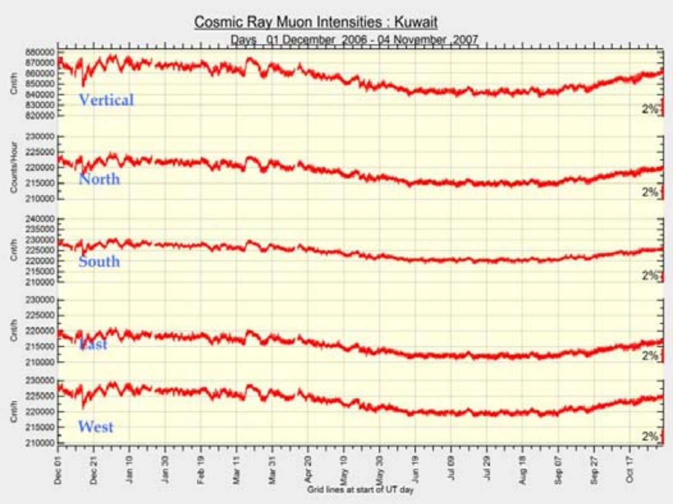


Fig. 7 Nearly two years of KPC data: atmospheric pressure corrected count rates from vertical and all N, S, E and W directions.

All five GMDN telescopes have been in the position to detect the last huge CME-event in December 2006. The CME launch time at Sun was 13 December 2006 2:30 UT and the arrival time at ACE was 14 December 2006 14:38 UT [29]. The transition time was 36 hours and the GMDN telescopes have detected a cosmic ray anisotropy in the same time period: the next figure displays a three days plot of the event. Top: the ACE spacecraft magnetic field data are shown in a space weather user friendly – green for positive and red for negative B_z. The ACE magnetic field data are needed to receive the actual cosmic ray anisotropy. Middle: cosmic ray muon density on ground in % deviation from the yearly mean density. Lower image: cosmic ray anisotropy (circle size in %) in interplanetary space as a function of pitch angle (angle 0° towards Sun, angle 45° - interplanetary magnetic field line direction at Earth orbit, 90° angle - Earth motion direction). First, small anisotropies were measured on 13 December 2006 between 33° to 120°. Strong anisotropies were detected in the second half of 14 December 2006 in a very broad region (10° to 180°).

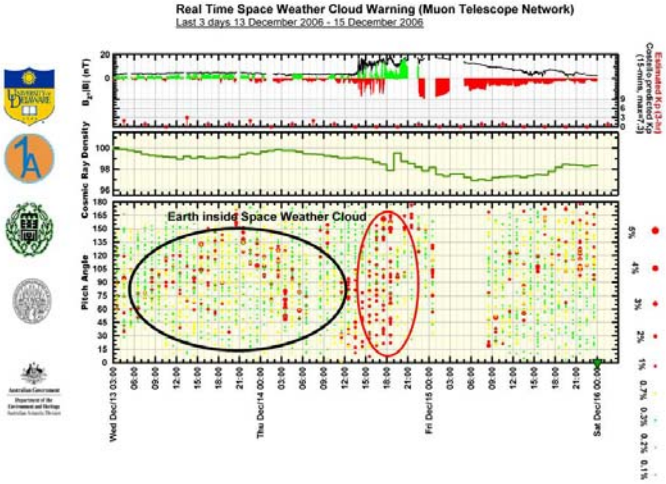


Fig. 8 Data of all five GMDN telescopes: the interplanetary CME was measured more than 24 hours on the way towards Earth (red anisotropy circles within the black line) and during the arrival time at Earth respectively the sojourn of Earth in the CME (red line). The anisotropy scale is given on the right (red dots 1% … 5% and greater, yellow dot 0.75 %, green dots 0.1 …0.3 %). Details see text.

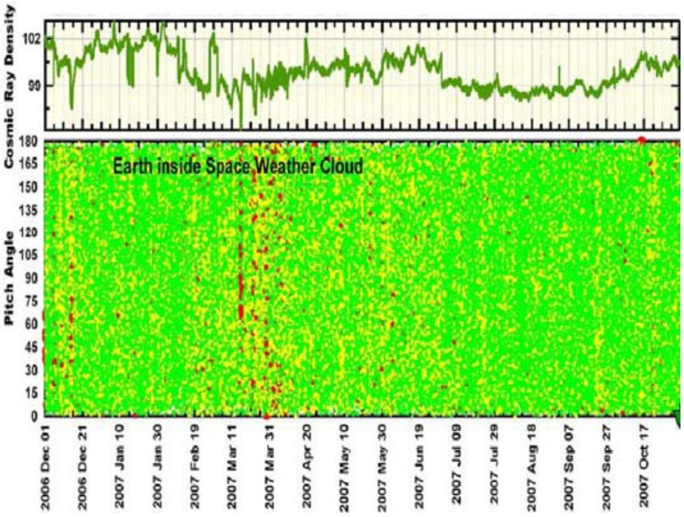


Fig. 9 Nearly two years of data of cosmic ray density and anisotropy (scale like in figure 8) of GMDN (all five telescopes, 1 December 2006 – 4 November 2007). Due to the very low number of solar activity there is just a very low number of anisotropies.

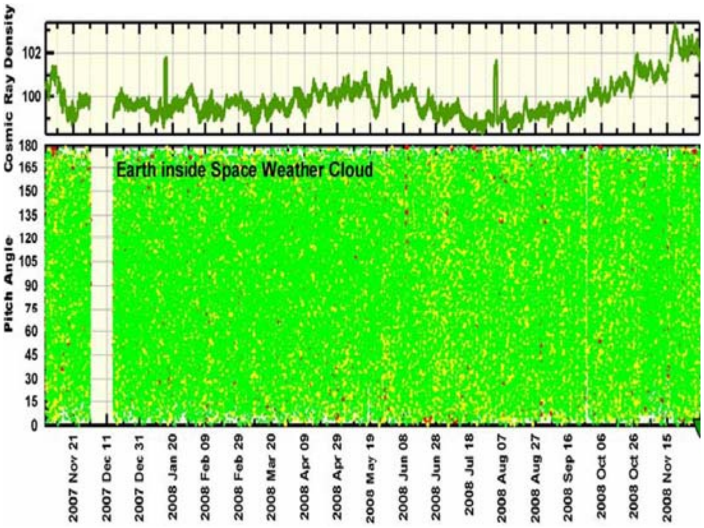


Fig 10 More than one year data of cosmic ray density and anisotropy (scale like in figure 8) of GMDN (all five telescopes, 4 November 2007 to 4 December 2008). There is no cosmic ray anisotropy measured because of the lack of CMEs due to the minimum of solar activity.

4. CONCLUSIONS AND FUTURE PERSPECTIVES

The ground based GMDN allows an effective monitoring of interplanetary CME for a SSA service. For the purpose of a 24 hours real time SSA service in Europe it is proposed to established the GMDN data centre at the DLR Institute in Bremen. The number of telescopes in the ground based GMDN may be increased by Armenian and Russian cosmic ray muon telescopes. In addition there are still two observation gaps in the network - the northern American and southern African continents are not yet covered.

A space based cosmic ray telescope for SSA purposes will be studied soon. The so-called EU / NESTEC proposal (NEw Space TEChnology with German, Dutch, Czech, Slovak and Greek partners) have foreseen to develop a space weather dedicated spacecraft with CME and solar telescopes based on several new concepts: an Innovative Core spacecraft (ICE) bus demonstrator, a new space based cosmic ray Particle Detector Technology (PDT) for a novel space weather storm imaging monitor and a completely new EUV Solar imager for solar Eruption (EUVSUN) detection. Parts of NESTEC are already tested on balloon and satellite flights. Russian NUCLEON space experiment may be also a good method to study above 100 GeV CMEs by means of cosmic rays [30].

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