Space Weather Forecasting at the New Athens Center: The Recent Extreme Events of January 2005

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Abstract—**From the beginning of this year a new data analysis Center [Athens Neutron Monitor Data Processing (ANMODAP) Center] is operated in Athens University producing a real-time prediction of space weather phenomena. At this moment there has been a multi-sided use of twenty-three neutron monitors providing real-time data on the internet. Moreover, interplanetary space parameters data from Geostationary Orbiting Environmental Satellite and Advanced Composition Explorer (ACE) satellite are also collected in this Center. The ANMODAP Center in real-time is of high potential interest, as it is expected to give alerts for ground level enhancements (GLEs) of solar cosmic rays (CRs) and geomagnetic storms and therefore to provide crucial information for Space Weather applications. Forecasting of the last GLE and the geomagnetic variations of CRs on January 2005, is presented.**

Index Terms—**Cosmic rays (CRs), neutron monitor (NM) network, forecasting, solar energetic particles, space weather.**

I. Introduction

SPACE WEATHER describes the state of the environment as a result of dynamic solar, heliospheric and magnetospheric phenomena in the context of potential impacts on technological systems. This term covers the conditions on the Sun and in the solar wind, magnetosphere, ionosphere and thermosphere that can influence the performance and reliability of space born and ground-based technological systems and endanger human life and health (US National Space Weather Program, 1995). Nowadays, there is a close relation and integration between space weather and the internet, as it becomes one of the most important tools for research in the field of solar-terrestrial physics. Information updated every minute or even more frequently, is provided by tens of instruments for studies of different solar, interplanetary and geophysical effects.

On the other hand, relativistic (galactic and solar) cosmic rays (Crs) registered by neutron monitors (NMs) can play a key-role in space weather storms forecasting [1] and in specifying magnetic properties of coronal mass ejections (CMEs), interplanetary shocks and ground level enhancements (GLEs), such as the ones observed onf January 20, 2005 (Fig. 1). As a result, an Earth-based NM network can be used to perform real-time prediction of space weather phenomena. Therefore, at the beginning of this year, a new fully functional real-time data analysis Center operates in the Athens NM Station [2], [3] for research applications [Athens Neutron Monitor Data Processing (ANMODAP) Center]. A suite of NMs consisting of twenty-three stations operating in real-time provides crucial information on space weather phenomena. The ANMODAP Center can issue a preliminary alert for GLEs of high energy solar CRs providing a pre-warning of the potentially harmful (to space-born and ground-based technological systems) low energy part of the event. Therefore, these energetic solar CRs provide the advantage of forth warning. Moreover, the monitoring of the precursors of CRs gives a prior estimation of the expected solar-terrestrial event type, geomagnetic storms and/or Forbush decreases [4]. In other words, the network of NMs is a unified multidirectional spectrograph/detector characterized by considerable accuracy, providing an important tool of forecasting the arrival of interplanetary disturbances at the Earth.

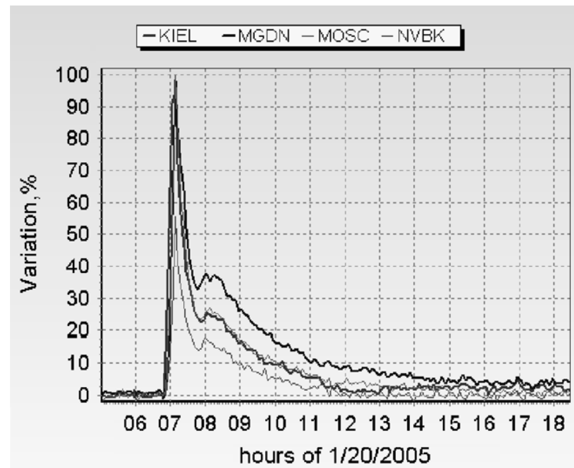

Fig. 1. New GLE on January 20, 2005 as recorded at the NM stations of Kiel, Magadan, Moscow, and Novosibirsk.

In this paper, the declared goals of the new data analysis Center of Athens University are presented and results of the alert programs applied to recent events of January 2005 are discussed.

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TABLE I
LIST OF REAL-TIME NEUTRON MONITOR STATIONS CONNECTED TO ATHENS CENTER.

Stations	Abbrev.	Lat (^{0})	Long(^{0})	Alt (m)	H_0 (mb)	R_C (GV)
APATITY	APTY	67.55	33.33	177	977.80	0.55
ATHENS	ATHN	37.97	23.72	260	974.70	8.53
BAKSAN	BKSN	43.28	42.69	0	818.50	6.91
BARENTSBURG	BRBG	78.12	14.42	0	964.70	0.20
CAPESCHMIDT	CAPS	68.92	180.53	0	1021.30	0.52
EREVAN	ERVN	40.17	44.25	2000	798.30	7.36
EREVAN-3	ERV3	40.17	44.25	3200	683.90	7.36
ESOI	ESOI	33.30	35.79	2025	800.00	10.41
FORTSMITH	FSMT	60.00	-112.00	0	996.10	0.30
INUVIK	INVK	68.35	-133.72	21	1019.10	0.14
IRKUTSK	IRKT	52.47	104.03	433	965.00	3.49
KIEL	KIEL	54.34	10.13	54	981.40	2.36
LOMNICKY STIT	LMKS	49.20	20.22	2634	733.00	3.88
McMURDO	MCMD	-77.85	166.72	48	985.10	0.00
MOSCOW	MOSC	55.47	37.32	200	991.90	2.30
NORILSK	NRLK	69.26	88.05	0	1015.30	0.53
NOVOSIBIRSK	NVBK	54.80	83.00	163	999.20	2.69
NEWARK	NWRK	39.68	-75.75	50	1008.60	2.21
OULU	OULU	65.05	25.47	0	990.00	0.77
SOUTH POLE	SOPO	-88.00	210.00	2820	687.70	0.05
THULE	THUL	76.50	-68.70	260	1011.50	0.00
TIXIE BAY	TXBY	71.60	128.90	15	1019.90	0.43
YAKUTSK	YKTK	62.02	129.73	105	1020.70	1.55

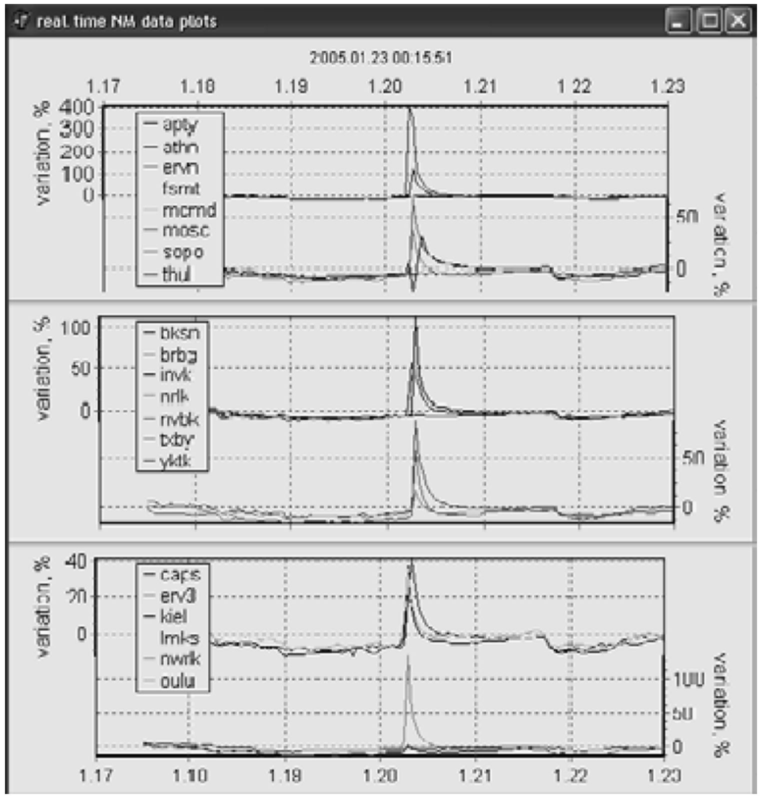
TABLE II
SATELLITE DATA PARAMETERS BEING PRESENTED BY ANMODAP CENTER.

SATELLITE DATA	
Symbol	**Explanation**
Solar wind temperature (K)	ACE interplanetary ion temperature (K)
Solar wind density (cm^{-1})	ACE interplanetary proton density
Solar wind velocity (km/s)	ACE interplanetary bulk speed (km/s)
Interplanetary Magnetic Field B (nT)	ACE interplanetary magnetic field B in GSM coordinates
IMF Bx component (nT)	ACE interplanetary magnetic field (nT)
IMF By component (nT)	ACE interplanetary magnetic field (nT)
IMF Bz component (nT)	ACE interplanetary magnetic field (nT)
Dst (nT)	Preliminary Dst index in nT
Particle Flux (pfu)	GOES-10 particles at > 2 MeV
Particle Flux (pfu)	GOES-10 particles at > 10 MeV protons
Particle Flux (pfu)	GOES-10 particles at > 100 MeV protons
X-ray flux ($\mu W/m^2$)	GOES 12 X-ray at wavelength = 0.1-0.8 nm ($\mu W/m^2$)

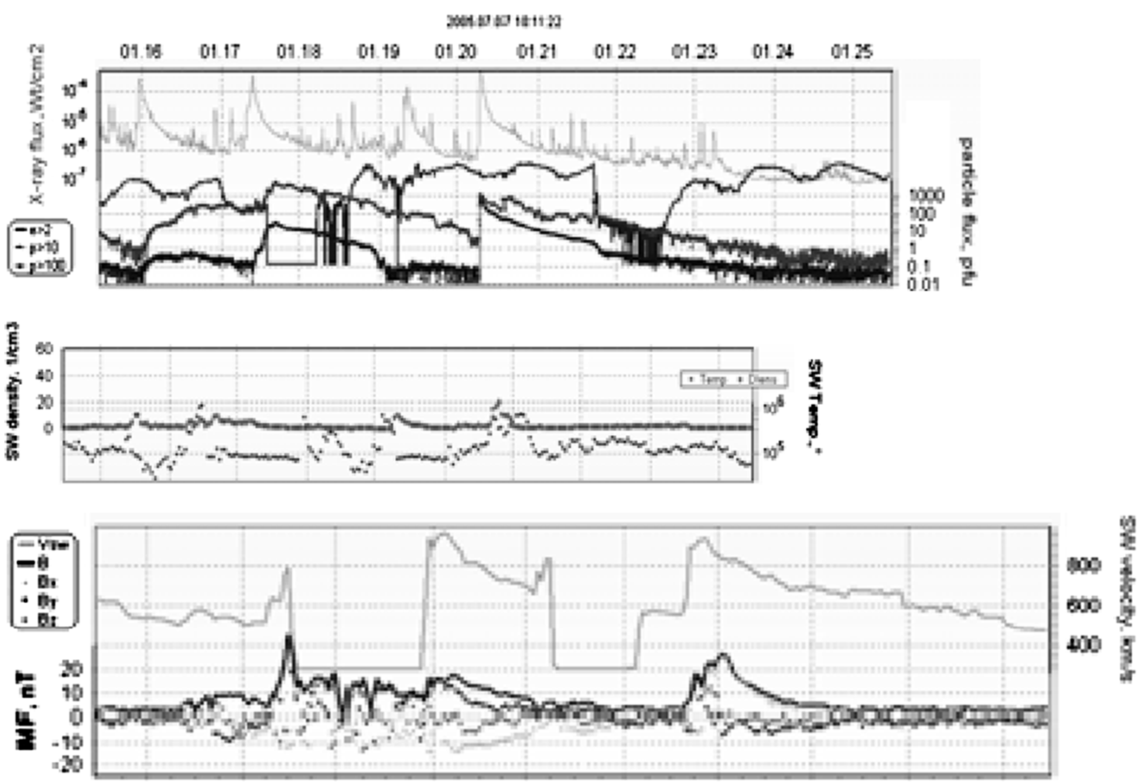
II. COLLECTION SYSTEM

In order to perform real-time prediction of space weather phenomena, only real-time data from a NM network should be employed. The system of the ANMODAP Center collects data in real-time from twenty- three widely distributed real-time CR stations using the Internet. The characteristics of these stations (geographic coordinates, altitude, standard pressure, cutoff rigidity) are listed in Table I. The main server in Athens station collects 1-min, 5-min, and hourly CR data. The station measurements are processed automatically and converted into a suitable format for forecasting purposes. All programs have been written in an expandable form for easy upgrade of the NM network. Programs that make use of these data for forecasting purposes have already been running in experimental mode. The increased number of NM stations operating in real-time gives a good basis for using NM network as a tool of forecasting the arrival of the interplanetary disturbances at the Earth.

The properties of each station in the network are input to a database program, the "Properties Database." This program includes the characteristics that are described in Table I, the ftp directory of each station, the station operating mode (active or not) and the data update period for each station. A "Scheduler" program reads the properties of each station and decides whether or not to make a data collection call. Each station has a separate data collection programme (triggered by the scheduler) which uploads data from the remote station to the database in Athens. Every station has a recording system and a local database. The data collection program of each station interfaces with the recording system of the remote station and transfers 1-min, 5-min or hourly data to the main server. The main database in Athens can be refreshed with customizable rate (usually every 5 min or every hour). For our study not only collecting data but also data presentation is very important A special program that interfaces with the "scheduler" program creates a graphical file once per hour which is displayed on the web page of the station presented at the server of Athens Center. An advanced and quick data processing system of 1, 5, 15, and 60 min refreshes the ANMODAP database providing both graphical and digital form of the measurements (http://cosray.phys.uoa.gr).



(a)



(b)

Fig. 2(a) NMs plots at ANMODAP Center. (b) Satellite data at ANMODAP Center.

On the same page interplanetary space parameters data from Geostationary Orbiting Environmental Satellite (GOES) and Advanced Composition Explorer (ACE) satellites are also presented (Table II). An example of presentation of the collected data can be seen in Fig. 2(a) and (b) where the data from different NMs and the various data from GOES and ACE satellites respectively are presented for the time period 15–26 January 2005.

III. Method of Prediction

The early detection of an Earth-directed solar proton event by NMs gives a good chance of preventive prediction of dangerous particle flux and can provide an alert with a very low probability of false alarm [5], [6]. The flux cannot be recorded on satellites with enough accuracy because of their small detecting area. However, it can be measured by ground-based NMs with high statistical accuracy (in average, 0.5% for 5 min) as GLE. The first step toward collecting data from a number of stations and analyzing them in real-time has been made by the Bartol CR group [Bartol Research Institute (BRI)] in the frame of the Space Ship Earth project (http://neutronm.bartol.udel.edu//). Subsequently, a new real-time data collection system was developed by the IZMIRAN CR group (http://Helios.izmiran.rssi.ru/cosray/main.htm) using the latest networking methods in order to get data from the maximum possible number of the stations to provide sufficiently reliable data of the further analysis. The use of all stations as a unified multidirectional detector substantially improves the measurement accuracy (<0.1% for hourly data).

The ANMODAP Center is being developed by the CR group of Athens University during the last two years. The prediction is mainly based on a feasible and statistically proven method [7] using total counts from several stations in real-time. It consists of the following steps:

A. For GLE Onset

Data from at least three NM stations at the Earth (two high latitudinal and one/two low latitudinal) and two independent satellite channels, for example X-ray on GOES10 and GOES12, are processed to search for the start of GLE. The initiation of a GLE is identified as simultaneous detection of enhancement in at least two NMs and in an X-ray channel. If these conditions are met, data is collected from all other NMs.

The real-time algorithm in order to be accurate takes different kind of inputs from all the available sources. For large events the Alert stage is envisaged to be of about 99% accuracy. Our statistic is still poor because of the continuous upgrades of the input data source code in the program. It is possible that very soon we will present a full analysis of all the old available GLE data. It is well-known that GLEs accompany only small fractions of the strong solar proton events as well as not all proton events result in ground enhancements. However, a technique of calculating the relative flux increases using the data of high latitude stations eliminates the possibility from loosing an event.

An improved version of the ALERT program will soon be available via a link from the main page of the Athens NM station visualizing all the forecasted events in real-time.

Also, it calculates spectra and other parameters for the estimation of the expected CR profiles for lower energies at different altitudes, several hours ahead. After the alert is obtained by the procedure described in the previous paragraph, the forecasting is sent by e-mail to the whole NM network in order to activate a system of minute data collection. During the last two years GLEs Alerts were also estimated using this program. Usually we don't get false alarms. Taking into consideration that in the analysis the data from high latitude stations are included and also the fact that our program uses 5-min averages and X-ray data from GOES for a comparison, the probability that the observed increase is not associated with GLE is very low.

TABLE III
Alert Results for GLE of 20 January 2005

Name of station	Moscow (2.30 GV)	Kiel (2.36 GV)	Oulu (0.77GV)
Event started at	6:51 UT	6:51 UT	6:52 UT
Established alert signal	6:55 UT	6:55 UT	6:56 UT
Maximum of the event	7:05 UT	7:05 UT	7:00 UT

B. For Geomagnetic Storms

According to the proposed method [5], [3] for the analysis of geomagnetic storms the system collects hourly data from at least fifteen stations. An analysis based on the global survey method (GSM) results in the derivation of certain parameters such as CR density, the spectral parameters of density, and the three components of CR anisotropy vector (in x, y, and z axes), the amplitude of isotropic variation and the characteristics of the CR anisotropy at this current hour. In summary, a first analysis of the current heliospheric situation is being performed. To carry out more reliable analysis, it would be desirable to use these results together with other data on solar and solar wind measurements.

IV. Recent Events of January 2005

During January 2005 many extreme events of solar activity took place, such as geomagnetic storms and a great GLE (GLE68). Results of these events forecasted by the ANMODAP Center are presented in this paper.

An unexpected giant proton event occurred in January 2005 close to the end of solar cycle 23. The flux of the very first relativistic protons associated with the flare X7.1 on 20 January at 6:36 UT in AR720 (N12 W58) reached the Earth at 6:50 UT and was recorded by many NMs (Fig. 1). This GLE (GLE68) exceeds almost all previous events having a peak of about several thousands of percentage in some stations. A further detailed presentation of this event is given in Figs. 2(a) and (b) as recorded by the ANMODAP Center. The results from the analysis of the event of 20th of January, 2005, after having applied our ALERT program using data from three NM stations, are presented in Table III.

It is clearly seen that the predicted, by the ALERT program, onset time of the event is very close to the value calculated with the 2.5 sigma criterion [3]. For the case of this event, the time delay between the onset and the maximum is found to be about 8–14 min. This is due to the fact that during this very special event all fluxes of low and mid energy particles increased almost simultaneously, causing a sharp peak in the observed variations.

The warning time for the proton and GLE events is not standard. Our alert program needs about 5 min to determine the onset of the event. The time between the onset of the event and the time of maximum flux varies between different events depending on many parameters as well as the nature of the event itself. There are cases of solar energetic particle events in which the maximum flux occurred several minutes after the beginning

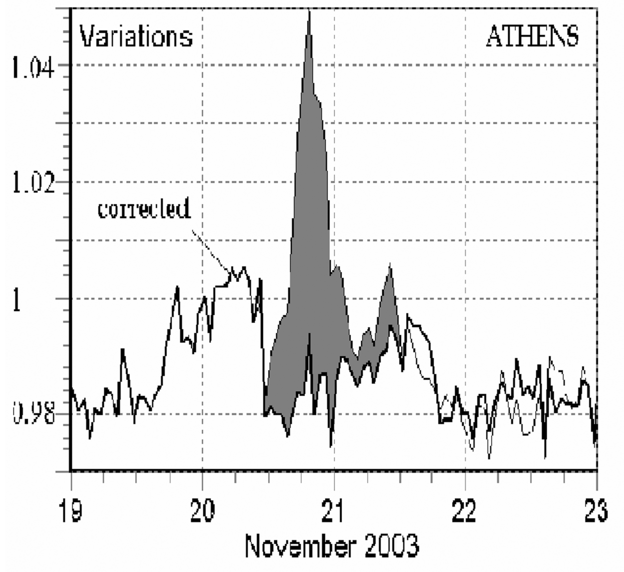


Fig. 3. Geomagnetic effect recorded by ANMODAP Center in November 2003.

of the event. On the other hand, the maximum in the case of a GLE event usually comes after a time interval of 5 up to 15–20 m. Subsequently, the time period between the onset and the maximum of a low/mid/or high energy event can be more than 20–30 min depending on the diffusion coefficient of the low energy particles. Thus, after the determination of the onset of the event, there is at least a time lag varying from 5 up to 20 min or more until the maximum of the event is reached.

Moreover, this unexpected burst of the solar activity in January 2005, although it was weaker than those in October-November 2003 (Fig. 3) and November 2004 led to a series of strong geomagnetic storms. Changes in the geomagnetic cutoff rigidities, dRc, during the geomagnetic storms on 7–8 and 17–22 January 2005 were observed on data of the worldwide NM network for middle and low latitude stations. The storm of 20–21 January occurred on the recovery phase of a large Forbush effect (sudden decrease of CR intensity) after the powerful flare of the 20th of January and after a gigantic GLE (GLE68) and caused the most significant changes of the cut off rigidities compared with the other storms in January 2005. Unconnected and corrected values for the geomagnetic effect as seen at the Athens and Jungfraujoch stations are given in Fig. 4.

Dst index values together with CR variations recorded at the mid and low latitude NM stations of Potchefstroom, Sanae, Roma, Larc, and Jungfraujoch for the geomagnetic storm of the 22nd of January are illustrated in Fig. 5.

As seen in this figure, complicated CR variations recorded on different NMs during the geomagnetic storm on 21–22 January 2005 and seem to be caused not only by a disturbed magnetosphere but also by unusual conditions in the interplanetary space at that time. Experimental values of the changes of cutoff rigidity (dRc) were compared with results of the trajectory calculations [8]. The recent models of the magnetosphere were adequately valid for low levels of the geomagnetic disturbances with Dst index higher than −140 nT. This has been confirmed

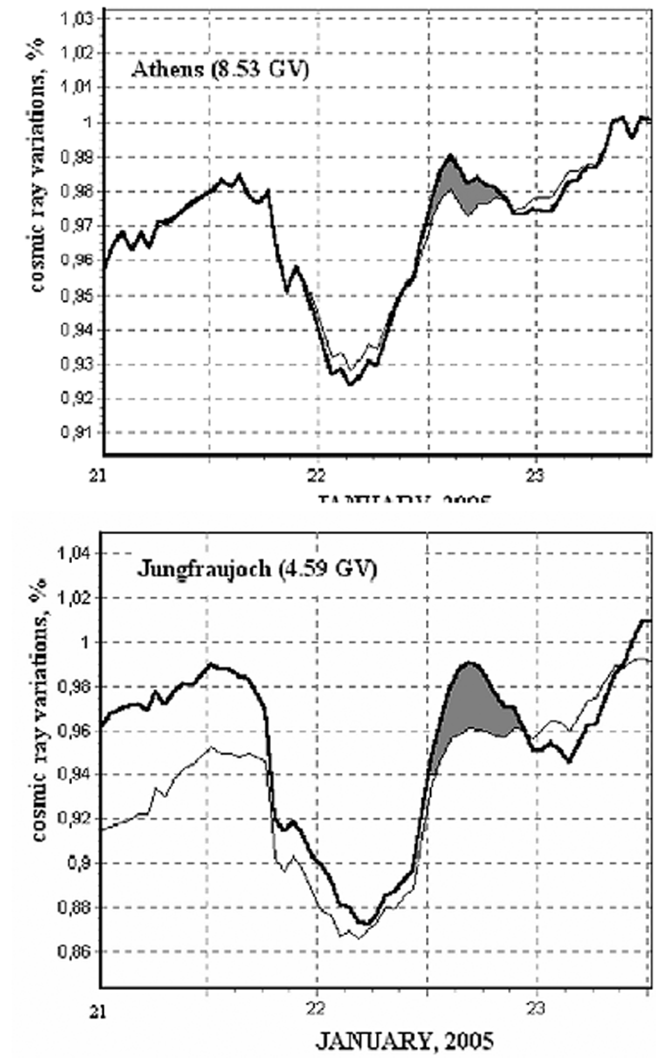


Fig. 4. Black area expresses the difference between corrected and uncorrected for the geomagnetic effect values of CRs in the stations of Athens and Jungfraujoch recorded by ANMODAP Center in January 22, 2005.

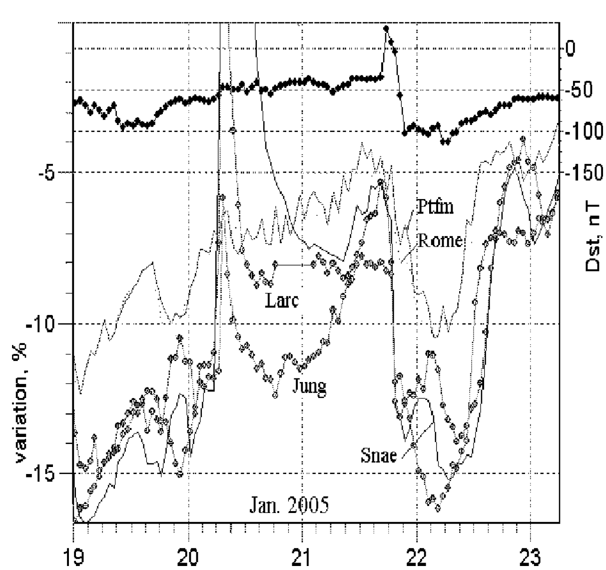


Fig. 5. Dst index and CR variations during the geomagnetic storm of 22 January 2005.

TABLE IV
ALERT RESULTS FOR EVENT OF 24 AUGUST 2002

NM STATIONS	Event started at (UT)	Established alert signal (UT)	Maximum of the event (UT)
NORILSK	1:29	1:33	1:44
OULU	1:28	1:32	1:49
CAPE SMIDT	1:27	1:31	1:41

TABLE V
ALERT RESULTS FOR EVENT OF 28 OCTOBER 2003

NM STATIONS	Event started at (UT)	Established alert signal (UT)	Maximum of the event (UT)
CAPE SMIDT	11:46	11:50	12:07
IRKUTSK	11:40	11:44	11:54
OULU	11:44	11:48	11:51

by our analysis of these models and the experimental values of dRc for the storms of January 2005 [9].

V. CONCLUSION

The new data analysis center ANMODAP Center based on the activity of the CR groups of Athens University and IZMIRAN, provides real-time monitoring of CR variations.

- This system elaborates programs with the possibility of successful prediction of the behavior of low energy part of the SEP events near Earth by the ground-based CR measurements.
- Joint complex analysis of the relevant information from space borne and ground-based detectors will minimize the number of false alarms and will maximize the reliability and the timely forecasting of the arrival of dangerous fluxes and disturbances from space.
- The new GLE registered in NM on 20 January 2005 was successfully forecasted by our system.
- A successful correction of the CR variations recorded by NMs during the recent magnetospheric effect on 22 January 2005 was performed.

In conclusion, we can say that the new data analysis Center of Athens University ANMODAP, based on the use of NMs and satellites data in real-time is expected to give alerts for GLEs and geomagnetic storms for Space Weather applications. Results from tests in historical data are very satisfactory. Two more examples are given in Tables IV and V for the events of August 2002 and October 2003.

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