Instructions for Exercises about Neutron Monitor Measurements

Rolf Bütikofer

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1 Introduction

The aim of this laboratory course is to determine the solar cosmic ray (SCR) characteristics during a single time interval during the initial phase of the Ground Level Enhancement (GLE) on 20 January 2005 based on neutron monitor (NM) data of the worldwide network.

Goals of this lab course:

- Get familiar with the NM data during a GLE
- Assess the SCR characteristics during a GLE based on NM data by using a trial and error procedure
- Present the scientific outcome of the study

Within the framework of the HORIZON 2020 project “HESPERIA” (**H**igh **E**nergy **S**olar **P**article **E**vents fo**R**recasting and **A**nalysis) we are developing a GLE inversion software with which it will be possible to determine the characteristics of the SCRs at the source, i.e. at the Sun.

For the today’s lab course we have adapted the software to determine the SCR characteristics near the Earth but outside of the geomagnetosphere, i.e. the transport from the Sun to the Earth in the interplanetary space is not included.

2 Neutron monitor measurements

Thanks to NMDB (Neutron Monitor Database, `http://www.nmdb.eu/`) NM data are easily available today. In a first step of our course we investigate the GLE by making graphs of NM data during the GLE on 20 January 2005 (superposition of data of different NMs, anisotropy plots).

2.1 Worldwide network of NMs

A world map with the NM stations that sends data to NMDB can be plotted under the URL `http://www.nmdb.eu/?q=node/8`. In addition, the locations of selected NM stations can be shown on an extract of the world map.

Reflect:

- How are the NM stations distributed over the world?
- Which are key stations for the GLE analysis? To answer this question, see also the effective vertical geomagnetic cutoff rigidity of the NM stations listed in Table 1 and the asymptotic directions in Figure 2.

NM station	Country Region	Geogr. Lat. [°]	Geogr. Long. [°]	Altitude [m]	R_c [GV]	Type of NM
Alma Ata	Kazakhstan	43.25	76.92	3340	6.16	18-NM64
Apatity	Russia	67.55	33.33	177	0.48	18-NM64
Aragats	Armenia	40.50	44.17	3200	6.93	18-NM64
Athens	Greece	37.98	23.78	260	8.40	6-NM64
Baksan	Russia	43.28	42.69	1700	5.68	6-NM64
Barentsburg	Russia	78.12	14.42	0	0.00	6-NM64
Climax	USA	39.37	253.82	3400	2.98	12-IGY
Fort Smith	Canada	60.00	-112.00	0	0.00	18-NM64
Hermanus	South Africa	-34.42	19.22	26	4.40	12-NM64
Inuvik	Canada	68.35	-133.72	21	0.00	18-NM64
Irkutsk2	Russia	51.37	100.55	2000	3.37	12-NM64
Jungfraujoch	Switzerland	46.55	7.98	3570	4.52	18-IGY
Jungfraujoch1	Switzerland	46.55	7.98	3475	4.52	3-NM64
Kiel	Germany	54.30	10.10	54	2.25	18-NM64
Kingston	Australia	-42.99	147.29	65	1.79	18-NM64
LARC	Chile	-62.20	301.04	40	2.84	6-NM64
Lomnicky Stit	Slovakia	49.20	20.22	2634	3.75	8-NM64
Magadan	Russia	60.12	151.02	220	1.90	18-NM64
Mawson	Antarctica	-67.60	62.88	0	0.30	6-NM64
McMurdo	Antarctica	-77.51	166.43	48	0.00	18-NM64
Mexico	Mexico	19.33	-99.18	2274	7.65	6-NM64
Moscow	Russia	55.47	37.32	200	2.18	24-NM64
Nain	Canada	56.60	-61.70	0	0.49	18-NM64
Newark	USA	39.70	284.30	50	2.40	9-NM64
Nor Amberd	Armenia	40.50	44.17	2000	6.95	18-NM64
Norilsk	Russia	69.26	88.05	0	0.45	18-NM64
Novosibirsk	Russia	54.80	83.00	163	2.64	24-NM64
Oulu	Finland	65.05	25.47	15	0.69	9-NM64
Potchefstroom	South Africa	-26.68	27.10	1351	6.93	15-IGY
Sanae	Antarctica	-71.67	357.15	856	0.67	6-NM64
South Pole	Antarctica	-90.00	0.00	2820	0.00	3-NM64
Terre Adelie	Antarctica	-66.65	140.00	32	0.00	9-NM64
Tibet	Asia	30.11	90.53	4300	13.65	28-NM64
Tixie Bay	Russia	71.60	128.90	0	0.30	18-NM64
Thule	Greenland	76.60	-68.80	260	0.0	9-NM64
Tsumeb	Namibia	-19.20	17.58	1240	9.02	18-NM64
Yakutsk	Russia	62.01	129.43	105	1.38	24-NM64

Table 1: Characteristics of NM stations from which the data can be used for the GLE analysis in the lab course. NM station, geographic latitude [°], geographic longitude [°], altitude above sea level [m], effective vertical geomagnetic cutoff rigidity R_c [GV], number of counter tubes and type of NM station.

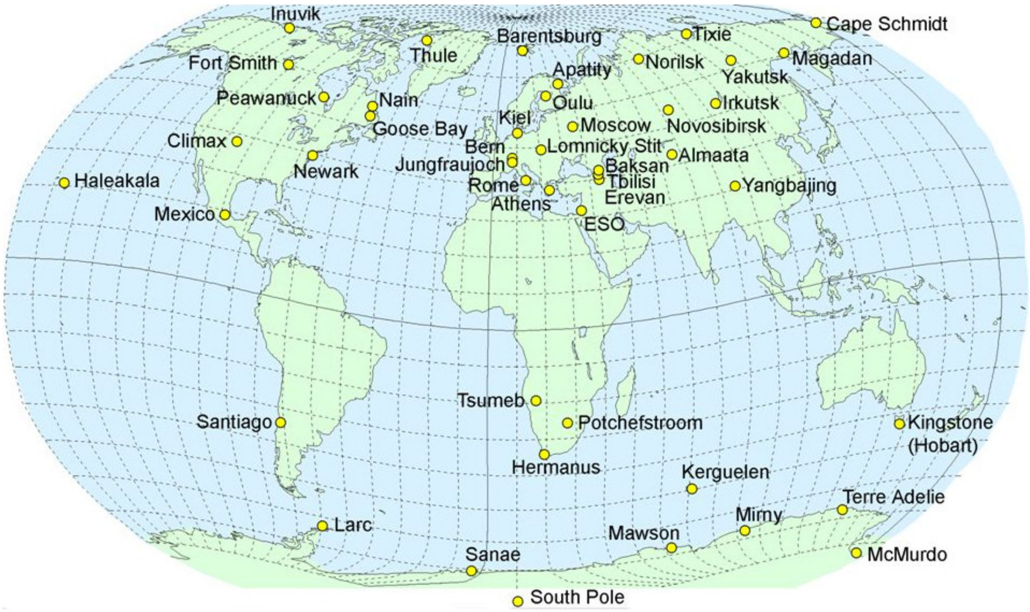

Figure 1: World map with the locations of selected NM stations.

2.2 NM Measurements

The NM data can be retrieved from NMDB and plotted with the application NEST (**N**MDB **E**vent **S**earch **T**ool) by selecting `http://www.nmdb.eu/nest/search.php` in your browser.

The study of the NM data with graphical displays of the count rates plays a key role to start the GLE analysis and to understand fundamental GLE characteristics.

Graphical plots can help to be find out:

- Characteristics of the GLE (onset, main phase, decay phase)
- NM stations that have seen an effect and NM stations that have not seen the effect → information about anisotropy and hardness of the SCR spectrum
- Different onset times at different NM stations
- If a NM station produced erroneous data?

Annotation: Not all data of the NM stations, that are compiled for this lab course (GLE on 20 January 2005), are available from NMDB.

Reflect:

- The data of which NM stations should be plotted (superposed)?
- For which time interval(s)?
- Pressure corrected or not pressure corrected data? Comment.
- Absolute count rate or relative count rate (relative scale)?

After you have made a series of NM data plots. What do the graphs say about the characteristics of the GLE near Earth:

- Onset (form, time, ...)?

- Duration of GLE?
- Maximum count rate increase?
- Direction of main flux of SCR near Earth?
- Pitch angle distribution (anisotropy)?
- Spectrum of SCR?

3 Asymptotic directions and effective vertical geomagnetic cut-off rigidity of selected NM stations

Figure 2 shows the asymptotic directions of selected NM stations for vertical incidence at the NM location for 20 January 2005, ~0700 UT in alphabetical sequence. The approximate effective vertical geomagnetic cutoff rigidities are listed in Table 1.

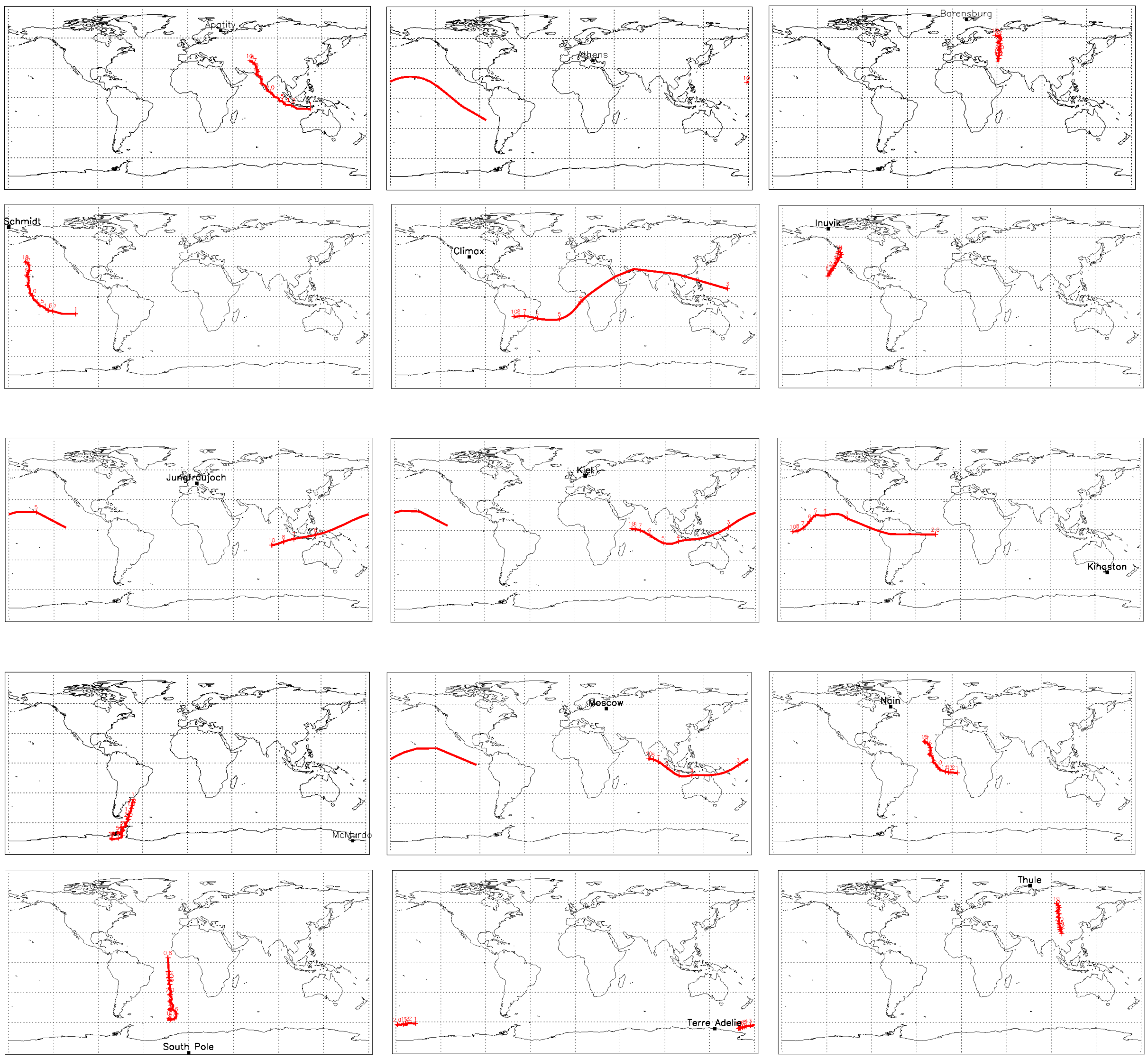

Figure 2: Asymptotic directions for 20 January 2005, ∼ 0700 UT for the NM stations: Apatity, Athens, Barentsburg, Cape Schmidt, Climax, Inuvik, Jungfraujoch, Kiel, Kingston, McMurdo, Moscow, Nain, Oulu, South Pole, Terre Adelie, and Thule

4 GLE inversion software

4.1 Program

The GLE inversion program is written in the programming language Python[1]. If you do not know Python, this is no problem as you will not change the program. You have to edit only one file, the file with the parameters: `Parameter.py`.

The directory of the program contains the following files and directory:

`asy`	directory. This directory contains the files with the asymptotic directions for all NM stations and for the time 20 January 2005, ∼ 0700 UT, i.e. the asymptotic directions that are used in this course
`main.py`	main program that has to be executed
`main_plot.py`	same as `main.py`, in addition the simulated neutron monitor relative count rate increases during the GLE vs. the measured are plotted.
`map_all.ps`	This file contains plots of the asymptotic directions of all used NM stations in this exercise. The graphs can be shown at the screen e.g. with the command: `gv map_all.ps`
`myformulas.py`	file with own routines
`Parameter.py`	file in which the input parameters are defined
`PitchangleDistribution.py`	definition of pitch angle distribution
`SCR.py`	definition of rigidity spectrum
`stations.dat`	file which contains information about the NM stations, for details see Section 4.1.1
`YieldFunction.py`	Definition of yield functions.

4.1.1 File `stations.dat`

Format of the file `stations.dat`:

```
 2005   1 20   0653  0655
AATB         alma-b.gle     669.2    1245.8    1248.3     3.23
APTY        apatity.gle     977.8     128.2     163.6     1.17
ATHN         athens.gle     974.7      52.8      52.8     0.66
 .             .              .         .         .         .
 .             .              .         .         .         .
 .             .              .         .         .         .
```

Content of the file `stations.dat`:
First line: year, month, day of month, start of time interval, end of time interval

1st column Short name of NM station

2nd column File name of the file with the asymptotic directions

3rd column Reference atmospheric pressure in mbar

4th column Pressure corrected count rate during the reference time interval (pre-increase baseline time interval)

[1]Python is a widely used high-level, general-purpose, interpreted, dynamic programming language. Its design philosophy emphasizes code readability, and its syntax allows programmers to express concepts in fewer lines of code than possible in languages such as C++ or Java.

5th column Pressure corrected count rate during the time interval given in the first line of the file

6th column Absolute error of the value in the 5th column

4.1.2 File `Parameter.dat`

Content of the file `Parameter.dat`:

```
# GLE parameters
# for details see instructions for exercises

# Parameters of differential rigidity spectrum
SpecPar = -6.0
DeltaSpecPar = 0.0

# Direction of anisotropy in geographic coordinates in [deg]
SourceLatitudeDeg = -0.0
SourceLongitudeDeg = 0.0

# Parameter for pitch angle distribution
FPar = 1000.0
```

`SpecPar`, `DeltaSpecPar`

The differential rigidity spectrum is described by a modified power law:

$$I(R,t) = A(t) \cdot R[\mathrm{GV}]^{-(\gamma(t)+\Delta\gamma(t)\cdot(R[\mathrm{GV}]-1.0))} \tag{1}$$

where

$I(R,t)$	SCR flux spectrum in direction of maximum intensity $[\mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}\,\mathrm{GV}^{-1}]$ as function of time, t
$A(t)$	intensity of SCR flux at 1 GV in the direction of maximum intensity in $[\mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}\,\mathrm{GV}^{-1}]$
$\gamma(t)$	exponent of power law → `SpecPar`
$\Delta\gamma(t)$	parameter describing the change of the exponent → `DeltaSpecPar`

`SourceLatitudeDeg`, `SourceLongitudeDeg`

Direction of maximum intensity at the border of geomagnetosphere correlates typically with the direction of the interplanetary magnetic field near Earth at the time of the event. This direction has to be given in geographic coordinates by the geographic latitude and longitude: `SourceLatitudeDeg`, `SourceLongitudeDeg`

`FPar`

The pitch angle distribution $F(\vartheta)$ is described by:

$$F(\vartheta) = e^{-\frac{\vartheta^2}{FPar}} \tag{2}$$

where

ϑ	pitch angle in [°]
$FPar$	parameter describing the pitch angle distribution → `FPar`

4.2 Output of the program

The result of a program run is written on the screen and printed in the file `GLEresult.dat`. Content of the file `GLEresult.dat`:

```
 GLE  2005      1         20 653 - 655 UT

 Source:      Latitude =    -84.5  deg
              Longitude E =  264  deg

 Spectrum:    Power law exponent gamma = -7.88
              Change of power law exp. =  0
              Factor A =     7.2976E+10 #/(m^2 s sr GV)

 Pitch angle distribution:  Parameter =   700

---------------------------------------------
 STATION                dNobs/N0   dNcalcP1/N0
                          (%)         (%)
---------------------------------------------
 Alma Ata                 0.2        0.0
 Apatity 18NM64          27.6        0.4
 Athens                   0.0        0.0
 Baksan                   0.9        0.0
 Barensburg               1.4        0.0
    .                     .           .
    .                     .           .
    .                     .           .
 Tsumeb                   0.2        0.0
 Tixie Bay                1.2        0.3
 Yakutsk                 17.3        0.6
---------------------------------------------
Correlation Coefficient            0.6258
Chi-square                      2.389E+06
---------------------------------------------
```

Description:

`Source`	direction of anisotropy in geographic coordinates
`Spectrum`	parameters of the differential rigidity spectrum of the SCR near Earth
`dNobs/N0`	observed relative count rate increase at the corresponding NM station
`dNcalcP1/N0`	simulated relative count rate increase

4.3 Procedure to run the GLE inversion program

1. Edit the file `Parameter.dat`, i.e. give the input parameters as described in Section 4.1.2
2. Run the program `main.py` by entering the command: `python main.py` on the prompt of the terminal under the directory where the program `main.py` is located
3. Go back to step 1. Repeat steps 1 and 2 until the simulated relative count rate increases best fit the observed relative count rate increases

Suggestions:

- In a first step do not use the data of all NM stations. Only use a few selected NM stations. Therefore delete all the lines in the file `stations.dat` that you do not want to use for the first runs. Attention: Before editing the file `stations.dat` make a backup of the file.
- If there are outliers, i.e. the simulated count rate increases largely differ from the observed data, check if the "observations" may be erroneous. E.g. compare the measured data of the corresponding NM station with the data of nearby NM station(s) or NM station(s) with comparable asymptotic directions. If needed, exclude the corresponding NM station from the analysis.