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New multi-directional muon telescope and EAS installation on Mt. Hermon (Israel) in combination with NM-IQSY

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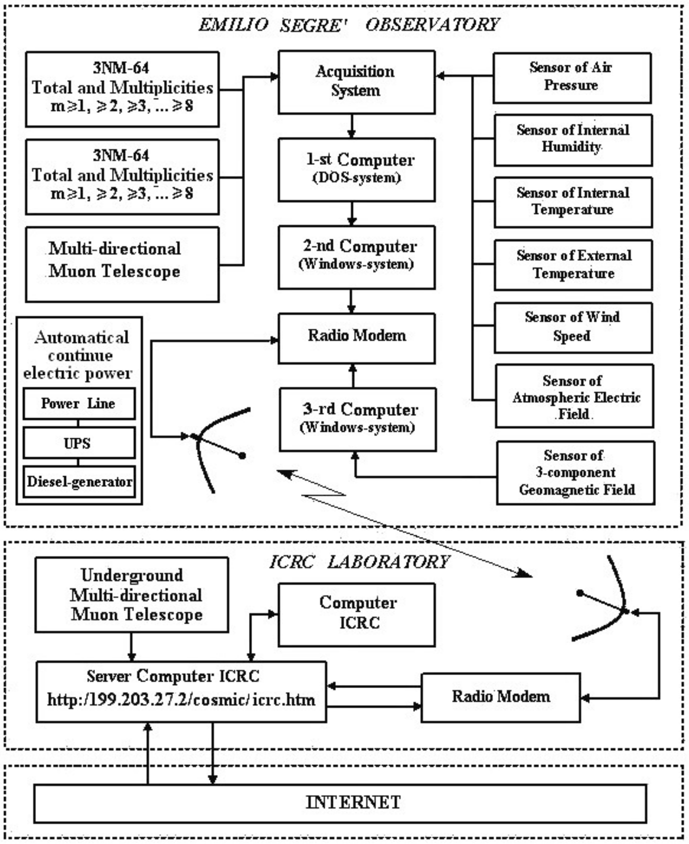
On Mt. Hermon in the Emilio Segre' Observatory of the Israel Cosmic Ray and Space Weather Center, a plastic scintillation multidirectional muon telescope is under construction, with 144 two-coincidence channels in combination with NM-IQSY. We calculate the angle diagrams of telescope sensitivity and coupling functions for many directions at different zenith and azimuthal angles. We give a description of the electronics scheme and registration system. We also discuss possibly using the telescope in combination with the detection of the total neutron component and different neutron multiplicities. The scintillators of the telescope will be used also for continued measurement of electron-photon and muon EAS arriving in vertical and at different inclined directions. We also calculate the expected coupling functions (or response) functions for different types of EAS. We consider also how NM-IQSY will work in combination with EAS installation for measuring of nucleonic component of EAS.



1. Israeli-Italian Emilio Segre' Observatory on Mt. Hermon: short description

In Figure 1 we show a block scheme of the main components of the Emilio Segre' Observatory (ESO) on Mt. Hermon and their connection with the Central Laboratory of Israel Cosmic Ray and Space Weather Center in Qazrin and with the Internet.

Figure 1. Schematic description of the main components of the Israeli–Italian Emilio Segre' Observatory (ESO) and their connection with the Central Laboratory in Qazrin and with Internet. Also shown multi-directional muon telescope which will work in combination with NM-IQSY and EAS (see Figure 2).

2. Muon telescope and EAS installation combined with NM IQSY

Figure 2 depicts the cross-section of Emilio Segre' Observatory and disposition of both sections of NM-IQSY, as well as the multi-directional muon telescope to be installed in combination with NM-IQSY.

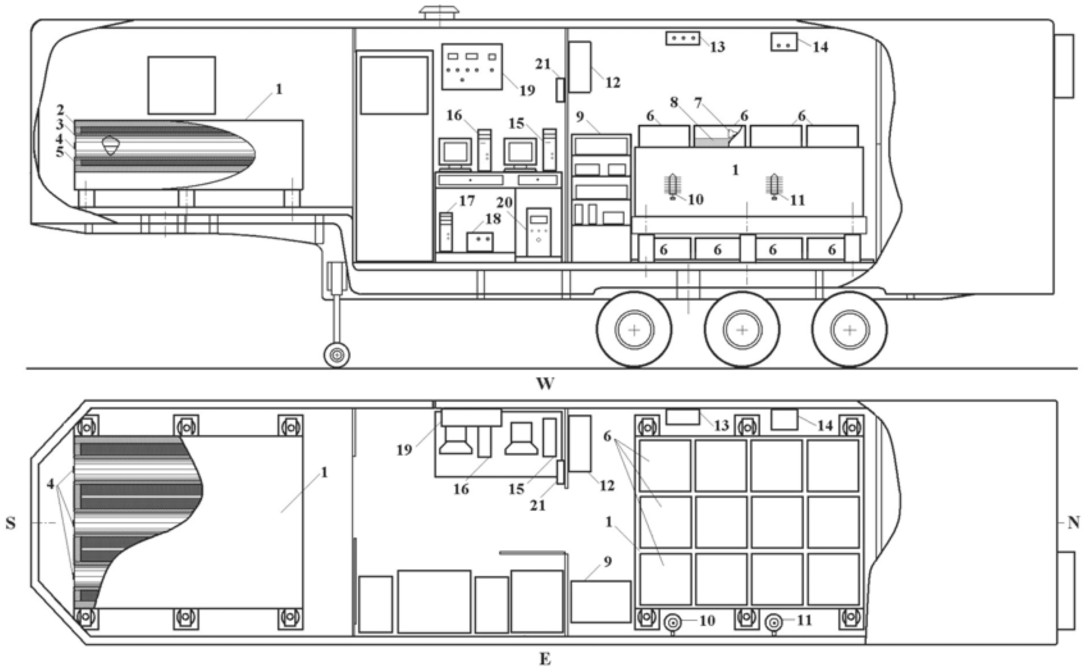


Figure 2. Schematic view of the Israeli-Italian Emilio Segre' Observatory (ESO) on Mt. Hermon, showing both sections of NM-IQSY and the multi-directional muon telescope (the lead of NM will be used as a shield for the muon telescope): the top – vertical cross-section; the bottom – view from above. 1 – two 3-counters sections of NM-IQSY; 2 – polyethylene plates; 3 – polyethylene tubes; 4 – neutron counter $^{10}BF_3$; 5 – lead tubes; 6 – scintillation detector; 7 – photo-multiplayer; 8 – plastic scintillator 50 cm×50 cm×10 cm; 9 –acquisition system; 10 – sensor of humidity inside Observatory; 11 - sensor of air temperature inside Observatory; 12 – the system of continuous electric power supply; 13 – radio-modem; 14 – recording instrument of EFS-1000 (for measurements of atmospheric electric field); 15 – 1-st computer (DOS-system); 16 – 2-nd computer (Windows system); 17 – 3 rd computer for geomagnetic field (Windows system); 18 - recording instrument for registration of the 3 components of geomagnetic field; 19 – control panel of electric power; 20 – UPS.

From Figure 2 it can be seen that multidirectional muon telescope consisted 24 scintillation detectors 50 cm × 50 cm × 10 cm (12 under NM and 12 above NM, see Figure 3) with 144 double coincidences formed 12 vertical and 132 inclined telescopes at different zenith and azimuthally angles (see Table 1).

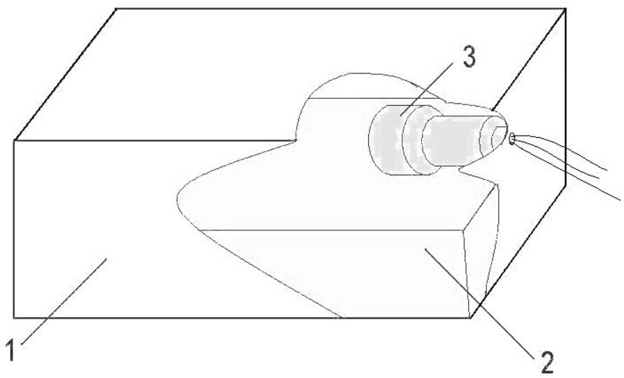


Figure 3. Scintillation detector for the semi-underground multi-directional muon telescope in Qazrin (Israel). 1 – box with reflector, 2 – plastic scintillator 50 cm × 50 cm × 10 cm, 3 – photomultiplier.

Table 1. Channels of multi-directional muon telescope on Mt. Hermon, combined with 3NM-IQSY.

No	Channel title	Azimuth angle, degree	Zenith angle, degree	Number of telescopes	Expected counting rate	Statistical error for 1 hour, %
1	VERTICAL (0)		0	12	162000	0.08
2	N1, S1	0, 180	26.6	8	552960	0.13
3	W1, E1	90, 270	26.6	9	622080	0.13
4	NW1, SW1, SE1, NE1	45, 135, 225, 315	35.3	6	240000	0.20
5	N2, S2	0, 180	45.0	4	19999	0.71
6	W2, E2	90, 270	45.0	6	30000	0.58
7	N1W2, S1W2, S1E2, N1E2	63.4, 116.6, 243.4, 296.6	48.2	4	47407	0.46
8	N2W1, S2W1, S2E1, N2E1	26.6, 153.4, 206.6, 333.4	48.2	3	35555	0.53
9	NW2, SW2, SE2, NE2	45, 135, 225, 315	54.7	2	33750	0.54
10	W3, E3	90, 270	56.3	3	11797	0.92
11	N1W3, S1W3, S1E3, N1E3	71.6, 108.4, 251.6, 288.4	57.7	2	6298	1.26
12	N2W3, S2W3, S2E3, N2E3	56.3, 123.7, 236.3, 303.7	60.7	1	1759	2.38
13	TOTAL			144	4094748	0.05

3. Description of EAS array combined with multi-directional muon telescope and neutron monitor on Mt. Hermon

By coincidences in different combinations of upper scintillators, we obtain a counting of EAS (electron-photon component). This array can be considered as local because the distances between detectors are much smaller than the effective radius of EAS on the level of observations. In this case, on the passage of EAS of density ρ (mean number of particles per 1 m^2) the probability that not a single particle will pass through detector of effective area σ will be $\exp(-\rho\sigma)$. The probability of at least one particle crossing through detector will be $\omega = 1 - \exp(-\rho\sigma)$. The particle distribution in EAS may be represented in the form $\rho(r) = u(r)N_e$, where *r* is the distance from the EAS axes, N_e is the total number of particles in electron-photon component of EAS, and $u(r)$ is the function satisfying the normalization condition and has the form:

$$2\pi \int_0^\infty u(r) r dr = 1; \qquad u(r) = \begin{cases} ar^{-1}\exp(-r/r_o) & \text{if } r \le r_o, \\ u(r) = br^{-2.6} & \text{if } r \ge r_o. \end{cases} \tag{1}$$

Here r_o is the effective radius of the shower. Coefficients *a* and *b* are determined from the condition of normalizing and of tie-in of the function $u(r)$ at the point $r = r_o$. This gives on the basis of Eq. (1):

$$a = er_o^{-1}\left[2\pi(e(1-1/e)+1/0.6)\right]^{-1} = 0.12781\times r_o^{-1};\ b = r_o^{0.6}\left[2\pi(e(1-1/e)+1/0.6)\right]^{-1} = 0.04702\times r_o^{0.6}. \tag{2}$$

Eq. (2) gives for Mt Hermon (altitude 2 km, r_o = 72 m) $a = 1.775\times10^{-3}$ m^{-1}, $b = 0.6119$ m$^{0.6}$.

Let us suppose that the axis of EAS with total number of particles N_e crossed the observation level in some point *P* and actuated simultaneously any *n* detectors of array with total *m* detectors (meaning that through each of these *n* detectors crossed at least one particle from total number N_e in EAS) and not actuated other any *m – n* detectors. Let the distance from point *P* to the detector *i* is r_i (*i* = 1, 2, … *m*). In this case the probability to detect this EAS will be

$$\omega_{nm}(P) = C_m^n \prod_{i=1}^{n}(1-\exp(-\rho_i\sigma)) \prod_{i=n+1}^{m}\exp(-\rho_i\sigma) \approx C_m^n (1-\exp(-u(r)N_e\sigma))^n \exp(-(m-n)u(r)N_e\sigma), \tag{3}$$

where $C_m^n = m!(n!(m-n)!)^{-1}$. In Eq. (3) we take into account that in our case the distances between detectors $<< r_o$, and therefore we can put for all $r_i \approx r$, where r is the distance from point P to the center of installation. Let us take into account also that $N_e \approx 0.3E_o^s$, where E_o is the energy of primary particle in GeV, and $s \approx 1.1$ at mountain level 3 km, and $s \approx 1.2$ at sea level (so we expect that for Mt Hermon it will be $s \approx 1.13$). Because P may be elsewhere, the total probability to detect EAS with N_e particles (generated by primary particle with energy E_o) simultaneously by any n detectors of the local installation with total m detectors (in our case m = 12) will be in the unity of time

$$\omega_{nm}(N_e, r_o, \sigma)dN_e \approx 2\pi C_m^n D(N_e)dN_e \int_0^\infty (1-\exp(-u(r)N_e\sigma))^n \exp(-(m-n)u(r)N_e\sigma)rdr; \tag{4}$$

$$\begin{aligned} &\omega_{nm}(E_o, r_o, \sigma)dE_o \approx 2\pi C_m^n D(E_o)dE_o \times \\ &\times \left\{ \int_0^{r_o} \left(1-\exp\left(-0.03834 r_o^{-1} r^{-1} \exp(-r/r_o) E_o^s \sigma\right)\right)^n \exp\left(-0.03834 r_o^{-1} r^{-1} (m-n) \exp(-r/r_o) E_o^s \sigma\right) rdr + \right. \\ &\left. + \int_{r_o}^\infty \left(1-\exp\left(-0.01411 r_o^{0.6} r^{-2.6} E_o^s \sigma\right)\right)^n \exp\left(-0.01411 r_o^{0.6} r^{-2.6} (m-n) E_o^s \sigma\right) rdr \right\}, \end{aligned} \tag{5}$$

where $D(N_e)$ and $D(E_o)$ are differential spectrums of EAS, and E_o is in GeV, r_o is in m, σ is in m^2. The expected counting rate $I_{nm}(r_o,\sigma)$ (i.e. number of detected EAS per unity of time by any n coincidences from total m detectors with effective area σ each) will be

$$I_{nm}(r_o,\sigma) = \int_0^\infty \omega_{nm}(N_e, r_o, \sigma)dN_e = \int_0^\infty \omega_{nm}(E_o, r_o, \sigma)dE_o \,. \tag{6}$$

The coupling functions characterized the sensitivity of installation to detect EAS will be

$$W_{nm}(N_e, r_o, \sigma) = \omega_{nm}(N_e, r_o, \sigma)/I_{nm}(r_o,\sigma); \; W_{nm}(E_o, r_o, \sigma) = \omega_{nm}(E_o, r_o, \sigma)/I_{nm}(r_o,\sigma). \tag{7}$$

It is easy to see that these coupling functions are normalized for any E_o, σ, n and m:

$$\int_0^\infty W_{nm}(N_e, r_o, \sigma)dN_e = \int_0^\infty W_{nm}(E_o, r_o, \sigma)dE_o = 1 \,. \tag{8}$$

The differential energy spectrum of primary CR can be represented by (in units m^{-2}sec^{-1}GeV^{-1}sr^{-1}):

$$D(E_o) = \begin{cases} 2.2\times10^4 \times E_o^{-2.7}, & if \quad E_o \le 3\times10^6\, GeV \\ 3.8105\times10^7 \times E_o^{-3.2}, & if \quad E_o \ge 3\times10^6\, GeV \end{cases} \tag{9}$$

The dependence of expected counting rate $I_{nm}(r_o,\sigma)$ for Mt. Hermon (m = 12, σ = 0.25 m^2) from number of coincidences n is shown in Figure 4, and the coupling functions – in Figure 5.

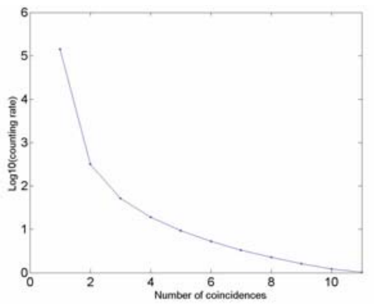


Figure 4. Expected of EAS counting rate per sec for Mt Hermon installation.

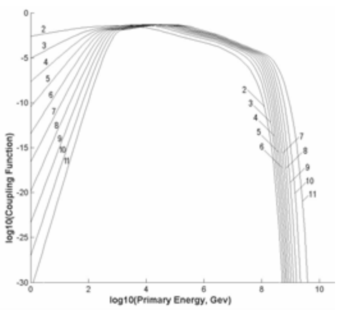


Figure 5. The coupling functions for Mt Hermon installation