The asymptotic directions of approach and the magnetic rigidity cutoff of cosmic ray particles calculated for different airports.

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Abstract:

The calculation of asymptotic directions of approach of cosmic ray particles is an important tool in the determination of the rigidity cutoff for a given geographical site. We present the results of computations of the asymptotic latitude and asymptotic longitude and the magnetic rigidity cutoff for the airports (Apatity, Oulu, Warsaw, Lae, Buenos Aires, Wellington and Mc Murdo) located at different latitudes and longitudes based on the numerical integration of equations of motion of charged particles of cosmic radiation in the Earth's magnetic field. The initial distance from the center of the Earth was taken as 20 km above the surface. At about this altitude, most cosmic rays undergo nuclear collisions. Calculations were made for the model of the International Geomagnetic Reference Field (IGRF) in 2015.

Introduction

The equation of motion of the particle in the Gaussian system of units is:

$$m\frac{d^2\vec{r}}{dt^2} = \frac{e}{c}(\vec{v} \times \vec{B})$$

and this may be written in terms of the spherical coordinate system as follows

$$\begin{cases} \frac{dv_r}{dt} = \frac{e}{mc}(v_\theta B_\varphi - v_\varphi B_\theta) + \frac{v_\theta^2}{r} + \frac{v_\varphi^2}{r} \\ \frac{dv_\theta}{dt} = \frac{e}{mc}(v_\varphi B_r - v_r B_\varphi) - \frac{v_r v_\varphi}{r} + \frac{v_\varphi^2}{r\,tg\,\theta} \\ \frac{dv_\varphi}{dt} = \frac{e}{mc}(v_r B_\theta - v_\theta B_r) - \frac{v_r v_\varphi}{r} - \frac{v_\varphi v_\theta}{r\,tg\,\theta} \end{cases}$$

$$v_r = \frac{dr}{dt}$$

$$v_\theta = r\frac{d\theta}{dt}$$

$$v_\varphi = r\sin\theta\frac{d\varphi}{dt}$$

$$\begin{cases} \frac{dt_r}{ds} = \frac{e}{vmc}(t_\theta B_\varphi - t_\varphi B_\theta) + \frac{t_\theta^2}{r} + \frac{t_\varphi^2}{r} \\ \frac{dt_\theta}{ds} = \frac{e}{vmc}(t_\varphi B_r - t_r B_\varphi) - \frac{t_r t_\theta}{r} + \frac{t_\varphi^2}{r\,tg\,\theta} \\ \frac{dt_\varphi}{ds} = \frac{e}{vmc}(t_r B_\theta - t_\theta B_r) - \frac{t_r t_\varphi}{r} - \frac{t_\varphi t_\theta}{r\,tg\,\theta} \end{cases} \quad (5)$$

$$U = r_z \sum_{n=1}^{\infty}\left(\frac{r_z}{r}\right)^{n+1} \sum_{m=0}^{n}(g_n^m \cos m\varphi + h_n^m \sin m\varphi)P_n^m(\cos\theta) \quad (6)$$

$$\begin{cases} B_\theta = -\frac{1}{r}\frac{dU}{d\theta} = -\sum_{n=1}^{\infty}\left(\frac{r_z}{r}\right)^{n+2}\sum_{m=0}^{n}(g_n^m \cos m\varphi + h_n^m \sin m\varphi)\ \frac{dP_n^m(\cos\theta)}{d\omega} \\ B_\varphi = -\frac{1}{r\sin\theta}\frac{dU}{d\varphi} = -\sum_{n=1}^{\infty}\left(\frac{r_z}{r}\right)^{n+2}\sum_{m=0}^{n}(m g_n^m \sin m\varphi + m h_n^m \cos m\varphi)\ \frac{P_n^m(\cos\theta)}{\sin\theta} \\ B_r = -\frac{dU}{dr} = -\sum_{n=1}^{\infty}\left(\frac{r_z}{r}\right)^{n+2}(n+1)\sum_{m=0}^{n}(g_n^m \cos m\varphi + h_n^m \sin m\varphi)\ P_n^m(\cos\theta) \end{cases} \quad (7)$$

Experimental Results And Discussion

Table 1. Localization parameters of selected eight airports

No	Airport	Geographic latitude [degrees]	Geographic longitude[degrees]	Height [m]
1	Oulu	64,91	25,37	14
2	Apatity	67,45	33,58	160
3	Warsaw	52,15	20,96	110
5	Lae	8,92	166,25	1
6	Buenos Aires	-34,82	-58,53	20
7	Wellington	-41,32	174,8	13
8	Mc Murdo	-71,85	166,47	10

Table 2. Cut-off rigidities and the width of the penumbra zone for vertical components for seven airports

No	Airports	Vertcal penumbral zone			
		R_{st} [GV]	R_{ef} [GV]	R_m [GV]	Width of penumbral zone in GV
1	Apatity	0,53	0,54	0,58	0,05
2	Oulu	0,74	0,75	0,81	0,07
3	Warsaw	2,61	2,85	3,13	0,52
5	Lae	15,34	15,34	15,35	0,01
6	Buenos Aires	7,54	8,17	8,84	1,3
7	Wellington	2,91	3,27	3,41	0,5
8	Mc Murdo	0,09	0,1	0,12	0,03

	Inclined components			
Mc Murdo	R_{st} [GV]	R_{ef} [GV]	R_m [GV]	Width of penumbral zone in GV
Azimuth angle		Zenith angle	16	
147	0,04	0,04	0,05	0,01
237	0,04	0,04	0,05	0,01
327	0,04	0,04	0,05	0,01
417	0,04	0,04	0,05	0,01
Azimuth angle		Zenith angle	32	
147	0,04	0,04	0,05	0,01
237	0,04	0,04	0,05	0,01
327	0,04	0,04	0,05	0,01
417	0,04	0,04	0,05	0,01

	Inclined components			
Apatity	R_{st} [GV]	R_{ef} [GV]	R_m [GV]	Width of penumbral zone in GV
Azimuth angle		Zenith angle	16	
65	0,53	0,54	0,57	0,04
155	0,53	0,54	0,56	0,03
245	0,52	0,53	0,56	0,04
355	0,51	0,52	0,54	0,03
Azimuth angle		Zenith angle	32	
65	0,53	0,54	0,56	0,03
155	0,53	0,54	0,56	0,03
245	0,52	0,53	0,57	0,05
355	0,52	0,53	0,57	0,05

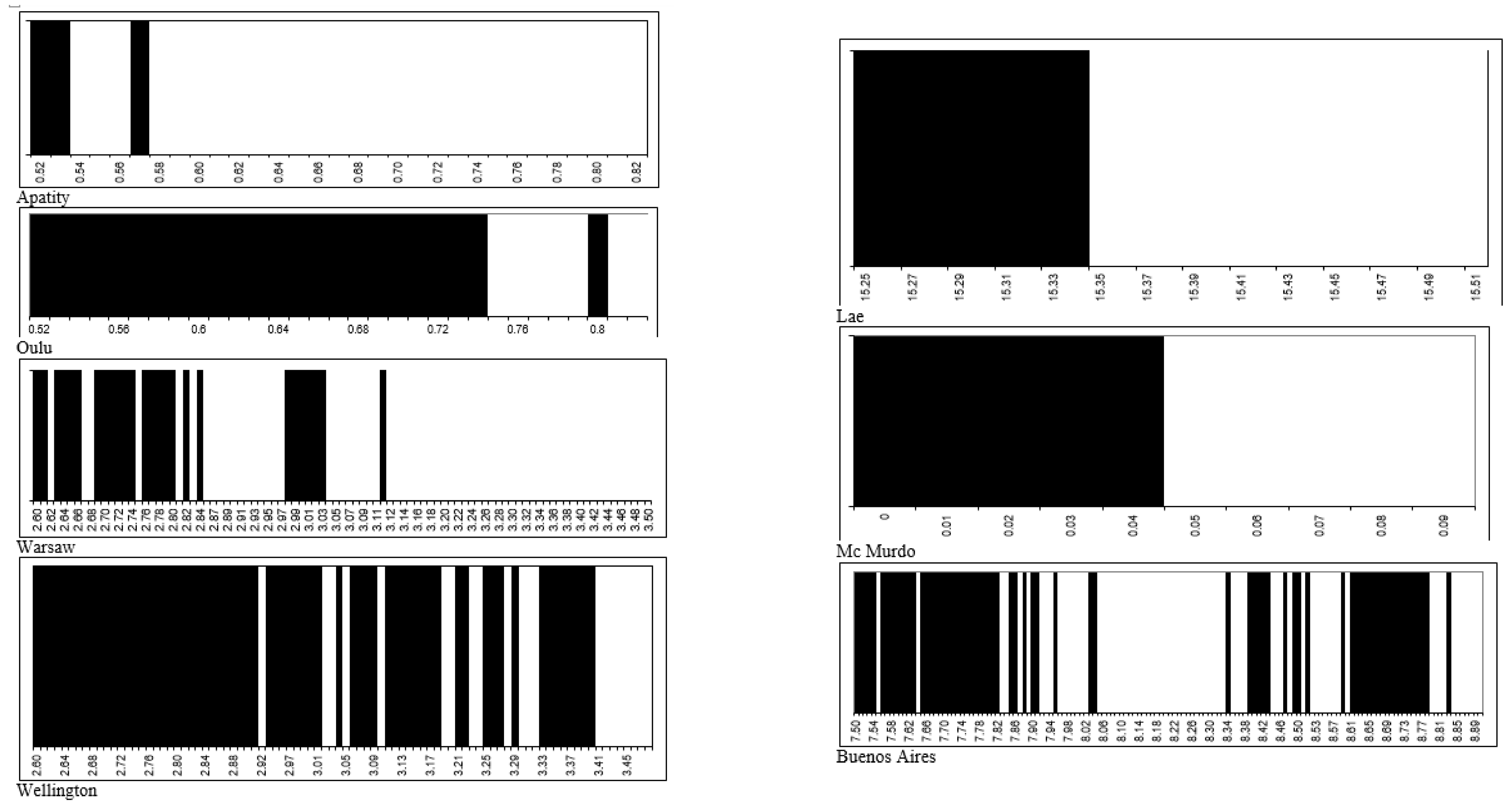
	Inclined components			
Oulu	R_{st} [GV]	R_{ef} [GV]	R_m [GV]	Width of penumbral zone in GV
Azimuth angle		Zenith angle	16	
65	0,74	0,77	0,83	0,09
155	0,74	0,75	0,82	0,08
245	0,73	0,74	0,8	0,07
355	0,74	0,75	0,81	0,07
Azimuth angle		Zenith angle	32	
65	0,75	0,77	0,8	0,05
155	0,75	0,77	0,8	0,05
245	0,72	0,73	0,79	0,07
355	0,73	0,74	0,8	0,07

	Inclined components			
Warsaw	R_{st} [GV]	R_{ef} [GV]	R_m [GV]	Width of penumbral zone in GV
Azimuth angle		Zenith angle	16	
71	2,65	2,96	3,23	0,58
161	2,65	2,92	3,09	0,44
251	2,51	2,72	2,99	0,48
341	2,58	2,82	3,15	0,57
Azimuth angle		Zenith angle	32	
65	2,75	3,14	3,52	0,77
155	2,64	2,97	3,23	0,59
245	2,36	2,63	2,91	0,55
355	2,57	2,78	3,12	0,55

	Inclined components			
Lae	R_{st} [GV]	R_{ef} [GV]	R_m [GV]	Width of penumbral zone in GV
Azimuth angle		Zenith angle	16	
99	17,84	17,84	17,85	0,01
189	15,52	15,52	15,53	0,01
279	13,59	13,59	13,6	0,01
369	15,68	15,68	15,69	0,01
Azimuth angle		Zenith angle	32	
99	21,42	21,42	21,43	0,01
189	16,22	16,22	16,23	0,01
279	12,38	12,38	12,39	0,01
369	16,57	16,57	16,58	0,01

	Inclined components			
Buenos Aires	R_{st} [GV]	R_{ef} [GV]	R_m [GV]	Width of penumbral zone in GV
Azimuth angle		Zenith angle	16	
87	8,87	9,41	10,21	1,34
177	7,56	7,77	8,56	1
267	6,98	7,36	7,94	0,96
357	7,58	8,61	9	1,42
Azimuth angle		Zenith angle	32	
87	10,78	11,35	12,07	1,29
177	7,69	8,1	8,69	1
267	6,42	6,77	7,33	0,91
357	9,16	9,21	9,32	0,16

	Inclined components			
Wellington	R_{st} [GV]	R_{ef} [GV]	R_m [GV]	Width of penumbral zone in GV
Azimuth angle		Zenith angle	16	
104	3,03	3,39	3,58	0,55
194	2,92	3,31	3,48	0,56
284	2,7	3,13	3,28	0,58
374	2,9	3,31	3,42	0,52
Azimuth angle		Zenith angle	32	
104	3,07	3,54	3,78	0,71
194	3	3,4	3,57	0,57
284	2,94	3,07	3,23	0,29
374	3,11	3,41	3,46	0,35



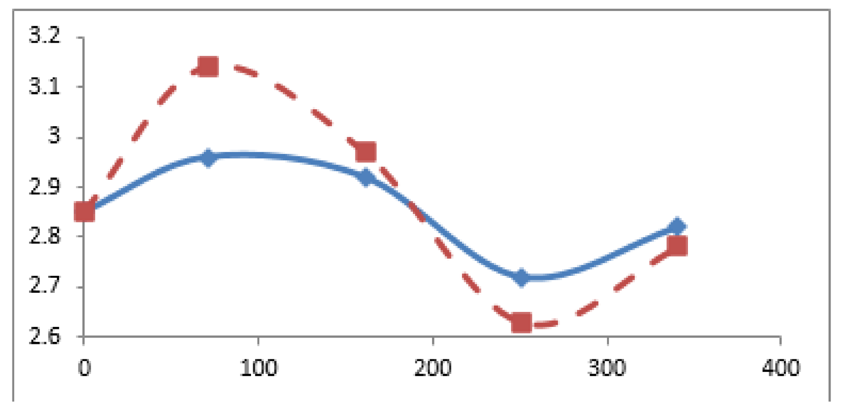


Figure 2. Dependence of the cutoff rigidity on azimuth for particles approaching the surface at an inclination angle of 16 and 32 from vertical for airport in **Warsaw** (the solid line represents the azimuth relationship for the zenith angle 16, the dashed line for the zenith angle 32

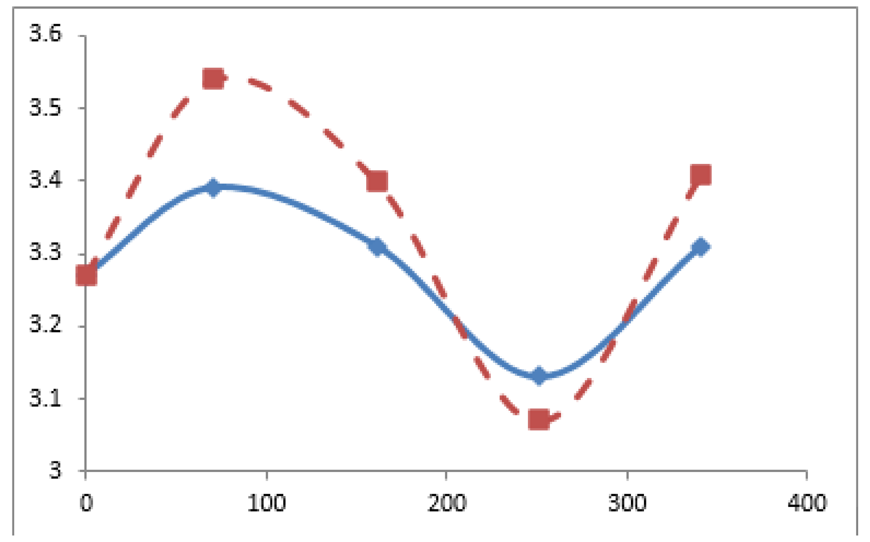


Figure 3. Shows the same as Fig 2 for airport **Wellington** (southern hemisphere)

Conclusions

1. Asymptotic directions (asymptotic latitude and longitude) of the arrival of charged particles and magnetic cutoff rigidity were determined for the airports: Apatity, Oulu, Warsaw, Lae, Buenos Aires, Wellington and Mc Murdo.
2. The magnetic cut-off rigidity depends on the latitude. With the increase of latitude, the magnetic stiffness decreases, i.e. cosmic ray particles reach the Earth more easily from the poles than the equator
3. For the airports located at medium latitude, we observe a penumbra zone, that contains a family of allowed and forbidden trajectories of cosmic ray particles and magnetic cutoff rigidity is expressed by R_{ef} (Warsaw, Buenos Aires, Wellington)
4. For the airports located at high latitude, (Apatity, Mc Murdo and Oulu) the penumbra does not exist or is very narrow and magnetic cut-off rigidity is expressed by R_{st} in the absence of penumbra or by R_{ef} if penumbra exists.
5. In low latitudes (Lae airport), the penumbra does not appear and magnetic cutoff rigidity is expressed by R_m
6. Analysis of the magnetic cut-off rigidity for the inclined components, we observe east-west asymmetry.
7. Knowledge of asymptotic directions and the magnetic cutoff rigidity, it is important from the point of view of the flight safety of both passenger and military aircraft and study of the different classes of the cosmic rays variations intensity and anisotropy