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Atmospheric Monitoring Using Radiosonde Data for TA

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We found that the systematic error of $X_{\max}$ determination is less than 10 g/cm^2 for the Telescope Array fluorescence detector when we correct the data using the atmospheric parameters collected by the radiosonde launched at the nearest meteorological observatory of TA site within 6 hours of the air shower event. This is a result of analyzing Monte Carlo simulated events using atmospheric parameters taken by the radiosonde launched every 12 hours. Each state of the U.S. has more than one such observatory to launch radiosonde, and the data are available through the World Wide Web. We conclude sufficient accuracy can be obtained for the determination of $X_{\max}$ by correcting the TA fluorescence telescope data using such public data.

1. Introduction

The existence of the super-GZK cosmic rays observed with AGASA [1] is one of the important unsolved problems in astrophysics. The Telescope Array (TA) experiment, which is now in construction in Utah, has been planned to clarify the origin of cosmic rays at the highest energies (ultra high energy cosmic rays, hereafter UHECRs) [2]. In the Telescope Array experiment, we observe air showers of UHECRs both with the ground detector array and with the fluorescence detectors.

The key in the air fluorescence technique is the atmospheric monitoring. The variations in atmospheric conditions as pressure and temperature affect atmospheric depth, fluorescence yields, and photon scatterings, which lead to uncertainties of air shower reconstructions. Above all, atmospheric depth directly affect the longitudinal development of air showers, therefore affect determination of $X_{\max}$ (the depth at the maximum shower development), which is important to identify the primary particle.

A use of the US Standard Atmosphere model (US-SA model) [3] is one of the solutions to include atmospheric conditions in shower analysis. However, it is not clear whether the actual atmosphere at the moment of an air shower event is the same as such a stationary model because of the temporal and spatial variations in the atmospheric condition. In this work, we consider to use the atmospheric data obtained by the radiosonde, launched at the meteorological observatories near the TA site, for analysis of air showers observed with fluorescence detectors. We carried out Monte Carlo studies to generate air shower events and to reconstruct the shower profile by using the atmospheric informations from both of the US-SA model and the radiosonde data. By examining systematic errors in the shower parameter determinations in each case, we discuss the feasibility of the use of the radiosonde data for atmospheric monitoring in TA.

2. Variations of Atmospheric Condition

A radiosonde is a meteorological instrument carried by a balloon to measure pressure and temperature etc. up to an altitude of about 30 km. Each state of the U.S. has more than one meteorological observatory to launch such radiosondes every 12 hours, and the data are available through the World Wide Web [4]. In this analysis, we use the data at the six stations near the TA site (Table 1). The nearest station is SLC 180km away from the TA site, and the second is Elko 320km away.

Table 1. Radiosonde Observatories Near the TA Site

Station	State	Latitude [deg]	Longitude [deg]	Elevation [m]
Flagstaff	Arizona	35.23N	111.82W	2179
Grand Junction	Colorado	39.12N	108.53W	1472
Boise	Idaho	43.57N	116.22W	871
Elko	Nevada	40.87N	115.73W	1608
Salt Lake City	Utah	40.77N	111.97W	1288
Riverton	Wyoming	43.06N	108.47W	1688

First, we examined seasonal variations of atmospheric condition. Figure 1 shows the average and the standard deviation of the differences of atmospheric depth from the US-SA model versus altitude, which are calculated from the measurements at SLC in February, May, August, and November, 2004. From the left side, it is found that the seasonal variations is about 25 g/cm^2 at altitudes of 8-10km, while they are small at higher altitudes.

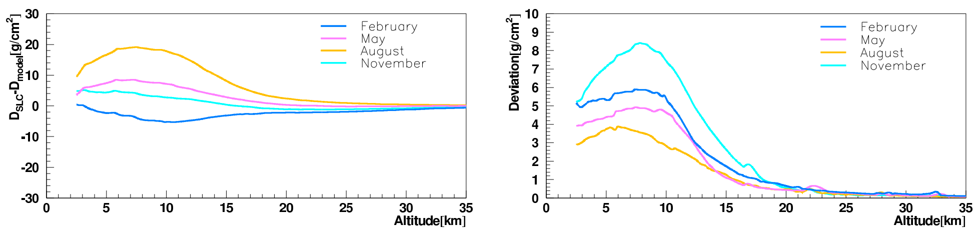

Figure 1. Differences of atmospheric depth from the US-SA model (left: average, right:standard deviation)

Next, we can see daily variations from the right side of Figure 1. The deviation of atmospheric depth from the average is the largest at altitudes of 8-10km, 8 g/cm^2 in November for example, and is small at higher altitudes. Moreover, the variations are moderate in summer compared to in autumn or winter: the maximum deviation is 4 g/cm^2 in summer, while 8 g/cm^2 in autumn.

We also investigated differences of atmospheric condition at among the six stations listed in Table 1. Figure 2 shows the differences of atmospheric depths between the data at SLC and others in February and in August, respectively. The maximum differences of atmospheric depth is 4±5 g/cm^2 in winter, and 3±3 g/cm^2 in summer at altitudes of 8-10km. However, they are small compared to the daily variations.

3. Influence on Air Shower Analysis

3.1 Seasonal Variations

Since there are seasonal variations of atmospheric condition as we saw above, we need to know how they affect the analysis of observed fluorescence light. For this purpose, we performed air shower simulations using Gaisser-Hillas function and the TA fluorescence detector Monte Carlo [5].

First, we selected one day in February, and another day in August. For each day, 2500 proton-induced showers with the energy of 10^{20} eV at zenith angles of 15, 30, 45, 60, and 75 degrees were simulated using the radiosonde data on that selected day measured at SLC. Then, these simulated events were reconstructed under the two types of atmospheric conditions: the radiosonde data and the US-SA model.

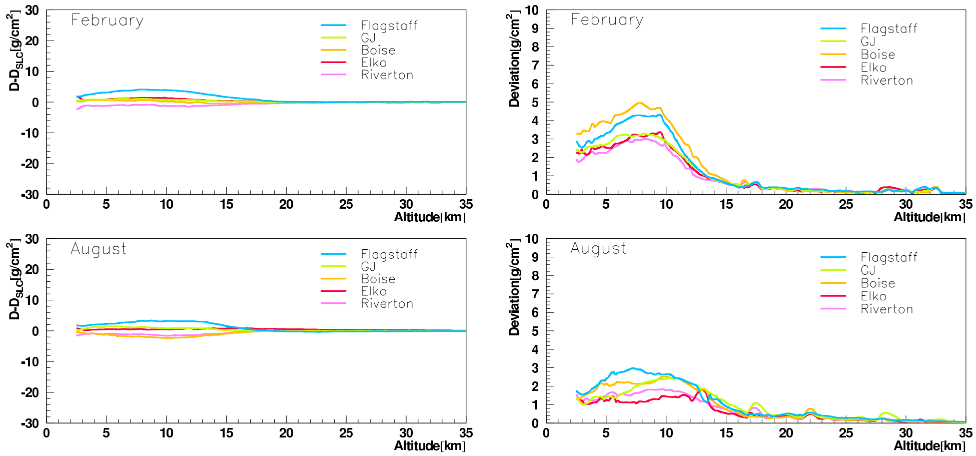

Figure 2. Differences of atmospheric depth between the data at SLC and others in February and in August (left: average, right: standard deviation)

Table 2. Differences of Shower Parameters

	$\Delta \log E$ [eV]	$\Delta X_{\rm max}$ [g/cm^2]	$\Delta\theta$ [deg]
February	0.007	4.84	0.00
August	0.001	33.64	0.02

Table 2 is lists of the differences of the shower parameters (primary energy, $X_{\rm max}$, and direction) for the reconstructed events under the atmospheric conditions between the radiosonde data and the US-SA model. While the primary energy and the direction are hardly affected by the difference in atmospheric conditions, $X_{\rm max}$ is affected. The systematic error on the $X_{\rm max}$ determination is about 5 g/cm^2 in February and 30 g/cm^2 in August. From this, we can say that stationary atmospheric models as the US-SA model are not satisfactory for air shower analysis, and actual atmospheric conditions should be taken into account.

3.2 Daily and Local Variations

When we use radiosonde data taken at the observatories every 12 hours for the TA fluorescence detectors, we have two problems: we cannot use the atmospheric condition at the time of an air shower event, and we cannot use that at the TA site. Thus, we evaluated the systematic errors caused by these effects and examined the feasibility of use of such public data for atmospheric monitoring in TA.

First, we selected three days in February and other days in November, which are the season when the fluctuation of atmospheric conditions is relatively large. For each day, 500 proton-induced showers with an energy of 10^{20} eV at zenith angle of 60 degrees were simulated using the radiosonde data on those selected days at SLC. In reconstruction, the six types of atmospheric conditions were used for the examination of the first effect described above: using the radiosonde data of the simulation, 12 hours after, 1 day after, 3days after, 7days after, and 10 days after. For the examination of the second effect, six types of atmospheric conditions were used similarly in the reconstruction: the radiosonde data at the six stations listed in Table 1.

The results are shown in Figure 3. It shows the differences in $X_{\rm max}$ of the reconstructed events between using

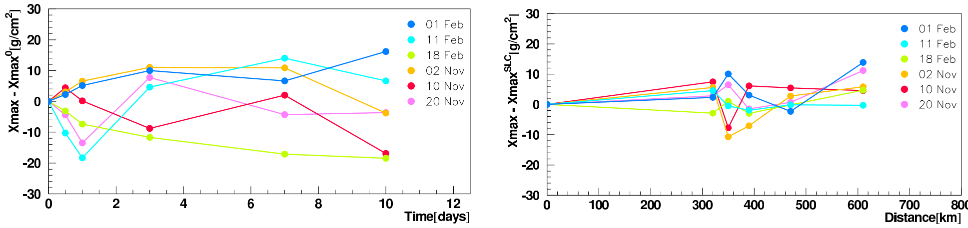

Figure 3. Systematic error of $X_{\max}$ (*left*: the vertical axis is a time interval between a shower event and a radiosonde launch, *right*: differences of the errors in radiosonde observatory location.)

the data same as that in simulation and using other radiosonde data. From the left panel of Figure 3, we found that when we use an atmospheric condition within 6 hours of an air shower event in the shower analysis, the systematic error of $X_{\max}$ is less than 5 g/cm^2, while it is 20 g/cm^2 when we use the conditions after more than 1 day of the event. On the other hand, we found from the right panel that the systematic error of $X_{\max}$ with the local variations of atmosphere is small compared to that with the daily variations. In particular, the error is small at Elko 320km away from SLC, it is about 8 g/cm^2. Recalling that the TA site is 180km away from SLC and 320km away from Elko, we can say that the systematic error of $X_{\max}$ is less than 8 g/cm^2 using the atmospheric conditions measured at SLC.

4. Conclusion

For air shower analysis, the stationary atmospheric model should not be used and the actual atmospheric condition have to be taken into account. We conclude that the systematic error of $X_{\max}$ is less than 10 g/cm^2 for the TA fluorescence detectors, because we can use atmospheric conditions measured by the radiosonde launched at SLC within 6 hours of an air shower event.

5. Acknowledgments

References

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