ORIGINAL PAPER

Measurement of atmospheric conductivity on the Qinghai-Tibet Plateau in China

Lei Li[1,2] · Jianfeng Su[1] · Tao Chen[1] · Shuo Ti[1] · Han Wu[1,2] · Jing Luo[1] · Wen Li[1] · Renkang Li[3]

Abstract

Two feasible methods (the current–voltage method and the voltage decay method) for measuring atmospheric conductivity were introduced in this paper, both variants within the Gerdien tube method. To explore the characteristics of atmospheric conductivity, we performed two balloon flight experiments on the Qinghai-Tibet Plateau on 27 August 2019 and 14 September 2020, and these two approaches were used. Detailed experiments and methods and a series of experimental results are presented in this paper. The current–voltage method was used during the first experiment, and we further demonstrated that atmospheric conductivity changed with changing altitude, primarily under the action of atmospheric gas and ionic composition. The balloon passed through the clouds by chance, and we found that clouds caused abnormal variation in atmospheric conductivity; the measured conductivity of the atmosphere changed suddenly by $7.5 \times 10^{-13} - 1.5 \times 10^{-12}$ $\Omega^{-1}\,m^{-1}$, which may have been caused by water vapor or charges in the clouds. For the second experiment, the voltage decay method was used to explore further characteristics of atmospheric conductivity at the same location on the plateau. Unfortunately, the balloon did not fly because of the device, and positive conductivity and negative conductivity were measured on the ground at an altitude of 3.2 km. The feasibility of the two methods was proven by the two experiments. At the end of the paper, we have discussed the experimental error and details of the two measuring methods, which can be used as a reference for researchers concerned with atmospheric electricity.

1 Introduction

Atmospheric conductivity refers to a physical quantity that describes the conductive ability of the atmosphere, which is an important parameter in space electrodynamic processes. There is a global atmospheric circuit between the positively charged ionosphere and the earth, and it provides a combination of charge generation in disturbed weather regions and current flow in fair weather regions.

✉ Tao Chen
  tchen@nssc.ac.cn

[1] State Key Laboratory of Space Weather, National Space Science Center, Chinese Academy of Sciences, Beijing 100190, China

[2] University of Chinese Academy of Sciences, Beijing 100049, China

[3] College of Physics and Electronic Information, Yunnan Normal University, Kunming 650500, China

The atmospheric conductivity in the low-altitude atmosphere is mainly affected by meteorological processes and human activities, while the atmospheric conductivity in the high-altitude atmosphere is influenced by solar activities (Rycroft et al. 2000). Therefore, atmospheric conductivity is the key to determining the coupling between the lower atmosphere and ionosphere (Volland 1987), and there are irregular changes in atmospheric conductivity values at different moments of a day or at various geographical locations, because the factors that affect atmospheric conductivity are changeable; therefore, they have attracted much attention (Holzworth et al. 1987; Kokorowski et al. 2006). In addition, there are many other factors that influence atmospheric conductivity, including aerosol concentration and water vapour pressure (Sun 1987). In meteorology, visibility has been found to be inversely proportional to atmospheric conductivity (Ruhnke 1966; Brazenor and Harrison 2005). Therefore, atmospheric conductivity measurements are used for monitoring air pollution and cosmic rays and for detection of radioactive materials (Guo et al. 1996).

Kites, balloons, rockets, aircraft and other platforms have been used to measure atmospheric electricity for over

200 years (Nicoll 2012). Artificial balloons have been utilized since the end of the nineteenth century to measure atmospheric electricity, including the atmospheric potential gradient, conductivity or current (Venkateswaran and Mani 1962; Harrison and Bennett 2007). Kraakevik (1958) used airborne measurement results to show that atmospheric conductivity was dependent on the altitude above the Greenland fjord. Moreover, in August 1968, Mozer and Serlin (1969) measured horizontal and vertical electric fields with two balloons flown from Fort Churchill, Canada. Based on their observations, they provided a detailed discussion of global electric and magnetic fields. Byrne et al. (1988) observed stratospheric conductivity and its change at three latitudes (10–30 km) by using nine high-altitude balloons, and they discussed the effects of aerosols and latitudinal temperature variations. In addition, Hu and Holzworth (1996), Bering et al. (2005) and John et al. (2009) have completed measurements of stratospheric conductivity. They used the relaxation probe method, which saves space and electricity and is also applicable to space missions (Berthelier et al. 2000). With the development of technology, ionization sensors can now be flown with standard meteorological radiosondes, as evidenced by sensors developed at the University of Reading (Harrison et al. 2013). The use of an existing radiosonde provides an opportunity to monitor space weather between the earth and the ionosphere.

This paper primarily describes two balloon flight experiments that were used to study the characteristics of atmospheric conductivity on the Qinghai Plateau in China. Altitude refers to distance above the mean sea level, and the time used in this paper is local time (UTC + 8). In the following, we describe the procedures and experimental results of these two experiments in detail.

2 Laboratory experiments

The current–voltage method and the voltage decay method are both variants within the Gerdien tube method, and they both use a central electrode tube to collect positive ions (for positive conductivity measurements) or negative ions (for negative conductivity measurements). The difference between them is that the current–voltage method measures the change of current between the central electrode and the external electrode, while the voltage decay method measures the change of voltage between these two electrodes. They can both be used to measure the atmospheric conductivity. Importantly, it should be mentioned that based on the work of Nicoll and Harrison (2008), the voltage decay method uses the change of voltage (not voltage decreases) to measure atmospheric conductivity, because negative ions were collected by the central electrode during the measurement of negative atmospheric conductivity, then the voltage was

continuously increasing (the voltage increases only when positive atmospheric conductivity was measured).

To ensure the success of the two balloon flight experiments, we performed a laboratory experiment at the National Space Science Center (Beijing, China) on July 14, 2019. Two instruments using different methods (the current–voltage method and the voltage decay method) were combined, and the measurements were started at the same time. The measurement results are shown in Fig. 1, in which panel (a) depicts the results of a laboratory current–voltage measurement, dots represent original data, straight lines represent the result of fitting, red lines represent positive conductivity results, and blue lines are negative conductivity results. Panel (b) shows the results of laboratory voltage decay measurements, and the red and blue lines have the same meanings as in panel (a). In panel (b), the period of the voltage change
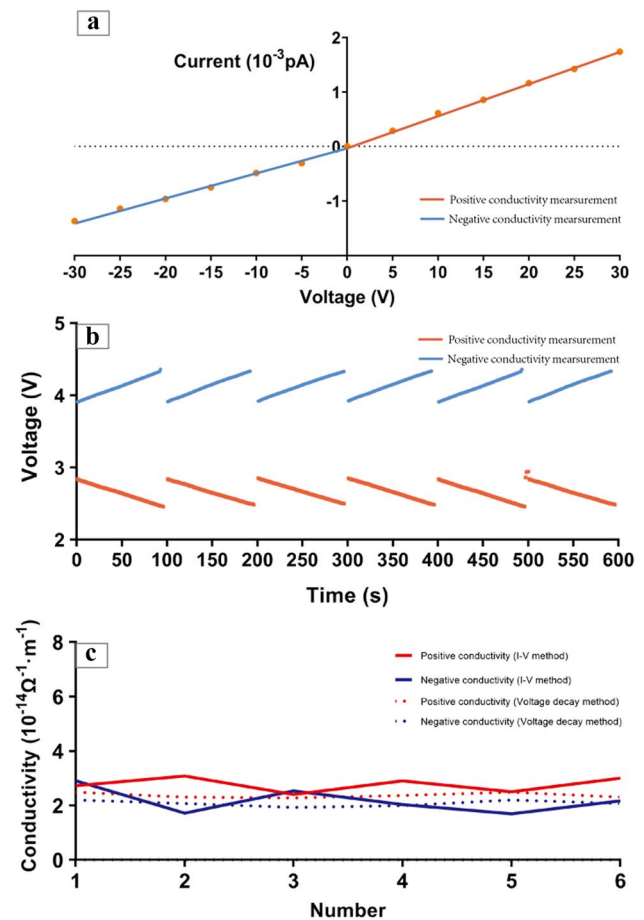

Fig. 1 Laboratory current–voltage (**a**) and voltage decay (**b**) curves and the comparison of conductivity measurement results (**c**). The dots represent original data, the straight lines represent fitting results, the red lines represent the measurement of positive conductivity, and the blue lines represent the measurement of negative conductivity. The solid lines indicate the results by using the current–voltage method, while dashed lines are the results obtained by using the voltage decay method

is 100, the first 5 s was used for resetting the voltage, and the next 95 s was used for measurement of the voltage. The voltage value changes in this period can be calculated to obtain an atmospheric conductivity value, so the variation of voltage in 100 s is an average value of atmospheric conductivity. Then panel (c) compares conductivity measurement results where the red lines represent the measurement of positive conductivity, the blue lines represent the measurement of negative conductivity, and the solid lines indicate the results from the current–voltage method while dashed lines are the results of the voltage decay method.

In the laboratory experiments, the average atmospheric conductivities measured by our first instrument (using the current–voltage method) were as follows: $\sigma_+ = 2.77 \times 10^{-14}$ $\Omega^{-1} \cdot m^{-1}$ and $\sigma_- = 2.17 \times 10^{-14} \, \Omega^{-1} \cdot m^{-1}$. The average values of atmospheric conductivity measured by our second instrument (using the voltage decay method) were as follows: $\sigma_+ = 2.37 \times 10^{-14} \, \Omega^{-1} \cdot m^{-1}$ and $\sigma_- = 2.08 \times 10^{-14} \, \Omega^{-1} \cdot m^{-1}$. Figure 1c is the comparison of the results measured by these two methods. Figure 1c shows that: (1) The results measured by these two methods are close, and σ_+ is 0.3×10^{-14} -$0.6 \times 10^{-14} \, \Omega^{-1} \cdot m^{-1}$ times larger than σ_- measured in the Beijing laboratory experiments. (2) The voltage decay method measurement is more stable than the current–voltage method. Finally, we consider these two results as similar and reasonable, so the measurement equipment and the two methods are appropriate.

3 Two balloon flight experiments

The Qinghai-Tibet Plateau, an inland plateau in Asia, is the largest plateau in China and the highest in the world. There are few factors that can interfere with experiments on the Qinghai-Tibet Plateau, so it is possible to obtain excellent experimental results. Golmud is located in the midwestern area of Qinghai Province, China. There are many mountains with high-altitude strong ultraviolet rays in Golmud, which is a useful experimental site.

To better compare the two atmospheric conductivity measurement experiments, we planned to use the different measurement methods and conduct two balloon flight experiments at the same location; a map of this location is shown in Fig. 2. The Dachaidan Town Area in Golmud is part of the Qinghai-Tibet Plateau.

Meteorological data (mentioned below) from two balloon experiments were provided by the local Meteorological Bureau, and the wind speed was measured with an anemometer on the grounds of the local Meteorological Bureau.

3.1 First flight experiment (current–voltage method)

On August 27, 2019 (the air temperature was 12–24 °C, and the northeast wind had a wind speed of 1–2 m·s^{-1}), a balloon flight experiment was conducted on the Qinghai-Tibet
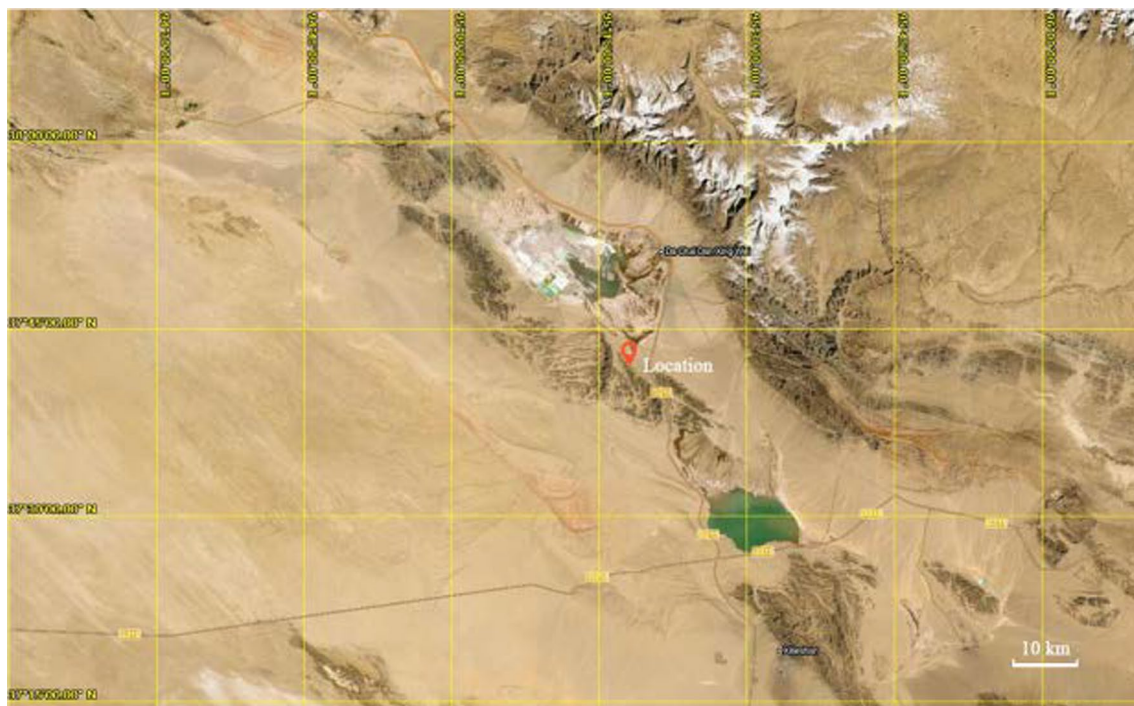

Fig. 2 Map of the location for the two balloon flight experiments

Plateau in China (Golmud is at 95.3°E, 37.7°N, and the altitude is 3.2 km). The balloon was a sounding balloon with good elasticity and filled with a few kilograms of helium. The other sensors included ozone detectors, wide energy spectrum neutron detectors, neutron radiation effect detectors, ultraviolet radiation detectors, etc. The conductivity measurement device had a built-in storage card. The data were recorded in real time during the flight at a rate of one per second. After the flight ended, the balloon platform was

recovered, and the storage card was removed. Finally, we obtained the stored data.

The experiment balloon took off at 3:50 am and rose to a maximum altitude of 22.8 km at 7:21 am. Then, the balloon was controlled from the ground and flown horizontally (the height was kept constant). Finally, the level flight ended at 7:29 am, and the experimental tank landed. Then, we recycled our equipment, including the conductivity metre, parachute, ozone detector, wide energy spectrum neutron detector, neutron radiation effect detector, ultraviolet radiation detector, etc. The trajectory of the balloon flight is shown in Fig. 3. The blue curve represents the trajectory and red arrows are the direction of the balloon flight.

The voltage was set to 12.4 V and kept constant, and the current in the Gerdien probe and the corresponding altitude were measured during the experiment. After this balloon flight experiment, the data obtained and the voltage (a constant 12.4 V) were combined to obtain a profile of the atmospheric conductivity and its variation with altitude, as shown in Fig. 4a. For this method, the current was measured once per second, which corresponded to a value of atmospheric conductivity.

In Fig. 4a, the green curve represents the original conductivity, and the red curve is the value after smoothing. For the original conductivity, there are many fluctuations suggesting that atmospheric conductivity is unstable and can be affected by many factors. Figure 4a shows that the average atmospheric conductivity was approximately $1–5\times10^{-14}$ $\Omega^{-1}\cdot m^{-1}$ at an altitude of 3.2 km on the Qinghai-Tibet Plateau. As the altitude increased, there were increasing

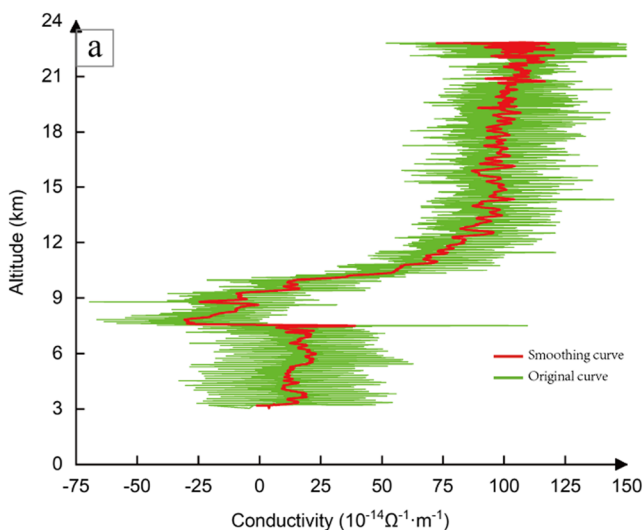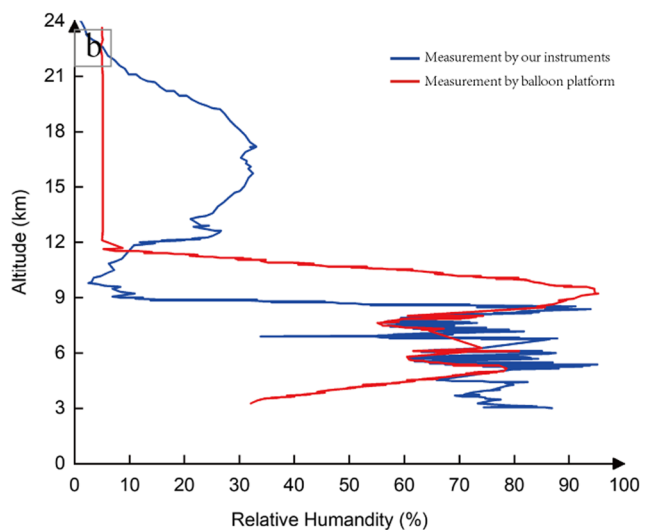**Fig. 3** Trajectory of the balloon flight on 27 August 2019

Fig. 4 Results from the first balloon flight experiment on 27 August 2019 where panel (**a**) is the profile of atmospheric conductivity with increasing altitude measured during the first balloon flight experiment on August 27, 2019. In panel (**a**), the green curve represents original data, and red curve shows the result after smoothing. Panel (**b**) shows

the humidity during this balloon flight experiment. The blue curve indicates results measured by our instruments, and the red curve indicates results measured by a relative humidity sensor placed on the balloon platform

numbers of small ions, and the atmospheric conductivity increased gradually. At an altitude of approximately 7.5 km, the conductivity suddenly became negative and did not return to positive until 10 km. From 10 to 11 km, it increased rapidly and soon became normal. Above 11 km, the conductivity increased significantly with height. At the highest altitude (22.8 km), the atmospheric electrical conductivity was approximately $1.1 \times 10^{-12}\ \Omega^{-1} \cdot m^{-1}$.

Panel (b) in Fig. 4 shows the humidity measured during this balloon flight experiment. The blue curve indicates data measured by our instruments, while the red curve refers to data measured by a relative humidity sensor placed on the balloon platform. These two curves were not completely coincident because there was a distance of approximately 100 m between the balloon platform and the instrument. We can obtain effective information based on these two curves: the relative humidity increased significantly from 7.5 km to 11 km, which indicates that there may be clouds with a large amount of water vapour at 7.5–11 km. We did not obtain detailed data for the clouds, and it was unclear whether the clouds were charged. However, water vapour in clouds has a substantial effect on atmospheric conductivity.

We believe that the abnormal change in atmospheric conductivity was caused by water vapour in the clouds. When the conductivity metre passed through the water vapour in the clouds, the ions around the atmospheric conductivity metre was affected by water molecules, the mobility of the ions decreased, and the atmospheric conductivity decreased significantly. Then, because the clouds might be charged, the conductivity meter could also be charged. In this way, the magnitude and direction of the current in the conductivity meter changed, so the conductivity measured by our conductivity meter suddenly became negative at approximately 7.5 km and remained negative for a period of time, as shown in Fig. 4b. As the height of the balloon increased, the conductivity meter gradually moved away from the clouds, and then the measured conductivity gradually returned to a normal value at 7.5–11 km. In addition, Harrison et al. (2020) showed that extensive layers of clouds were charged at their upper and lower horizontal boundaries, and we can see from Fig. 4a that there were sharp changes in atmospheric conductivity at approximately 7 km and 11 km. We think these results fit Harrison's theory well.

Measurements of conductivity in clouds are rarely described in relevant publications. Because large numbers of cloud droplets hinder the measurement of conductivity, which is usually dominated by small ions, this is a difficult task. Despite these difficulties, reasonable measurements of conductivities in clouds do exist. The balloon-borne conductivity measurement of Jones et al. (1959) is an example. They showed that conductivity decreased significantly inside clouds. Raj et al. (1993) measured the atmospheric conductivity over India with an airplane and found that the

atmospheric conductivity in clear skies was several orders of magnitude higher than that in clouds. Venkateswaran and Mani (1962) also discovered abnormal behaviour by balloon instruments measuring conductivity inside cirrus clouds. They found that the positive conductivity inside cirrus clouds was 70% higher than that under cirrus clouds. In their view, the most likely explanation for the increase in conductivity is that there were many ice crystals in the cirrus clouds; these were adsorbed by the conductivity sensor and resulted in abnormal conductivity.

3.2 Second flight experiment (voltage decay method)

To study the characteristics of atmospheric conductivity on the Qinghai-Tibet Plateau in more detail and to make a comparison with the first experiment, another flight mission was planned for the same location in 2020. We improved the experimental instrument and used the voltage decay method based on the research of Nicoll and Harrison (2008). The Gerdien tube shown in Fig. 5 measures the voltage change between the outer electrode and the central electrode, and then the atmospheric conductivity is determined by the rate of the voltage change. It is necessary to set the bias voltage and measure the voltage between the two electrodes at the same time, and this can be achieved by implementation of a voltage reset, as shown in Fig. 5. Two junction field-effect transistor (j-FET) diodes were switches used for resetting the electrode voltage, and they were connected in anti-parallel fashion to realize bipolar current. If a fault was found in the experiment, the system easily recovers from the fault state. In time–course experiments, the switch was set at "Measure", and the two diodes became blocking elements. The two diodes conduct, and the central electrode voltage was V_{reset} if the transfer switch was set at "Reset". The V_{reset} of the positive Gerdien capacitor was usually set to 2 V, and the reset voltage of the negative capacitor was usually set to 5 V. In this case, the voltage changed during 100 s, and the voltage value during this period was calculated to obtain an average atmospheric conductivity value. Thus the 100 s
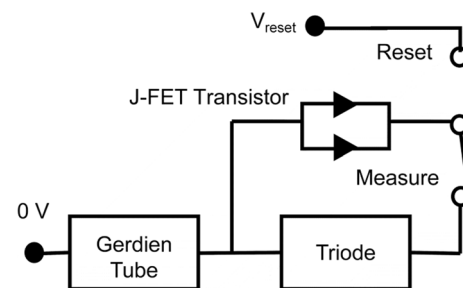

Fig. 5 Basic implementation of voltage reset and measurement in the voltage decay method

voltage variation curve corresponds to an average value of atmospheric conductivity, for positive or negative atmospheric conductivity.

After a half-year of preparation, another balloon flight experiment was planned for implementation at the same location (shown in Fig. 2) on the Qinghai-Tibet Plateau in China (the altitude is 3.2 km) on September 14, 2020. To avoid mistakes with the experimental equipment, at 15:39 (local time, UTC + 8) on the day before the balloon flight test (13 September 2020; the air temperature was 7–21 ℃, and the speed of the northwest wind was 1–2 m·s^{-1}), a test experiment was implemented in Golmud for nearly 9 h until 0:33 the next day (14 September 2020; the air temperature was 6–19 ℃, and the speed of the northwest wind was 1–2 m·s^{-1}). As shown in Fig. 6, in this test experiment, we obtained a complete dataset describing the fluctuations in atmospheric conductivity on the Qinghai-Tibet Plateau. At approximately 7:00 AM, when we were preparing for the balloon flight experiment, due to the overall device, the balloon unfortunately did not fly.

Figure 6 shows the data measured on the ground on the day before our second balloon flight experiment. In Fig. 6, the red curves are the measurement of positive conductivity and the blue curves denotes the measurement of negative conductivity; the solid line indicates positive conductivity, while the dashed line is negative conductivity. Figure 6 shows clearly that both positive and negative voltages changed over time and exhibited sawtooth waves. Every 100 s constituted a period, the first 5 s was used for resetting the voltage, and the next 95 s was used for measurement of the voltage. Using the voltage change data, we easily obtained positive and negative conductivity values, as shown in Fig. 6. There was little difference between positive conductivity and negative conductivity, but the positive conductivity was slightly larger than the negative conductivity. In the early morning on the ground of the Qinghai-Tibet Plateau at an altitude of 3.2 km, the value for positive conductivity was approximately 2×10^{-14} Ω^{-1} m^{-1}, the negative conductivity was approximately $1 \times 10^{-14} - 1.5 \times 10^{-14}$ Ω^{-1} m^{-1}, and the total atmospheric conductivity was approximately $3 \times 10^{-14} - 3.5 \times 10^{-14}$ Ω^{-1} m^{-1} on the ground in Golmud. Although the second balloon flight experiment did not occur, we obtained data for positive conductivity and negative conductivity on the ground at an altitude of 3.2 km, and the feasibility of the voltage decay method was also evaluated.

Comparing Figs. 1c and 6, we can conclude that (1) the atmospheric conductivity is slightly larger in Beijing laboratory larger than on the Qinghai-Tibet Plateau, and the reason may be that the different environments between in lab and out of lab. (2) The positive atmospheric conductivity is slightly larger than the negative atmospheric conductivity by 0.3×10^{-14}-1×10^{-14} Ω^{-1} m^{-1} either in the Beijing laboratory or on the Qinghai-Tibet Plateau.

4 Conclusion and discussion

Based on the two experiments described above; (1) the atmospheric conductivity on the Qinghai-Tibet Plateau ground at an altitude of 3.2 km is approximately $1 \times 10^{-14} - 5 \times 10^{-14}$ Ω^{-1} m^{-1}, the value at an altitude of 22.8 km is approximately 1.1×10^{-12} Ω^{-1}·m^{-1} and it increases with increasing altitude; (2) either in the Beijing laboratory or on the Qinghai-Tibet Plateau ground, the positive atmospheric conductivity is slightly larger than the negative conductivity by $0.3 \times 10^{-14} - 1 \times 10^{-14}$ Ω^{-1} m^{-1}; (3) atmospheric conductivity is easily affected by clouds,

Fig. 6 Measurements obtained during the ground experiment on 13 September 2020. The red curves depicts the measurement of positive conductivity, while the blue curves denote measurements of negative conductivity. The solid line indicates positive conductivity, while the dashed line is negative conductivity
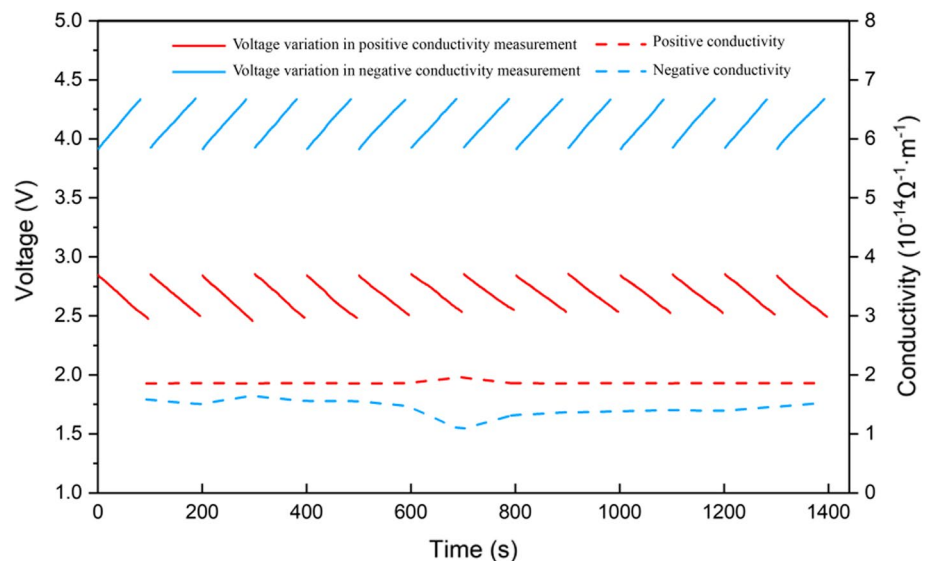
and if the conductivity detector passes through the clouds, the measured conductivity of the atmosphere changes suddenly by $7.5 \times 10^{-13} - 1.5 \times 10^{-12}\ \Omega^{-1}\ m^{-1}$. The height of the clouds can be determined by measuring the relative humidity in the atmosphere; and (4) the atmospheric conductivity in the Beijing laboratory is about $5 \times 10^{-14}\ \Omega^{-1}\ m^{-1}$, which is slightly larger than that on the Qinghai-Tibet Plateau by 0×10^{-14}-$1.5 \times 10^{-14}\ \Omega^{-1}\ m^{-1}$, and this difference may be caused by the different environments between in lab and out of lab.

The value for atmospheric conductivity is determined by the concentration of light ions multiplied by their mobility. As the altitude increases, the intensity of cosmic radiation increases, an increasing number of molecules in the air are ionized, and then the concentration of small ions increases. Furthermore, at high altitudes, the air density is low, and the mobility of ions is large. Hence, the atmospheric conductivity increases as the altitude increases.

There may be reasonable errors in the measurements of atmospheric conductivity, including systematic errors and external errors. First, the air flow inside the short tubes was uneven, and the edge effect made it preferable to use the measured capacitance (Aplin and Harrison 2001). Furthermore, the smoothness of the inner and outer electrodes affected air turbulence and changed the measurement accuracy. During the flight experiments, the ambient temperature changed, and the measurements were significantly affected, especially with the current–voltage method (because of the high resistance and greater susceptibility to temperature). Finally, for the current–voltage method, the current measured was very weak and susceptible to interference from surrounding environmental charges.

There may be reasonable errors in the measurements of atmospheric conductivity, including systematic errors and external errors. First, the air flow inside the short tubes was uneven, and the edge effect made it preferable to use the measured capacitance. (Aplin and Harrison 2001). According to the parameters marked on the capacitor, the total error due to the capacitor was approximately $\pm 4\%$. Furthermore, the smoothness of the inner and outer electrodes affected air turbulence and changed the measurement accuracy, this error was small and depended on the smoothness of electrodes. During the flight experiments, the ambient temperature changed, and the measurements were greatly affected, especially with the current–voltage method (because of the high resistance and greater susceptibility to temperature), and the resistance error due to ambient temperature was estimated to be $\pm 1\%$. Finally, for the current–voltage method, the measured current was very weak and susceptible to interference from surrounding environmental charges.

In summary, two balloon flight experiments were implemented at the same location with different methods, as shown in Fig. 2. Both the current–voltage method and the voltage decay method use a Gerdien tube. The difference is that the voltage decay method has simple requirements for the circuit system, but the air in the tube must have stable and uniform flow for a long time, or large measurement errors can result. The I–V method requires a high impedance with a low temperature coefficient to amplify the weak current, which results in higher requirements for the amplification circuit, but it has higher accuracy and greater precision than the voltage decay method. By comparison, the two methods have their own advantages and disadvantages. Additional research on the characteristics of atmospheric conductivity will be conducted by our academic team in different environments, such as volcanoes, landslides, and earthquakes.

Declarations

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