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Progress of research on anomalies of astronomical time and latitude observations before earthquake

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This paper introduces the discovery of the phenomenon that short-term anomalous fluctuations appeared in residuals of astronomical time and latitude observations before earthquakes and the progress of related researches carried out for many years. The relations between the anomalous variations of time and latitude residuals of astronomical time and latitude instruments in different regions and the earthquakes around these instruments as well as the characteristics of residuals' anomalous variations are analyzed. The significance of the anomalous fluctuations in residuals of astronomical time and latitude caused by the anomalous variations of the local plumb line before earthquake and detecting the vertical variation with astronomical time and latitude observations as well as the importance of carrying out further researches are discoursed. The possibility that the phenomenon will become an effective short-term earthquakes precursor, the current situations and the problems to be solved, are discussed. Also we offer the proposals to develop new roboticized astrometric instruments with high-precision and set up test observation networks in earthquake-prone areas in order to do research in-depth, optimize methods of observing and extracting anomalous information for short-term earthquake prediction, and so on.

earthquake, residuals of astronomical time and latitude, the vertical variation, astronomical observation, DZT

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Earthquake is one of the most serious natural disasters. A strong earthquake may create a large number of casualties and huge property losses. The earthquakes, which occurred in Tangshan of China in 1976, in Indonesia in 2004, in Wenchuan of China in 2008, in Haiti in 2010 and in Fukushima of Japan in 2011 all brought about huge disasters. Accurate and timely earthquake prediction is the effective means to mitigate earthquake disaster, especially to reduce casualties. The crustal structure and geotectonic movement are very complex. There is an extremely complex geophysical process during the gestation and occurrence of earthquake. So it is still very difficult to detect the movement and variation of ground mass. Although institutes and researchers in many countries are committed to earthquake observations and researches for many years, modern science's level of comprehending the process of earthquake gestation as well as occurrence and the law of earthquake occurrence is still very shallow. So earthquake research, especially earthquake prediction, is accepted as a worldwide difficult scientific problem, even some researchers hold that earthquake could not be predicted [1]. However, more researchers believe that, by continuous studies, the law of the occurrence of earthquake can be recognized gradually and earthquake can be predicted. Many scholars continuously carry out the researches and attempt to find valuable precursory phenomena and earthquake prediction methods, although there will be a long and tough way to go [2–5].

Not long after the strong earthquake of M=7.8 in Tangshan in 1976, Zhang and Li et al. astronomers of Beijing Astronomical Observatory (the predecessor of the National Astronomical Observatories) analyzed the astronomical time and latitude observations obtained by visual astrolabe a classical astrometric instrument (relative to the later new technique such as VLBI, SLR, the former ground astromet-

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ric instruments, such as astrolabe, zenith telescope, zenith tube, are called classical instruments) of the observatory and found anomalous fluctuations appeared in astronomical time and latitude residuals (ATLR) before the major earthquake. They analyzed the data of classical astrometric instruments and vicinal earthquakes in other countries, and found similar phenomena appeared on the eve of many earthquakes [6]. The classical instruments take the local plumb line (direction of gravity field) as observation reference. They thought the anomalous variation of the local plumb line due to the motion of the ground mass before earthquake might be the main reason of the anomalies in ATLR [7]. The result has been submitted to the 19th Generally Assembly of the International Astronomical Union (IAU) in 1985. The 19th Committee (Earth Rotation Committee) pointed out that classical astrometric observations of latitude and universal time might be valuable for studying geophysical phenomena [8]. The significance of optical astrometric observations in research of variation of the plumb line was emphasized by the 19th commission of IAU again in 1991 [9]. During these years, Chinese researchers continued to carry out a series of studies, and proposed to set up observation networks to do further systemic researches to form a new method for providing earthquake prediction information [10–30]. However, because of the lack of funding and instruments, observation networks could not be set up.

It is a progressive process for people to understand the characteristics of any natural phenomena even the process will be very long due to the complexity of the phenomena and the restrictions of the science and technology development level in corresponding period. However, only by continuous research, will the characteristics of these natural phenomena gradually be understood. Therefore, research on the characteristics of earthquake and earthquake forecasting methods should be carried out continuously, which is extremely important for the development and progress of human society. It is always a question considered by some astronomers and seismologists continuously how to develop the short-term anomaly of ATLR before earthquake to become an effective earthquake precursor. This paper will briefly introduce the discovery and the progress of related researches about this phenomenon as well as the problems should be solved to develop the phenomenon to become an effective earthquake precursor, and offer our proposals for how to develop the research deeply and to do earthquake prediction test.

1 Significance and research progress of ATLR anomaly before earthquake

1.1 Discovery of the anomalous ATLR phenomenon before earthquake

Classical astronomical time and latitude observations are the process of observing the apparent motions of stars on celestial sphere due to the rotation of the earth with dedicated classical astrometric telescopes, calculating the variation of the earth's rotation rate, that is the variation of the universal time UT (denoted by UT1−UTc) and variation of observation station's latitude, and getting the information of the earth's polar motion (expressed by polar coordinates X, Y). These data are called Earth rotation parameters (ERP). The dedicated international organization (in early stage it was International Latitude Serves—ILS, later were Bureau International de I'Heure—BIH and International Polar Motion Serves—IPMS. Now the International Earth Orientation and Reference Systems Service—IERS is in charge of these works) to calculate ERP by integrating the observations obtained by the instruments in every country [6,31].

After the occurrence of a great earthquake of M=7.8 in Tangshan in 1976, in Shahe observation station of Beijing Astronomical Observatory which is about 160 km apart from the epicenter, the astronomers found that during nearly a month before the earthquake deviations appeared in the observations obtained by an astrolabe which worked steadily in the station for many years. So some data could not be used to calculate ERP. Zhang and Li et al. considered whether this was related to Tangshan Earthquake. After examining the observations of the astrolabe before the earthquake (M=7.2) in Xingtai of Hebei Province ($\Delta\approx 300$ km) in 1966, they found the similar phenomenon appeared in time observation. In order to show these anomalous deviations clearly, they analyzed the ATLR of observations of the instrument [6]. Simply speaking, due to the effect of local factors and errors in the observation process, the result obtained by every instrument is different with the global integrated result. These kinds of differences are called residuals of astronomical time and latitude observations (ATLR). Time residual RT_i and latitude residual RF_i of instrument i are expressed separately as

$$\begin{aligned} RT_i &= (UT0-UTc)_i + \Delta\lambda_i - (UT1-UTc)_s, \\ RF_i &= d\Phi_i - d\Phi_{ci}. \end{aligned} \tag{1}$$

Here $(UT0–UTc)_i$ is the observed value of universal time obtained by the instrument. $\Delta\lambda_i$ is the longitude correction for the transformation from initial observed value $(UT0–UTc)_i$ to $(UT1–UTc)_i$. $(UT1–UTc)_s$ is the integrated value of universal time of this day obtained by global observations. $d\Phi_j$, $d\Phi_{ci}$ are separately the influences of the polar motion in latitude and longitude variations of the day obtained by the instrument. $\Delta\lambda$, $d\Phi_c$ are expressed as

$$\begin{aligned} \Delta\lambda_i &= \frac{1}{15}(X\sin\lambda_i - Y\cos\lambda_i)\tan\Phi_i, \\ d\Phi_{ci} &= X\cos\lambda_i + Y\sin\lambda_i, \end{aligned} \tag{2}$$

where X and Y are integrated values of the polar coordinates. λ_i, Φ_i are the longitude and latitude adopted for the instrument. The ERP, that are *X*, *Y* and (UT1−UTc), used in formula can be obtained from BIH or IERS.

After analyzing, Zhang and Li et al. found large anomalous fluctuation appeared in RT and RF of the instrument in advance by over a month before Tangshan Earthquake. Similar large anomalous fluctuation appeared in RT too before Xingtai Earthquake. After then, analysis of the relationships between the classical astrometric instruments observations from Tianjin of China, Tokyo and Mizusawa of Japan and the earthquakes of $M\geqslant6$ in the area of about 100 km radius around and $M\geqslant7$ in the area of about 300 km radius around showed that short-term anomalous fluctuations in ATLR appeared before some shallow major earthquakes [6].

They gave a summary of the relations between ATLR and major earthquakes as the following: (1) there was an obvious relationship between anomalies of RT and major earthquakes. Earthquakes all occurred in years which had high σ of annual sequence of residuals. In 8 of the 10 earthquakes that occurred around Beijing, Tokyo and Mizusawa, a pair of opposite sign anomalies (double-peak anomalies) appeared during about half of a year before earthquakes, only two exceptions. Every instrument had its own characteristic of anomaly mode before earthquake. In Beijing and Tokyo, negative anomaly appeared firstly, and then positive anomaly appeared, whereas it was the opposite mode in Mizusawa. There was no earthquake after the anomaly with single peak. In the 96 years of time observations collected by instruments counted, there was only one pair of double-peak anomalies which did not have any corresponding earthquake. (2) The relevance between anomalies of RF and earthquakes was less obvious than RT. In all the 21 anomalies of RF, 10 had corresponding major earthquakes. And 2 earthquakes did not have corresponding anomaly in advance.

1.2 Significance and research progress of ATLR anomalies before earthquakes

Just as the 19th Committee of the 19th Generally Assembly of the International Astronomical Union (IAU) in 1985 pointed out, classical astrometric observations of latitude and universal time might be valuable for studying geophysical phenomena [8]. Classical astrometric observations take local plumb line as reference. The variations of local plumb line can affect classical astrometric observations directly.

After analyzing, Zhang [7] thought the anomalous variations of the local plumb line due to the motion of the ground mass (such as ground water) in earthquake area before earthquakes might be the main reason of the phenomenon, because these instruments take the plumb line as observation reference. Before the earthquake of M=7.8 in Tangshan, obvious anomalous variations in ground water level appeared in large area among Tangshan, Tianjin and Beijing [32]. Chen et al. [33] studied the gravity variations before and after Haicheng Earthquake in 1975 and Tangshan Earthquake in 1976, and put forward the possibility of deep material migration to explain the great gravity variations observed.

Therefore, the data obtained by observing stars apparent motion on celestial sphere with classical astrometric instruments contain the absolute variation information of local plumb line, which is valuable for some earth scientific researches, such as the research of earth gravity field variations, and can make up the shortage of gravimeter which can only measure the vertical component of gravity field. At the same time, because there are physical relations between ATLR short-term anomalies and the severe changes of earthquake foci before earthquakes, this phenomenon may be developed to be an earthquake precursor by carrying out further research continuously. If we can understand the characteristics and the law of the phenomenon more deeply, and obtain the method to provide valuable information for earthquake short-term prediction by astronomical time and latitude observations, it will be very significant.

With this in mind, Li and Zhang [11] analyzed the observations during 1977 to 1984 in Tokyo and from 1977 to 1981 in Mizusawa, and found in the 5 earthquakes of $M\geqslant6$ occurred in Tokyo, double-peak anomalies appeared before 3 earthquakes that occurred in the south of the instrument. No anomaly appeared before the 2 earthquakes that occurred in the north of the instrument. Two earthquakes occurred after the 2 obvious RF anomalies in Mizusawa, but the double-peak characteristic of RT was not obvious [11]. Han et al. and Hu et al. analyzed observations of a photoelectric astrolabe (PA) in Yunnan Observatory [10,13], and Liao et al. analyzed observations of a PA in Shanghai Astronomical Observatory. They also found anomalous fluctuations appeared in ATLR separately before some earthquakes that occurred around the instruments [16]. Han analyzed PA observations during 1980 to 1991 in Beijing Astronomical Observatory. Because there are many sunny days in Beijing region, the observations of the instrument had good continuity. The results showed obvious anomalies appeared in RF before Datong Earthquake of M_L=6.1 ($\Delta\approx210$ km) that occurred in 1989, and Xiaotangshan Earthquake (M_L=4.2, $\Delta\approx17$ km) that occurred in 1990. The amplitude of the anomaly in RT was relatively small without obvious double peak. At the same time, during the 9 years before Datong Earthquake, there was no strong earthquake around the instrument. And there was no obvious anomaly appeared in RT and RF of the instrument observations [17] (see Figure 1). Liao et al. analyzed the relations between the ATLR observations of 6 instruments in China and the earthquakes of $M\geqslant5$ around these instruments. They gave some examples that short-term anomalies appeared in ATLR before earthquake [21]. Yunnan is a region where earthquake prevails. The work of carrying out time and latitude observations and studies of the relation between residuals and earthquakes was taken seriously. The PA of

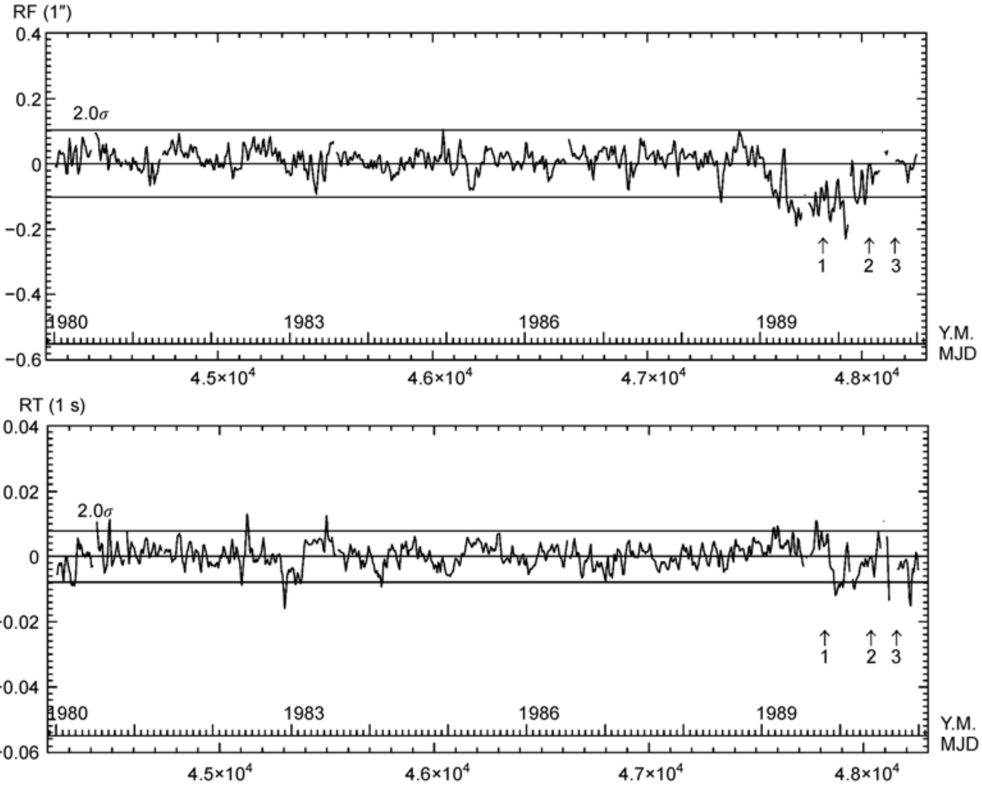

Figure 1 Variations of RF and RT of the PA in Beijing Observatory during 1980–1991. 1 is the Datong Earthquake of M_L=6.1, $\Delta \approx 210$ km, on October 19, 1989; 2 is the Xiaotangshan Earthquake of M_L=4.2, $\Delta \approx 17$ km, on May 23, 1990; 3 is the Xiaotangshan Earthquake of M_L=4.5, $\Delta \approx 20$ km, on September 22, 1990, and there was no observations before this earthquake because the instrument was being repaired.

Yunnan Observatory never stopped to observe. Yunnan Observatory also ever attempted to report ATLR anomalies to the Earthquake Prediction Research Center of Yunnan Province in time. Within several weeks or several months after some reports submitted, earthquakes occurred around the instrument [22,23]. Although these reports could not provide exact information about the three key factors of earthquake, they gave strong support to the relations between earthquake and anomalies of ATLR.

In the middle and the late of 1990s, available observations for the study were reducing due to the reduction of instruments. We ever proposed to set up test observation networks to carry out further systemic observations and researches, but it was not realized because of the difficulty of funding [18]. However, the research did not stop. Several years ago, Zhang et al. did further discussion on the relevance between ATLR and earthquake and how to study the relations between residual anomaly and three key factors of earthquake. They also thought setting up observation networks to obtain many instruments' observations can provide significant information for three key factors of earthquake especially the estimating the position of epicenter [24,28]. In 2011, Hu et al. analyzed residuals variations of time and latitude observations during 2008 to 2009 obtained by PA in Yunnan Observatory, and found obvious synchronous anomalies appeared in March, April and early September of 2008. They thought these anomalies might be separately corresponding to Wenchuan Earthquake on May 12, 2008, Panzhihua Earthquake on August 30, and Kunming Earthquake on December 26 [34]. These researches further show the significance of the phenomenon that anomaly appeared in ATLR before earthquake and the possibility that the phenomenon may become an effective short-term precursor for earthquake.

By integrating the research results of several scholars, the major characteristics of the phenomenon are generalized as follows: (1) before earthquakes that occurred in the area of several hundred kilometers radius around the instruments, short-term anomalies appeared in the three point smoothing sequence of five days average values of astronomical RT and RF or one of them; (2) anomalies appeared in advance by about several weeks to several months before earthquakes; (3) short-term anomalies often appeared before the earthquakes as follows: earthquakes of $M\geqslant 7$ within 3 or 4 hundred kilometers around instruments or $M\geqslant 6$ within 1 or 2 hundred kilometers around instruments as well as the moderate earthquakes that occurred at close range; (4) situations of residuals anomalies without earthquake and earthquakes without residuals anomaly existed.

Analysis showed that ATLR variations contain the following information: (1) effect of abnormal atmospheric refraction on stellar position. It behaves as random error and the fluctuation value is less than ±0.1″ after being processed; (2) horizontal displacement of observation site. The displacement before earthquake is tiny and can be neglected because instruments are usually set on steady areas; (3) effect of variations of the local plumb line. Based on analysis, the effect of variations of the plumb line is considered as the main factor of the anomalous fluctuations of ATLR before earthquake [11,20].

Over twenty years ago, Barlik and Rogowski used repeated gravitation data to study variations of the plumb line at Jozefolaw astro-geodetic station of Warsaw University, Poland, and compared the results with the ATLR obtained by observations [35]. They were the first to do the scientific experiment to study variations of the vertical by combining astronomical and gravimetric techniques together. On the 1991 IAU, the 19th commission pointed out "modern astrometric observations provide a unique set of data sensitive to variations in the deflection of the vertical" [9]. Li et al. noticed their results, and did improvement to the algorithm. They studied the annual variations instead of the high frequency part of the vertical variations. Their results preliminarily showed that the variations of plumb line and ATLR had remarkable consistency in low frequency part. Also, it confirmed that it was possible to study variations of the vertical by combining astronomical and gravimetric techniques [23]. Later, they analyzed the time-variation of plumb line deflection at Shahe station of Beijing Observatory with astronomical and gravimetric techniques. They found the amplitude reached 0.05″, the annual amplitude reached 0.02″ [26], and the variations of the plumb line of Tangshan was related to the earthquakes near or around Tangshan [29]. Their results further showed the variations of the horizontal component (plumb line) of gravity field existed before earthquake, and the variations of horizontal component are the variations of plumb line. The anomalous variation of the plumb line may be a valuable premonitory phenomenon before earthquake [30]. In 1991, commission 19th (Rotation of the Earth) of IAU hoped Shanghai Astronomical Observatory can continue to collect these data in order to investigate the possibility of getting the long period variations of the plumb line.

Before great earthquakes, gravity anomalies might appear in large area because of the activity of ground water. When studying the relations among activity of ground water, gravity anomaly and earthquake, Gu et al. [36] found before Datong Earthquake of M_L=6.1 in October 1989, during June to July anomaly appeared in the water level of Gaocun logging which was located on southeastern of Beijing and was about 270 km apart from Datong. The characteristic of the anomaly was very similar to the response of the residual gravity variations obtained by Baijiatuan Station in which the effect of surface water was deducted. The depth of the logging is 3200 m deep, and its water level variations were nearly not affected by precipitation, revolution of the seasons and other ground factors. They thought the gravity variations and the water level variations of Gaocun logging reflected the same morphology of dynamical earthquake formation process [36]. The time when the anomaly appeared was almost the same with the time of the appearance of ATLR anomaly in Beijing Observatory's PA which was located about 16 km east of Baijiatuan Station [17].

Through the above analyses, we have reason to believe that it is hopeful to develop ATLR anomaly before earthquake to become an effective short-term earthquake precursor. If we carry out systematic network observations in certain areas with high-precision astronomical time and latitude instruments, and do further researches to understand the characteristics of ATLR anomalies before earthquake and the laws related to earthquake more clearly especially the relations with three key factors of earthquake, it is hopeful to develop the phenomenon of short-term ATLR anomalies before earthquake to become an effective earthquake precursor. After getting experience, we can establish observation networks in earthquake-prone areas to do systematic observations of local plumb line variations. Then the short-term anomalies related to earthquake will be found possibly in advance by systemic observations of the local plumb line with high-precision instruments which can provide valuable reference information for predicting earthquake that will occur around instruments.

2 Problems that need to be studied in-depth

To find effective earthquake precursors is the key to improve the level of earthquake forecast. The so called effective earthquake precursors should at least have these characteristics: they should directly or indirectly be related to the process of earthquake formation. And, these phenomena can be detected definitely in advance with certain methods and instruments. The characteristic of earthquake precursors is related to geological structure. Some precursors present obvious anomalies before some kinds of earthquakes that occurred on certain geological structure belts, but there may be no obvious anomaly before other kinds of earthquakes. Therefore, some anomalous phenomena that appeared before earthquakes should be studied sufficiently in order to understand their characteristics and correlative law with earthquake in-depth. This is significant to find effective earthquake precursors and apply these precursors in earthquake prediction aright. Some valuable preliminary results about the research of relations between ATLR and earthquakes have been got. There are physical relations between ATLR anomaly and the process of earthquake formation. The anomaly can be observed by astronomical time and latitude instruments. Perhaps ATLR anomaly can be developed to be a valuable short-term earthquake precursor. However, the effect that the process of earthquake formation brings about on time and latitude observations is extremely complicated, so ATLR anomalies before earthquakes are also very complicated. If we want to develop ATLR anomaly to become an effective earthquake precursor, we should carry out further researches for the following situations by earthquake prediction test.

(i) The variation pattern of ATLR anomalies before earthquakes. Just as Li et al. pointed out that every instrument has its own ATLR anomalous mode before earthquakes [6]. The current results show that different kinds of instruments even the same kind of instruments present different residual anomaly mode before different kinds of earthquakes. For example, the RT anomalies before earthquakes are positive-negative double peaks in the astrlobe and PZT observations analyzed by Li et al. In Beijing and Tokyo, negative anomaly appeared first, and then positive anomaly appeared, whereas it is the opposite mode in Mizusawa [6]. When analyzing observations during 1977 to 1984 in Tokyo and from 1977 to 1981 in Mizusawa, Li et al. found in the 5 earthquakes of $M \geqslant 6$ that occurred in Tokyo, the double-peak anomalies appeared before 3 earthquakes that occurred in the south of the instrument. No anomaly appeared before the 2 earthquakes that occurred in the north of the instrument. Followed by the 2 obvious RF anomalies in Mizusawa earthquakes occurred, but the double-peak anomaly of RT was not obvious [11]. After analyzing the rise and fall of ground water before the Tangshan Earthquake and the variations of gravity field possibly caused by the east-west direction transfer of ground water's variations, Zhang [7] pointed out RT should present positive-negative double-peak anomaly, and RF should present single-peak anomaly. He also indicated the RT anomalies from negative peak to positive peak of Beijing might be explained by the variations of ground water level. At the same time, he assumed the sequence and the transferring direction of ground water's rise and fall might cause the different sequence of positive and negative peak in RT anomalies. That preliminary interpreted the difference of the RT anomalies of Mizusawa with Beijing and Tokyo [7].

Whether positive-negative double-peak anomaly appears before earthquake should also be studied. Han [17] analyzed the PA observations after 1980 of Beijing Observatory. The result showed that single-peak anomalies before the Datong Earthquake and the Xiaotangshan Earthquake were obvious. RT anomalies were relatively small, and did not show positive-negative double peak. Liao et al. [21] analyzed the relations between time-latitude observations during 1986 to 1991 obtained by 6 instruments in China and surrounding earthquakes of $M \geqslant 5$. They also did not find obvious positive-negative double-peak anomaly in RT residual. Kan et al. analyzed the relations between the PA observations of Yunnan Observatory and earthquakes that occurred around the instrument. They did not detect the positive-negative double-peak anomalies must appear in RT [22,34]. For the RF anomalies before earthquakes, in all the authors' results RF showed single-peak anomalies. Some were positive, and others negative, which might be related to the relative location of the epicenter and instruments [6]. Kan et al. found before many earthquakes in Yunnan, short-term anomalies appeared almost synchronously in RT and RF. And usually there was no earthquake when there were no synchronous anomalies. They particularly emphasized the synchronous feature of residual anomaly before the earthquake [22,23].

(ii) On the relations between earthquake magnitude and epicenter distance reflected by time and latitude residuals anomaly. Li et al. thought ATLR anomaly can be brought about by earthquakes of $M \geqslant 6$ within 100 km around instrument or earthquakes of $M \geqslant 7$ within 300 km around instrument. The correspondence of these earthquakes and the residual anomalies was very high [6,14]. In subsequent researches of some scholars, earthquakes of $M \approx 6$ in the area of 200 km radius around and middling earthquakes in closer areas were included. In the instances analyzed by Hu et al. [37] and Kan et al. [22] for studying the relations between ATLR of Yunnan Observatory's PA and earthquakes, some earthquakes were far away from the instrument. For example, before earthquakes of M=7.2 ($\Delta \approx 670$ km) in Burma in 1991, M=6.3 ($\Delta \approx 290$ km) in Puer in 1993, M=6.7 ($\Delta \approx 550$ km) in Burma in 1994, and M=7.3 ($\Delta \approx 500$ km) in Menglian in 1995, anomalies all appeared in ATLR. Han [17] analyzed the relations between PA observations of Beijing Observatory and Datong Earthquake that occurred in 1989, and found significant anomaly appeared in RF before this earthquake with M_L=6.1 and relatively larger epicenter distance ($\Delta \approx 210$ km). Liao et al. [21] adopted the data of earthquakes with $M \geqslant 5$ to study the relations between time and latitude observations during 1986 to 1991 obtained by 6 instruments in China and surrounding earthquakes. The location of the earthquake of M=5.1 that occurred on May, 23rd, 1986 was 150 km away from Shanghai Observatory. However, anomaly appeared in RF of this Observatory. Two to three decades ago, it was difficult to completely collect foreign data about earthquakes of M<6. Recently we collected earthquakes of $M \geqslant 5$ occurred in the area within 100 km around Tokyo and Mizusawa. During the period mentioned in [6] and [11], no residuals anomaly appeared before some earthquakes with middling or small magnitude and short epicenter distance.

It is easy to understand that the variations (rise and fall or flow) of ground water level are influenced by the geological structure. When studying earthquakes of northern China from 1981 to 1991, Gu et al. [36] found the water level variations just responded to part of the earthquakes that occurred during this period. The explanation they provided was that the earthquakes which brought about responses might locate in the same hydrogeological system of Jiluyu fault-block. The other earthquakes might locate in another fault-block tectonics of Yanshan fault-block. And between the two fault-block tectonics, there was a non-osmosis belt. As the water level of Gaocun logging could respond to Datong Earthquake 270 km away, there must be an extremely superior hydrogeological system which is helpful for underground fluid's circulation. And every tectonic block has its own earthquake formation process. This is beneficial for us to understand why within certain area around instrument before some earthquakes ATLR anomaly appeared, and the other not.

(iii) The advanced-time of ATLR anomalies before earthquakes. Similar to other earthquake precursors, sometimes the advanced-time of ATLR anomalies before earthquakes is relatively long. Most of the earthquakes appeared before the residuals anomalies disappeared or soon after the residuals anomalies. But some earthquakes appeared several weeks or 2 to 4 months after the residuals anomalies [5,14,17,21,22,37]. The situations that we think should to be studied seriously are: after ATLR anomalies, ATLR fluctuation became normal in a longer period, and then earthquakes occurred. When studied the relations between subsurface fluid and earthquakes, Gao et al. [38] pointed out that although stress-strain could explain some precursory phenomena, there were some other earthquake precursors could not be explained. For instance, "precursor quiet period" appeared before some earthquakes, and some earthquakes occurred after the peak value of precursor even after the precursor (time delay even reached more than half of a year). After analyzing the relation between time and latitude observations during 1986 to 1991 obtained by 6 instruments in China and surrounding earthquakes of $M\geqslant5$, Liao et al. [21] pointed out: anomalies which appeared in time and latitude residuals in advance by about 3–4 months (half of a year for some earthquakes) before earthquakes occupied 55% in all the anomalies, and anomalies without sequent earthquakes occupied 45%.

The problems mentioned above are not unique in ATLR. The complexity of geological structure and the formation process of earthquake may be the main reason for the extremely complicated feature of all kinds of earthquake precursors. There is an obvious example to illustrate that ATLR is related to geological structure. In 1992, the PA of Beijing Astronomical Observatory in which significant anomalies appeared in RF before Datong earthquake, was set up on San Juan Observatory of Argentina where weather is fine, to carry out cooperation of astronomical observations and researches. Abundant high-precision observations were obtained during nearly 10 years. But the relations between ATLR and surrounding earthquakes are not similar to that in Beijing. Different with the observatories mentioned above, San Juan Observatory is set on alluvial layer with great thickness and extent. That may explain why the relations between ATLR and earthquakes were not obvious. The current objective difficulties to understand the problems are time and latitude observation instruments were just set up on observatories formerly, types and accuracies of these instruments and affects caused by atmospheric refraction are different, and they were set on different tectonic zones. The types of earthquakes that occurred around these instruments and geological structures of areas around hypocenters are also different, which make the characteristics of fluctuations and anomalies of ATLR before earthquakes are very complex. In addition, the total amount of astronomical time-latitude observation instruments is small. Because residuals anomalies are just related to earthquakes in local areas, the total amount of earthquakes related to every instrument is also very small, which makes the total amounts of earthquakes analyzed in former researches are just several tens. All the situations mentioned above increase the difficulty of finding the regularity and similarity of residuals anomalies before earthquakes, as well as analyzing the relations between anomalies and three key factors of earthquake. Currently, by further research we urgently need to know which kinds of earthquakes on which kinds of tectonic zones are easier to cause short-term residuals anomalies in instruments that located in which kinds of tectonic zones; what is the main reason for the differences in characteristics of anomalies and interval length between anomalies and earthquakes; where is the anomalous ground mass reflected by residuals anomalies; and how can we detect the possible motions of underground anomalous mass. At the same time, the methods for observing, analyzing data and extracting effective anomalous information also need to be improved. So we should set up observation networks with high-precision instruments to carry out systemic observations, and obtain abundant data of instruments on different geological structures to do further research with more earthquakes.

3 Conclusions and suggestions

As mentioned above, the researches of the relationships between ATLR and earthquake have got lots of valuable results. ATLR anomalies may be developed into a kind of valuable short-term precursor phenomenon for some kinds of earthquakes, but there are still some problems need to be studied deeply. To solve these problems need to carry out astronomical time and latitude observation to get abundant accurate data by setting up instrument networks, to study the characteristics of ATLR anomalies before earthquakes in-depth and to carry out theoretical study on the physical mechanism of the phenomenon and applied research for optimizing the methods of exacting earthquake precursor information. Now, an important problem is observation instrument is rare because the classical astrometric instruments gradually retired in many observatories since their tasks, ERP determination, were occupied by new technologies and instruments with higher accuracy, such as VLBI, SLR, GPS, since the late 1980s. In China, only one classical astrometric instrument, a PA in Yunnan Observatory, works continuously. However, the observations of new technological are not related to local plumb line, and their observation data cannot reflect the variations of the local plumb line. This situation makes no more available real-time observation data can be used to study the relationships between plumb line variations and earthquakes.

Therefore, we offer some suggestions, and hope to resolve this conflict to promote the further development of the study.

(1) To establish test observation networks. Formerly, observation stations and instruments of astronomical time and latitude are rare, and observations from one instrument or one station can only reflect the plumb line variations within a certain range around the instrument, so ATLR of one station can not afford the position information of underground anomalous mass which could cause the plumb line variation. And many classical astrometric instruments have retired. Therefore, we should make new type instruments with high precision and establish trial observation network, which are the base for further research. Observation networks should be built in the region with good weather and strong seismic activity; each network consists of several instruments separated by the interval of about 80–150 km. The networks could be considered to be built in seismic activity regions in northern, southwestern, and northwestern of China. If there is adequate fund, the seismic activity regions in western of China should also be considered to build a network. The instrument sites in the network should carefully be investigated and it may be better if a similar geological structure has at least two instruments in order to do comparative analysis. Abundant high-precision data of multiple observing sites are helpful for studying relations between the plumb line variations and three key factors of earthquake. Although the proposals of this kind of observation network were submitted some years ago, it unfortunately could not be materialize due to financial difficulties [18,20]. With the improvement of our country's economy, the appearance of new devices and the development of automation technology of instruments, the difficulties of the cost for developing new instruments, establishing observation networks and maintaining instruments' working are reducing. The condition for formatting observation networks is already possessed. The ATLR data include multiple errors caused by many local factors, which need to be solved and eliminated by analyzing a long time observations. So observing networks should be built to carry out experimental observation as soon as possible in order to accumulate accurate data and promote the further development of the study.

(2) To develop new type instruments. This is the basis for establishing observation network. Utilizing the same type instruments with high precision which can simultaneously observe astronomical time and latitude can increase the comparability and reliability of observations, such as photographic zenith tube (PZT) and PA. Especially, the observed objects of PZT are stars near the zenith, which will be advantageous for reducing errors from abnormal atmospheric refraction. New type equipment should be smaller, highly automated and low cost in order to reduce the required manpower, material and errors of ATLR from observers and instruments.

The application of CCD technology in astronomical telescope promotes the progress of astronomical observations. Several years ago, University of Hannover in Germany and the Geodesy and Geodynamics Laboratory (GGL), ETH Zurich of Switzerland upgraded the simulated zenith photographic instrument TZK2 and TZK3 with CCD sensor instead of quondam photographic film, and respectively, developed digital zenith camera systems TZK2-D and DIADEM [39,40]. Vienna University of Technology in Austria also developed a small CCD Zenith camera system ZC-G1 [41]. These instruments observe the apparent motion of stars for the rapid determination of the vertical deflection. This kind of instrument can also be used for astronomical time and latitude observations. The National Astronomical Observatories is currently developing a similar instrument called Digital Zenith Telescope (DZT), through the cooperation with Geomatics College of Shandong University of Science and Technology. DZT has the characteristics of high accuracy, high automation and miniaturization, and it is being debugged. And a plan to develop a DPA (Digital Photoelectric Astrolabe) with high accuracy, high automation and miniaturization is being considered. The observations of the instruments can be used to obtain the plumb line variations and the vertical deflections, which will be used to carry out earthquake and other related researches and finally to be used to extract short-term earthquake prediction information.

(3) To re-study the previous ATLR observations. Although the accuracies of former classical astrometric instruments are different and the accuracy of some old data is not very ideal, years of observation data is valuable. To re-analyze some data with relatively high precision and continuity will redound to understand the phenomenon and disciplinarian of ATLR anomalies before earthquakes.

(4) Strengthening the cooperation between astronomy and geoscience. Considering the limitations of all earthquake precursors and the lack of efficient earthquake precursor now, the cooperation between astronomy and geoscience is very important for recognizing the characteristics and physical mechanism of anomalous phenomena before earthquake and for making time and latitude residuals become an efficient earthquake precursor. If instruments of astronomical time and latitude observation can be collocated to observe with gravimeter, inclinometer, GPS, and to carry out comprehensive analysis of the multiple observations, it will be useful to detect all kinds of information and phenomena related to earthquake. Especially the collocated observations between astrometric instruments and gravimeters as well as the conjoint analysis of the observation data will be helpful to recognize the position of underground anomalous mass and the possible variations of the position over time, and maybe provide significant information for estimating the scale of underground anomalous mass. The information is valuable for determining the three key factors of earthquake. Carrying out cooperative researches with related scholars in geoscience field, will play a very important role to deal with the issues above and promote further development of the study.

(5) Meanwhile, the authors want to emphasize research

of earthquake activity regularity and earthquake prediction is a very difficult task; more often than not, desired results will not be got in a short time, so the development of the research needs steady and persistent supports from related departments.

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