Chapter 8
Experiments and Analysis of Soil Moisture Monitoring Based on GPS Signal-to-Noise Ratio Observables

Minsi Ao, Jianjun Zhu, Youjian Hu and Yun Zeng

Abstract Effective monitoring of soil moisture is the basis of meteorological, agricultural and environmental scientific researches. Using the SNR observables to monitor the fluctuation of soil moisture is a new approach which does not suffer from destruction of environments, difficult data assimilation, limits of temporal-spatial resolutions and so on. However, it also has many issues need to be discussed deeper such as too less examples, the effective areas, the parameter setting and even how to describe and model the relationship between the SNR results and soil moisture from other measurement ways. In this paper, with measured GPS SNR observables and simulated soil water content data, the comparative experiment is carried out to discuss them. As is shown from the experiment process and results, this approach can effectively retrieve the soil water content. The effective area is within about 45 m around the antenna phase center. The exponential function can be used to described the correlation between the relative delay phase of SNR reflected signal and soil water content well. Meanwhile, selection of the advanced satellites and recording of the L2C observables would be prone to obtain the high quality SNR observables that lead to the more robust and accurate monitoring results.

Keywords Global positioning system · Signal-to-noise ratio · Soil moisture · Multipath reflection

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J. Sun et al. (eds.), *China Satellite Navigation Conference (CSNC) 2013 Proceedings*, Lecture Notes in Electrical Engineering 243,
DOI: 10.1007/978-3-642-37398-5_8,

8.1 Introduction

The accurate measurements and long-term monitoring of soil moisture are the basis of meteorological, agricultural and environmental quantitative scientific researches [1]. The traditional approach to monitoring the fluctuation of soil moisture can be divided into two types: active and passive monitoring. The typical active approaches include baking, probes measurement and so on. The later are usually based on remote sensing technologies. The active approaches are intuitive and precise, but also unavoidable to destroy the observed object and environments. At the same time, the results from different networks and types of equipments are difficult to be assimilated, which limits their large-area applications. Due to the limits of temporal and spatial resolution, the passive monitoring of soil moisture is often used in large-area and long-term cases. In fact, using the GPS reflected signals for soil moisture monitoring have been studied for several years. The basic thought of these approaches is to organize a pair of GPS antennas respectively upward and downward, which are used to receive the direct and reflected signal from GPS satellites. With the power differences between the two types of signals, the inversion model is constructed and the soil moisture can be retrieved. Many experiments [2] have been conducted by National Aeronautics and Space Administration (NASA) in test bases which locate in Iowa, Georgia, etc. From experiments conducted by Guan et al. [3] and Yan et al. [4], the correlation between the GPS results and measured soil moisture were also proved. This approach successfully introduced the power characteristics into retrieve the soil moisture, but the high costs limit its applications and popularization.

Larson et al. [5, 6] proposed an approach to retrieve the soil moisture based on the Signal-to-noise ratio observables from conventional geodetic GPS receivers. Bilich and Larson [7] discussed how to separate the direct and multipath reflected signal from SNR observables, and the relationship between the reflected components and environments earlier. Further, Larson demonstrated how to retrieve the soil moisture using the amplitude, frequency and relative delay phase characteristics from the SNR reflected component signals within certain elevation angle interval. In the references [5, 6] and [8], with observations of stations TASH and P484 from International GNSS Service (IGS) and Plate Boundary Observatory (PBO), the possibility that using the amplitudes characteristics to retrieve soil moisture fluctuation was discussed. The test results showed that the correlation does exit, but the accuracy and stability is vulnerable to fluctuation of temperature, pressure or other weather factors. From results from [9] and [10], the relative delay phase characteristics are more stable to retrieve soil water content compared to amplitudes. Because this approach is based on SNR observables which could be easily obtained from the Continuous Operating GPS Reference Station (CORS), it can effectively reduce the costs and extend the applications of CORS. At the same time, it does not suffer from issues as data assimilation between soil moisture networks. However, there are many problems about this approach still have to be considered deeper. More references and experiments are necessary to be proposed and conducted to demonstrate the validity. Some important features of this approach and parameters during the data process such as effective area, selection of satellites and wavelength, are still need to be investigated. And even how to describe and model the relationships between the relative delay phase and measured soil moisture are still have to be considered. In this paper, with combination of the measured GPS observables and simulated soil moisture data, the problems mentioned above are to be discussed and analyzed.

8.2 Methodology

The signal-to-noise ratio of GPS is one of the most important indicators to describe the quality of signal from satellites. It is mainly decided by the antenna gain pattern, multipath effect and random noises. In order to mitigate the multipath effect, the designs of GPS antenna are principally that the large the elevation angle of satellite is, the more the gain is, otherwise the opposite. Furthermore, because the power of random noises is so small, the multipath effect becomes the primary factor when the elevation angle of satellite is low. According to Larson et al. [9] and Zavorotny et al. [10], the SNR observables can be expressed as,

$$SNR^2 = {A_c}^2 = {A_d}^2 + {A_m}^2 + 2A_d A_m \cos\phi \tag{8.1}$$

In Eq. (8.1), $A_c$is the raw SNR observables, A_d and A_m are respectively the amplitude of direct and multipath reflected signals, ϕ is the relative delay phase between reflected and direct signals. If there is only once reflection case, the relationship between the relative delay phase and elevation angle of satellite can be presented as,

$$\frac{d\phi}{dt} = 4\pi\frac{h}{\lambda}\cos\frac{d\theta}{dt} \tag{8.2}$$

In Eq. (8.2), h is the vertical distance from the antenna phase center to the ground. θ is the elevation angle of satellite, λ is the wavelength of carrier phase. If $x = \sin\theta$, the (8.2) can be simplified as

$$\frac{d\phi}{dx} = 4\pi\frac{h}{\lambda} \tag{8.3}$$

As is shown in Eq. (8.3), the linear correlation does exist between the relative delay phase ϕ and $\sin\theta$. Taking into account the Eq. (8.1), if the elevation angle is low, the SNR reflected signal can be expressed by $\sin\theta$ as,

$$SNR = \dot{A}_m(\dot{f}\sin\theta + \dot{\phi}) \tag{8.4}$$

In Eq. (8.4), $\dot{A}_m$ and $\dot{\phi}$ are respectively the amplitude and delay phase of the multipath reflected signals. $\dot{f}$ is the frequency, which is ideally equal to Eq. (8.3).

Generally speaking, the water in the soil can be supposed to be an equivalent reflection surface because the reflection coefficient of water is much more than soil. When the soil moisture increases, can be deemed as the antenna height from equivalent reflection surface decreases. The decreased antenna height will make the propagation path be shorter which would represents as increasing of $\dot{A}_m$ and decreasing of $\dot{\phi}$. Contrarily, the decreased antenna height will make the propagation path be longer which would represents as decreasing of $\dot{A}_m$ and increasing of $\dot{\phi}$.

There are three steps during the process of SNR observables. The first step is to separate the reflected signals from raw SNR observable series. During the separation, the signal which is caused by the antenna gain pattern can be treated as direct components signal, its amplitude is much larger than the reflected one, namely, $A_d \gg A_m$. Due to the design of antenna mentioned above, the second-order polynomial is introduced for realize the separation. The second step is to resample the reflected signal. The reflected signal from separation represents the relationship between the SNR and time, the resampling step is to achieve the relationship between the reflected signal and sin of satellite elevation angle. The cubic spline interpolation algorithm is used to fitting and sampling in this step. The third step is to calculate the characteristic parameters (amplitude, frequency and relative delay phase) in Eq. (8.4) by fitting in sin style. With the characteristic parameters, the further comparative study according to soil moisture data can be carried out.

In order to discuss the effective area of this approach, the Higgins-Fresnel principle which is usually used in electromagnetic theory is introduced. The effective area is composed by a series of ellipse regions correlated with satellite elevation angle, azimuth and antenna height. Considering that most of the GPS receivers in CORS network do not record when satellite elevation angle is below five or ten degrees, we simulate the effective areas nearly five degrees. The simulated effective areas are shown in Fig. 8.1.

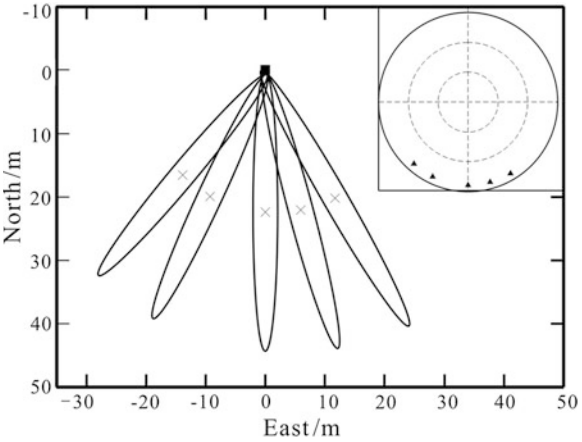

Fig. 8.1 The simulated Fresnel region of soil moisture monitoring using SNR observables. The sub-figure in *upper right corner* is the simulated trajectory of satellites which is nearly five degrees. The five elliptical regions are the reference area according to trajectory, the points centered in elliptical regions are the reflected points on ground. The original coordinate is the simulated GPS antenna phase center

As is shown in Fig. 8.1, the Fresnel region can reach as far as about 45 m. It indicates that the effective area is about 45 m around the antenna phase center on one hand. And on another hand, within this area we should avoid the reflection source and keep the homogenous soil type as much as possible to ensure the stable and precise monitoring.

8.3 Experiments and Analysis

In order to discuss the validity and core parameters selection during the process of SNR observables, comparative experiments based on the measured GPS observations and simulated soil moisture are conducted. The GPS observations are collected by station P041 from PBO, which locates in Boulder in United States. With supports of PBO, P041 started carrying out the research for GPS soil moisture study. It is continuously recording not only the conventional GPS observations but also the meteorological data such as humidity, temperature, precipitation, pressure, wind speed, etc. Meanwhile, it firstly started to record the L2C codes for high quality SNR observables. The simulated soil moisture data are calculated from the Noah_LSM model [11] which is often used to retrieve the earth surface parameters from the meteorological observations above the ground. During the simulation with Noah_LSM model, at least seven meteorological observations have to be collected to retrieve the soil water content. Due to the missing of precipitation records of station P041, the nearby data from NOAA/NWS was introduced for simulation. The short and long wave radiation data were collected from the Global Land Data Assimilation System (GLDAS) [12]. The other meteorological observations such as pressure, humidity, etc., were from the meteorology observation of GPS station P041. Excerpt the precipitation records were interpolated into 30 min interval by summation or average algorithm, the others were interpolated or resampled by cubic spline algorithm. For GPS SNR observations, the session from day of year (doy) 101–220 were selected. Furthermore, we used the SNR observables on L2 carrier phase of satellite PRN12. The elevation angle intervals were set to [7°–30°]. Two-order polynomial was adopted to separate the direct and reflected signals. The Non-linear Least Square Regression Algorithm was used to fit and get the relative delay phase of reflected signal. The relative delay phase, precipitation and simulated soil water content is shown as Fig. 8.2.

It is shown in Fig. 8.2, there are six significant precipitation events respectively on 9 doy 114, 131, 138–139, 171, 187–193, and nearly 208. According to each precipitation event, the soil water content (swc) significantly increases, which indicates that the reasons for fluctuation of swc are mainly the precipitations. Together with the relative delay phase of reflected signal, it is obvious that it changes corresponding to the swc. For example, for event on doy 114, the swc increases from 0.115 to 0.304 (by 0.189), the corresponding negative ϕ increases from -3.569 to -3.304 (by 0.265 rad). For event on doy 131, the swc increases

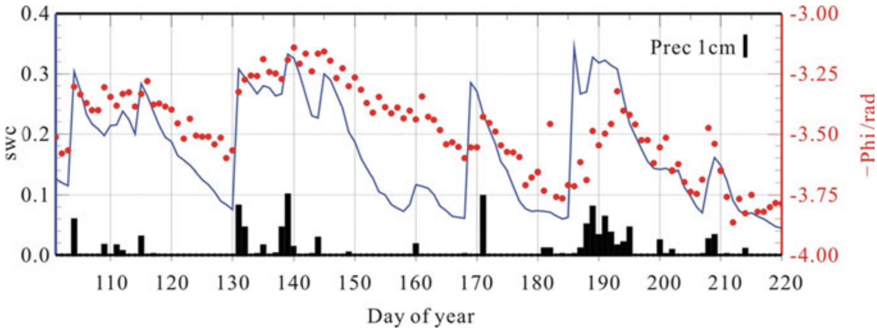

Fig. 8.2 Relationship among the soil water content, precipitation and relative delay phase at P041. The *solid line*, *point* and *bar* are respectively the swc, negative relative delay phase and precipitation. The unit of relative delay phase is rad

from 0.075 to 0.308 (by 0.233), the corresponding negative ϕ increases from −3.57 to −3.324 (by 0.244 rad). For event on doy 138–139, the swc increases from 0.263 to 0.333 (by 0.07), the corresponding negative ϕ increases from −3.249 to −3.191 (by 0.058 rad). Similarly, during the later three precipitation process, the significant correlations can be easily found between the relative delay phase and swc. It is worth noting that during the event on nearly doy 170 and 189 the delay phase does not correlated the swc well. With carefully analysis on the corresponding meteorological records such as temperature, wind states, etc., from GPS station, it may be caused by two reasons. The first reason could be the rapid weather changes which are clearly from the daily GPS meteorological records on these days. Another reason could be that the measurement time inconsistency between the GPS and simulated swc. Apparently, the effective time of GPS results are according to the satellite trajectory, but the simulated swc are according to the whole day. Both of the two reasons may lead to the differences between the relative delay phase and swc on these days. Overall, it is obvious that the relative delay phase of reflected signal changes oppositely with the swc. When the precipitation event comes, the swc arises and the relative delay phase decreases; when the precipitation finishes, the swc decreases and the delay phase arises oppositely. The scatters map of swc and relative delay phase is shown as Fig. 8.3.

The relative delay phase and swc scatters of station P041 are shown in Fig. 8.3. The correlation coefficient of the relative delay phase and swc is 0.6033, which is strongly correlated statistically. It is necessary to note that this correlation coefficient includes the error from measurement time inconsistency (e.g. doy 169–170, 186–192). The real correlation should be stronger. The exponential function used to fitting the scatters is shown in the low right corner of Fig. 8.3. During the fitting of scatters, some of the scatters which corrupted by measurement time inconsistency problem are eliminated. The R^2 index of fitting is 0.6848 which indicates that the correlation between the relative delay phase and swc can be well described with the exponential function.

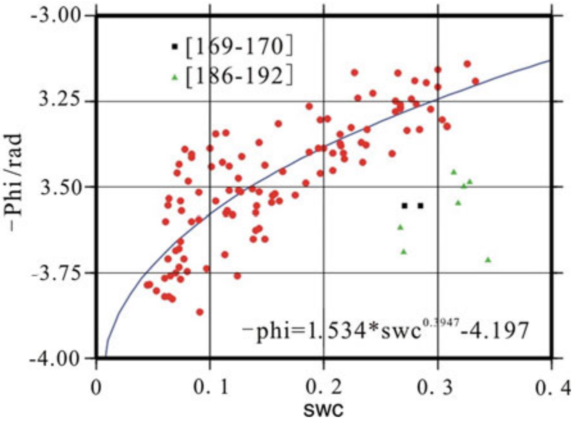

Fig. 8.3 Scatter and fitting relationship between the soil water content and relative delay phase. The *points* represent the normal scatters in session. The *square* and *triangle points* respectively represent the doy 169–170 and 186–192. The fitting result is shown in the low *right corner* in this figure

From the comparison and analysis, besides the measurement time inconsistencies there are still more factors to be noted further. The impact of the quality of SNR observables to monitoring results cannot be neglected. The high quality SNR observable is more likely to separate for reflected signal and fit it with function sin style successfully. From the aspect of GPS receivers, recording the L2C code can effectively improve the quality and amplitude of SNR observables. From the aspect of antennas, whether deploy the choke-ring and radome is also influential to the SNR observables. But their influences can be mitigated through adjustment the elevation angle of satellite. From the aspect of satellites, the SNR signals from advanced satellites (BLOCK IIR M satellites in this case) are more powerful and stable. These types of observables are more close to the SNR description model and lead to more reliable results. In summary, if the L2C is recorded, it is priori to select the advanced satellite and SNR observables on L2 wavelength; else, the observable from advanced satellites on L1 wavelength is the better choice. Despites the quality of observables, it is interesting that as if the decreasing speed of the negative relative delay phase is slower than the swc, for example, the doy 116–103, 140–168. Considering the fact that the deeper below earth surface, the slower the water evaporates, whether a more effective depth of soil layer exists is worth the further attentions.

8.4 Conclusions

Soil moisture and its fluctuation is one of the most important indicators to measure the water cycle statues. Its accurate measurement and long-term monitoring plays the significant role for meteorological, agricultural and environmental scientific research. With the introduction of methodology and principle of retrieval soil moisture based on GPS SNR observables, the effective area is discussed in this paper. Through the comparative experiments based on measured GPS observations and simulated soil moisture, the validity and selection of parameters during the data process is discussed and analyzed. The process and results from experiments show that this approach can effectively retrieve the soil moisture and its fluctuation. The correlation between the relative delay phase and swc can be described and modelled by exponential function well. Meanwhile, selection of the advanced satellites and recording the L2C code is prone to obtain the high quality observables and reliable monitoring results. With combination of different types and depth of soil moisture data, introduction of more meteorological observations, and even applications of this approach into other fields (such as ice depth, tide gauge, etc.) are the future work need to be paid more attentions.

Acknowledgments This work is funded by open project of Engineer Research Center for GIS Software & Application (No. 20111110) and National Science Foundation of China (No. 41204001). Thanks for the advices during the data process from Professor K. M. Larson, University of Colorado and Doctor Xubo Gao, China University of Geosciences.

References

1. Liu J, Shao L, Zhang X et al (2007) Advanced in GNSS-R studies and key technology. Geomat Inf Wuhan Univ 32:955–960
2. Masters D, Katzberg S, Axelrad P et al (2003) Airbone GPS bistatic radar soil moisture measurements during SMEX02. Proc Int IEEE Geosci Remote Sens Symp 2:896–898
3. Guan Z, Zhao K, Song D et al (2006) Measuring soil moisture using reflected GPS signals. Adv Earth Sci 21:747–750
4. Yan S, Gong J, Zhang X et al (2011) Ground based GNSS-R observations for soil moisture. Chinese J Geophys 54:2735–2744
5. Larson K, Small E, Gutmann E et al (2008) Using existing GPS receivers as a soil moisture network for water cycle studies. Geophy Res Lett 35:L24405
6. Larson K, Small E, Gutmann E et al (2008) Using GPS multipath to measure soil moisture fluctuations: initial results. GPS Solut 12:173–177
7. Bilich A, Larson K (2007) Mapping the GPS multipath environment using the signal to noise ratio (SNR). Radio Sci 42:(6)
8. Ao M, Hu Y, Liu Y et al (2011) Inversion of soil moisture fluctuation based on signal-to-noise ratio of global positioning system. J Geomat Sci Tech 29:66–69
9. Larson K, Braun J, Small E et al (2010) GPS multipath and its relation to near-surface soil moisture content. IEEE J Sel Top Appl Earth Obs Remote Sens 3:91–99
10. Zavorotny V, Larson K, Braun J et al (2010) A physical model for GPS multipath caused by land reflections: toward bare soil moisture retrievals. IEEE J Sel Top Appl Earth Obs Remote Sens 3:100–110
11. Chen F, Dudhia J (2001) Coupling an advanced land-surface/hydrology model with the Penn State/NCAR MM5 modelling system Part I: model implementation and sensitivity. Mon Wea Rev 129:569–585
12. Rodell M, House P, Jambor U et al (2004) The global land data assimilation system. Bull Am Meteor Soc 85:381–394