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Analysis to the Error and Accuracy of Differential Barometric Altimetry

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Abstract

The traditional barometric altimetry acquired the absolute height has poor precision mainly because of the climate and weather, gravity and temperature effect on atmospheric pressure. By introducing reference point correction into barometric altimetry can improve the accuracy of the height being measured and extend its application range since the error caused by slow variation of atmospheric pressure and temperature is eliminated. Users receive the meteorological data from barometric reference stations and calculate the local height through local measurement by high precision. To begin with, this paper describes the principle and mathematical model of differential barometric altimetry. And then analyze the main factors influence to the precision of differential barometric altimetry. Finally, accuracy and error of the method is to be analyzed in detail.

Keywords: *differential barometric altimetry, accuracy, error*

1. Introduction

There is a corresponding relationship between altitude and atmospheric pressure in atmospheric statics theory. We can obtain the altitude of a location base on the measured pressure value. Due to irregular change of pressure, the altitude of a location may be different at different time. There exists a model error in the mathematical model, so this directly results into the accuracy of solving absolute height is not high. Reference [1] used base point correct to calculate relative height, which can achieve high measurement accuracy. But this method did not consider factors of water vapor and acceleration of gravity change with latitude and elevation. Reference [2] has taken into account the effect of water vapor and acceleration of gravity and then deduced the completed Laplace formula suit for the surface barometric altimetry. Reference [3] analyzed the accuracy of barometric altimetry based on the completed Laplace formula [4-5]. We build the differential barometric altimetry model based on the completed Laplace equation in this paper. Creating a complete set of barometric altimetry system and using meteorological information of the nearly known reference [7-8] point and combining the meteorological information to solve the height of the test point. This method improves the availability and reliability of barometric altimetry and enlarges the scope of application [9-10]. In addition, differential barometric altimetry errors and accuracy are analyzed, theoretical analysis and experimental results are given in this paper.

2. Principle and Algorithm of Differential Barometric Altimetry

2.1. Theoretical Basis

When air in a quiescent state, the force to the surface of air block in the horizontal direction cancels each other, the up force and the gravity balance each other in the vertical direction. The atmospheric statics equation is substituted by [1]:

$$\frac{\mathrm{d}P}{\mathrm{d}z} = -\rho g \tag{1}$$

Where P is pressure, ρ is air density, z is height in the vertical direction. g represents the

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acceleration of gravity.

Gas equation of state as follows [2-3]:

$$p = \rho RT \quad (2)$$

Where T is the thermodynamic temperature of air, R is the universal gas constant, which is relevant with the molecular mass of gas. Equation (2) is substituted into the Equation (1), we can get:

$$\frac{dP}{P} = -\frac{g}{RT}dz \quad (3)$$

Taking into account the influence of water vapor, temperature T instead of virtual temperature Tv.

$$T_v = T(1 + 0.378\frac{e}{p}) \quad (4)$$

Where (e/p) is the ratio of air water vapor pressure and air pressure. Taking into account effects of the acceleration of gravity with latitude and elevation changes [4-6].

$$g = g_{45,0}(1 - a\cos 2)(1 - bz) \quad (5)$$

Where g45,0 is the acceleration of gravity in the average sea level at the latitude of 45 degrees, a=0.00265; b=3.14×10-7m-1, φ is the latitude [7-9].

Equation (4) and (5) are substituted into Equation (3), and then simplification as:

$$dz = \frac{\mathrm{RT}}{\mathrm{g}_{45,0}}(1 + 0.378\left(\frac{e}{p}\right)_m) \times (1 + a\cos 2\varphi)(1 + bz)\frac{dP}{P} \quad (6)$$

If the temperature units is Celsius, assume that T=273.15(1+αt), α =1/273.15 is a constant. t_m is the average temperature different gas surface, $(e/p)_m$ is average humidity parameter, instead of corresponding variables, due to b value is small, in the measurement range of applications on the surface, (1+bz) has little effect to the calculated height, which can be neglected. By the integral from (h_0, P_0) to (h, P), then obtaining Equation (7).

$$h - h_0 = 18400(1 + \alpha t_m)[1 + 0.378(\frac{e}{p})_m] \times (1 + a\cos 2\ )lg\frac{P_0}{P} \quad (7)$$

Equation (7) is called the Completed Laplace Equation, which the basic formula to complete differential barometric altimetry.

2.2. Method of Differential Barometric Altimetry

Differential reference station is needed to be established in the differential barometric altimetry system, the precise elevation of the base station measured by more precise method of surveying and mapping. Base station and user terminals are equipped with high-precision pressure, temperature, humidity and other weather parameters acquisition equipment. Acquisitions of meteorological data in base station and user are delivered to a data processing center to unified solve with grounded network or spatial network. Solved results transmitted by the data processing center to the user, the user can get real-time location of the elevation. Working schematic of differential barometric altimetry is shown in Figure 1.

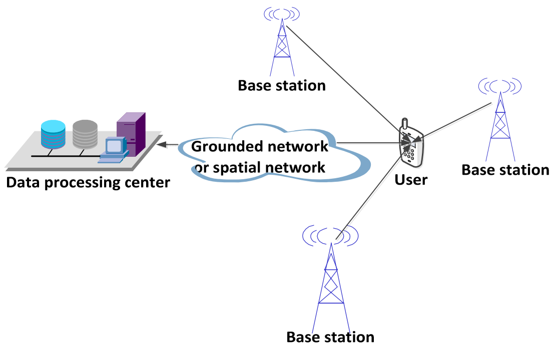

Figure 1. Principal of Differential Barometric Altimetry

Data processing center based on the Laplace pressure equation (Equation (7)) establishes a dynamic computing model. The assumption of differential barometric altimetry is that the distance between base station and a rough value. To begin with, whether there are stations within a certain distance of user, if there is, to find the nearest base station to solve the user elevation as a reference point. If the distance between user and base station is farther, there are three base stations around the user in different directions, the meteorological parameters of which will be fitted as meteorological parameters of one base station around the user to solve the user elevation as a reference point. Finally, the solved elevation value in user is smoothed with a filter. The height of user is output. The block diagram of differential barometric altimetry algorithm under normal circumstances is shown in Figure 2.

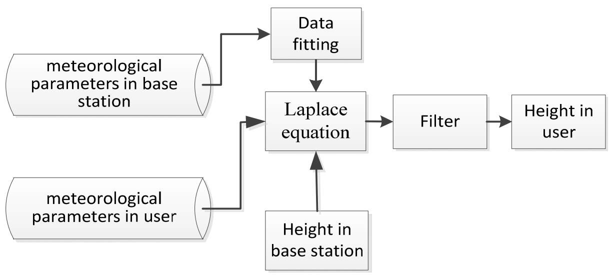

Figure 2. Algorithm Diagram of Differential Barometric Altimetry

3. Analysis of Error and Accuracy

Sources of error include model error, measurement error, data transmission delay error, the error caused by the dynamic changes of meteorological elements. In which the order of magnitude in model error is very small and can be negligible. Only the rest of the several errors are analyzed in this paper.

3.1. Measurement Error

Measurement error mainly depends on the accuracy of measured equipment, including pressure, temperature and humidity measurement error. The elevation error can be obtained according to the Laplace equation caused by the measurement error of these parameters.

3.1.1. The Elevation Error Caused by Pressure Measurement Error

The meteorological parameters as follows for example, assuming that (e / p) = 0.5%, latitude is 45 degree, pressure in reference point is 1020hpa, height in reference point is 0m. The curve of height with temperature change is shown in Figure 3 under different atmospheric pressure, this curve is called isobar.

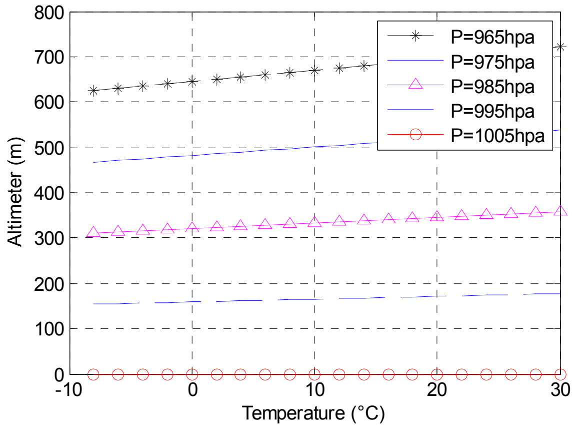

Figure 3. Curve: Altimeter with Air Temperature Changes

From Figure 3, we can conclude that height difference between the test point and reference point is increasing with the increasing pressure difference under same temperature. The air layer thickness between two isobaric surfaces will increase with the increased temperature. Under the case of a constant temperature, the height measurement error caused by pressure measurement error is approximately linear relationship, the linear coefficient is related with temperature. Pressure measurement error is the main factor result in barometric altimeter error.

3.1.2. The Elevation Error Caused by Temperature Measurement Error

Similarly, assuming that (e/p) = 0.5%, latitude is 45 degree, pressure in reference point is 1020hpa, height in reference point is 0m. The curve of height with pressure change is shown in Figure 4 under different temperatures, this curve is called isotherm.

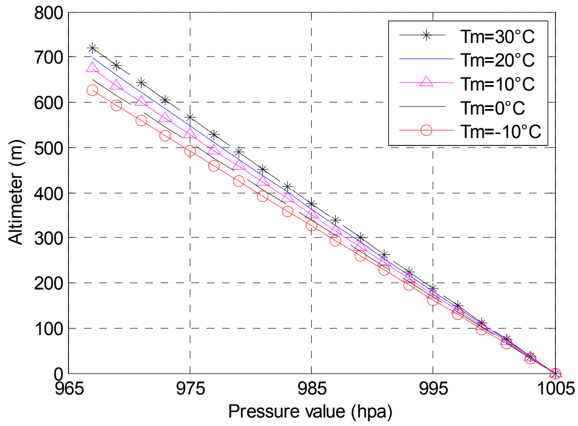

Figure 4. Curve: Altimeter with Air Pressure Changes

From Figure 4, we can conclude that the height difference between the test point and reference point is increasing slightly with the increased temperature under same pressure value. Where in large atmospheric pressure area, the air layer is thinner between the base station and measured point, height measurement error caused by temperature error is smaller. In the pressure 1005hpa area, the vertical distance between the base station and user less than 200m, the temperature error in 1℃ will cause the height measurement error approximate in 0.5m. In the pressure 998hpa area, the vertical distance between the base station and user less than 550m,the temperature error in 1℃ will cause the height measurement error approximate in 1m. In the pressure 966hpa area, the vertical distance between the base station and user less than 850m,the temperature error in 1℃ will cause the height measurement error approximate in 2m.

Atmospheric temperature change curve in a certain location of Beijing within 100 hours is shown in Figure 5 which can be used as a reference. Atmospheric temperature values are relatively stable over time, however, there are random changes in temperature lasted about 3 hours (time period of the Box-2 in the Figure 5), which has little influence to altimeter. Temperature rises rapidly in the Box-1 of Figure 5 caused by the sensor needed to warm-up. So when we need the sensor to measure elevation, the first few output values can be ignored.

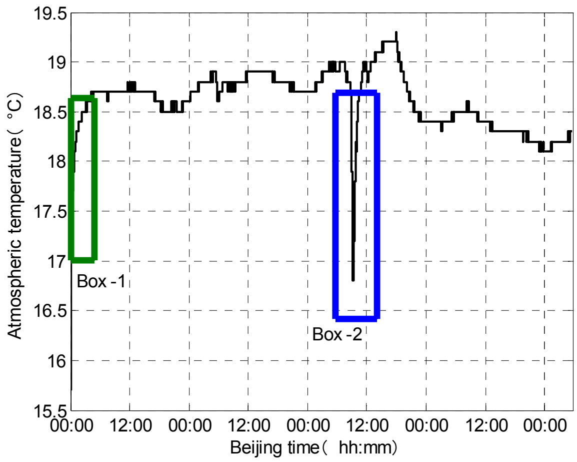

Figure 5. Curve: Atmospheric Temperature of a Place in Beijing within 100 Hours

3.1.3. The Elevation Error Caused by Water Vapor Measurement Error

Assuming that latitude is 45 degree, pressure in reference point is 1005hpa, height in reference point is 0m, the temperature is 15□.In the range (0 to 1%) of water vapor change, height change resulted from which is related to the air layer thickness between the reference point and user. If the air layer thickness is less than 300 meters, the water vapor pressure can be negligible. If the air layer thickness is more than 1000 meters, for the high-precision measurement, the water vapor effect to altimetry must be considered. When the air layer thickness between them is more than 2000m, the water vapor pressure in 0.2% will cause the height measurement error approximate in 2m.

3.2. Data Transmission Delay Error

Acquisition to the meteorological parameters both in base station and user will be delivered to the data processing center through the transmission link. Acquisition and transmission cycle of the meteorological parameters will result into larger measurement error in the air pressure rapid change. This phenomenon must be considered for high-precision altimetry system. The pressure value is an absolute factor for barometric altimetry. So, we only consider the effect of pressure in the height measurement error caused by the transmission delay. Pressure changes with the weather change, high-pressure value is in sunny and dry weather near ground, low-pressure value is in rainy weather. Atmospheric pressure change curve in a certain location of Beijing within 100 hours is shown in Fig.6 which can be used as a reference.

From Figure 6, we can conclude that in the pressure value changing fast stage (The box-1 in the Figure 6), the pressure change rate is approximately 1hpa/h which converts the change rate of altitude error is about in 8m/h. According to the statistics of continuous observation, under the rapid changes of air pressure in Beijing, time delay in 1 minute will bring less than 1m in the height measurement error. Under most circumstances time delay in 1 minute bring less than 0.3m in the height measurement error.

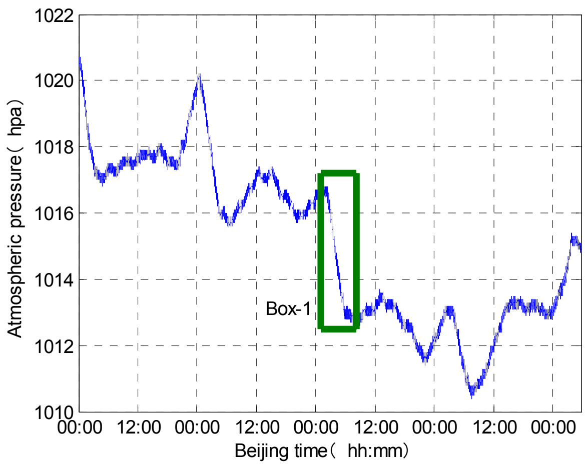

Figure 6. Curve: Atmospheric Pressure of a Place in Beijing within 100 Hours

3.3. Errors Caused by Dynamic Changes in Meteorological Elements

Laplace pressure-height equation is derived on the basis of atmospheric statics equation. Assume that the atmosphere is stationary, but the actual atmosphere is dynamic, the dynamic changes of the atmosphere result in errors for barometric altimetry.

The explanation to wind in meteorology: the air pressure difference caused a horizontal gradient force at the same horizontal plane, which resulting in air movement and generating wind. The horizontal gradient force is perpendicular to the isobar, direction from high-pressure to low-pressure which form the driving force of wind. Horizontal gradient decreases along the decreasing pressure direction, decreased value of air pressure in the unit distance. Average horizontal gradient is 1hpa/hkm in China, therefore which bring about the height measurement error in about 0.08m/km near surface of ground. Average gradient around the connection between the two benchmark stations which has similar height and average gradient of average height surface in three base stations can be obtained by data fitting. This method can reduce or eliminate the measurement errors caused by horizontal gradient.

3.4. Analysis of Accuracy

The accuracy of differential barometric altimetry mainly depends upon the factor of pressure, followed by temperature and water vapor. When the distance between the user and base station is relatively close (less than 10km) and the height difference is small (less than 1km), the influence of water vapor can be ignored, temperature measurement accuracy is not required (not more than 5°C), the high measurement accuracy depends largely on the accuracy of pressure sensor. In the near-surface region, the relationship of height measurement error and pressure measurement error is approximately linear. The scale factor is about 0.8. For example, the pressure sensor error in ±0.05hpa bring about the height measurement error in ±0.4m. The distance between user and base station or among base stations is more than 100km, the height difference is more than 2000m, the temperature error cause the height error in approximate 2m/℃. At this point, we must consider the impact of water vapor.

4. Conclusion

In this paper, an accurate and in-depth analysis of the systematic error causes in differential barometric altimetry is done. Differential barometric altimetry can improve the accuracy and enhance the availability and reliability compared to the traditional barometric altimeter. The height measurement error increases with the increasing distance from the base station to user. When this distance is less than 10km, the accuracy of altimetry is better than 1m. Therefore, differential barometric altimetry can be widely applied in the field of city navigation, mobile navigation, indoor positioning.

Differential barometric altimetry based on digital pressure sensors can greatly improve measurement accuracy in elevation which can make up for deficiencies of poor elevation measurement accuracy in satellite positioning system. We can use the accurate elevation information to constraint solving plane positioning solution in order to further improve the accuracy of the positioning system and then can enhance the role of auxiliary to the positioning system.

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