Optimal distance estimation for implementing the tomographic technique to retrieve the 3D water vapor profiles from a ground-based GNSS receiver network

V. Nagaswapna[1],Dr.G.Mamatha[2]
[1]PG Student, JNTUA College Of Engineering, Ananthapuramu.
[2]Assistant Professor, Department of ECE, JNTUA College Of Engineering, Ananthapuramu.

Abstract:

Water vapor is one of the prime elements of the atmosphere that alters its radiation budget directly and also for the fresh water management.But high accuracy with its measurement remains an important challenge. The total column water vapor and precipitation are well associated in the tropics.In this paper, we estimate precipitable water vapor (PWV) by using the observations from Global Navigation Satellite System(GNSS) .TheMeasurements which we taken from GNSS can be used to sense the atmosphere by measuring the refraction and the delay of the signals as they pass through the atmosphere. From These delays we can infer the column-integrated precipitable water vapor or precipitable water. When a network of GNSS stations is available, they can extensively improve the spatial and temporal coverage of humidity above the surface.Knowing the importance of water vapor Indian Space Research Organization (ISRO) has taken-up a challenging project to get three dimensional profiles of water in all weather conditions. In this regard a network of ground-based GNSS receivers is planning to installed in any one of the station. These receivers collect signals from the GNSS satellites in any direction based on the position of the satellites at that time. Thus the water vapor information obtained from the delay of the signals is total column slant water vapor which is fed to the tomographic technique algorithms to get the 3D water vapor profiles.The efficiency of tomographic methods depends on experimental setup and mathematical algorithms. The retrieval of water vapor profiles depends on the passages of signals in a given voxel.

Index Terms: **Global Satellite Navigation System(GNSS), Troposphere water vapor, GPS-tomography.**

1.INTRODUCTION:

The gaseous phase of water is called water vapor**.** It is very important gas in the atmosphere and it can influence many things like condensation and the formation of clouds and rain, as well as how hot or cold it feels at the surface. Different regions typically contain different amounts of water vapor and this can drastically affect the climate across these regions. Due to its high variability in the atmospheric processes it triggers the moisture motion transport on wide range of scales in space and time,influencing the evolution of metrological phenomena and current weather state.There are a variety of methods that have been used to measure the integrated water vapor content in the atmosphere,either from space or ground.Some existing techniques for measuring atmospheric water vapor[*Carter*,1997] are shown in figure1.The radiosonde measure atmospheric water vapor profiles with good accuracy, but these measurements are limited in space and time. Thus, radiosonde measurements are not sufficient to study the spatiotemporal variability of water vapor across a range of scales. On the other hand, ground-based radiometers experience problems during rainy periods, while space-based radiometer measurements degrade in the presence of clouds. Due to global coverage, low cost and continuous observations from GNSS receivers provide an excellent tool for monitoring integrated water vapour content in theEarth's atmosphere.

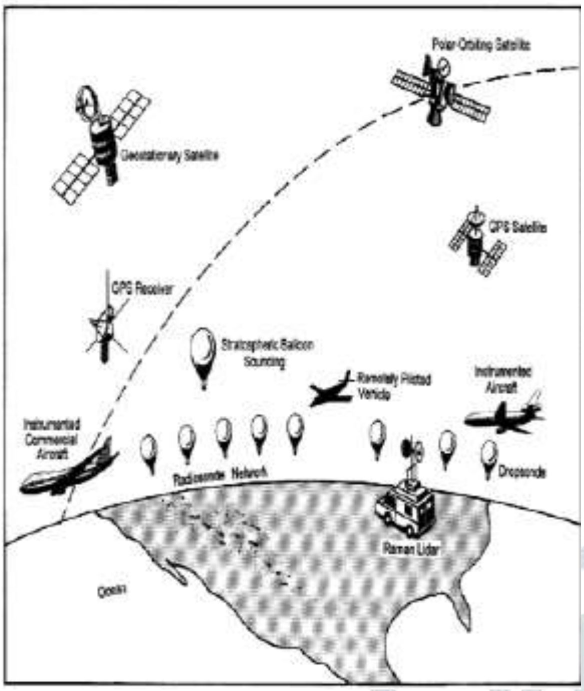

Figure 1: Some existing techniques for measuring atmospheric water vapor[*Carter*,1997]

However, IWV is a measure of the total amount of water vapor above a certain station, but it cannot provide information on the vertical distribution of water vapor. So In order to meet that requirement, GNSS water vapor tomography has been used for providing information on the three dimensional (3D) distribution of the water vapor in the troposphere.

2.PRINCIPLE CONCEPTS OF WATER VAPOR ESTIMATION:

In this section, first we give a brief overview of the atmospheric delays induced in GPS signals**.**

The Atmospheric Delay:

The Earth is surrounded by the atmosphere, which is composed by distinct layers, as shown in Figure 2. The GPS signal travel from satellites to receiver through the earth atmosphere. Due to the composing of atmosphere their speed and direction of the signals are changed. These changes causes the delay in GPS measurements when travel through the atmosphere are called Atmospheric delays. These delays are mainly occurred in two regions i.e tropospheric region and ionospheric region. If this delay is occurred in ionospheric region that delay called as Ionospheric delay.simillarly if delay occurred in tropospheric region then that delay called as tropospheric delay.let us discuss each delay as follows

Ionospheric Delay

The ionosphere is a layer or layers of ionized air surrounding the Earth extending from about 50 km above the Earth's surface to altitudes of 1000 km or more. The air is extremely thin at these altitudes. When the atmospheric particles (electrons) are ionized by radiation (principally by solar ultraviolet radiation and x-rays emissions), they tend to remain ionized due to few collisions between free negatively charged electrons, positively charged atoms and molecules. These ionized particles (called ions) characterize the ionosphere. Thus, the free electrons affect the propagation of radio waves, and thus the GPS signals.

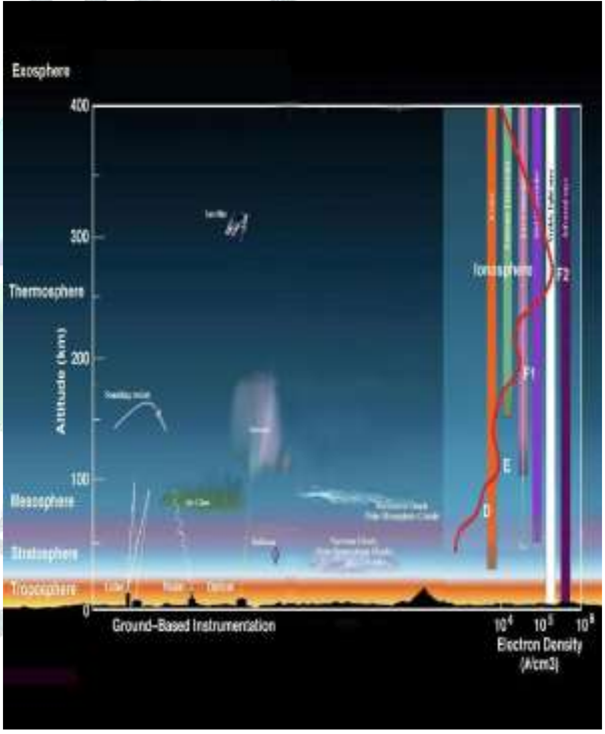

Figure 2: Different layers through which signal travels.

Tropospheric Delay

The neutral atmosphere which is below the ionosphere is including the stratosphere, tropopause, and troposphere. The troposphere is the bottom portion of the Earth's atmosphere, which is the layer of weather on the Earth and it extends up to 50 to 70 km from the earth's surface. The thickness of the troposphere varies from less than 8km over the poles to more than

16km over the equator. The temperature of the tropospheric layer decreases with an increase in altitude, by approximately -6.5°C/km [NOAA/NASA/USAF, 1976].

The troposphere contains about 75% of the atmosphere's mass and most of the water vapour in the atmosphere. Water cycling takes place in the troposphere as the exchange and movement of water between the Earth's surface and atmosphere. Solar energy causes water to evaporate, and wind circulates the moisture. Air rises, then expands and cools down condensing water vapour and thus developing clouds. Various types of precipitation happen depending upon size and temperature of water particles. Consequently, the troposphere is undergoing temporal and seasonal variations.

The effect of the neutral atmosphere due to non-ionised gases (e.g., carbon dioxide) and water vapour molecules on both the GPS carrier phases and code modulation, which is denoted as tropospheric delay, is identical and cannot be eliminated using dual-frequency observations. The tropospheric delay preferentially depends on temperature, pressure, and humidity as well as the physical location of the receiver, and reaches up to 2.5m in the zenith direction, and about 30m close to a horizon angle.

3.Estimation of atmospheric water vapor through GPS:

Measuring techniques of atmospheric water vapor with GPS relates the delay and bending of a GPS signal as it propagates through the atmosphere .The signal path through the atmosphere through the atmosphere is shown in figure5.

The excess delay (ΔL) caused by the atmosphere between the transmitting GPS satellite and the receiving GPS antenna can be expressed as.

$$\Delta \mathrm{L} = 10^{-6} \int \mathrm{N(s)ds} + \mathrm{S} - \mathrm{G} \quad \ldots\ldots (1)$$

Where N(s)= refractivity, S=path between satellites and receiving antenna

The excess delay describes the additional delay of a signal when compared to one propagating through a vacuum (G). Refractivity is related to the index of refraction (n).

$$N = 10^6(n-1) \quad \ldots \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

The refractivity is a function of atmospheric pressure (p, in millibars), vapor pressure(ew, in millibars) and temperature (T, in Kelvin) and isapproximated by equation

$$N = 77.6\left(\frac{P}{T}\right) + 3.73 * 10^5 \left(\frac{e_w}{T^2}\right) \quad \ldots\ldots \quad (3)$$

Substituting equation (3) into equation (1) we get the following integral**.**

$$\Delta L = 10^{-6} \int [77.6(\tfrac{P}{T}) + 3.73 * 10^5 (\tfrac{e_w}{T^2})] ds + S - G \quad \ldots\ldots\ldots\ldots\ldots\ldots.. \quad (4)$$

If atmospheric bending is ignored, Equation (3) can be simplified to contain only the integral of refractivity.

$$\Delta L = 10^{-6} \int [77.6(\tfrac{P}{T}) + 3.73 * 10^5 (\tfrac{e_w}{T^2})] ds \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

The delay described by the first term in the integral is called the slant hydrostatic delay (SHD). The second term is known as the slant "wet" delay (SWD). The summation of the two is the slant total delay (STD=SHD+SWD).Scaling the slant path delay to its equivalent delay if the satellite was at zenith is expressed below.

$$\mathrm{ZTD} = \mathrm{ZHD} + \mathrm{ZWD} = \mathrm{SHD} / m_h(\theta) + \mathrm{SWD} / m_w(\theta) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(6)$$

Where $m_h(\theta)$ and $m_w(\theta)$ are called the hydrostatic mapping function and the wet mapping function. The Expressions of these mapping functions have been formulated by Davis et al. [1985] and Niell [1996]. The ZHD can be computed using a surface pressure measurement [*Davis et al.*, 1985; *Saastamoinen*, 1972] and can be scaled to a SHD using the $m_h(\theta)$ mapping function.

The water vapor present in the atmosphere is imperfectly correlated to surface humidity measurements. Therefore, the ZWD (and therefore SWD) cannot be accurately computed using surface measurements. ZWD is therefore included as an estimated parameter in the inverse modeling of the observation equations. The output of the estimation results in a time varying ZWD value that represents the following integral.

$$ZWD = (3.73 * 10^5)(10^{-6}) \int \frac{e_w}{T^2} dz = (3.73 * 10^5)(10^{-6}) R_v \int \frac{\rho_v}{T} dz \ldots\ldots\ldots\ldots\ldots\ldots\ldots..(7)$$

Where $R_v$is the gas constant for water vapor and $\rho_v$is the water vapor density.
If we got ZWD value then we can calculate the PW.Next section describes the estimation of precipitable water vapor.

Determining the precipitable water vapor:

The vertically integrated water vapor overlying a receiver, in terms of an equivalent column of liquid water is known as Precipitable water vapor (M. Bevis, 1994).The precipitable water vapor can be calculated using a dimensionless constant of proportionality (M. Bevis, 1994), when ZWD can be known.

$$PW= \pi * ZWD \ldots\ldots\ldots\ldots\ldots\ldots\ldots..(8)$$

Here π is a dimensionless constant of proportionality constant proportionality is given by

$$\pi = \frac{10^6}{\rho R_v \ [\left(\frac{K_3}{T_m}\right) + K_2' \ ]} \ldots\ldots\ldots\ldots\ldots\ldots..(9)$$

Where ρ is density of liquid water

R_v is the specific gas constant for water vapor

T_m a weighted mean temperature of atmosphere

- The weighted mean temperature of atmosphere (T_m) defined is

$$T_m = \frac{\int (\frac{P_v}{T}) dz}{\int \left(\frac{P_v}{T^2}\right) dz} \ldots\ldots\ldots\ldots\ldots\ldots..(10)$$

Where $k_2^1 = k_2 - mk_1$ and m is M_w / M_d ,it is ratio of the molar masses of water vapor and dry air.

The water vapor content of the atmosphere is sometimes stated as the height of an equivalent column of liquid water, which we refer to as the precipitable water (PW). Numerically, the IWV is just the product of p and PW, where p is the density of water. PW and ZWD both have units of length, their ratio is a dimensionless quantity.

$$\frac{PW}{ZWD} = \frac{PW}{\Delta L^{\circ}_{w}} = \frac{K}{\rho} \ldots\ldots\ldots\ldots..(11)$$

If the Earth's atmosphere were isothermal, then Tm would be constant and equal to surface temperature. However, since the atmosphere usually has a negative temperature gradient up to the tropopause, Tm will be the average temperature of atmosphere weighted by the pressure of water vapor (shown in T_m definition).So Tm will depend on surface temperature, and tropospheric temperature profile, and on the vertical distribution of water vapor.

In this paper we calculated the precipitable water vapor from radiosonde data.Figure 6shows an example of data which is read from radiosonde of one station .Figure 7 shows the estimated precipitable watervapor values of radionde data.content of watervapor depends on altitudes of GNSS sites. In general, the PWV content decreases as the site altitude increases (see Fig. 3). However, IWV is a measure of the total amount of water vapor above a certain station, and GNSS cannot provide information on the vertical distribution of water vapor. In order to meet that requirement, GNSS water vapor tomography has been used for providing information on the three dimensional (3D) distribution of the water vapor in the troposphere.

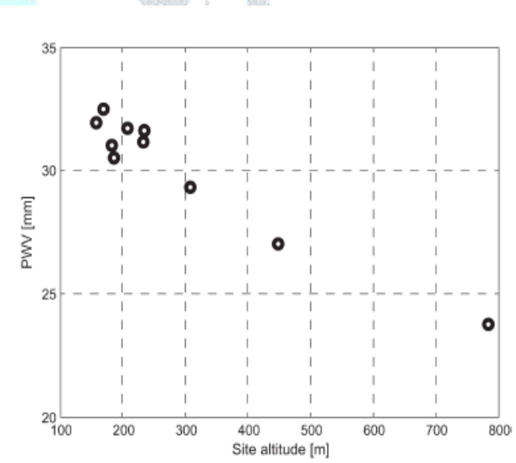

Figure 3:PWV estimates at ten GNSS sites plotted against the site altitude.(DOI: 10.1109/TGRS.2014.2382713,2015)

4.TOMOGRAPHIC METHOD:

From the above discussion we said that the for retrieving 3D water vapor in the troposphere tomography technique can be used.The GNSS Water vapor(WV) tomography technique was first proposed to monitor the 3D watervapor in 2000 (Flores et al., 2000; Seko et al., 2000; Hirahara et al., 2000). Since then, many scientists have been proposed different methodsto improve the GNSS Water vapor tomography (Flores et al., 2001;

Nilsson and Gradinarsky, 2006; Rohm and Bosy, 2011; Wang et al., 2014; Wang et al., 2014; Zhao and Yao, 2017). The tomography technique has following advantages (1) free ofweather conditions and (2) retrieve 3D WR field in near real time.

In the field of GNSS meteorology, the principle of tomography became applicable with the increasing numberof GNSS satellites and the build-up of densified ground-based GNSS networks in the 1990s (Raymond et al., 1994; Flores,1999).

Small deviations of the GNSS signals due to the atmospheric water vapor are used to evaluate the amount of water vapor between a GNSS satellite and each single GNSS ground station.

For retrieving the 3-D structure of the wet refractivity(water vapor), the troposphere is divided into a finite number of voxels (normally called boxes , finite volume pixels) where the refractivity is assumed to be constant. By doing this discretization , the slant wet delays can be described as linear combinations of the refractivities of the voxels ; hence the refractivity field can be obtained by solving a linear system of equations. Water vapor quantity in each voxel can then be estimated from a large number of integral water vapor ray paths using the tomographic technique. This requires each voxel to be crossed by a number of GNSS signals from different directions.

Each signal on the receiver – satellite path penetrates a certain amount of voxels. Each voxel (with water vapor) makes its individual contribution to the total delay of the signal .

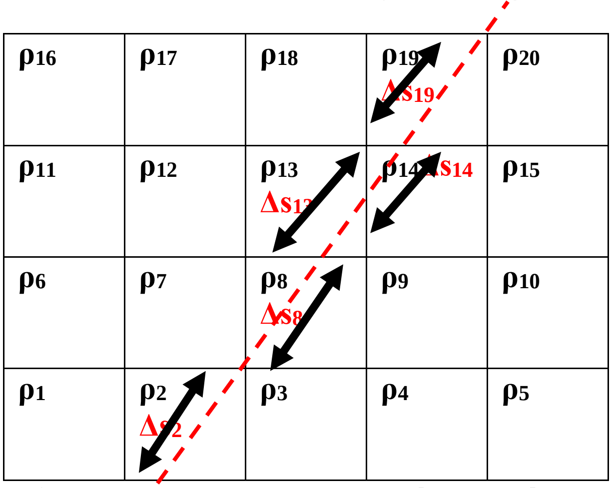

Figure 4:SW measurement within voxels

The full path of the signal is a sum of the paths in the intercepted voxels. The model can be interpreted as a system of linear equations

$$Sw=\sum(\rho_1 * \Delta s_1) = \rho_2\Delta s_2 + \rho_8\Delta s_8 + \rho_{13}\Delta s_{13} + \rho_{14}\Delta s_{14} + \rho_{19}\Delta s_{19}\ldots\ldots\ldots\ldots(12)$$

This equation gives the distribution of water vapor by the voxels.To solve the system of equations, the GPS-tomographic approach must satisfied some conditions.

a) In an ideal case, at least one GPS receiver should be present in each voxel. In that way, the system is solvable. However, this network configuration is usually not possible.

b) With slant delays it is possible to determine a voxel, even if no GPS receiver is inside this voxel.

c)Additional conditions for voxels can be used to obtain information and stabilize the system of equations.

Various methods exist to check the quality of the normal equation matrix. One possibility is using the Least Squares (LS) method. It can be solved also by Kalman Filter, using the prediction and correction step alternately.

The differences between the geometrical shortest path and the extra path, induced by the tropospheric water (depending on the temperature, humidity and air pressure at the point of measurement), are specified by the absolute term sw in the system of linear equation

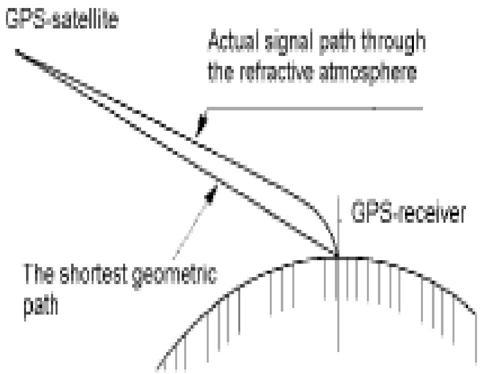

Figure 5: The signal path through the atmosphere through the atmosphere

According to the satellite constellation at a certain time instant the geometrical shortest paths are constructed from all satellites to all of the receivers. Each ray will penetrate only a minor part of voxels and the situation changes at each time step.

The simulation of monitoring consists of the generation of initial data for a certain mathematicalmodel and the data processing related to a specific scenario. The synthetic dataconsist of the outputs of GPS-receivers (including both (i) the data sent by a satellite and(ii) the data generated by a receiver).

The first one represents mostly the positions of the satellites and the time parametersof atomic clocks. These data consist of the GPS-satellite navigation message and canalso be obtained from GPS Ground Control Stations or some public databases via internet.The second one consists of data about the time instants the signal was received (receivertime), the carrier phase, the position of satellites (from the receivers point of view) and somesupporting information.

The simulation program compiled on the basis of the mathematical model is responsiblefor the generation of a situation as realistic as possible. The model situation must bedescribed by the real geographical location and the real constellation of GPS-satellites ata certain time instant. Based on this information additional analysis is performed to findsuitable locations for GPS-receivers in the monitoring network(i.eif we want the good quality of solution, calculate that how much distance we have to put the GPS receivers particularly in any one location).With the increasing number of satellite constellations (e.g., GPS, Galileo, and GLONASS), the spatial coverage of the atmosphere with slant PWV estimates is highly improved by combining observations from multiple systems [4].This information about water vapor,either integrated or tomographic, can be used to adjust the initialand the boundary conditions in atmospheric prediction models.Since these models often overestimate the PWV, particularlyunder high atmospheric advection, the GNSS-based PWV estimatescan be useful for suppressing the bias in the model.

5.RESULT:

In this paper we used radiosonde data for retrieving the watervapor.This data contains one month data of one station. This radiosonde data includes the pressure, temperature,height and relative humidity profiles above the stations.

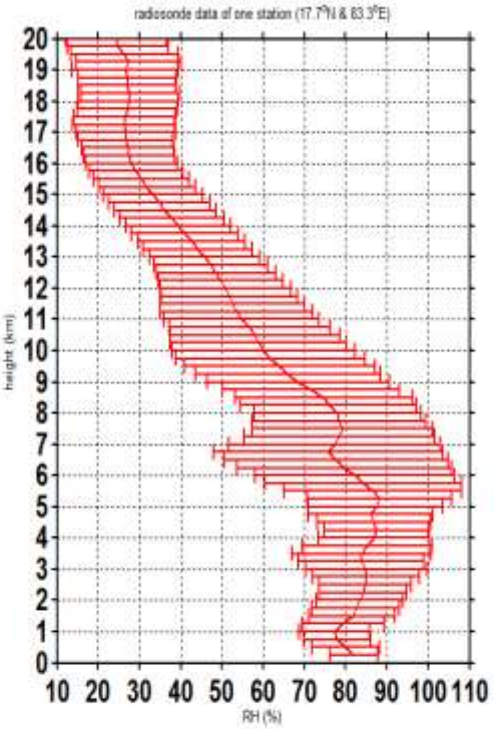

Figure 6: Graph for the radiosonde data of one station

For the above radiosonde data we can estimate the precipitable water vapor. The below shows the calculated precipitable water vapor for one month radiosonde data of one station. In that figure left side values shows that the each day water vapor values.

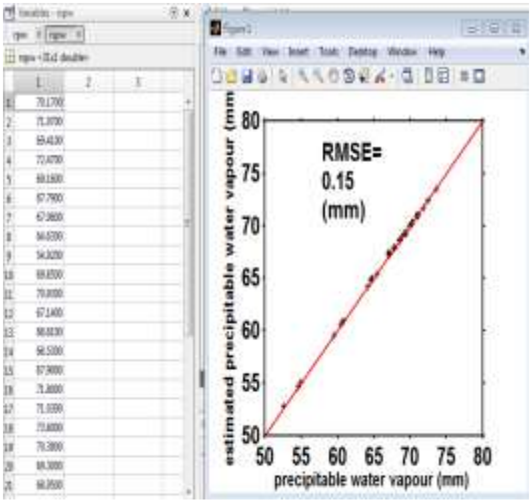

Figure7:precipitable water vapor values for one month data of radiosonde

6.CONCLUSION:

Water vapor is a very important gas in the atmosphere and can influence many things likecondensation and the formation of clouds and rain.It is themost important greenhouse gas in the atmosphere..It is a highly variable atmospheric constituent.IWV is a measure of the total amount of water vapor above a certain station, and GNSS cannot provide information on the vertical distribution of water vapor. In order to meet that requirement, GNSS water vapor tomography has been used for providing information on the three dimensional (3D) distribution of the water vapor in the troposphere. The GNSS tomography is an innovative technique which works under all weather conditions with a high temporal resolution.

7.FUTURE SCOPE:

Atmospheric tomography has additionally some specific sourcesof errors that cannot be ignored. The first source is related to the voxels (the meaning ofthe term will be given later), not giving any information (because of not being interceptedby any signal ray) and the second one is related to the real data acquisition at the point ofmeasurement (sudden malfunction of some of the sensors or loss of the data).The first category of problems is expected to be smoothed by Kalman Filtering (KF). The random measurement errors are also processed by KF. Finding the best modification of KF is one of the challenge, as numerical precision and stability is counterbalanced with computational load, directly related to the applicability of the monitoring concept and sensor network.

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