THE POTENTIAL OF GLOBAL POSITIONING SYSTEM IN WEATHER AND ENVIRONMENTAL STUDIES

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ABSTRACT: Malaysia is witnessing a rapid growth in the vicinity of urban cities with the construction of large engineering structures (e.g. towers, factories, high-rise condominiums, wide-span bridges and highways) to meet the requirement for the nation's economic growth, societal activities and the aspirations of its population. These manmade structures are, however, subject to deformation and structural displacement caused by severe weather conditions such as strong wind, fluctuating temperatures, seasonal monsoons, flash flooding and heavy rains. This paper gives an overview of the role of Global Positioning System (GPS) technology, in retrieving atmospheric parameters for monitoring and predicting severe weather conditions. As GPS technology is still relatively new to the Malaysian weather forecasting community, the principles presented in this paper deal with the two main approaches: the ground-based atmospheric sounding and the radio occultation method. If appropriate strategies are employed during the data acquisition and data processing phases, it is noted that GPS is potentially capable of being implemented as an alternative and promising tool to remotely sense the spatial and temporal variability of the Earth's atmosphere. Because of its practicality, accuracy and data continuity, GPS is adequate and effective in overcoming the shortcomings of other commonly-used atmospheric sounding techniques.

Keywords: environment, GPS, weather

1. INTRODUCTION

Artificial structures are subject to deformation and structural displacement caused by severe weather effects such as strong wind, extreme temperature variations, seasonal monsoons, flash floods and heavy rainfall. Given the agricultural cycles, human well-being, economic growth and societal activities are also greatly affected by climate variability, an in-depth understanding of critical atmospheric parameters (e.g. refractivity, pressure, temperature and humidity) is of paramount importance; especially in the case of tropical region (e.g. Malaysia) where most of the parameters are heterogeneous and extremely variables. Accurate determination of atmospheric profiles and their variations particularly humidity and temperature in the troposphere and stratosphere, are the basis for reliable weather forecasts and climate predictions. In general, weather predictions are performed by solving the atmospheric non-linear partial-differential equations of dynamics, thermodynamics, mass continuity and moisture conservation.

Due to increased global awareness of the importance of effective and practical atmospheric sensing for weather and environmental studies, a wide variety of platforms and approaches have been initiated during the past decades to satisfy the needs of meteorologists, climatologists and specialists in marine activities, forestry, urban and rural planning, agriculture, aviation and other fields. Being the only fully-operational state-of-the-art Global Navigation Satellite Systems (GNSS) technology currently available, there is considerable interest in the use of Global Positioning System (GPS) technology for retrieving relevant parameters for weather and environmental studies. Commencing from the first launch of a GPS satellite in 1978, this ingenious combination of applied science and technology has been responsible for many exciting and beneficial discoveries. Initially developed for United States' military purposes, GPS has been in full operational capability (FOC) since 17 July 1995, with 24 Block II/IIA satellites. Located at about 20,200 km above the Earth's surface, the GPS constellation has recently increased to 32 satellites.

The aim of this paper is to discuss the possibility of using a fully operational space-based radio navigation system to remotely sense the spatial and temporal variability of the Earth's atmosphere. In addition to the brief overview of the current commonly-used atmospheric sensing approaches in Malaysia, further discussions include a comparison of the two principal GPS meteorology techniques: the ground-based atmospheric sounding and the radio occultation method.

2. ATMOSPHERIC SENSING – THE MALAYSIAN PERSPECTIVE

At present, among the most commonly-used atmospheric sensing approaches in Malaysia are weather balloons (or radiosondes), surface observation stations, Radio Detection and Ranging (RADAR) and satellite images. The radiosonde is a package of miniature electronic meteorological devices (i.e. thermometer, hygrometer and barometer) attached to a helium-filled neoprene balloon that is allowed to ascend into the lower atmosphere at a rate of about 5 ms^{-1}. Capable of measuring atmospheric parameters up to at an approximate altitude of 30 km (before the balloon bursts), presently there are only eight sparsely distributed radiosonde observatory sites in Malaysia. Established by the Malaysian Meteorological Department (MMD), these include four (Kuala Lumpur, Bayan Lepas, Kota Bharu and Kuantan) in Peninsula Malaysia and four other stations (Kuching, Bintulu, Kota Kinabalu and Tawau) in East Malaysia. Routine surface observation stations have also been established. Consist of Stevenson screens, evaporation pan, rain gauge, rain recorder and sunshine recorder, these stations however are only located at major cities in Malaysia. As far as satellite imagery is concerned, the MMD is using NASA's polar orbiting satellite, the Moderate Resolution Imaging Spectroradiometer (MODIS) data from the National Oceanic and Atmospheric Administration (NOAA) Series and FY-1D satellites. Moreover, meteorological data retrieved from geostationary satellites e.g. China's FY-2C and Japan's Multi-Functional Transport Satellite (MTSAT) are also included. To receive and process MTSAT-1R and FY-2C data, downlinks are made at hourly intervals to either of two MMD Medium Scale Data Utilization Stations (MDUSs). Another two ground stations are receiving and processing satellite data from the NOAA Series (AVHRR), FY-1D and TERRA & AQUA (MODIS Data) satellites. It is noted that, however, there are certain limitations with the current suite of atmospheric sensors (Table 1). Given the predictability of the weather several days in advance is significantly influenced by the definition of the initial conditions based on the reliability of the atmospheric profiling as input into the numerical weather prediction (NWP), at present, it is noted that the uncertainties in the initial conditions do not permit meaningful forecasts more than 5~6 days in advance.

Table 1: Limitations of Current Atmospheric Sensing

Technique	Limitations
Radiosonde (Zipser & Johnson, 1998; Guichard et al., 1999)	- Insufficient spatial and temporal coverage - Labour intensive instrument - Very expensive - Poor accuracy at low temperatures - Subject to systematic and random errors
Surface Observation	- Inhomogeneous spatial coverage
RADAR	- Labour intensive instrument - Very expensive
Satellite Image (Loganathan et al., 2004; Kishtawal, 2003)	- Limited to cloud - free region (infrared sensors) - Limited to ice-free ocean region (microwave sensors) - Inadequate coverage due to limited orbiting path - Restricted spatial resolution

3. GPS-METEOROLOGY

GPS satellites transmit radio signals that can be used to measure atmospheric profiles of refractivity. There are two approaches to remotely sensing the spatial and temporal variability of the Earth's atmosphere using GPS: the ground-based atmospheric sounding approach and the GPS radio occultation.

3.1 GPS Ground-Based Atmospheric Sounding

GPS ground-based atmospheric sounding measures the latency in the transmitted signal arrival caused by the variability of the atmospheric refractive indices from a fixed point on the ground. By using existing continuously operating reference stations (CORS) as the fixed points on the ground, there has been a resurgence of interest, mostly among European countries and other developed nations, in the use of this all-weather satellite-based technique to provide precursor information on thunderstorms, flash flooding and seasonal monsoon events. Provided appropriate strategies were employed, dual-frequency GPS measurements over a CORS network can be processed to obtain the slant Integrated Water Vapour (IWV) values along the signal paths from the GPS satellites to the ground receivers, or the vertical IWV over the CORS stations with an accuracy of about 1mm (Bevis et al., 1992; Morland et al., 2006). The theories and methodologies are relatively mature and the ground-based GPS observations have been incorporated into several operational meteorological systems. For accurate weather predictions, such IWV values can be then assimilated into NWP models (Guerova et al., 2004). Using the tomographic technique it is also possible to estimate the three-dimensional structure of the water vapour (Nilsson & Gradinarsky, 2006). Table 2 lists other related studies on GPS ground-based atmospheric sounding worldwide.

In 2005, the Department of Survey and Mapping Malaysia (DSMM) established the CORS infrastructure known as the Malaysian Real-Time Kinematic Network (MyRTKnet). Equipped with Trimble 5700 dual-frequency geodetic GPS receivers with Zephyr geodetic-type antennas, these

Table 2: Related GPS Ground-based Atmospheric Sounding Studies

Project / Infrastructure	Location	Reference
NOAA GPS-IPW Project	U.S.	Wolfe & Gutman (1999)
GPS Earth Observing Network (GEONET)	Japan	Iwabuchi et al. (2000)
Australian Regional GPS Network (ARGN)	Australia	Feng et al. (2001)
Royal Observatory of Belgium	Belgium	Pottiaux & Warnant (2002)
Integration of RGP and REGAL Network	France	Champollion et al. (2004)
Goteborg GPS Network	Sweden	Nilsson & Gradinarsky (2006)
GPS Atmosphere Sounding Project (GASP)	Germany	GFZ (2007a)

RTK stations however are not being used for ground-based atmospheric sensing due to the lack of understanding about GPS meteorology. There are about 72 RTK stations currently operating within the Peninsula and East Malaysia. Figure 2 overviews the instrumentation at the RTK stations in Malacca and Pontian, Johor.

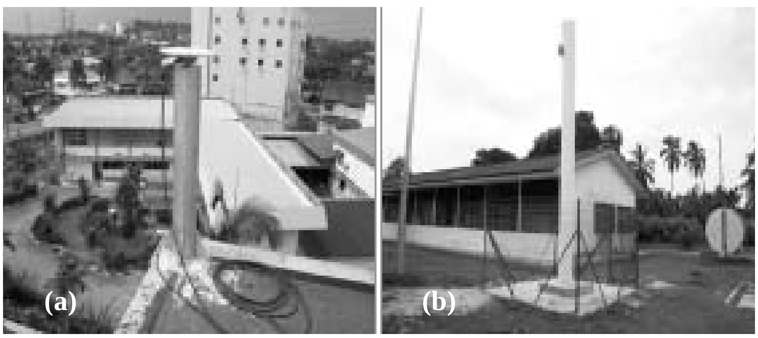

Figure 2: RTK Stations in (a) Malacca and (b) Pontian, Johor

Discussions on various data retrieval and processing strategies, as well as the algorithm used in GPS ground-based water vapour retrieval, have been given in Yahya & Kamarudin (2008a, 2008b). Unfortunately, as far as ground-based atmospheric sounding is concerned, regional CORS networks around the globe (including MyRTKnet) are land-based, i.e. there is no ocean surface coverage which accounts for 78% of the Earth's surface. Even so, some research has been initiated on the feasibility of using measurements from platforms at sea (Rocken et al., 2003). It is suggested that however the accuracy of GPS water vapour retrievals, ultimately depends on two factors: the accuracy of the measurements made in order to estimate the total refractivity of the neutral atmosphere from the GPS observables, and the accuracy of the assumptions and/or mathematical models used to perform these functions (Gutman et al., 2004). It is noted that integrated surface pressure measurements with an accuracy of about 0.5 hPa and surface temperature measurements with accuracy of about 2° are needed to keep the IWV retrieval error budget below 0.5 mm (Gutman et al., 2003). Although complex data processing and modeling is involved, the major advantages of GPS ground-based atmospheric sounding include 24-hour coverage under virtually all-weather conditions, arbitrary temporal resolution, no requirement for calibration, and low acquisition and maintenance costs. Figure 3 illustrates the example of precipitable water observed using water vapour radiometer (WVR) along the line of sight to GPS satellites, mapped to the zenith direction.

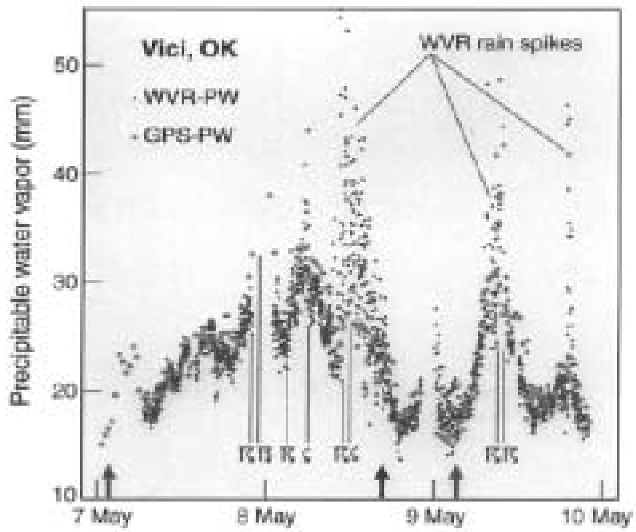

Figure 3: Overview of GPS-derived PW Data

Observed at Vici, Oklahoma, the vertical arrows denote the time of the observed surface dry line passages whereas the time of thunderstorm activity is indicated with conventional symbols (Businger et al. 1996).

3.2 GPS RADIO OCCULTATION

Since the early use of the occultation measurement principle for sounding planetary atmospheres and ionospheres, the exploitation of GPS radio occultation (RO) in atmospheric remote sensing has seen tremendous progresses. The atmospheric profiles obtained from RO observations extend from the fundamental variables (e.g., temperature, density, pressure, WV, trace gases, aerosols and cloud liquid water) to ionospheric electron density. In principle, RO utilises the bending and delaying of GPS signals caused by atmospheric refraction observed from low earth orbiting (LEO) satellites (see Figure 4). Unlike the GPS ground-based atmospheric sounding, RO on the other hand is capable of retrieving atmospheric parameters over both land and ocean. The retrieval of atmospheric profiles

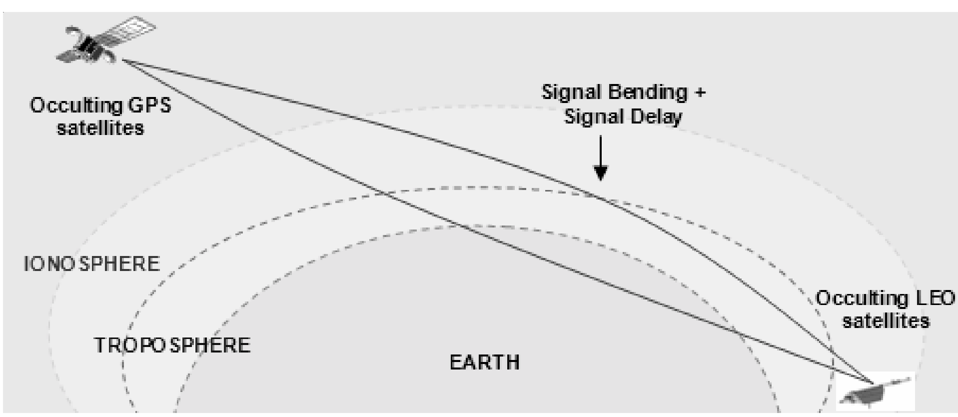

Figure 4: GPS Radio Occultation

from GPS occultation measurements has been described in detail by, e.g., Melbourne et al. (1994) and Kursinski et al. (1997). A considerable amount of effort however, has been devoted to developing an effective strategy for the assimilation of GPS RO data into weather prediction models.

With a GPS receiver on board a LEO satellite, setting or rising radio occultation events (ROEs) are observed by the RO antenna(s) as the transmitted GPS signals pass through the Earth's atmosphere. The excess phase delays of the signals introduced by the Earth's atmosphere are extracted from the phase measurements after the precise orbit of the LEO satellite, and the clock errors of both LEO and GPS satellites, are determined. The bending angle profiles over the RO points are then derived from the excess phase, amplitude, positions and velocities of the LEO and GPS satellites, from which corresponding refractivity profiles are inverted and water vapour profiles are retrieved using auxiliary atmospheric information (from other independent methods such as NWP models and radiosonde observations). Both bending angles and refractivity profiles are retrieved from excess phase and amplitude observations. The inverse problem, i.e. construction of the electromagnetic field from the refractivity profile (or the bending angle) and the path of the receiving and transmitting antennas, are solved using the principles of geometrical optics (Jensen et al., 2006). Either bending angle or refractivity can be directly used as observation operators in the data assimilation process. Recent research suggests inversion methods other than those based on classical geometric optical can improve this process (Gorbunov et al., 2006).

Following the highly successful GPS/MET experiment, several other RO missions have been launched. These include the German-US Challenging Minisatellite Payload (CHAMP), the Argentinean Satelite de Aplicaciones Cientificas-C (SAC-C) and the US-Europe Gravity Recovery and Climate Experiment (GRACE). Most recently, a further three GPS RO missions have been launched. These include the Constellation Observing System for Meteorology Ionosphere and Climate (COSMIC), the European Meteorological Operational satellite (MetOp-A) and the German TerraSar-X (GFZ, 2007b). Figure 5 illustrates typical temperature profile using RO, along with nearby radiosonde measurements for comparison. For a more comprehensive presentation of results from this experiment see Kursinski et al. (1997) and Rocken et al. (1997).

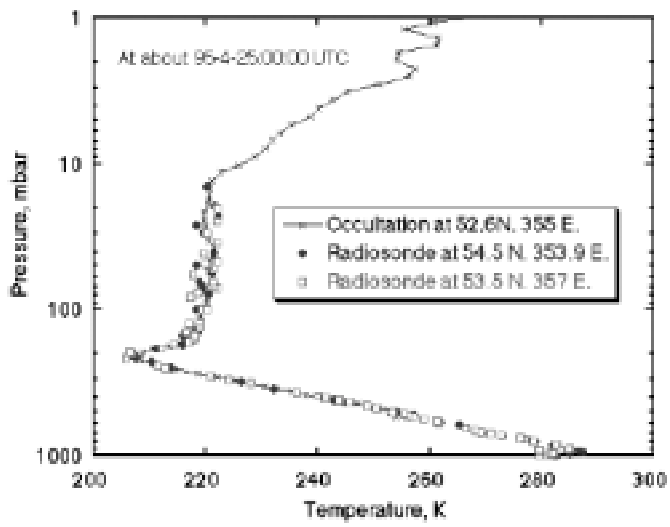

Figure 5: Comparison of RO and Radisonde Temperature Profile

4. CONCLUDING REMARKS

In addition to its distinct and valuable applications in navigation, surveying, mapping and deformation studies, GPS represents a milestone improvement in weather and environmental sensing technology. Although not yet implemented by the local weather forecasting community in Malaysia, from a series of comprehensive studies carried out abroad, GPS has proven to be a powerful, yet practical, sounding tool for retrieving information on the spatial and temporal variability of the Earth's atmosphere. Unlike commonly-used atmospheric sensing approaches, GPS not only provides 24-hour coverage under virtually all-weather conditions but also has arbitrary temporal resolution, no requirement for calibration, and low acquisition and maintenance cost. The GPS radio occultation technique can also be employed to retrieve atmospheric data over oceanic regions. This space-based approach can effectively provide an almost uniform global coverage, which is essential for NWP. Using appropriate procedures for data acquisition and data processing, GPS is very effective in overcoming the shortcomings of other commonly-used techniques and hence can play a crucial role in satisfying the demands for in-depth understanding of the subtleties of atmospheric and environmental processes.

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