The application of GPS/Glonass technology to atmospheric monitoring

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BIOGRAPHY

Richard Percival was born in 1976 in Kingston Upon Thames, London, UK. He read Physics with German at Imperial College, London, UK. He graduated in June 1998 with an Msci (First) after having spent the third of his 4 years doing research into semicondcutors for the new ATLAS detector in Freiburg, Germany. Since December 1998 he has worked for Quartzlock (UK) Ltd, a company specialising the generation , measurement and distribution of precise Time and Frequency. His work, as a physicist, involves Hydrogen Masers, Rubidium, GPS (& Glonass), Phase Comparators and Lf tracking receivers. This is his first ION technical meeting.

ABSTRACT

Quartzlock (UK) Ltd is a small UK company, specialising in the generation, distribution and measurement of stable and accurate time and frequency signals.

The GPS disciplined oscillator (GPS-DO) range has been in production since late 1994. Realising that the introduction of selective availability (SA) had introduced serious problems into the use of GPS-DO's as a precise time and frequency instruments, the company decided to design its own GPS engine. The result was a dedicated time and frequency engine, not a navigation engine pressed into time and frequency use. The engine uses the excellent Carrier Phase Tracking technology, in addition to the normal C/A code tracking used in most normal instrumentation.

The possible applications for such a high precision time and frequency standard are large. One area the company has recently entered is GPS meteorology. This is the application of GPS data to the monitoring and analysis of atmospheric conditions. Atmospheric monitoring can be done by both ground-based and space-based GPS applications. Ground based GPS receivers at locations can be used to gather data that can be shown to determine integrated Precipitable Water Vapor (PWV). The measurement of PWV is the backbone of operational weather forecasting, and weather and climate research. Present data systems provide inadequate resolution of the temporal and spatial variability of water vapor, and this is the main stumbling block to improving short-range precipitation forecasts. Recent studies have shown that GPS-determined PWV observations can significantly improve weather forecasting accuracy, both in the short and long term.

GPS can be used to establish precise location through the time of flight of L-band signals at different frequencies from multiple satellites to a single receiver. In this case, the parameter of interest to the user is the signal path delays recorded by GPS receivers at fixed locations. These delays will be caused by a variety of effects. One cause of these delays is due to the passage of the signals through the Earth' ionosphere and atmosphere. The delay of the signal through the ionosphere is frequency dependent, and may be determined by observation of both the L1 (P-code and C/A code) and L2 (P code only) signals using a dual band receiver. Information about their path delay difference, yields information about the PWV in the ionosphere.

The company has been actively investigating using the Russian Glonass system for some time, whereby it is hoped that a combination of GPS-Glonass technology will fulfil the requirements demanded by atmospheric monitoring equipment. Recent discussions have indicated the suitability of a dual band Glonass receiver for monitoring of L1-L2 path delays. The impact of new civilian frequencies on atmospheric modelling will be discussed.

The application of GPS/Glonass technology to Meteorology brings environmental sensing into a new era. Improvements in surface, coastal and air travel safety will all be effected by more accurate predication of storm systems. A better understanding of microclimates will benefit agriculture by improving crop yields.

This paper will outline the basic theory behind the monitoring of the atmosphere using GPS, detail both the GPS/Glonass technology in use as well as the atmospheric monitoring system used (MET3A from Paroscientific, Inc.). Recent developments and results will be presented, as will improvements necessary for successful and reliable civilian operation. A brief section on the benefits of, and future for, such technology will conclude the paper.

Introduction

Quartzlock are manufacturers of a broad range of accurate and stable time and frequency standards. The company has been involved in the development of top-end GPS-DOs for over 6 years now, and are one of the only commercial companies employing carrier phase tracking technology to discipline high stability OCXO and rubidium oscillators. The units have primarily been used to date as frequency standards but increasingly the company is interested in broadening the appeal of these units to the meteorology and time transfer community.

The company has been talking recently to the Met office in the UK, about contributing towards COST action 712, which concerns the application of microwave radiometry to atmospheric research. The company has also discussed the possibility of using the MET3A meteorological measurement system from Paroscientific, Inc in conjunction with the companies proposed integrated GPS-Glonass disciplined oscillators.

The MET3A proposal will be discussed, as will the idea behind using GPS-Glonass to supplement data gained from the MET3A system. The purpose of this paper is to give a brief outline into subject of atmospheric monitoring using GPS, but not to go into too much detail about the atmo spheric side due our relative inexperience on this. The state of play with developing a new integrated GPS-Glonass receiver will be discussed

GPS Meteorology

GPS meteorology is the application of GPS data to the monitoring and analyses of atmospheric conditions. Although atmospheric monitoring may be done with both ground and space based receivers, the purpose of this paper is solely to describe the use of ground based receivers to acquire and process useful meteorological date, unavailable continually through other means. The sending up of radio sondes twice a day is the traditional method of acquiring this data. However the expense of sending radio sondes up, prevents them being sent up more frequenctly. Therefore information about the rest of the day must be extrapolated from this limited if accurate data set. GPS provides continual source of accurate data. It has been shown the GPS method agrees with the radio sondes method very well.

One of the most important aspects of the use of ground based receivers is that they must be used at very accurately known positions. Why does the accuracy of weather forecasting need improving. This must be quantified if possible. There are two aspects to weather related works. One is the all-important day to day so called operational weather forecasting, vital to so many lives. There also is the longer-term weather and climate research, whereby long term trends are modelled and predicted, giving information of the evolution of global climate changes, such as the greenhouse effect. At the present time the single greatest inhibiting factor preventing better [short-term] weather prediction is the 'inadequate continual resolution of the temporal and spatial variability of water vapour' **[1]**

The satellites transmit two L-Band (390-1600 MHz) carrier signals, L1 and L2. The carrier frequencies of L1 and L2 are 1575.42 and 1227.6 MHz respectively. Each carrier is turn modulated (phase shifted by a wave of lower freq. to convey signal) with one or more binary codes.

L1 is modulated with first the C/A (Coarse/Acquisition) code, which is basis of the standard position service (civilian GPS provision). This is a pseudo random (i.e. random like but actually not) but regularly repeating noise like code.

L1 is also modulated with a 50Hz navigation message, which provides GPS satellites orbits, clock corrections etc.

The Precise (P) code modulates both the L1 and L2 carriers, and has a far longer (7 day) duration than the C/A code. It has a chipping rate of 10.23 MHz. C/A code was designed partly to help users acquire the P code. Through a method called anti-spoofing (AS) the P-code is encrypted to form the user restricted P(Y) code, available only to US military authorised users, through the use decryption keys.

The C/A code correlation length of 1µs limits dramatically the resolution of the C/A measurement. The substantially higher frequency of the L1 carrier (as compared to the C/A code), and the resulting shorter cycle of 635 ps will reduce its sensitivity to jamming and also improve the resolution 10000 fold over C/A code measurement. A 1-% noise induced change in the carrier and code signal amplitude results in a phase shift of 10ns and 1ps in the code and carrier respectively. **[2]**

The advantage of carrier phase tracking is that frequency measurements are achievable with almost no receiver noise contribution. This enables relative frequency determination with uncertainties of a few 10^{-11} within fractions of a second. The short dwell times (on each satellite signal) enable a single time multiplexing channel (tracking of multiple satellite signals by using a rapid sequencing process) instead of the costly multichannel method, with better results **[2][3]**

If you operate a GPS receiver in stand-alone mode (i.e. as a single receiver) the accuracy available to you as a user will always be limited by certain systematic factors, such as SA and ionosphere delays. The effects of SA can be partially or almost totally removed through static positioning and averaging techniques. Whilst this will improve the long-term performance, the short-term stability will still be affected (on the most basic of levels, without correction factors).

The effects of the delay due to the ionosphere, however, may only be partially eliminated by modelling the local conditions. In a stand-alone receiver this will never be completely removed. Therefore the user interested in top end time and frequency GPS usage must resort to differential GPS, the referencing of the users GPS to a local atomic clock synchronised GPS receiver. This GPS receiver will measure the clock offsets of all satellites in view (remember it's clock offset is zero due to its synchronisation to a local atomic clock, which is not subject to the delays like SA and the ionosphere). This useful data can then be made available to the user interested in quantifying his systematic delays. This can then be used to calibrate out the contribution of SA and the ionosphere (i.e. errors which are –roughly- the same magnitude at the reference and user positions). This necessitates the reference position being 'quite' nearby for this technique to be of any use.**[4]**

The single frequency user has the option of using a 'ionospheric compensation model developed for single frequency users' **[5][6]** However, only a relative precision of 50% may be obtained using this model.

The **delay** option enables the user to select the delay to be applied to the 1pps output with a maximum of ±500ms thus effectively providing any required time offset with 1ns resolution. This is used to calibrate out ionosphere and troposphere delays, and antenna/down-converter/cable delays. Note that changing the delay once the "locked" condition has been achieved may result in loss of lock and will almost certainly cause transient timing and frequency errors. The 1pps delay should be corrected before lock has been achieved.

The delay of a radio signal is inversely proportional to the square of the carrier frequency (i.e. L2 will be delayed more than L1) and proportional to the total number of electrons along the path from the satellite to the receiver (TEC). The total number of electrons will vary according to the current solar activity, time of day (at the receiver), and longitude and latitude of the receiver. By combination of the delay equations for L1 and L2, you obtain an equation relating the TEC to the difference between the delays of the L1 and L2 carrier signals (and the frequencies of L1 and L2). The original technique relied upon the cross correlation of L1 and L2 P-Codes emitted in phase. Cross correlation is the comparison of one signal with another to see how alike they are. In this case, this will give the difference between L1 and L2 ionospheric delays. This allowed calculation of the TEC 'along the line of sight of the GPS satellites, which allows for ionospheric correction on the *real* signal path'. This allows the delay on a L1 carrier signal to be calculated, and subsequently accounted for in the receiver. The purpose for this original technique was to improve international time transfer links, say between BIPM in France and USNO in the USA. **[6] [7]**

The problem with this original method is that is was very difficult to do, the risk of missing a carrier cycle was very high, for low elevations measurement noise was high and there existed a discrepancy between modelled and measured values.

However, it did allow for 1ns resolution of ionospheric delays along GPS satellite 'lines of sight'

Glonass and integrated GPS-Glonass

The introduction of the Russian Glonass system was made in 1982, but the lack of available timing receivers hampered the wide spread commercialisation of the system. As the timing community awoke to the benefits of using Glonass, several u nits have recently appeared on the market. Glonass offers users several advantages over GPS because on the most basic level the carrier signals are free of both selective availability and antispoofing. In the long term using GEODETIC methods and a carefully calibrated receiver GLONASS could be much better than GPS, because its high precision P code does not have military encryption. Non encryption of the GLONASS P-code means that the measurements are more precise and stable. For geodetic type links the use of more satellites in the solution, the better, as integer ambiguities are easier to solve. **[3] [8] [9]**. Despite the problems that seemed to beset the system in its early days, reliability has recently improved, as has the number of satellites.

Quartzlock have jointly developed a dual system 16 channel receiver module, with 8 channels being assigned to each system. Whilst theoretically 12 satellites from each system should be visible, only 5 are above the time transfer elevation angle threshold of 15% at any one time. The engine uses carrier phase tracking technology similar to that currently employed in the Quartzlock GPS-DO range. Evaluation of the module is being done to assess that quality of the unit and to determine the advantages/disadvantages over current engine used. It is hope that a production model will be ready by the end of the year, with the appropriate RINEX interface needed to support the MET 3A system

Calculation of the precipitable water vapour

As already stated, the ionosphere is a dispersive medium and will delay the passage of radio signals through it differently according to their frequency. Observing the difference in the delay between two radio signals of different frequencies gives important information about the structure of the ionosphere. One advantage of using this stand-alone method is that it eliminates necessity of using a costly local differential GPS station. The different types of receiver that could be used for this purpose will be discussed in the next section. However, this dual frequency differencing technique only quantifies the frequency dependant ionospheric delay, leaving the so-called 'neutral delay' or delay due to the rest of the atmosphere like the troposphere unquantified. The troposphere is non-dispersive, and so single station techniques are of little use.

A solution to the above problem is to use a pressure-sensing technique to estimate part of the delay and supplement this with the dual frequency difference data to obtain the parameter required for more accurate modelling. The explanation that follows on zenith delays owes a great deal to an application note on the MET 3A meteorological measurement system from Paroscientific. Quartzlock are grateful for being able to use this information **[1]** The Met 3A module will be used in conjunction with any integrated GPS-Glonass receiver developed by Quartzlock for meteorological monitoring.

The non-dispersive neutral delay may be split into the hydrostatic delay due to the dry atmosphere and the wet delay due to the permanent dipole moment of water vapor (caused by equal and opposite charges at opposite ends of the water molecule. The product of their charge and distance apart create a dipole moment). The hydrostatic delay is called the zenith hydrostatic delay, and the wet delay is given the name zenith wet delay.

The total zenith neutral delay (ZND) affecting each receiver at a particular location may be calculated using differential techniques if the receiver is in a (geodetic) network of GPS receivers. Using geodetic inversion techniques this total delay may be ascertained very accurately for each receiver.

The zenith hydrostatic delay (ZHD) is the major part of this delay and may be worked out with extreme accuracy using a pressure sensor. The MET 3A is an extremely advanced pressure sensing module capable of at least 0.3 hPa (millibar) resolution.

Unfortunately the zenith wet delay (ZWD) may not be accurately calculated with the same surface measurement technique. However, it is possible to derive this value by subtracting the pressure sensed ZHD from the differentially derived ZND. It is very important to obtain information on the ZWD because it can vary greatly between desert like climates (few mm) and tropical climates (>350mm). It is the accurate knowledge of this delay that will improve all aspects of weather/climate forecasting and knowledge. This value is then transformed into the all important Precipitable Water Vapor (PWV) using 'standard numerical weather models and/or statistical/analytical models of the *vertical* temperature distribution at the receiver site' **[1]**

New civilian GPS frequencies?

GPS is concerned about the growing availability of the Glonass system; its freely available P code and wide variety of frequencies make it ideal for ionospheric modelling. It is been proposed that the next generation of GPS satellites will broadcast a second and perhaps even a third civilian frequency. This would greatly assist in calibrating out the effect of the ionosphere and greatly assist civilian time transfer and atmospheric monitoring.

Conclusion

This brief paper has really been an attempt to document the intentions of the company to move into GPS meteorology. The necessary components have been identified, with the two major ones being the production of a dual frequency receiver using GPS or GPS/Glonass and the integration of the MET 3A pressure, temperature and humidity-sensing module from Paroscientific with this receiver. Work is underway to produce a working prototype within six months. Apologies are made for the lack of figures or diagrams in this paper. This is due to lack of appropriate materials during the writing of the paper.

Acknowledgements

I would like to sincerely thank Peter Swift of Paroscientific, Inc for allowing me to use information from the MET 3A data sheet and for useful discussions at MSC2000. I am also grateful for fruitful discussions with both Jon Clarke and Dr John Davis of NPL regarding the (potential) on integrated GPS-Glonass. Quartzlock are thanked for supporting this work.

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