A New GPS-Glonass disciplined Rubidium Time and Frequency Standard

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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 a 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.

This paper describes work done at the company in improving a GPS-Disciplined Rubidium Oscillator, incorporating improvements in the Rubidium local oscillator, refinements in the disciplining algorithm, progress in new engine design and additional satellite availability. The existing GPS disciplined Rubidium uses Carrier Phase Tracking Measurement in addition to the normal C/A code tracking, which enables it to extract exceptionally stable and accurate frequency information from the complex GPS signal format. This proven method results in a time and frequency resolution, which is as much as 10,000 times better than that capable of being resolved using C/A code tracking alone. This enables the receiver to detect almost instantaneously any local oscillator frequency excursions and make fast corrections, so that the short to medium term stability (typically severely degraded by the deleterious effects of SA) is well controlled. The Carrier Phase Tracking technology enables all satellites in view to be tracked and fast time and frequency averaging is performed which minimises errors due to any single satellite. Several additional techniques have been developed which increase the precision of the receiver.

The production model has been extensively tested at several National Standards Laboratories during the past 2 years, including NPL (UK), PTB (Germany) and IEM Kvarz (Russia). Tests were conducted against these laboratories Active Hydrogen Masers and Primary Cesium over periods as long as 150 days. These tests have shown exceptional performance in the short, medium and long term. Extended testing at NPL (UK) showed an Allan Deviation (σ_y) at 1000s of 5E-13 and a mean fractional frequency offset at 1000s of 6.3E-13. Potential transients were detected and fixed, further improving the performance. At the PTB a mean fractional frequency offset at 5….33 days of 5E-14 was recorded. The stability levels in the short to medium term were primarily determined by the quality of the Rubidium local oscillator, into which extensive R&D has been done and will be presented. A control loop time constant of >1 day ensures no SA degradation of the excellent local oscillator stability, and virtually eliminates SA influence.

Recent developments have been underway to produce an integrated dual GPS-Glonass Receiver. It is hoped that such a production model will provide wider satellite coverage through an increased number of satellites, provide position information in areas where the satellite are liable to be blocked and improve signal tracking capability. It will also free the system up from being dependant on the US military, a concern for many civilian non US users. In addition, a receiver capable of supporting and process the WAAS (wide area augmentation system) and EGNOS (European geostationary navigation overlay system) is being designed. The present state of development will be presented

Such an instrument will be vital in standards laboratory calibration of counters, timer, radio test equipment and all quartz based instrumentation, for telecoms synchronisation, Stratum 1&2, GSM PCN base station commissioning, time transfer, atmospheric monitoring etc. It is vital for Europe that such work also is also done outside the US. A GPS-disciplined Rubidium provides a viable alternative to Cesium at 1/5 the cost and no wear beam tube. This will also be presented.

BRIEF INTRODUCTION TO GPS

GPS is a satellite navigation system conceived, designed and operated by the US DoD. Originally intended to be used for precise positioning through the determination of pseudoranges from the satellites (of which there are ~26 in low earth orbit) to the (normally ground based) receiver. The key idea is that by measuring the time of flight of a radio signal from 4 or more satellites to the receiver, the position of the receiver may be accurately determined. In addition the time offset of the receiver (from composite clock GPS time) may be calculated from information within the orbit data (modulated onto carrier). By taking the time differential of these two quantities, the velocity of the receiver and the frequency offset of the receiver may be ascertained. The reader is referred to **[1]** for further background and historical information on GPS.

SATELLITE SIGNALS

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) **[2]** with one or more binary codes.

L1 is modulated with first the C/A (Coarse/Acquisition) code, which is the basis of the standard positioning service (civilian GPS provision). This is a pseudo-random (i.e. random like but actually not) **[2]** but regularly repeating noise-like code. It has a chipping rate (rate at which binary digits are produced) of 1.023 MHz. The code modulation effectively spreads the spectrum of the carrier signal (i.e. over a far a wider frequency band than is actually required by the quantity of information sent) **[3]**. This gives it high resistance to interference and non- authorised jamming. The code length is limited to 1023 bits, giving a refresh rate (or duration of the code) of 1ms. The C/A code has a fast acquisition time and is easy for users to lock onto. Each of the ~26 active satellites modulates their L1 carrier with a satellite characteristic C/A code, enabling easy satellite identification through C/A code demodulation. **[4]**

L1 is also modulated with a 50Hz navigation message, which provides GPS satellite 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**. [4]**

The normal civilian users can all but forget about the P-code due to its encryption. Unfortunately the situation was made worse still in the 1990's through the introduction of Selective Availability (SA); a deliberate distortion of the satellite signals, preventing civilian users from fully utilising the full capabilities of even C/A code. SA is a time varying bias involving either manipulation of the data message (epsilon) and/or clock frequency, with the SA bias being different for each satellite **[4].** Just as the pseudoranges are combined, so must the SA biases from each satellite being tracked at a particular time be combined to form the navigational solution. The real problem for SA users is that SA is a time varying bias with low freq. terms in excess of a few hours. This makes averaging of individual pseudoranges (to effectively average away the SA effects) impossible for times less than a few hours. Fortunately for many time and frequency applications, a technique known as static positioning may be used. This allows for position determination using a stationary receiver, allowing implementation of averaging techniques, which greatly improved accuracy. **[3]**

One of the advantages of the GPS system and indeed an essential feature of operation is that despite deliberate degradation of, and partial restriction to, the carrier and codes, the carrier and data modulating frequencies are held to very precise tolerances. **[5]**

PURE C/A CODE RECEIVERS

Many low cost receivers track the low frequency (w.r.t. the carrier frequency) 1 MHz code phase. Internal synthesisers (to the receiver) produce SV specific PRN codes, which are then correlated, with the C/A code as received from each SV (with unique PRN) at the antenna **[4].** This method enables this arriving code phase to be evaluated (to within a 1ms ambiguity) using the auto correlation method (as described excellently in **[6]**) to within 10ns within an observation time of about 1s (for an explanation of exactly what happens see **[4]**). By using the time tagged data within the navigation message it is possible to remove the final 1ms ambiguity.

The auto-correlation method (auto correlation is the method by which a signal is compared with itself to find the extent of correspondence between the signals) measures the difference between the propagation time as expected according to the orbital data and the propagation delay as actually measured at the receiver. This gives the time offset of the internal receiver clock relative to the (apparent) GPS time as realised using the satellites in view. It can be calculated that the 10ns code phase evaluation in 1s translates to a frequency determination capability between two successive code phase measurements 1 s apart of 10^{-8}. A pure code phase receiver is therefore only able to discipline an oscillator (say an OCXO) to within 10^{-8} of its nameplate frequency. This is simply not good enough for modern day time and frequency applications. **[5][6]**

Receiver noise limits this accuracy and this may be partially overcome by using averaging. The problem with averaging is that, as always, short-term frequency fluctuation detection is delayed according to the averaging time (similar to τ in the Allan deviation) used. This will mean that the receiver will have a slow response time to any frequency errors in the oscillator that it is disciplining. Therefore using only a pure C/A code receiver, only oscillators, which have a good inherent stability, are capable of being disciplined. **[5]**

CARRIER PHASE

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. **[6]**

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 **[6]**

CARRIER AND CODE PHASE

The problem of the carrier phase evaluation method is that different cycles are incapable of being distinguished from each other. This makes it impossible to determine the propagation time of the signal. In a normal time and frequency oriented (i.e. not a costly geodetic receiver where different techniques are often used) receiver the modulated coded sequence must be utilised to determine the propagation time (from which all other properties are derived). The advantage with measuring the carrier phase is that it yields a very precise calculation of the rate of change of the time of flight (i.e. the time differential of the propagation time). Integration of carrier phase gives you a very accurate propagation time. **[5]**

Therefore the ideal solution is to somehow combine the code and carrier phase measurements so that you get the absolute but noisy information from the C/A code and the extreme (relative) precision from the carrier phase. This will give you the smoothed propagation time without time delay (which results from averaging). This method reduces the receiver noise to nearly zero, making the accuracy of the evaluation not receiver dependant but signal dependant.

The receiver actually performs several independent carrier phase measurements once a second dwelling on each satellite for approximately 80 to 640 ms (quasi simultaneous satellite tracking), the results from which are averaged. By performing an Allan deviation on this measurement method the limiting effect seems to be white frequency modulated noise and not some systematic error. As stated earlier this method enables you to get away with one time multiplexed channel with parallel evaluation.

DIFFERENTIAL GPS

However good you make your receiver, if you operate it 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 may be partially eliminated by modelling the local conditions, but in 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. **[5]**

One test of the accuracy of your receivers is not their absolute accuracy, rather the ability of two co-located (i.e. subject to the same systematic delays like SA and ionosphere) to agree. Each receiver is assumed to be independent (which in a sense it is not because each is subject to the same systematic errors) and tracks a satellite with SA activated. The resulting plots of the time development of the internal clock offset of each receiver clearly show the results of the SA perturbation of the signals. This is apparent for each receiver. Taking a closer look at the difference between the code phase measurements made by each receiver, reveals that whilst a certain common factor is removed (i.e. each receiver suffers from similar though not identical delays and perturbations) the remaining amount does not show noise-type characteristics. It is probably due to multipath reflections (i.e. the signal can be received at the antenna after reflecting off an object not by the direct route), which differ between receivers. This illustrates the importance of carefully selecting antenna positions for timing applications and the use of quad helix antennas. **[5]**

This problem can be partially eliminated if carrier phase measurements are taken into account. The higher frequency of the carrier c.f. the code reduces the effect of reflections and improves the accuracy between two co-located receivers to ~5-10ns wrt apparent GPS time. This is an excellent demonstration of the ability of combined carrier and code phase evaluation to deliver high accuracy (agreement between two co-located receivers) in short observation times

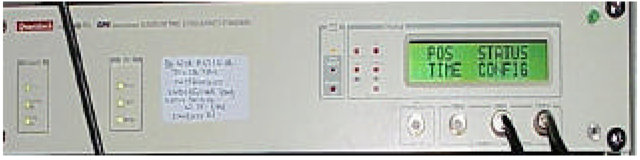
THE QUARTZLOCK GPS-DO SERIES

The Quartzlock line of GPS disciplined oscillators is based upon the type of combined carrier and code evaluating receivers described above. More detailed information on the Quartzlock GPS-DO operation may be found in **[5]**

i) **Down-converter**:

This is not just a signal preamplifier, it has been designed as an integral part of the receiver. Its purpose is to reduce the frequency of the signals travelling down to the receiver. The arriving signal at the antenna is referenced to the receiver local oscillator. Travelling up the down-converter cable to the receiver will be a 92.07 MHz reference frequency from the local oscillator and DC power from the receiver. The 2nd IF signal (the first being at 102.3 MHz and is confined to the receiver) at 10.23 MHz travels down the cable to the receiver. This will reduce the cable loss cf. the 1.6 GHz carrier signal frequency and thereby allow the use of lighter and more flexible cable.

Figure 1: Quartzlock A8-Rb GPS disciplined rubidium.



ii) **Antenna**:

This is a quad-helix antenna and is mounted to the down-converter by means of type N connectors (due to the frequency being transmitted between them). If cable must be fitted between the antenna and down-converter then the maximum (theoretical) loss when carrying the 1.6 GHz carrier signal should be not greater than 3 dB. Thus a short length of RG213 (<2.5m) would acceptable. In order to obtain the peak performance out of the unit, the antenna must have a good view of the sky. Ideally the antenna position should be known accurately (i.e. to within +/- 2m latitude/longitude and +/-4m altitude) before operation, as this will reduce the time to first fix (TTFF). One advantage of using the quad helix antenna is that troublesome multipath effects are all but eliminated. **[7]** Multipath is a signal arrival at a receiver's antenna by way of two or more different paths such as a direct, line-of-sight path and one that includes reflections off nearby objects. The difference in path lengths causes the signals to interfere at the antenna and can corrupt the receiver's pseudorange and carrier-phase measurements. Multipath error is the GPS positioning error caused by the interaction of the GPS satellite signal and its reflection. The positioning error is due to interference between the radio signals, which pass from the transmitter to the receiver by two paths of different electric length. **[3]**

iii) **Time constant**

A short (loop) **time constant** will give a very fast response time to time errors. The problem with this is that little or no averaging is done to eliminate SA, leading to a significant degradation of the short-term frequency stability. (c.f. free running oscillator stability). This is fine for timing applications. A long time constant will allow for slow response to time errors but will 'ride' over many of deleterious effects of SA and allow the short-medium term stability to be primarily determined by the local oscillator. However, the user must be careful that he does not select a large maximum time constant without knowledge of the (frequency) performance of the local oscillator. The loop time constant may approach the maximum time constant too quickly for the LO, and not correct for errors in the LO. This could cause LO time errors to exceed a certain threshold for a small period of time. However, if this is only for a short period of time, time coherence will not be lost (time accuracy will be restored without any loss or gain of cycles-cycle slips- at a frequency output wrt the 1pps output). This ensures coherence between the time and frequency outputs. A far worse situation will occur if the unit has undergone a power failure. In this case, the error that will have build up in the LO that only way to restore synchronisation will be to reset the time counters in the receiver. Such total loss of synchronisation would cause a red LED to flash, alerting the user to this problem. If the apparent time error δt relative to apparent GPS time has exceeded a predetermined threshold for more than a set time, then the oscillator control time constant is automatically reduced 1s/s until the error drops back below the threshold value. **[5]**

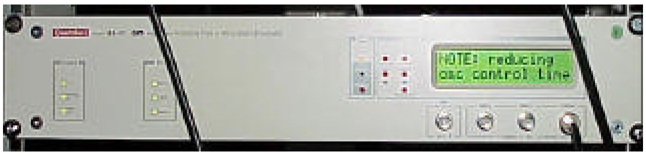


Figure 2: A8-Rb indicating that the time constant is being reduced automatically

iv) **Positioning**-

Ideally the antenna position should be known accurately (i.e. to within +/- 2m latitude/longitude and +/- 4m altitude) *before* operation, as this will reduce the time to first fix (TTFF). If this is impossible (likely), then the receiver must attempt to estimate the position for itself. This necessitates at least 4 satellites being visible (3 for spatial dimensions and 1 time dimension). In order to be able to assist the receiver, the user has the option of entering an approximate position (and also approximate time) which will help the receiver search for satellites that *should* be visible according to the almanac stored in the receiver. This is a set of parameters similar to the more precise ephemeris data, which is used for approximating GPS satellite orbits. In order for the required 4 satellites to be visible for an acceptable period of time, the aforementioned antenna position must be good. An obstructed view of the sky will reduce the time when at least 4 satellites are visible will drop, the geometry of constellation will be degraded (complicated and difficult to model) and the overall time to determine an accurate position and time will increase. **[5]**

Studies **[8]** have shown that there appears to be a ‘hole’ in the GPS constellation looking north. It is therefore doubly important that the antenna have a ‘good look’ south. In order to eliminate single position estimate errors an position averaging procedure is carried out in receiver, with up to a day’s worth (86400) of 1-second estimates capable of being averaged. Due to the way memory is assigned in the unit, no further updates are made subsequent to this. One way of improving the position determination is to turn the unit on for 2 days, note the ~24hr average and then repeat the process as many times as you see fit. Taking the standard deviation will give the precision of the position determination, and will allow manual entry at switch on. The receiver can be forced to then operate on this (entered) position. Determination of accurate altitude, whilst more difficult to do, is more important. This is because the satellites are always at a positive altitude **[1]**

Tests have shown that using this method the Quartzlock model can ascertain it’s position to within +/- 2m latitude/longitude and +/-4m altitude to within a 95% (2σ) certainty **[8]**. The last digit on the display in the position menu has a resolution of about 1.8m longitude and 1.8cosX, where X is the latitude of the receiver. At 55°N this gives about 1.2m. This means that if two co-located receivers agree down to this last digit, they agree to within to within 1.8m and 1.2m in longitude and latitude respectively. However, in the serial port data, which is viewable through specially designed monitoring software, an extra digit is supplied, allowing precision down to the ~10cm level **[9]**. By performing the manual averaging procedure at this level of precision the user gets unrivalled antenna position determination, and the associated benefits this brings.

Like most GPS receivers of this type, this series references its position to the world geodetic system 1984 (WGS 1984) with the altitude being relative to the geoid. Whilst the geoid is much more complex than the simple ellipsoid, it is an approximation of the true shape of the earth and is therefore closer to mean sea level for most places on earth. The difference between the ellipsoid and geoid is stored within the almanac data contained in the navigation message. The receiver has a plausibility checking method to ensure that erroneous entered positions are not used, making continuous comparisons against it’s own averaged position. This should prevent undue timing errors resulting. The user should also ensure that after 24 hours the averaged position agrees with the entered position to within +/- 3m latitude/longitude. If this is not the case, the entered position was wrong! It is also important to tell the unit what position to use. If the user has a very accurate position, determined either through a geodetic survey or repeated position averages (both with same unit and different co-located similar units), then the user must instruct the unit to use this (not the result from the last position average estimate)

v) **Warnings**

In order for the unit to operate properly the unit must be set up as detailed in **[5]**. If a fault exists at the power up of the unit, indication is likely to be given via a front panel warning display. An common example is if the entered position failed the plausibility check, i.e. the receiver has switched to using averaged position or if satellites have been found that *should* be below the horizon according the almanac data for that position). Many of these initial problems will go away as the averaged position is used or the almanac data is updated (after about 15-20 minutes after switch on). Other problems like a missing antenna, down-converter or cable (or indeed if any of these are faulty) will only be detected once the internal LO (normally OCXO or rubidium) has warmed up. These can take up to 10 minutes depending on the type of oscillator used. Such messages would need to be thoroughly investigated if normal operation is to be obtained from the unit. Indeed, the amount of noise detectable is a good indication of the health of the receiver. A partially or totally obscured antenna could cause insufficient or no satellites to be seen.

However, quantification of GPS-DO signal degradation due to different levels of antenna obstruction is difficult, but work is on hand to do this. It is important to remember that the RMS errors in apparent (i.e. as realised locally) GPS time will be greater than with a full constellation. The solution, as always, is to improve the antenna position, to reduce the instances when this might happen. Other errors may occur if the user was tracking a particular satellite and it went (temporarily) out of view. The receiver in this case would resort to an ‘all in view’ mode.

Another important message indicates whether the control voltage, which is applied to the local oscillator to correct for frequency excursions, is above a certain normal threshold. Abnormally high voltages being applied (c.f. what the receiver believes should be applied) indicate problems with the local oscillator associated primarily with drift/ aging of quartz crystals or possible failure of the rubidium physics package. Normal operation (i.e. output precision is not necessarily adversely affected) is continued whilst this message is displayed, but future investigation should take place. If it occurs during the first few minutes of operation in a rubidium oscillator, it may well simply be a result of the control DAC limiting. This is due to the very small adjustment range of the Rb oscillator (the software for the rubidium option is different for the rubidium LO than for the OCXO LO, to account for their different characteristics). This message will then go away after the rubidium has warmed and settled.

vi) Delay

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 designed to calibrate out ionosphere and troposphere delays, and antenna/down-converter/cable delays. This is important if the GPS-DO is to be used for time dissemination i.e. not as a frequency standard. 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.

vii) Time

The time will be displayed including seconds as soon as the receiver has started tracking at least one satellite. Upon turn on the seconds are suppressed because of the uncertainty associated with only having the internal back-up clock as a reference. During the period between power up and satellite tracking commencement, the user is free to alter the time manually because the internal master clock is not ‘set’. Setting involves confirmation by a satellite. Manually altering the time to within ~30 minutes of GPS time reduces the TTFF by providing a time estimate for the receiver to ‘going-on’ with. Occasionally almanac data stored in the receiver will be too old for UTC to be calculated from GPS (i.e. once locked) until new almanac data is downloaded from the space vehicles. During the time taken to achieve lock (i.e. δt & $\delta f/f$ are within prescribed limits-different for each LO and are of opposite signs) the 1pps remains inactive.

Testing of the A8-Rb

The unit has undergone a variety of tests at major timing centres around the world in the period since its first production back in 1995. These results will be presented below along with a brief outline of the apparatus used to test such high performance unit

a) NPL 1997

During the period between January-March 1997 Quartzlock participated in the extensive study into GPS-DO’s undertaken at the centre for time metrology at NPL, UK **[8].** The full description of the equipment set up is detailed in the report on the study. During the study the reliability and performance of the overall unit, as well as the component parts of the GPS-DO like the slaved rubidium oscillator, the disciplining algorithm and the antenna was examined. Performance testing involved the testing of both the 1pps time output and 5 MHz frequency output using a 1ns counter timer and a high resolution phase comparator respectively. Data was recorded for an extended period of time. All the following results came from **[8]**

i) Position determination

The ability of the GPS to ascertain position was examined by comparing the results of the units estimation with that of a precise ordnance survey site survey. The results showed an accuracy of ~2.5m in both latitude and longitude and ~ 5m in altitude (ellipsoid). The total GPS-DO co-ordinate error was 5.79 m. The spread of values for other manufacturers ranged from ~1.7m to 51m with the mean being ~20m. Whilst NPL reported no correlation between ‘frequency performance of the GPS-DO and the accuracy of the determination of their antennae co-ordinates’, it did report that frequency transfer performance of the GPS-DO is limited by the co-ordinate determination. Whilst theoretically good antennae position determination is critical for absolute time transfer performance of the GPS-DO, in practice NPL found that GPS-DO hardware delays dominated the time dissemination error budget. Reducing hardware delays will bring the accuracy of the GPS-DO antenna co-ordinate determination into focus.

ii) Time dissemination performance

Of paramount importance for a GPS-DO is the quality of the 1pps output. NPL sampled both once per second and also once per hour, enabling them to compare the hourly mean of the individual readings against the readings sampled once per hour. It was noted that for a GPS-DO where the medium term stability was well controlled, like in the rubidium-based model A8-Rb, the standard deviations of the above two measurements agreed. The A8-Rb had a data spread of 145ns (14 unit mean being ~350ns, with the data from one model, 3400s, being left out in this mean), with a standard deviation of 31.2ns and 31.4ns for the individual and hourly mean readings. The mean of the 15 units was 47 and 32 for the individual and hourly mean readings. The standard deviation, however, of the typical 24 hour reading (minute means) of the 1pps reading was excellent for the A8-Rb at 2.4ns, the lowest of all units tested and compared to a mean of 34.3ns. The excellent performance of the A8-Rb on the 24 hour readings could be attributed to the excellent medium term frequency stability of the unit (10,000 to 100,000 seconds). It was also noted that at times the cheap Motorola Oncore receiver outperformed some GPS-DO, as locking to an oscillator did not seem to improve time dissemination capability.

iii) Frequency dissemination performance

NPL used a phase comparator to compare the standard frequency outputs of all the units under test, having first ascertained the phase stability of the unit. Both the 1pps and phase data was used in calculating the frequency stability’s and frequency offsets of the units. Due the 1ns counter timer resolution the results from the 1pps data are slightly noisier than those obtained from the phase data. As the 1pps and phase data on the A8-Rb are correlated, this should be borne out in the statistical analysis. However, due to the extreme short-medium term stability of the A8-Rb, the amount of noise from the counter timer, degrades the stability of the data from the 1pps at this level. The Allan deviation at $\tau = 1$s, 1000s and 100,000s from the phase data was 8E-12, 4E-13 (mean 2E-11) and 2E-13 respectively, with the 1000s 1pps stability being 1E-12 (mean 3.7E-11). The mean frequency offset of the unit at 1s, 1000s and 100,000 seconds was 1.2E-11, 5E-13 (mean 1.53E-11) and 1.6E-13 respectively, with the 1000s 1pps offset 1.3E-12. This excellent performance can be attributed to the quality of the internal rubidium LO, which enables long time constants to be used to smooth/ride over the SA perturbation and prevents degradation of frequency stability of the rubidium oscillator. It was stated in the NPL study, that the long term frequency stability and offset were slightly disappointing. Upon reflection, this may be because the unit was operated with the time constant at its maximum of one day. Whilst this allowed for degradation-free short-medium term performance, quite naturally it created the characteristic bump at averaging times similar to the loop time constant. It was noticed that other models had much shorter time constants, which would degrade their medium term performance, but allow for their long-term performance to approach that of the onboard Cesium/Rubidium clocks.

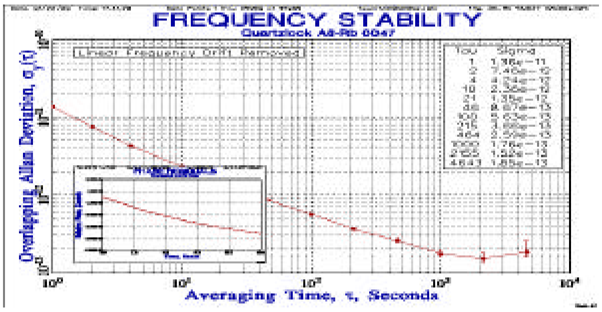


Figure 3 Plot of short term stability against averaging time for a very stable rubidium with a long time constant.

As mentioned earlier, this loop time constant can have a upper limit imposed upon it, which may differ according to the intended use of the unit. If the frequency stability at 1 day is important, say if it is operated as clock, then the user may wish to impose an upper limit of say 20000s, which would improve the stability at 1 day, without the medium term stability suffering an unacceptable degradation. These results are summarised in **Table 1**

iv) Free running oscillator/Holdover

In order that the quality of the local oscillator be assessed, the access to GPS signals was blocked for a period of time through placement of the antenna in an absorbing medium (or setting of the mask angle to 90°). One way to do this with the A8-Rb would be to inhibit the automatic disciplining of the oscillator by turning of the control switch, which allows the user to manually set the DAC value to zero. At the time of test, the A8-Rb did not freeze its DAC value at all, either optimally or sub-optimally. Subsequent to this test, Quartzlock have built in a ‘holdover mode’. The A8-Rb would go into holdover and 'flywheel' on the internal rubidium oscillator. The mode would be activated if no satellites were detected for >20s provided that the position meets certain criteria. It is maintained for no longer than three times the current control time constant at the time of loss of GPS signals. Basically the control voltages are maintained to the LO (i.e. the rubidium) and so the frequency offset will remain approx. the same for this period of time). The control time constant can be up to 64400s for an A8-Rb, which has a very good internal rubidium and has been running for many weeks. Basically a week after installation with a medium quality rubidium, the control time constant could be ~28800-42000 s. i.e. the A8-Rb can stay in holdover mode for up to about 1.5 days, with the max being just over

Table 1

Parameter	**Quartzlock A8-Rb**	**Mean**
Position determination	5.79m	20m
Time dissemination (standard deviations)		
Individual 1s readings	31.2ns	47ns
Mean of individual readings	31.4ns	32ns
24hr reading (minute means)	2.4ns	34.3ns
Frequency dissemination		
Stability (Allan deviation) (5 MHz)1s	8E-12	
1000s	4E-13	2E-11
100,000s	2E-13	
(1pps) 1000s	1E-12	3.7E-11
Fractional Frequency Offset(5 MHz)1s	1.2E-11	
1000s	5E-13	1.53E-11
100,000s	1.6E-13	
(1pps) 1000s	1.3E-12	

2 days. It is unheard of that the user would have his GPS signals blocked for this period of time. If he can't get any signals for period of time, then his unit (antenna, downconvertor, cable etc...) is faulty and should be replaced. By flywheeling off the internal rubidium you ensure continuous operation of the 1pps (which is not activated until first time lock is achieved), Work is currently underway at USNO to advise users concerned about what happens when your GPS signal is blocked. Quartzlock have detailed to USNO what happens to the A8-Rb when this happens.

b) **IEM Kvarz**

IEM Kvarz is a manufacturer of both active and passive hydrogen masers, and have the worlds 'best' measurement capabilities. The active maser ensemble is one of the most stable ensembles in the world and is used for testing and characterisation of all active masers before shipment. Using a phase comparator taken from the active maser and a signal from the active maser ensemble, a 5MHz signal from the A8-Rb was tested for its frequency offset over a long period of time. The idea was to supplement the short to medium term data gathered at NPL, and show that if the time constant is appropriately set for long term frequency offset and stability, the A8-Rb is capable of reproducing the extremely good long performance conferred by the Cesium derived GPS system. The results were that the mean fractional frequency offset over 33 days was ~5E-14. This is similar to other high quality GPS-DO's, that have well implemented disciplining algorithms. **[10]**

c) PTB

The PTB have some of the most stable clocks in the world, with 3 laboratory primary Cesium clocks contributing towards the correction introduced into TAI from primary frequency standards (like NIST-7 and LPTF-01). This makes it ideal for long term testing of frequency standards. Using time interval counting techniques the 1pps from the A8-Rb was compared with the 1pps from one of the clocks. The sub nanosecond resolution of the time interval counter gives <1E-14 frequency resolution over 1 day. The mean fractional frequency offset over 5 days was ~5E-14, providing an independent verification of the results from Kvarz. Hydrogen masers were also used to verify these data. **[11]**

d) NIST

An A8-Rb will be shipped at the start of February for testing and analysis over a period of, hopefully, about 3 months. The results of this study will be eagerly awaited. Quartzlock also use the NIST frequency measurement service **[12]** Using this system we are able determine the offset of our Passive Hydrogen Maser (PHM) against GPS using hourly measurements on a 25 ps time interval counter. We are then able to determine the offset of 4 other standards against the (NIST traceable) PHM. Using this method the PHM was ~1.5E-12 high –vs- GPS averaged over 1 month whereas the A8-Rb was 1.5E-12 low against the maser. A simple calculation (not necessarily that accurate) would indicate a frequency offset for the A8-Rb in the low E-13 or E-14 over 10 days. Future tests should bear this out.

THE INTEGRATION OF GPS AND GLONASS

The introduction of the Russian Glonass system was made way back in 1982, but the wide spread commercialisation of the system was hampered due to the lack of available timing receivers. As the timing awoke to the benefits of using Glonass, several units have recently appeared on the market. Glonass offers users several advantages over GPS because on the most basic level the carrier signal is free of both selective availability and antispoofing, and is thereby freely available to both the civilian and military user alike. Currently there exist about 4 commercial integrated GPS-Glonass receiver, with some out of action due to Y2K failures. At the present time the Glonass system consists of ~14 operational satellites with the system designed to accommodate up to 24, Like GPS the carrier signals are modulated by both a C/A and P code. The use of an unencrypted P-Code has the major advantage that it's frequency is 5 times that of the GPS C/A code (whose P-Code is not worth considering for civilian users as it requires decryption techniques). This has the advantage of improving pseudorange measurement precision. Unlike the GPS C/A code, the Glonass P-code is transmitted on both the L1 and L2 frequencies. As is detailed in **[13]** this may be used for ionospheric corrections (the delay of a signal through the dispersive material like the ionosphere will depend on the frequency, so using two different frequencies will enable this delay to be calibrated out of receiver).

As always, there are complications with using a new system.

i) The Glonass system transmitted its message on 48 frequencies (as opposed to 2 for GPS). This is coming down to 24 eventually, but nevertheless problems ensue with frequency dependant delay biases. This is not a serious problem, but does make matters more complicated. One advantage of this method, however, is the reduction in jamming (intentional or unintentional) through the disabling/rendering unusable of carrier signal. Safety in numbers! **[14]**

ii) A more serious problem up until recently was that no post processed Glonass precise ephemerides were available. The reason these are needed are that the standard broadcast ephemeris is not good enough (orbit determination not accurate enough) for the highest accuracy time transfers **[15]**. There is a standard format for IGS precise ephemeris. The situation is that these are now available, as a result of the intensive IGEX, in the desired International Terrestrial Reference Frame. The GLONASS precise ephemeris may be downloaded from the WWW from key IGS analysis centres It is continuing on a "best efforts" basis, until all the GLONASS satellites fail or the Russians launch some more! **[15]** This is the biggest single reason for concern amongst the time community and also the reason even more intensive work is not going on. We are just guessing on the long-term future of GLONASS. IGEX will become an International GPS Service (IGS) working group, and will become an IGS service if GLONASS survives in the long term. **[15]**

iii) Until towards the end of 1996, the Russian Time scale UTC (SU) was not synchronised to UTC, and differed by 35ms (modulo 1s). Several improvements during the last 3 years of 9000 [UTC(SU)] and 35300 [Glonass time] nanoseconds on the 27th Nov. 1996 and 10th Jan 1997 respectively moved UTC(SU) nearer to UTC (BIPM). In response to this the Glonass time scale was frequency adjusted to be nearer the frequency of UTC (SU). Both these measures have helped synchronise Glonass to be nearer internationally accepted time scales like GPS time and UTC (BIPM) to within a few hundred nanoseconds and further changes are expected in the near future **[14]**

iv) Due to the lack of absolute calibrators, Glonass receivers, until recently, did not have their total internal delays quantified. GLONASS has no broadcast ionospheric corrections, and so the simplest common-view GLONASS time transfers will us poor broadcast GLONASS ephemeris and no ionospheric corrections. The results are not as good as GPS. This limited knowledge of UTC Glonass to several hundred nanoseconds (cf. tens of nanoseconds for GPS with SA operational. Therefore real time dissemination of UTC through Glonass was until recently severely hampered. Using IGS analysis centre precise ephemeris and ionospheric maps the time transfers may be dramatically improved. This is a lot of work and more will not be done until people are sure that GLONASS is here to stay. 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.

v) The reference frames used by GPS (WGS84) and Glonass (PZ90) are different. The conversion is a global problem and has been done. However, the two frames keep moving wrt. each other. It would better to use the same frame with precise ephemeris. You may however want to use GLONASS "stand-alone" when you need to sort out the co-ordinate transforms.

vi) By increasing the number of satellites that are available at any one time, (it has been shown that with an integrated system the user is able to see 9 satellites 90% of the time)

EGNOS and WAAS compatibility

WAAS provides for the FAA and air navigation a performance level higher than SPS or other differential GPS systems. It improves accuracy, availability, integrity and continuity of service. GPS signals are continually monitored and the WAAS satellites transmit an augmentation message. The format and bit rates are different from L1 even though they are on the same frequency. **[16]**

EGNOS is a good idea, EGNOS is the European GPS overlay system. GPS like signals, GPS integrity information, and differential corrections will be supplied, and there will be no SA. It's here to stay. It is great for time transfer because you can use a cheap directional antenna with the geostationary satellites and eliminate multipath. This also affects the performance for a disciplined oscillator. Galileo is the European follow-on that should be completely independent of GPS. The navigation message is different to GPS. **[15]**

Special receivers are necessary for to use the capabilities of WAAS and EGNOS. However the integrated GPS-Glonass engine is capable of processing both WAAS and EGNOS signals. This capability will be discussed in future papers.

Future issues to address

i) As already pointed out by many better-qualified people **[14],** the problem of temperature cycling must be addressed in the unit. There are two areas where attention is needed. Firstly to quantify the effect of temperature variation at the antenna, and especially downconvertor. Secondly examine the effect of temperature change on the rubidium local oscillator. For the first case, the ideal solution seems to be some method of oven encasing either antenna/downconvertor, or all of the elements exposed to the outside (this includes the cable). For the second case a preliminary temperature controlled fan has been built to temperature stabilise the rubidium, although it has only gone through the first stage of development. More work is needed.

ii) Whilst preliminary investigations have been carried out into the integrated GPS-Glonass engine, the company is still some way from having a production model. At the time of writing, a prototype 16-channel engine is being thoroughly tested. It is hoped to have a production model by the end of the year.

iii) The unit must be absolutely calibrated to compensate for cables, ionospheric/tropospheric and other delays. A setting resolution of 1ns should make this easy once work is done to quantify these delays. Until recently this was unnecessary as the unit was primarily promoted as a frequency dissemination tool.

Potential users for the A8-Rb

i) Due to the ability of the receiver to be set to track a particular satellite, one use could be to integrate the BIPM tracking schedule into the receiver and make it operate as a common view receiver. The cost would be greatly reduced cf. receivers available to user at the moment

ii) Due to the excellent short to medium term (1-100,000s) frequency stability of the unit, it is more than capable of being a 21st century replacement for Cesium for many applications. It is important to bear in mind that in the short term, the frequency dissemination performance is determined by an excellent rubidium oscillator, with performance equal to or better than commercial Cesium for averaging times up to about 10,000s. After this time, the loop time constant will cause a slight perturbation in the frequency stability, where after it will improve once again due to GPS disciplining. The cost of the unit is ~1/3 that of a commercial Cesium (with high performance tube). The imposed 7-year life time of the tube and the associated costly replacement is removed. Upon failure of the rubidium physics package, replacement costs are far less

iii) With the proposed integration of a new GPS-Glonass engine into the unit, the unit will then have the capability of providing ionospheric correction required for atmospheric monitoring. This is furthered detailed at this conference in my paper in the atmospheric effects session.**[13]**

iv) Due to its effective holdover mode, the A8-Rb may be implemented for telecom network synchronisation at the Stratum 1 and 2 levels. Telecoms users are naturally concerned about synchronising a network to carrier controlled standards, but flywheeling off the rubidium oscillator during any GPS outage or blockage prevents any degradation in either the frequency offset or the frequency stability during such an event. The unit meets and exceeds all time deviation requirements and indeed can also be used for GSM PCN base station commissioning.

v) It's medium cost enables it to be used in laboratories seeking traceability to the national time scale in their country, and may be used for used in the laboratory for calibration of counters, timers, radio test equipment and quartz based instrumentation

vi) Integration of Glonass prevents the user being totally dependent upon the US military. Despite repeated declarations regarding the continuation of service to the civilian GPS community, there are still users concerned about, or prevented from, using the system in their area or country. Glonass should hopefully bring more people into contact the benefits of GPS/Glonass technology

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