POSSIBLE APPLICATIONS OF ATOMIC FREQUENCY STANDARDS WITH AN INTERNAL HIGH RESOLUTION DIGITAL SYNTHESIZER

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1 INTRODUCTION

This paper reviews the applications of Atomic Frequency Standards with an internal synthesizer (thereafter referred as "Synthesized Frequency Standards or Oscillators") with a special emphasis on the Rb oscillator. A fractional frequency synthesizer, developed by SEPA, has been incorporated in the Frequency Locked Loop of a TFL Rubidium Frequency Standard. This combination allows a frequency settability in steps of $1.5 \cdot 10^{-12}$ (optional $1 \cdot 10^{-13}$) over a range of $6 \cdot 10^{-9}$ without having to resort to change the C-field to tune the output frequency of the device. This capability, coupled to the excellent short term stability of the Rb frequency standard, opens new possibilities for time and frequency users in the various fields (time metrology, navigation, communication, etc.) in which stable frequency standards find their application.

In time metrology, the capability to precisely tune the frequency of the atomic standard will provide the same benefits that are now achieved by the combination of a frequency standard and a phase microstepper; the immediate application will be the generation of primary and secondary time scales, by steering the output frequency of the synthesized standard with reference to some other physical device or to a computed time scale: this will provide a hardware implementation of the "paper clock" which constitutes the "ideal" time scale in primary and secondary laboratories.

The high resolution frequency settability of the output signal of the standard may have some uncommon applications, such as the generation of other time scales, as the sidereal time for astronomical uses. Fine frequency and time offsets, the latter with a resolution as small as a few picoseconds, can be generated with the synthesized standard, allowing remote clocks to be precisely set at the same frequency and time, or with controlled offsets in time (and eventually in frequency) to provide a "coordinated" time network. This is important in communications networks, where clocks at the nodes must be kept not only syntonized but synchronized with offsets which account for the relative propagation delays within the same nodes in the network.

Electrical-power generation and distribution systems, and ground-based positioning systems will, for the same reasons, undoubtedly benefit from atomic standards incorporating a synthesizer, but applications exist to exploit the settability and stability of the atomic frequency standard for other navigation applications. In GPS receivers, for instance, where, once synchronized to the GPS System Time, the local oscillator can provide a flywheel to split the solution in its time and space components; in this way, no degradation is expected if the number of available satellites is reduced to 3 because of intentional jamming or satellites masking due to banking manoeuvers.

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In some particular communication and navigation applications, where minimum exposure is required, keeping the internal Pseudo Random Noise (PRN) generator of the receiver synchronized to the transmitted PRN code, even when this is not actually received, will minimize the exposure by reducing or zeroing the acquisition time when required to track GPS satellites or to communicate through a secure data link.

2 DESCRIPTION OF THE SYNTHESIZED Rb OSCILLATOR

A few frequency standards with a built-in digital frequency synthesizer (for a good review of frequency synthesizers see ref. 20) are currently available on the market: most of the H-masers (refs. 8, 9 and 10) and both Hewlett-Packard (HP) and Frequency and Time Systems (FTS) new cesiums (refs. 16 and 17) incorporate a synthesizer within their frequency locked loop. The HP 5071A Cesium Beam Frequency standard claims a ultra-high resolution of $6.3 \cdot 10^{-15}$ over a range of $1 \cdot 10^{-9}$ and a stability of $2 \cdot 10^{-14}$ for an averaging time of 5 days.

In the Synthesized Rb Oscillator, jointly developed by TFL and SEPA (refs. 1 and 2 and fig. 1), a high resolution fractional frequency synthesizer has been inserted in the frequency locked loop to effectively control the output frequency of the device with a resolution of $1.5 \cdot 10^{-12}$ [optional $1 \cdot 10^{-13}$, since the short term frequency stability of the TFL Rb oscillator may reach $2 \cdot 10^{-13}$ for an averaging time $\tau = 1000\ s$], without resorting to the C-field method for frequency control. In the final device, many other novelties are introduced for the first time in a small Rb oscillator (see the block diagram in fig. 1):

- a.c. C-field modulation, with the aim to reduce the sensitivity of the device to external magnetic fields;
- auxiliary outputs, to provide 50 Ω impedance, TTL-level compatible, 1 pps and standard frequency outputs, in addition to the main 10 MHz sinewave standard output. The TTL output frequency can be electrically selected to be 10, 5, 1 or 0.1 MHz, and the 1 pps output is automatically synchronizable to the leading edge of a reference pulse.

These features make the device ideally suited for stand-alone operation or to be incorporated in timing systems, in the full range of possible applications. For additional informations on the device, the reader is referred to refs. 1 and 2; in the following we will cover in general the benefits deriving from the use of synthesized oscillators in a non-exhaustive list of possible applications.

An immediate benefit, which should be mentioned here since it relates directly to the performance of the atomic standard, derives from the recognition of this basic fact: the operation of an atomic frequency standard can be optimized, even of an order of magnitude, if no constraint is placed on the output frequency derived from it. This means, for instance, that its frequency stability can be improved if we allow a slight detuning of the output frequency due to adjustments in the interrogation RF power, magnetic field, etc. Years of research in this direction, carried on mainly by Andrea De Marchi at NIST, have resulted in an impressive list of papers (refs. 11-14 and 18-19) supporting these claims.

However, the end-user needs a "nominal" output frequency from its reference oscillator, and the incorporation of a synthesizer within the locked loop of the standard allows to "recover" a nominal value for the output frequency, since it controls the output frequency independently from the parameters of interrogation of the atomic resonance. This has been a major factor in improving the performance

of atomic standards, resulting in specifications as those boasted by the HP 5071A Cesium Beam frequency standard.

3 FREQUENCY AND PHASE CONTROL

In the majority of existing frequency standards, based on frequency or phase locked-loops to atomic resonances, the frequency control is achieved by means of changing the magnetic field (C-field control): this may result in unpredictable changes due to residual hysteresis effects and changes in the magnetic susceptibility of the standard. Moreover, the control is non-linear over a wide range, non-repeatable from unit to unit and non-reproducible even in the same unit due to (frequency) aging. These limitations have prevented the precise control of the output frequency of atomic frequency standards; as a matter of fact, for accurate oscillators, like Cs-beam frequency standards, it is strongly advisable not to change at all the C-field setting, if not for very important reasons. As a consequence, precision timing systems had to resort in the past to external devices, such as phase microsteppers, to adjust the output phase and frequency. Neglecting the noise, the output signal of an oscillator can be written as:

$$V(t) = V_0 \cdot sin[2\pi\nu_0 t + \varphi_0] \tag{1}$$

where V_0 and ν_0 are the amplitude and the nominal frequency of the signal, and φ_0 is the initial, arbitrary, phase angle. The frequency $\nu(t)$ [t is used only to indicate a dependency on time] and the phase $\varphi(t)$ are related by a simple equation, namely:

$$\nu(t) = \frac{1}{2\pi} \cdot \omega(t) = \frac{1}{2\pi} \cdot \frac{d\varphi(t)}{dt} \tag{2}$$

where $\omega(t) = \frac{d\varphi(t)}{dt}$ is the instantaneous angular frequency of the signal. If a change $\Delta\nu$ in the nominal frequency of the signal is desired, the resulting equation can be written as:

$$V(t) = V_0 \cdot sin[2\pi\nu_0 t + 2\pi\Delta\nu t + \varphi_0] \tag{3}$$

and the second frequency term can be rewritten in terms of phase drift using (2):

$$V(t) = V_0 \cdot sin[2\pi\nu_0 t + \frac{d\varphi}{dt}t + \varphi_0] \tag{4}$$

A microstepper is capable of stepping the phase of the output signal in precise amounts with extreme resolution, implementing the mechanization of eq. (4); it has been effectively used in timing systems to control the output frequency by applying phase steps at precise intervals in time, in order to simulate the phase drift due to a frequency offset: the main disadvantage of this technique is in the granularity of the control, since phase can be adjusted only in discrete steps, whose minimum value is equal to the resolution of the microstepper. Conversely, frequency control can be applied to adjust the phase of the output signal, using the same basic relationship (2); in this case a continuous phase shift Δx (see the definition below) is obtained, from the current phase to the desired phase, in a predefined time interval Δt, by applying a proper frequency offset $\Delta\nu$ for the duration Δt:

$$\Delta x = \frac{\Delta\nu}{\nu_0} \cdot \Delta t \tag{5}$$

where we have used the definition of the "time deviation" x(t), which represents the phase normalized in units of time, according to the relationship:

$$x(t) = \frac{\varphi(t)}{2\pi\nu_0} \tag{6}$$

Alternatively, the time deviation x(t) can be related to the fractional frequency error y = $\Delta\nu/\nu$ as:

$$x(t) = \int_0^{\Delta t} y(t) \cdot dt \tag{7}$$

Again, two variables ($\Delta\nu$ and Δt in eq. (5)) can be used to control the process, and no discontinuities are apparent in the phase x(t) for any choice of $\Delta\nu$ and Δt; the "granularity" appears in the frequency settability, being a direct consequence of the resolution of the internal synthesizer. Therefore, the resolution on frequency control $\Delta\nu_{min}$ constrains the minimum phase shift allowable, and, since Δt cannot be smaller than the loop time constant of the standard τ_{loop}, this effectively limits the phase resolution $\Delta x_{min}$to:

$$\Delta x_{min} = \Delta\nu_{min} \cdot \tau_{loop} \tag{8}$$

In our case, the minimum time step is given by:

$$\Delta x_{min} = 1.5 \cdot 10^{-12} \cdot 196\ ms = 0.3\ ps \tag{9}$$

where: $\Delta\nu_{min} = 1.5 \cdot 10^{-12}$ and $\tau_{loop} = 196\ ms$. However, the rms time-error noise is given roughly by:

$$\sigma_x(\tau) \approx \tau \cdot \sigma_y(\tau) = 7 \cdot 10^{-12} \cdot \sqrt{\tau} \tag{10}$$

for our Rb oscillator, where τ is measured in seconds. The minimum time error noise is obtained at the smallest integration time, which is $\tau_{loop} = 196\ ms$, and:

$$\sigma_x(\tau = 196\ ms) \approx 3\ ps \tag{11}$$

i.e., in order to resolve the time step above noise one has to perform a step larger than 3 ps.

4 APPLICATIONS IN PRECISE TIMING SYSTEMS

A synthesized atomic standard is ideally suited to drive a precise timing system; more than one oscillator can be incorporated into such a system to provide redundancy, with additional benefits compared to a standard, non-controllable oscillator. Consider the situation in which, in a redundant timing system, one oscillator fails and automatic switchover to another unit occurs. If the phase and frequency of the two oscillators are not precisely aligned, a frequency deviation and a phase jump will likely occur, and a disturbance will be generated and propagated downstream to the users of the timing signal. While the frequency offset is usually limited by the relative accuracy and settability of the standards, the phase jump can be as large as the period of the main output of the oscillator, namely 100 ns for a 10 MHz output, if indipendent control of the phase of the oscillators is not accomplished.

This situation can be avoided if precise frequency control is applied, since we can control independently the frequency and phase of each output, with a resolution adequate to keep the output signals aligned; therefore, switchover transients can really be neglected and the failure recovery procedure appears now completely transparent to any user. While these considerations already provide benefits in basic timing systems, sophisticated systems may gain additional benefits; disciplined frequency oscillators can be built, since they rely on intrinsic frequency control of the output signal. Digital versus analog implementation of the control loop is a preferrable mean of locking the output source to one or more indipendent input references, since infinite memory can be provided in the loop and more complex control laws can be easily built in the device.

In many applications of Synthesized Atomic Frequency Standards, we have a phase or frequency locked loop with a very long time constant, from hours to days. This includes also the cases where manual frequency control closes the loop. The long time constant results from the fact that the local oscillator used in the loop, the atomic standard, exhibits the best stability at these long time constants of hours and days. In these applications, the use of a synthesized atomic standard provides the following important benefits:

a. **Digital control**: is the only scheme that can be used to reliably implement very long time constants (analog schemes require high values for resistance and capacitance);
b. **Predetermined fixed frequency steps**: this allows immediate frequency control response: there is no need for experimenting first the loop response to a frequency change and then making a suitable correction.

As an example, we can consider a multiple-input system as the Frequency Combiner Selector described in refs. 3 and 4. The system accepts multiple reference signals as input and performs a near-simultaneous phase intercomparison on the input and output signals with high resolution, since the measurements are carried on using the beat signals (1 Hz) between the various sources and an offset oscillator. The phase relationships are derived by the time of occurrence of the positive zero crossing of the beat signals as measured by a high resolution multichannel event clock, with a total ambiguity (data fold-over) of one full day. A computer steers the output frequency to the best estimate of the input signals, weighted according their accuracy and statistical characteristics, and drives an output crystal oscillator through a high resolution D/A converter. The system works in a closed loop mode, since the system output (from the digitally controlled oscillator) is split and fed back to one of the input (reference) channels; therefore, a continuous measurement of the output phase is provided to effectively servo the output oscillator.

The use of a crystal oscillator as a control element prevents open loop operation of the system; open loop operation is possible only if enough accuracy and repeatability of control is available in the output oscillator: this is the case of synthesized frequency standards, since frequency changes can be programmed (open-loop) with the same accuracy by which the frequency of the standard is known. This does not imply that no measurement feedback is required at all. The frequency of the standard acting as the system output device must be measured and known; however, the time required to precisely measure the frequency of the output oscillator is no longer related to the response time when frequency changes are commanded to the output oscillator. In this case, the system effectively acts as an open loop in terms of servo control, since the output frequency is measured only to steer its nominal value to some preset figure.

The capability **to decouple the time constant of the measurements and of the system response** is the main characteristic that allows a new degree of flexibility in designing redundant timing systems, in which redundancy is not bounded to a local ensemble of oscillators, but is extended to remote clocks as well, providing cost-effective solutions in distributed timing networks. But additional applications are possible, thanks to the capability to effectively and precisely steer the frequency and phase of each oscillator. As an example we can consider another timing system, recently proposed by TFL, in which a novel way of combining reference signals from various clocks is proposed. The arrangement (ref. 5) requires a coarse phase alignement of the signals to be combined. This can be solved with additional hardware: delay lines and switches. But, the introduction of synthesized frequency standards offers this feature for free, without additional hardware and with increased resolution versus what is presently available.

Primary laboratories and national time scales are based on "paper time scales" A **paper time scale** or **software clock** is based on a weighted average of an ensemble of individual clocks. It is convenient to use a synthesized atomic oscillator in such a system in two ways:

1. to implement a **physical output** to the "paper time scale", instead of using a phase microstepper;
2. if the ensemble is constituted of independent Synthesized Atomic Standards (Rb's or Cs's), it is possible to steer all the clocks in the ensemble to follow their weighted average, i.e., to follow the software clock; in this way a very **high redundancy** of the physical output is provided, since system time can be taken from any of the Rb or Cs oscillators in the ensemble.

Indeed, this idea is even more appealing when extended to an **ensemble of distributed clocks**, not clustered in a single location but widely dispersed at the nodes of a telecommunication network. The software clock will act as a single master to the whole network, and each clock in the network will be remotely controlled by it. The frequency and phase of each clock shall be remotely compared at the higher hierarchy nodes, and the comparison made with a long time constant, to improve the filtering of the added noise induced by the communications links. The resulting data will be used to generate the weighted average for the software clock driving the whole ensamble. But more on this subject at para. 6.... The concept of "Software clock" with a physical output provided by a Synthesized Atomic Frequency Standard can be extended to the implementation of time scales related to UTC, such as TAI or Sidereal Time, where a fixed time or frequency offset may exist between the various time scales.

5 SPACEBORNE OSCILLATORS: REMOTE CONTROL

The remote control of the most valued characteristics of a frequency standard, frequency and phase, is especially important in those applications where remoteness adds an additional difficulty to the synchronization and control problems. Current atomic frequency standards used in space applications are tuned through C-field control, with all the disadvantages peculiar to this technique, or via an additional phase microstepper or external synthesizer, which represent a further load to be carried onboard, and are not immune of pitfalls: "granularity" in frequency control is peculiar to a phase microstepper, and a basic synthesizer is not capable of the resolution which can be obtained by placing the synthesis process within the servo loop of the atomic frequency standard.

Again, the possibility of decoupling the sampling time over which the frequency is measured (usually, for remote clocks, via a sequence of phase, or time interval, measurements lasting a few hours if not days) and the capability to precisely control the oscillator with a different time constant, is the main advantage in this situation. Indeed, the intrinsic stability of the oscillator is much better than the capability to measure its frequency, due to the noise on the communication channel and the fact that several effects affecting any synchronization measurement must be removed by post-processing the data, before a reliable estimate of the frequency and phase of the oscillator can be extracted from the raw data.

A typical operational scenario involving such a spaceborne synthesized standard may require a few hours of measurements in order to have a preliminary estimate of its frequency; once this is obtained, any correction to steer the frequency is only limited by the propagation delays of the telemetry and command links, since the frequency can be steered at will with the same accuracy of the estimate of the frequency itself. In comparison, closed-loop operation is less agile, since in a feedback system

the settling time is determined by the slower component in the loop, in this case by the frequency estimation process.

6 NETWORK SYNCHRONIZATION: COMMUNICATIONS AND POWER GENERATION

Other ground-based systems require precise frequency and phase control of remote oscillators in the exceptions noted above. If the oscillators constitute a network, coordination within the network nodes (each oscillator constitute a node in a generalized timing network) adds a degree of complexity to the task of generating and distributing a common reference signal. Examples of networks requiring such a coordination are power generation (electric utilities) and especially telecommunications network.

Electric utilities networks are less demanding: timing must be provided to within a millisecond in the network. In the recent literature, vector measurements techniques place tighter requirements, in the order of microseconds, especially for the applications of fault diagnosis and location within the network (ref. 7).

Telecommunications networks are more demanding (ref. 6); phase noise must be carefully considered when frequency multiplication is involved. Frequency stability and accuracy requires atomic standards as primary standards in the network: for Time Division Multiplexing (TDM) Systems, the CCITT Recommendation G811 demands a frequency accuracy less than $1 \cdot 10^{-11}$ for the long term (> 1 month) accuracy of the network frequency, and less than $20\mu s$ of maximum Time Interval Error (TIE) for sampling times between 1000 s and 1 month.

Redundancy can be achieved by multiple oscillators in one location. Frequency and phase (time) coordination is achieved by use of internal (within the network) synchronization measurements, or by using external timing references, such as Loran-C or GPS timing receivers. Frequency coordination is absolute, in the sense that each node within the network must run at the same frequency (if coordination in relativistic sense is neglected); phase coordination is a more difficult task, since it involves the relative propagation delays between the nodes; for many applications, this is not a serious problem.

Moving toward a network in which redundancy is obtained by the use of distributed oscillators at each node in the network instead of being clustered in local ensembles poses the problem of both frequency and time coordination at the highest level, since failure in any node should be transparent to the users at the node and within the network. No frequency change or phase jump shall be apparent in any point of the network itself. This requires the precise determination not only of the relative frequency and phase between two oscillators at separate nodes, but of the propagation delay between them, corrected by any effect, including relativistic ones, that may affect the accuracy of the determination.

Again, since the measurement time is the slower component of the system and readjustment of phase and frequency in the network oscillators can be independently performed on each oscillator following any failure or restructuration of the network topology, the capability of precise control of frequency and phase of the oscillators is of the greater importance. The capability to decouple the time required to estimate the frequency and the response time associated to the remote control of the oscillators is a tremendous advantage in running such a network, and significant savings and operational benefits can be obtained using this strategy: instead of *clustering* redundant oscillators in one location, these

can be *distributed* in the network, insuring the same numeric redundancy but better frequency/phase coordination, provided that is possible to control these parameters with the highest precision.

7 NETWORK SYNCHRONIZATION: TRACKING SUPPORT

Some of the considerations already made can be extended to the use of frequency standards in satellite tracking networks, with some additional remarks, since accuracy and stability are here important not only for the communications functions (carrier generation, data modulation and demodulation, etc.) but also for the accuracy and correlation of the ranging measurements. The most demanding applications in this field involve precision laser ranging to Earth orbiting satellites for scientific purposes, the most notable of which is the measurement of small deformations of the Earth crust due to the relative movements of tectonic plates.

Two problems arise in this application: high stability and accuracy are required over relatively short time intervals for ranging purposes, while long term stability is needed to generate an accurate local time scale, tied to UTC: this is used to correlate measurements taken at separate tracking sites (no cross-station, or interferometric, ranging is possible using optical links, since the pulse is always reflected back at the transmitting site, and no correlation is possible on the satellite, since this is generally a passive craft carrying an array of retroreflectors)

To achieve centimeter accuracy in ranging a Rb oscillator performs better than a Cs oscillator in many applications; however, laser ranging sites have traditionally used Cs clocks to maintain the long term time accuracy required for range measurements correlation. A disciplined oscillator, based on a frequency-controllable Rb oscillator tied to a GPS timing receiver, can meet all the above requirements at a fraction of the cost of a Cs oscillator, and with a considerable reduction of ancillary costs related to logistics and maintainance. With a synthesized oscillator, it is possible to physically steer the frequency and time, to track **at the station** the nominal values without resorting to timing data post-processing to recover the corrected time of the measurements; this is an additional benefit that can further reduce the operating costs of such a network.

8 APPLICATIONS IN NAVIGATION SYSTEMS

Some interesting considerations find their application when using frequency standards in navigation systems, such as GPS. Neglecting any further considerations on the use of frequency standards in space, already covered before, we will restrict our discussion to the users segment, where additional benefits can be achieved by the use of frequency control in high stability local oscillators.

Multi-channel receivers are used to reduce the exposure time for selected users, namely submarines, during the signal acquisition phase. However, the acquisition and signal tracking steps must be perfomed sequentially, to lock the carrier, SPS (Standard Positioning Service) code, extract the navigation message, lock the PPS (Precision Positioning Service) code and finally perform the pseudo-range measurements. If the PRN code is acquired once, and then continuously updated in the receiver even when the signal from the satellites is not received, the acquisition and lock time of the receiver can be dramatically reduced; this requires that the frequency of the oscillator driving the local PRN code generator is stable enough that, in the time interval between two successive exposures to obtain a fix, the frequency offset between the satellite and the local oscillators is such not to produce a slippage of more than 1 cycle, or a few cycles if some limited search technique is applied when reacquiring

the signal. Since the period of the PPS code is roughly 100 ns, and the time interval between fixes can be one day, the required accuracy for the oscillator frequency is:

$$\frac{\delta f}{f} = \frac{1 \cdot 10^{-7}[s]}{1 \cdot 10^{5}[s]} = 1 \cdot 10^{-12}$$

that can be met only by a Cs standard. However, a greater uncertainty is introduced by the position estimate: current inertial systems can propagate the user position over the same period of time with an uncertainty ranging from a few hundreds meters to a few kilometers. This is the major error factor determining the pseudo-range uncertainty at the time at which the signal is reacquired, since the satellite position can be computed with a better precision by propagating forward the orbital elements. Therefore, it is likely that a limited search is conducted over at least 10-20 cycles of the PPS code when reacquiring the signal. Then a standard Rb oscillator can meet the requirements, provided that some form of frequency control is available to precisely set its frequency to the nominal value and to correct for frequency drift affects (aging).

A second application arises from more basic considerations: the standard GPS navigation solution solves for a minimum of 4 variables, i.e., three spatial coordinates {x,y, z} and time. However, the two sets of coordinates, space and time, are not quite equivalent in their behaviour:

- time changes with a **constant and predictable rate**, the accuracy of the prediction being only a function of the accuracy and stability of the local frequency standard. In contrast,
- space coordinates change in a **completely unpredictable way**, and the main purpose of the GPS is indeed to measure spatial coordinates changes.

Frequency stability in the receiver is not a problem, since the standard navigation algorithm uses the local oscillator only to correlate a minimum of 4 independent measurements, and no stringent requirements are placed on the local oscillator stability or accuracy, as long as a minimum of 4 satellites are in view. However, if a stable and accurate frequency standard is available, the solution can be modified to exploit its capabilities; the navigation estimator time constants should be modified, and the dynamics related to the time solution can be reduced (since the clock is very stable), allowing a heavier filtering of the time offset estimate. As a result, the bulk of the information provided by the pseudoranging measurements contributes to the navigation solution alone.

Taken to the extreme, we are lead to consider two separate solutions running in parallel: one solving for time, as a function of the current position (as provided by the navigation solution), but with heavy filtering and a long associated time constant, and the second solving for position only, the time being available and synchronized to the GPS system time, running with a shorter time constant and using all the data available to improve the precision of the solution: this implies **full decoupling of the time and position solutions**.

The assumption that time and space are separate entities in the GPS solution follows from simple considerations. The first one is rather puzzling when stated the first time: a GPS timing receiver needs to account for the length of the cable connecting the receiver to the antenna, while for a GPS navigation receiver no calibration of the cable is needed, and the coordinates reported are always the coordinates at which the antenna is located (fig. 2), irrespective of the length of the same cable. This rather puzzling behaviour arises from the fact that all common delays in the system (in this case the common propagation delay along the cable) **enter the solution as a clock offset**, i.e. the cable delay appears in the navigation solution as a clock offset, while for the positioning solution this is a term that can be simply neglected.

The fact that considerable benefits can be obtained is apparent by a second example, shown in fig. 4. Here, four GPS satellites are shown at the vertexes of a tetrahedron, equidistant from the user. This provides the best geometry in terms of GDOP (Geometric Dilution of Precision), but results in a total uncertainty in the position of the observer. The uncertainty arises, in such a situation, since any ambiguity in the user position along the axis of the tetrahedron contributes equal delays in the solution, and is simply accounted by a different clock offset; it is like having a cable from the receiver to the antenna of variable length, so that the antenna can be moved in any position along the axis; the coordinates reported will be different and the uncertainty due to the length of the cable will affect the time estimate only.

If the time offset (user clock minus GPS system time) is known, no ambiguity is possible about the location of the user, and from a total uncertainty regarding the user position we move to a situation in which the best possible geometry is exploited to obtain a very good position fix. The situation depicted is extreme in its geometry and consequences for the navigation process; a moving user entering such a situation is aided by its previous estimates of time offset and position to bound the ambiguity to within the error of the previous estimate; nevertheless, the example is striking in the sense that shows what the implications of a synchronized clock are when performing precise navigation. The challenge is therefore to investigate the new possibilities offered by decoupling the time solution from the spatial solution, since:

- the local oscillator is stable, and stability means that we can characterize its behaviour over a longer time constant that is required, for all practical purposes, by the navigation solution; this provides, a better estimate for the time solution and, in turn, a better positioning solution;
- if only three coordinates are to be solved instead of four, marginal geometries can still provide a good solution, since more satellites contribute to the position fix;
- during high-dynamics manoeuvers (such as an aircraft banking rapidly) or shadowing conditions (when one or more satellites are not visible) the "normal" operating conditions can be maintained with a greater margin than that offered by a "conventional" processing receiver.

A possible mechanization is shown in fig. 4, in which the local frequency standard is physically kept in-frequency and synchronized by a solution derived by a "virtual" timing receiver. For high accuracy, this timing processor tracks only the best satellite available, with long time constant and high accuracy, while the current receiver coordinates are provided at a faster rate by the position processor. The latter solves for the spatial coordinates only, by using all the satellites available; the time information is obtained directly from the local clock, synchronized to the GPS Time, so that actual range measurements are performed instead of the pseudo-ranges (biased by the time error). This situation can provide savings also in the implementation of the navigation algorithm. Obviously, the system is initialized by a "classical" GPS solution (position plus time) and the two estimation processes split only when the estimation errors of the combined solution are reduced to within reasonable limits.

9 MILITARY TELECOMMUNICATIONS APPLICATIONS

Military telecommunications systems require precise frequency and time for the very same reasons of civilian telecommunications systems; however, security requirements and data protection place additional constraints on the specifications of reference oscillators in the network. Some communication security (COMSEC) requirements dictate the use of long keys to insure maximum protection of access and information decoding; when keys have a length such that they do not repeat for the

expected lifetime of the system, a "one-time pad" operation results, and no cryptanalytic attack is reputed possible with pure mathematical means without resorting to external intelligence.

"One-time pad" keys, when applied to serial data streams, require precise synchronization of the key generators at both sides, and synchronization can be achieved only after entering the system. This means that it is up to the reference oscillator to maintain the code synchronization when no communication is performed between the two COMSEC terminals. The better the stability and the frequency coordination of the oscillators, the longer the time interval that can be spent without accessing the system, and this is especially important for covert operations, where minimum exposure is required, as is the case of communications to strategic nuclear submarines. Besides communications, the same access and data protection technique is applied to remote control of vital military satellites, since also the command uplinks must be protected against unauthorized access, in addition to jamming and spoofing. Again, the capability to precisely control the frequency and phase of the reference oscillators can increase the protection or lengthen the time interval between resynchronizations, minimizing the exposure and providing additional benefits without the penalty of a sizable increase in costs and hardware complexity.

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FIGURE 1:TFL-SEPA Synthesized Rb Frequency Standard

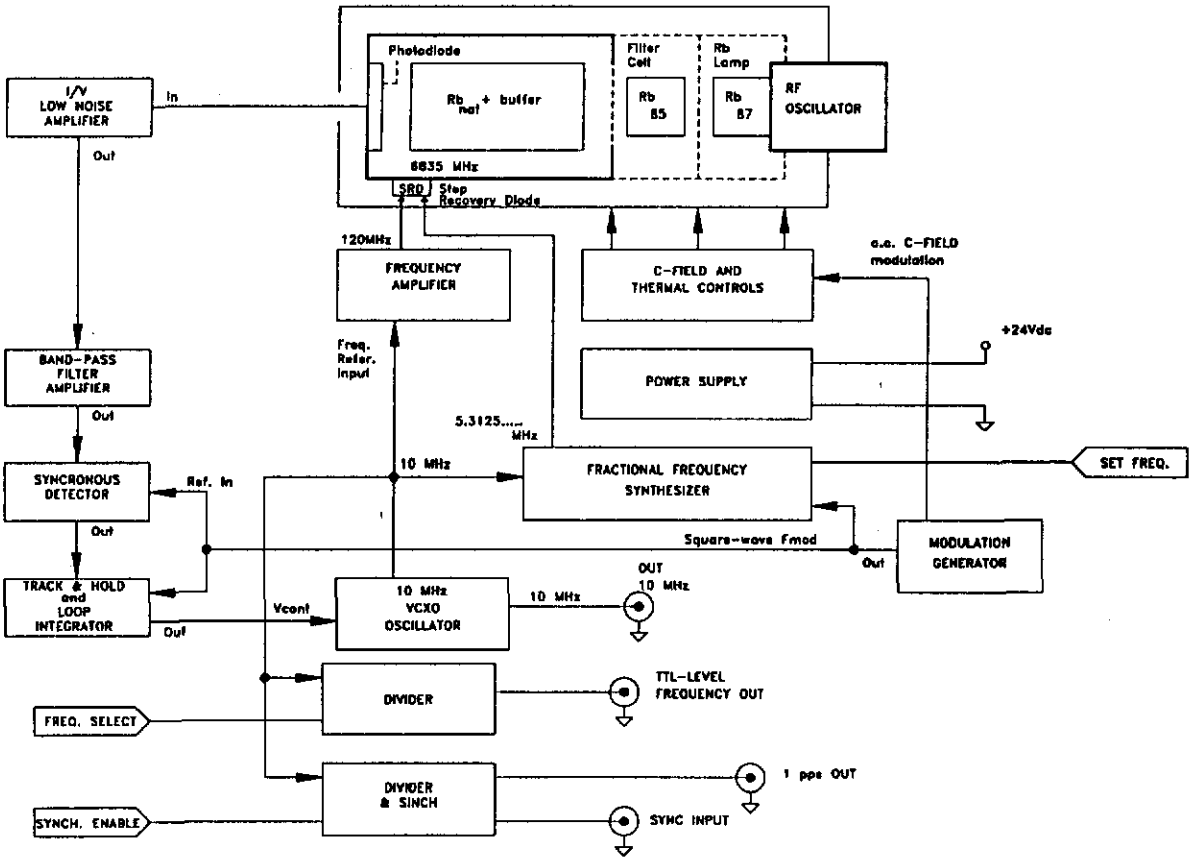
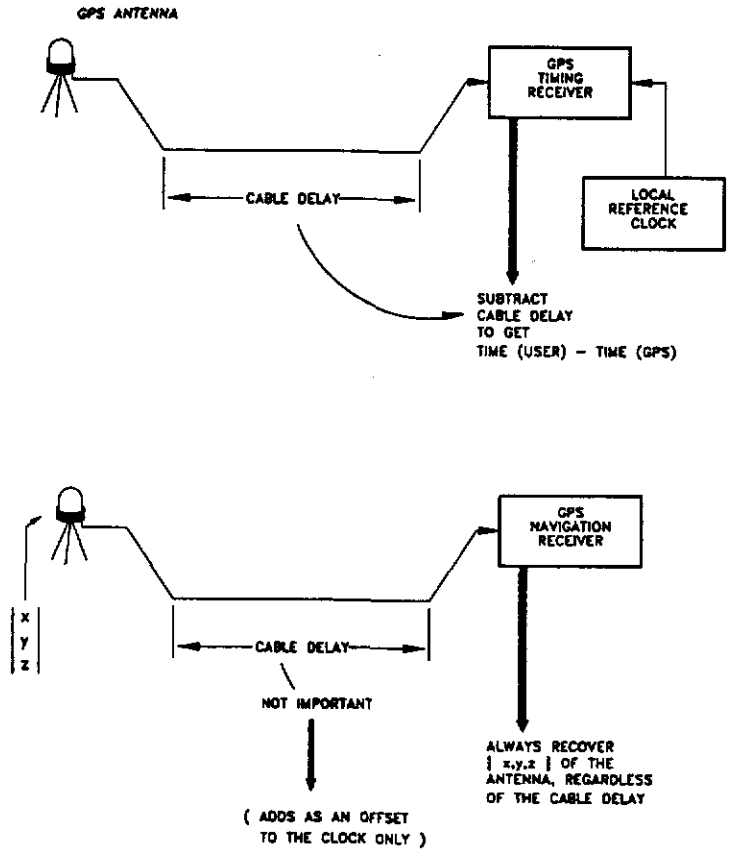


FIGURE 2:GPS System - Non-reciprocity of Antenna Cable Delay



GPS – NON-RECIPROCITY OF ANTENNA CABLE DELAYS IN TIMING AND POSITIONING SOLUTIONS

FIGURE 3:GPS System - Navigation Pseudo-Ambiguity

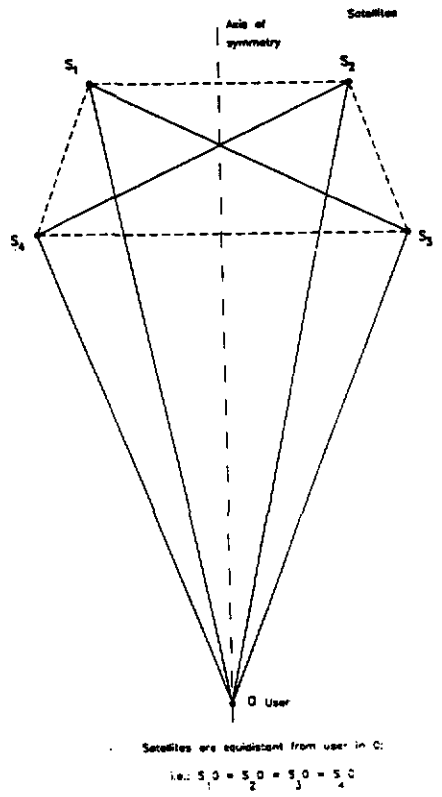
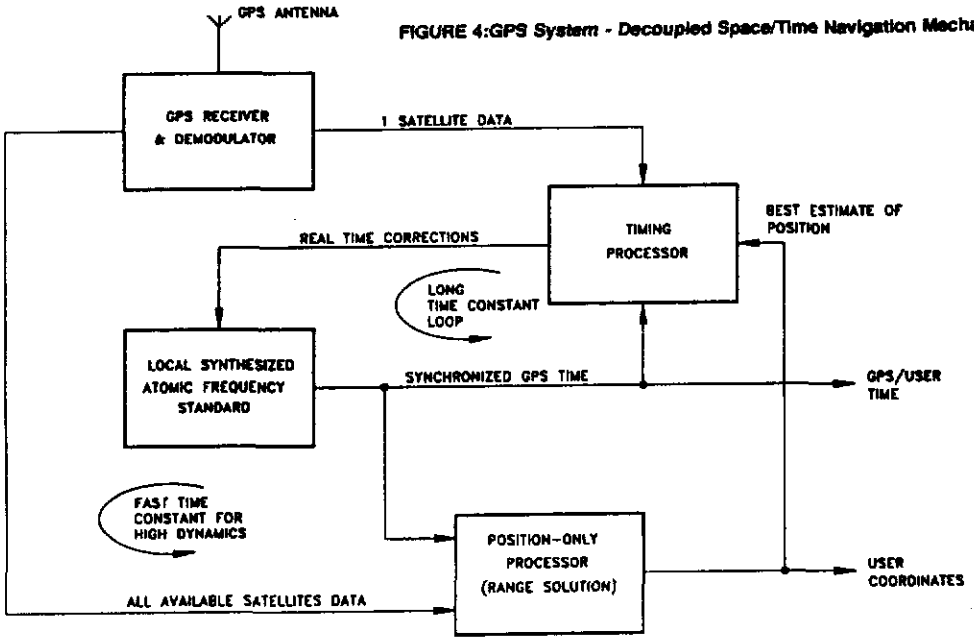


FIGURE 4:GPS System - Decoupled Space/Time Navigation Mechanization



QUESTIONS AND ANSWERS

B. Alam, NRAD: I have a general question regarding the three above papers. In those we were aiding an oscillator from GPS time. Has anyone considered the opposite problem of aiding a GPS receiver with an oscillator or with a frequency standard for direct wide acquisitions for high dynamic platforms. Not only cesium standards but to minimize the size for high dynamic aircraft, for example.

Dr. Winkler, USNO: Yes, in fact several groups have considered that but not merely from that point of view. In the interest of gains of autonomous integrity detection capability by providing additional parameters to the receiver. Not only time as averaged and predicted over periods of 100 or a 1000 seconds which is sufficient but also shows them inertial information. Any parameter which aids the receiver allows you to reduce the dynamic problem to a stationary one, where you can integrate over a longer time constant. The inertial and timing information to the receiver allows you predict in a short time where you are, even if in a very high dynamic environment. You can then reduce the averaging to a stationary problem.

Question: Besides considering the repetition of the P code for example. If you have lost a satellite because of shading or something, what parameters would one need to consider when specifying an oscillator or a rubidium standard keeping in mind a small size for aiding your receiver? What would be the parameters, I am not sure?

G. Winkler: It is efficient for stability of that oscillator to be very good to the one part in ten to the eleventh over periods of 100 to a 1000 seconds.

E. De Toma, FIAT CIEI: There are some other advantages that you may consider from a solution like these. If really all the common mode effects are going into only the timing solution, you can consider also the situation in which you have propagation effects. In the first order tropospheric propagation is common to all the satellites. If the conditions are not too wide the atmospheric propagation is the first order common to all the satellites. Now these affects, if not properly accounted for will contribute to the full solution and mainly to the timing process. Again if you add a longer time the position accuracy also will be degraded. Now if you use this approach you track for time, only the satellites by which these affects are less evident like the one that is directly overhead. So you try to minimize what are the system errors from the timing solution. Then if it is true that all the timing of the common mode effects, just going into time and not the range, you should have a better solution for positioning the satellites which do not have a very high elevation angle. In this case the common mode propagation will not enter into the solution. At least for tropospheric this is certainly true but for atmospheric you have to be more careful because within the time and length of the path and the condition of the propagation.

G. Winkler: I would like to add to that one more point you are absolutely correct. If you compare the situation today with the situation 10 years ago, today it is very much easier to have 8 or even 9 channel receivers because an additional channel is not as expensive as it use to be. By having all the satellites in view at all times for a receiver you not only approve your aim capability, but you also have a system solution which identifies other problems. It is much stronger and much more robust, reliable and it has in fact the capability of giving an internal figure of merit, as if you only use a minimum number of satellites.

E. Detoma: Yes, but remember at this point the position processor solves for real ranges. So you may also have some simplification of the algorithm because it is no longer a completely nonlinear solution that you have to iterate.