Fine Time Aiding and Pseudo-Synchronisation of GSM Networks

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BIOGRAPHIES

Dr Tony Pratt graduated with a B.Sc. and Ph.D. in Electrical and Electronic Engineering from Birmingham University, UK. He was on the teaching staff at Loughborough University, UK from 1967 to 1980. He held visiting professorships at Yale University, IIT, New Delhi and University of Copenhagen. In 1980, he joined Navstar Ltd, as Technical Director. In 1995, with Peek plc, he was involved in the formation of Tollstar Ltd, a 5 company consortium developing of Electronic Road Tolling. He left Peek in 1997 and joined Navstar Systems Ltd as Technical Consultant. Subsequently he was Technical Director (GPS) with Parthus. He is also Special Professor at the IESSG at the University of Nottingham, UK. He is a Consultant to the UK Government in the development of Galileo Satellite System. He is a Member of the EC Signal Task Force and sub-groups and was closely involved with the EU-US Agreement on GPS Galileo Cooperation. He is Senior Consultant with the GPS Telematics Group at QinetiQ Ltd, UK.

Ramsey Faragher graduated from the University of Cambridge in 2004 with a first-class degree in Experimental and Theoretical Physics. He is currently studying multi-path radio-wave propagation in urban environments at GSM and W-CDMA frequencies for his PhD with Peter Duffett-Smith.

Peter Duffett-Smith is the founding director of Cambridge Positioning Systems Limited and is its Chief Scientific Officer. He is also Reader in Experimental Radio Physics at the Cavendish Laboratory, University of Cambridge. His PhD is in Radio Astronomy and, with others, he is the inventor of the Matrix positioning method and E-GPS technologies mentioned here.

ABSTRACT

The integration of CDMA and GPS within a single mobile terminal, in support of the FCC E911 initiative, has greatly benefited from the GPS-based synchronisation of the CDMA network. Similar synchronisation is not available in GSM and W-CDMA networks which are, by design, asynchronous in operation, and this makes GPS integration into GSM and W-CDMA mobile terminals more complex and costly. Duffett-Smith & Tarlow [1] have described a new technology for pseudo-synchronising a GSM system which can provide a time reference to an embedded GPS receiver with an accuracy better than 2 μs.

This paper examines the scientific basis for GSM pseudo-synchronisation, i.e. for using GSM base station clock signals as receptacles for GPS (universal) time in the mobile terminal (GSM handset). There are several key elements required to support this capability, including (a) measuring the position of the mobile terminal using the base station signals with a technique known as Matrix [3 - 6] and (b) receiving BTS signals of sufficiently-good quality from the GSM network from which the GPS time (or frequency) may be derived.

In order to support Fine Time Aiding for GPS, we report the first measurements of the time stability of *received* GSM modulation signals through Allan standard deviation graphs for two independent networks at 900 and 1800 MHz over a range of distances from base stations. These support a systems engineering approach in which the GSM base stations are able to provide stable time references, after calibration, which is usable for many hours. A degradation of the calibration performance with increasing distance from a base station is noted in the measurements, and this is tentatively ascribed to delay-spreading in the propagation channel for GSM signals primarily due to multi-path.

INTRODUCTION

Duffett-Smith *et al.* [1,2] have described a method by which fine time aiding (FTA, i.e. time transfer within an accuracy of 2 μs) may be supplied to mobile terminals containing GPS receivers in unsynchronised networks such as GSM and W-CDMA. The method, called Enhanced GPS or E-GPS, relies on the Matrix system [3-6] to find the position of the terminal using the signals transmitted by the network. In addition, the Matrix system also computes a synchronisation table of the network transmitters, containing a list of the relative transmission time offsets of the base stations. When coupled with the calculated position of the handset and sufficient stability of the network timing signals, an initial calibration of the receipt of the signals from one base-station against GPS time can be carried around within the terminal and used, at a later time, to infer GPS time from the receipt of the signals from the same or another base station. This method, in effect, uses the unsynchronised, but stable, network signals as a remote repository of accurate GPS time.

Duffett-Smith and Tarlow [1] demonstrated the E-GPS FTA method in a particular set of circumstances. What is now needed is a general scheme of analysis by which any network signals may be assessed for stability and suitability for the method, so that an E-GPS system may be designed on a sound systems engineering basis. We address this problem here by using the Allan standard deviation [7] of the signals *received* by a terminal as an indicator of the accuracy of FTA provision. The Allan standard deviation measured in this way incorporates the stability of the base station clock signals as transmitted, the effects of the propagation channel between transmitter and terminal, and the ability of the terminal to extract timing information from the received signals.

INITIAL EXPERIMENTS

We set up stationary receivers at the Cavendish Laboratory in Cambridge in order to make an initial set of measurements for mobile terminals not in motion. We made repeated measurements over several days on the signals received from base stations of two independent networks at 900 MHz and 1800 MHz between about 300 m and 8 km distant from the laboratory. These measurements were made to demonstrate the best stability which might be expected from the fine time aiding concepts as the propagation channels were considered to be (relatively) stable without user motion. Additional propagation errors can be expected as a result of the motion of the mobile terminal in a multi-path dominated propagation model.

These results demonstrate that the GSM signals can indeed be used as a repository of GPS time for periods extending from hours to days. The preliminary observations are encouraging, but they need to be extended to other networks, and in other cities, especially with more variety of environments from dense urban to rural. The authors expect to report such further findings in future papers. As noted above, the measurements also need to be extended to moving terminals, and make measurements at street level using terminal-style antennas. The present experimental set-up is not ideal for this requirement.

ASSESSMENT OF NETWORK STABILITY

The signals radiated by a GSM base station include a synchronisation burst repeated every 50 ms or so in the logical control channel called BCCH. This is carried on the primary physical radio channel. GSM channels are spaced at 200 kHz intervals, and the bandwidth of the signals radiated in each channel is about 130 kHz. The synchronisation burst consists of a word of 63 bits which is the same for every GSM base station, and is readily detected using a cross-correlation.

We determined the times of arrival of synchronisation bursts from a selected GSM base station using a receiver with a time-base locked to a rubidium oscillator. The GSM base stations were chosen using the frequency of the radio transmission (or channel number). The equipment was thus able to measure the variation in the time intervals between the arrival of synchronisation bursts from a chosen base station over elapsed times of many hours or days. An example of such a measurement is shown in Figure 1. In this case, the 900-MHz signals from a base station about 1.2 km from the receiver demonstrated extraordinary stability with the variation in arrival time of the synchronisation bursts rarely exceeding 0.1 μs over 15 hours or so (after removal of a constant slope which corresponded to the normalised frequency offset between the rubidium oscillator and the primary reference of the base station).

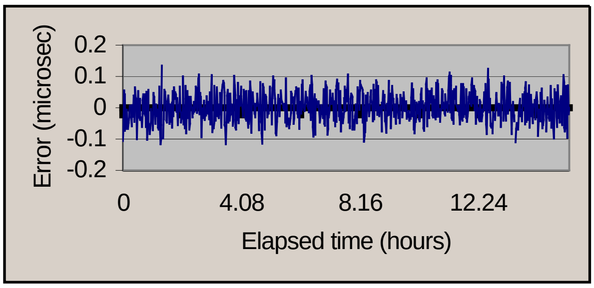

Figure 1: the variation in time of receipt of the signals from a 900 MHz GSM base station

Another example is shown in Figure 2. This time the base station was about 8 km distant from the receiver and was transmitting on a frequency of 1800 MHz. There is evidence here for the additional perturbing effects of propagation (see below).

Although the curves shown in Figures 1 and 2 go some way as indicators of received signal stability, taking into account the constant frequency offset between mobile terminal and base station, a better metric is provided by the Allan standard deviation [7]. This is a dimensionless quantity which, when multiplied by the elapsed time interval, gives the standard deviation of the time error.

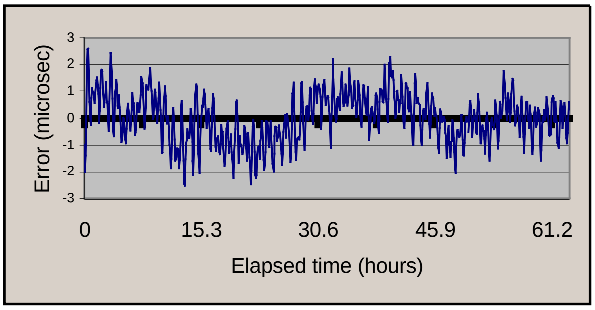

Figure 2: the variation in time of receipt of the signals from an 1800 MHz GSM base station

ALLAN VARIANCE OF ARRIVAL TIMES

We made measurements of the times of arrival of the synchronisation bursts from each base station at constant intervals of T seconds (in our case either 61.2 s or 306 s) using a sampling clock locked to a rubidium oscillator. Let the measurements of arrival times be t_1, t_2, t_3, …, t_k, … t_N, where t_k is the kth time-of-arrival measurement in a total series of N measurements. The Allan standard deviation, $\sigma_A(\tau)$, corresponding to an elapsed time interval τ, is formed from

$$\sigma_A^2(\tau) = \frac{\sum_{k=1}^{N-2m}(t_k - 2t_{k+m} + t_{k+2m})^2}{8(N-2m)m^2T^2}, \qquad (1)$$

where $\tau = mT$, and m = 1, 2, 3, …., (N-1)/2. This equation has been derived from [7]. Thus, if $\sigma_A(10{,}000\ \text{s})$ is 10^{-9}, the standard deviation of the time error after an elapsed time of 10,000 s is $10{,}000 \times 10^{-9} = 10\ \mu\text{s}$.

A time series (of arrival times) with constant standard deviation over the observation interval, such as that shown in Figure 1, would display a slope of –1 on a plot of the logarithm of the Allan standard deviation, $\sigma_A(\tau)$, vs. the logarithm of the elapsed time, τ (see e.g. curve C of Figure 6). A time series with a uniform growth of standard deviation with elapsed time would have a slope of 0 (flat) on the same plot. This corresponds to a uniform diffusion model. We anticipated seeing such characteristics as environmental effects (e.g. temperature, pressure, magnetic fields, etc) start to influence the stability of the oscillators used.

EQUIPMENT AND METHOD

A schematic diagram of the equipment which we used to measure the Allan standard deviation of signals received from a number of base stations is shown in Figure 3.

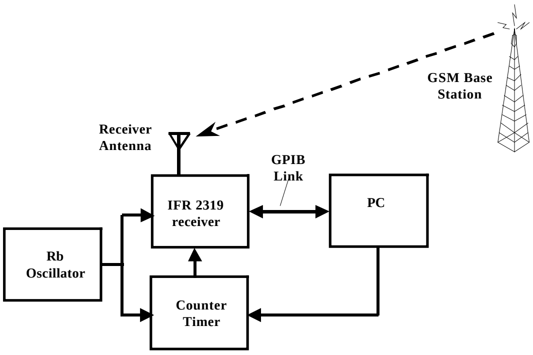

Figure 3: a schematic diagram of the apparatus

An IFR 2319E digitising broad-band receiver formed the core of the system. This received the signals transmitted by a GSM base-station via a fixed antenna, and was controlled via a GPIB interface by a lap-top computer (PC) which was also used to control the data capture triggering with a counter/timer card. An Efratom FRK-H Rubidium atomic oscillator provided the common frequency reference for both the receiver and the counter/timer card. The digitizer's antenna was placed on a mast on the roof of the Cavendish Laboratory, ensuring good signal strengths and minimising any local multi-path effects caused by the laboratory buildings.

As mentioned above, the times of arrival of the synchronisation bursts transmitted by the GSM base station were measured against an internal sampling clock of the IFR receiver which sampled the complex modulation envelope at 2.04MHz. This was locked to the rubidium oscillator. We detected the arrival of a synchronisation burst by cross-correlating the receiver base-band digitised output, transferred to the computer via the GPIB interface, with a known replica of the synchronisation burst, taking the instant of maximum power in the cross-correlation as the time of receipt.

However, a random timing measurement error component was introduced in the samples since the *phase* of the sampling oscillator was not controlled with respect to the start of the measurement process. The timing measurement error for each sample had a uniform distribution in time of width about 490 ns, corresponding to a standard deviation of about 140 ns. In the process of correlating the known synchronisation sequence with the received signal samples, 63 samples were combined to form each cross correlation value.

The duration of the synchronisation burst was approximately 280 μs (approximately 560 sample intervals). As a result, the sample clock slid across the GSM data bit intervals allowing a time averaging process to occur. The synchronisation signal bandwidth to receiver bandwidth was in the ratio of 280:5. The effect of this averaging was to reduce the measurement noise standard deviation to approximately 19 ns.

The maximum speed of data transfer across the GPIB interface was limited so that the measured signal samples for 50 ms required 30 seconds of readout time. By triggering the data capture at an integer multiple of the GSM hyperframe repeat rate, the position of the cross correlation peak remained at a fixed sample number within each measurement set. (The useable data capture intervals were 61.2 s or 306 s for this configuration of equipment.) Variations in this position were then caused by the normalised frequency offset between the rubidium and the base-station oscillators, their respective frequency stabilities, the stability of the signal's propagation path, and the measurement noise of our system.

We calibrated the performance of the equipment using the signal generated by a RACAL GSM signal generator in place of the signal from the base station. The RACAL generator was phase locked to a second FRK-H rubidium oscillator. The resulting Allan standard deviation is shown in Figure 4 as the red curve and it provided an estimate of the noise background as the benchmark for the equipment and the experiment.

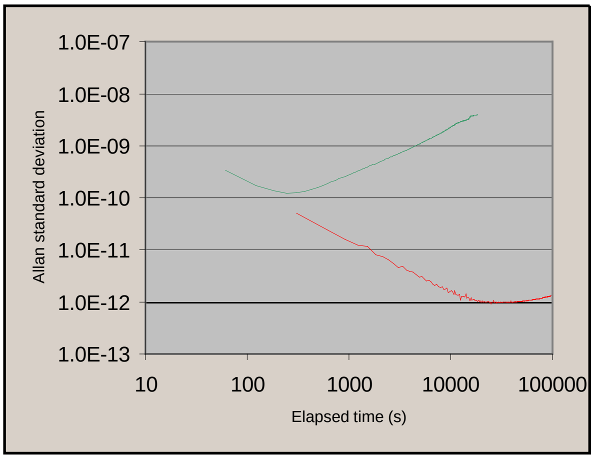

Figure 4: Allan standard deviation measurements of a GSM signal generator locked (a) to a second rubidium oscillator (red curve) and (b) to an oven-controlled crystal oscillator (green curve)

The red curve shows that, for time scales less than about 30,000 s, the equipment's sensitivity was limited by measurement noise. The curve is initially straight with gradient –1, as expected for white noise, and its position with respect to the axes is determined by the random noise level. At an Allan standard deviation of about 10^{-12} the curve flattens off and the gradient becomes first zero then positive. Here we were limited by the stabilities of the rubidium oscillators.

The red curve of Figure 4 defined the noise level floor of the experiment. As long as the Allan standard deviations generated from measurements of a base station were substantially above this curve then they were not significantly affected by the limitations of the apparatus.

The red benchmark curve can be modelled in two parts. The initial negative slope in the region $0 < \tau < 30{,}000$ seconds can be modelled by an equation for the Allan standard deviation, $B(\tau)$, given by

$$B(\tau) = \frac{n}{\sqrt{2\tau}}, \qquad (2)$$

and is derived directly from the Allan standard deviation equation (1) given above. In equation (2), n is the standard deviation of the random measurement noise in seconds. A good fit to the red calibration curve is found by setting n equal to 20 nanoseconds. Note that this is similar to the estimate of timing noise due to the random phase of the sampling process in the IFR receiver. Consequently, it appears that the Rubidium oscillator contributed less timing noise than this for intervals less than 30,000s.

The second part of the curve for values of elapsed time between 30,000 s and 100,000 s is adequately represented by a constant value of $B(\tau) = 10^{-12}$.

Also shown in Figure 4 is a curve, in green, of the Allan standard deviation measured using the RACAL GSM signal generator as the signal input to the receiver as before, but this time locked to its own oven-controlled crystal oscillator. Initially, the slope is –1 exactly as for the red baseline curve, but flattens off and then rises for values of elapsed time beyond about 300 s. This is as expected for a crystal oscillator with a single oven.

MEASUREMENTS OF GSM BASE STATIONS

We made measurements of the signals received from five GSM base stations, two at 900 MHz and three at 1800 MHz over elapsed times exceeding 10,000 s.

Identifier	**Frequency/ MHz**	**Distance/ m**
C	**900**	**1219**
D	**1800**	**337**
E	**900**	**8123**
F	**1800**	**8105**
G	**1800**	**1957**

Table 1: The frequencies and distances of the five base stations reported here

Different distances between mobile terminal and base stations were chosen to establish estimates of delay spread in the propagation channel as the result of distance. The details are listed in Table 1.

Figure 5 shows the geometrical dispositions of the five measured base stations together with a rough outline of Cambridge city. In practice, there are many more base stations within the environs of Cambridge but it has so far not been possible to measure all of them. We have included results which are characteristic of the different types. The blue cross indicates the position of the receiver in the Cavendish Laboratory. Green circles indicate the 900 MHz base stations C and E whilst the orange circles indicate the 1800 MHz base stations D, F, and G.

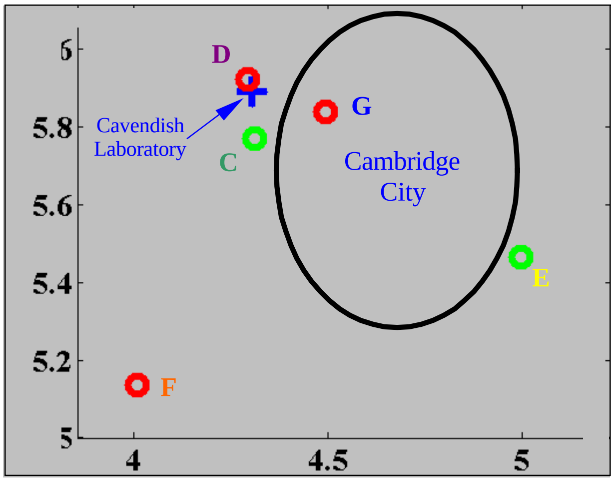

Figure 5: the geometrical disposition of the base stations. The dashed oval indicates approximately the built-up part of the city. One unit on the scale is 10 km

The curves of the Allan standard deviation measured for each base station are shown in Figure 6. Also shown, for comparison, are dashed curve A, corresponding to the red baseline curve of Figure 4, and dashed line B, indicating the 2 μs FTA line. At any given elapsed time (horizontal axis), points lying below the line B have standard deviations of less than 2 μs, whilst those above have standard deviations of more than 2 μs. We see at once that all the measured curves lie well below the 2 μs line for τ less than about 20,000 s, and that three of the curves appear to lie below it even up to 100,000 s.

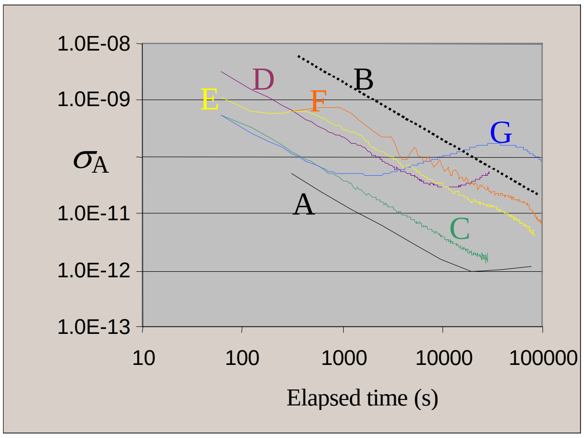

Figure 6: Allan standard deviation measurements of received GSM signals. See text for details.

Curve C corresponds to the measurements shown in Figure 1. There was probably a direct line of sight between the transmitter and receiver antennas for this set of measurements, so that the timing noise added by the radio propagation channel was probably small. We see a constant slope of –1, indicating that the reference oscillator for this base station was as good as our rubidium oscillator. This was to be expected for this particular base station as it was part of a well-engineered mature network in which the oscillators of individual base stations were phase-locked to a common clock signal derived from the communications backbone. We were thus measuring the stability of a single master oscillator in the Master Switching Centre, and this itself could have been controlled by GPS signals. The other base station of this network was E. In this case the base station was much further away and there was probably not a direct line of sight between transmitter and receiver antennas. The measurements indicate substantial additional timing noise, probably caused by the radio propagation channel, which flattens the Allan standard deviation curve for $100 < \tau < 500$ s. For elapsed times greater than 500 s, the curve resumes its –1 slope at least as far as 80,000 s.

It is interesting to note the similarity between curve E and curve F. Both these base stations were at approximately the same distance from the receiver, slightly more than 8 km, but the latter was part of another network at 1800 MHz.. We note that both curves display the same characteristics of a flattening before continuing downwards on a slope of –1. Curve F, however, is displaced rightwards and upwards relative to curve E, so that the flat portion extends to a value of τ equal to about 1000 s. The right-ward shift (by about a factor of two) may be caused by the difference (a factor of two) in their radio frequencies. The prolonged region with a slope of –1 shows that the stability of the reference oscillator controlling this base station was as good as that controlling base station E.

The time series for base station F is shown in Figure 2. It is interesting to compare this with the time series for base station E, shown in Figure 7. Both the time series of Figures 2 and 7 display similar quasi-periodic oscillations. Further investigation is needed to determine whether these are intrinsic to the base stations themselves, or are caused by multi-path effects in the radio propagation channel. Nevertheless, it would be hard to explain periodic behaviour in a radio propagation channel which is basically terrestrial with both transmitter and receiver stationary.

Curve **D** of Figure 6 corresponds to a nearby base station at 1800 MHz for which a line of sight existed between transmitter and receiver antennas. The effects of multi path on the radio propagation channel were therefore likely to be small in this case. We see that the Allan standard deviation displays a constant slope of –1 up to an elapsed time of about 10,000 s, but thereafter flattens and turns upward. This behaviour is consistent with the base station being controlled by a high stability crystal oscillator (perhaps one using a double oven temperature control), possibly not being locked to a clock signal derived from the communications backbone. Curve **G** shows more complex behaviour. This 1800 MHz base station was within the built-up region of the city. More investigation is needed, but a preliminary analysis suggests that there may have been some degree of multi-path present, together with a base station oscillator less-stable than any of the others.

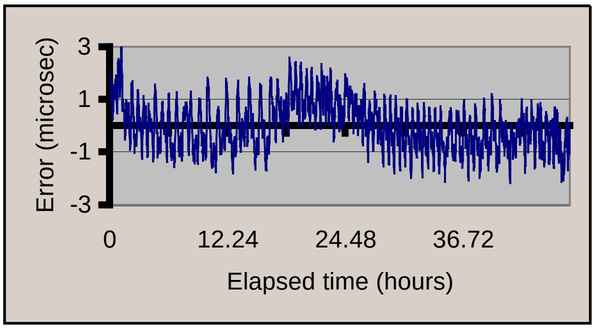

Figure 7: time series for base station **E**

CONCLUSIONS

- These measurements demonstrate that, on the two GSM networks considered, FTA within 2 µs can be provided to a mobile terminal containing a GPS receiver for elapsed times to at least 10,000 s. Note that this time transfer accuracy does not depend upon the oscillator or clock within the mobile terminal as this is not used to provide the time aiding, except perhaps as a transient transfer mechanism.

- We have noted a difference in the underlying stability of the two networks. The 900-MHz network appeared to be controlled by a reference source which was at least as stable as the rubidium oscillator used in the measuring apparatus, and may have been controlled by a GPS receiver. Two of the base stations of the other network, at 1800 MHz, displayed lower frequency stabilities (e.g. curves **D**, and **G**. of Figure 6) suggesting that they were controlled by high-stability crystal oscillators.

- We have seen a degradation of the stability of the received signals with distance. The signals from distant base stations (> 8 km) display random variations which limit the Allan standard deviation to just below 10^{-9} for elapsed times between about 100 and 500 s (curve **E** of Figure 6) and 1000 s (curve **F** of Figure 6). The difference in these times may have been related to the frequencies of operation (900 and 1800 MHz respectively).

- Measurements with a moving terminal are expected to show more complex behaviour as the multi-path propagation effects will show complex variations. These are likely to be as a result of the vectorial addition of several signals each travelling by a different path from transmitter to receiver. We estimate that the spatial coherence distance may be of order 1m. This implies that the coherence time for a mobile terminal travelling at 30 m s^{-1} would be approximately 30 ms, but this is long enough to decode the synchronisation sequence.

  A second effect will be caused by the appearance of new transmission paths and the disappearance of others during the trajectory of the mobile terminal. Both of these effects will provide important signatures to the time stability, but the second may be the more important in respect of the available time stability because of the delay spread in a propagation channel with motion-induced characteristics. We find this effect is harder to predict but could cause errors in the ±200 m range, degrading the FTA accuracy by two-thirds of a microsecond. However, the coherence time in the delay spread will demand more frequent measurements on the channel. In its current mode, the IFR2319 will not be able to download measurement samples to the PC sufficiently quickly.

ACKNOWLEDGMENTS

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