IMPORTANCE OF "ACCURATE" TIME TO TEST AND MEASUREMENT OF COMPLEX DYNAMIC SYSTEMS

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ABSTRACT

This paper discusses the importance of time measurement and the necessity of time measurement accuracy to data acquisition and analysis. It briefly reviews how time is used in data analysis and how to determine what amount of jitter, latency and phase error is acceptable for various data acquisition systems and analysis methodology. It discusses the relevance of various measurement timing errors and how some of them may be corrected. Finally, this paper discusses various approaches to time tagging of measurements in a distributed network based data system where data is packetized for efficient transmission.

KEY WORDS

Accuracy
Determinism
Precision

INTRODUCTION

What is Time?

Time is one of the four dimensions in the fabric of Space-Time with which most people are familiar. The measurement of time and space position are all necessary to completely describe an event, or state of any system being measured. These measurements are analyzed to allow us to gain knowledge of how dynamic systems behave in response to stimulus. Various dictionaries define time in multiple ways and of course, like most English words, its meaning depends on the context in which it is used. As technologists and engineers, our use of the term is best defined as:

> A nonspatial continuum in which events occur in apparently irreversible succession from the past through the present to the future

How is Time Defined for Measurement Systems?

From this definition one can observe that time implies a dimensional (but non-spatial) relationship between events and that an event occurring after another event in time cannot have been the cause of the preceding event, but may have been caused by the preceding event, or by some unrelated event. What is unique about the time dimension, in addition to being a non-spatial dimension, is that from the words in the definition, "events occur in apparently irreversible succession from the past through the present to the future" it is apparently not possible for events and phenomena to have a negative value for time dimension. This means that while it is always possible to return to a specific point in space, it is not possible to return to that point to observe a particular event or phenomenon, in real-time, after it has occurred. This is why it is necessary to capture and record the physical evidence of the event or phenomenon, along with a measurement of the time in which the event or phenomenon actually occurred. In this way, events can be reconstructed so that engineers and analysts can construct a picture of what occurred in relation to other events.

Another use of time in measurement systems is related to measurement of characteristics of certain phenomena occurring continuously over extended periods so that no distinct "event" is of specific interest as related to other distinct events. What may be important about time in the context of these measurements isn't exactly when they occur, but the periodic nature of the phenomena. In this case, the actual time of a measurement may not be important at all, but accurate measurement of the precise time interval between peaks and valleys observed in the phenomenon and the transformation of the measurement from the time domain to the frequency domain would be of primary significance.

What are Events?

Events themselves are often considered distinct measurable phenomena, occurring at discrete moments in time. In fact however, all observable events unfold over some definite time interval. In the process of understanding an event, which on a human time scale appears to occur "instantaneously", it is necessary to make several observations of the event (i.e. measurements) over ever smaller time intervals, so that the cause and effect relationships between the physical phenomena can be implied, if not directly observed.

Once we can imply a cause and effect relationship between events, we can design an experiment to validate our hypothesis. If then, by observation, we show that event B inevitably follows event A, we can be relatively certain that there is a cause and effect relationship between these two events.

A Brief History of Time Measurement Technology[1]

The link provided in reference 1 provides a fascinating look at another aspect of time measurement, i.e. the relationship of time measurement precision to the events being recorded over some period of time. The temporal interrelationship of these events determines the units, or fractions of units of time we use. When we consider events occurring over many human life times, we measure time in years, eons, centuries, thousands or millions or billions of years. We call this time measurement on a historical or geological scale. At the same time, measurement of rapidly changing phenomenon must be made over very short periods of time such as milliseconds, microseconds, nanoseconds or even picoseconds. Of course, the more rapidly events change, the shorter the time measurement interval and the more precise the time measurement must be. It follows that it must be more accurate as well.

BODY

Understanding motion in 3D spatial frame

The measurement of time is essential to understanding how things change, at what rate they change as well as the rate of change of the rate of change. This in turn helps to understand the nature of the phenomena/events being measured. For example, in measuring motion of an airplane, we measure distance traveled in a certain direction over a defined time period (i.e. velocity), we also measure the increase, or decrease in velocity over a period of time (i.e. acceleration). This kind of information is sometimes referred to as Time, Space, Position Information, or TSPI for short. We need the fourth dimension (i.e. time) to understand motion in 3 dimensional space.

It is often of vital interest to understand the temporal relationship between events occurring at widely separated points in space. For example the simultaneous recording of aircraft noise on the ground, aircraft TSPI information and the engine, landing gear and control surface settings on the airplane. In this case, it is necessary that all data recording platforms have a common sense of time. This can be accomplished by synchronizing all clocks in the system to a single time master. In most modern applications, GPS time is the obvious time source to be used for this purpose. When users are concerned about time differences in the tens of microseconds or less, one needs to account for satellite transmission delay differences in synchronizing clocks to GPS time.

Another important experimental observation that is often made is that of determining a characteristic frequency of a structure or circuit etc. This tells us how a particular system can be expected to behave in a dynamic environment. In some cases, we are asked to gather information on periodic motion phenomena, referred to as vibration. Understanding vibration requires that we know the amount of energy at each frequency of interest. This, of course presumes that we have some fore-knowledge of the phenomenon we are trying to characterize. If we fail to sample the phenomenon at a high enough rate, we will miss capturing frequencies much above twice our selected sample rate. To measure frequency, it is necessary to measure the characteristics of the phenomenon over a period of time. The higher the frequency we are trying to observe, the more observations we must make in a defined time period. As

[1] See reference 1

the frequency increases, the allowable time between observations gets smaller and the required "accuracy" of the timed measurement becomes tighter. In general, it is not physically possible to measure frequencies higher than half the sample rate[2]. In addition, our measurement of the energy distribution at each frequency requires a higher sample rate yet (usually at least 5 X the highest frequency we are trying to characterize.

Generally, the frequency content of a measurement recorded in the time domain is computed using a fast Fourier Transform (FFT). The results of this transform depend for accuracy on the uniformity of the time increments provided by the sampling clock. To the extent that there is jitter and/or phase noise in the clock signal used for data capture, there will be errors in the resulting frequency output produced by the FFT.[3]

An equation for the effect of jitter on the Signal to Noise Ratio of a frequency measurement is:

$$SNR = -20\log(2\pi f t_{JITTER_{RMS}})dB$$

Understanding events

An event is defined as "the fundamental entity of observed physical reality represented by a point designated by three coordinates of place and one of time in the space-time continuum postulated by the theory of relativity".[4] Another way to say this is that events are defined as the occurrence of some physically observable phenomenon at a unique point in space and at distinct point in time. In reality, this definition is not very precise at all. In the first place, for a phenomenon to be "observed" or measured, a period of time, as opposed to a distinct point in time is required to actually make the observation. In the second place, during the period of observation, the phenomenon, if it meets the definition of an event, is changing as well. In philosophical terms then, it is not actually possible to observe any actual event as defined above. In engineering terms however, if we can make an observation over a period of time that is short enough to ensure that the changes in the observed phenomenon are "negligible". This requires making some assumptions about the phenomenon, and that is exactly what we do to determine such time related characterizations as sample rate, time tagging accuracy[5] and precision[6].

[2] See reference 2
[3] See reference 3
[4] Merriam-Webster Online Dictionary definition of event #4.
[5] Accuracy - degree of conformity of a measure to a standard or a true value, ref: Merriam-Webster Online Dictionary
[6] Precision - the degree of refinement with which an operation is performed or a measurement stated – Ref: Merriam-Webster Online Dictionary.

How accurate is "Accurate"?

In determining how accurate a time measurement needs to be, we can define some engineering rules of thumb. In general, the time uncertainty, which we will define as (1 - Time Accuracy) needs to be small enough to ensure that the relationships between events can be determined. If the expected time between events in question is δt, our time uncertainty should be less than $\delta t/2$, to ensure that we will always be able to distinguish between events. If the observation time required is greater than $\delta t/2$, our measurement system will be unable to distinguish between the events in time.

A Common Sense of Time among Measurements

In order to distinguish between events measured at disparate places on an airplane, we plan to use a distributed data acquisition system base on network architecture. Data captured by remotely located acquisition elements often need to be correlated with what is happening elsewhere on the airplane. The only method available to accomplish this is to ensure that time tagging is done by the remote acquisition element when the data is captured and that all acquisition elements have a common sense of time.

Two developments offer a means to accomplish this with the accuracy and precision required for flight test measurements. These are network based time distribution i.e. Network Time Protocol (NTP) and Precision time Protocol (PTP) or IEEE 1588 and microfabricated atomic clocks[7]. Each of these technologies offers advantages and may be applicable to measurement applications on airplanes. The advertised uncertainties available with these technologies are as follows:

- NTP — $< \pm 1$ ms[8]
- PTP (IEEE 1588-2002) — $< \pm 1$ µs future $< \pm 1$ ns[7]
- Microfabricated atomic clocks[9] — Drift $<$ - 0.1 µs/day, $U_t \sim \pm 1$ µs /day

Each technology can serve a useful purpose in distributed measurement systems, depending on the actual measurement requirements. NTP is an inexpensive, software based protocol that should work well for measurements with sample rates up to 500 sps. PTP IEEE 1588 distributed time is also currently available, but requires special network switch hardware with boundary clocks to implement. Use of microfabricated atomic clocks is still some time in the future, but offers great potential for accurate timing on wireless networks.

[7] See reference 4
[8] See reference 5
[9] See reference 4

What are the consequences of timing errors?

Timing errors can have a significant adverse impact on data quality. For systems that depend on sample clocks to produce a fixed time interval for clocking data at a known sample rate, time interval errors add to measurement uncertainty and/or frequency distribution (band width) or phase error (Distortion), as illustrated in figure 1.[10]

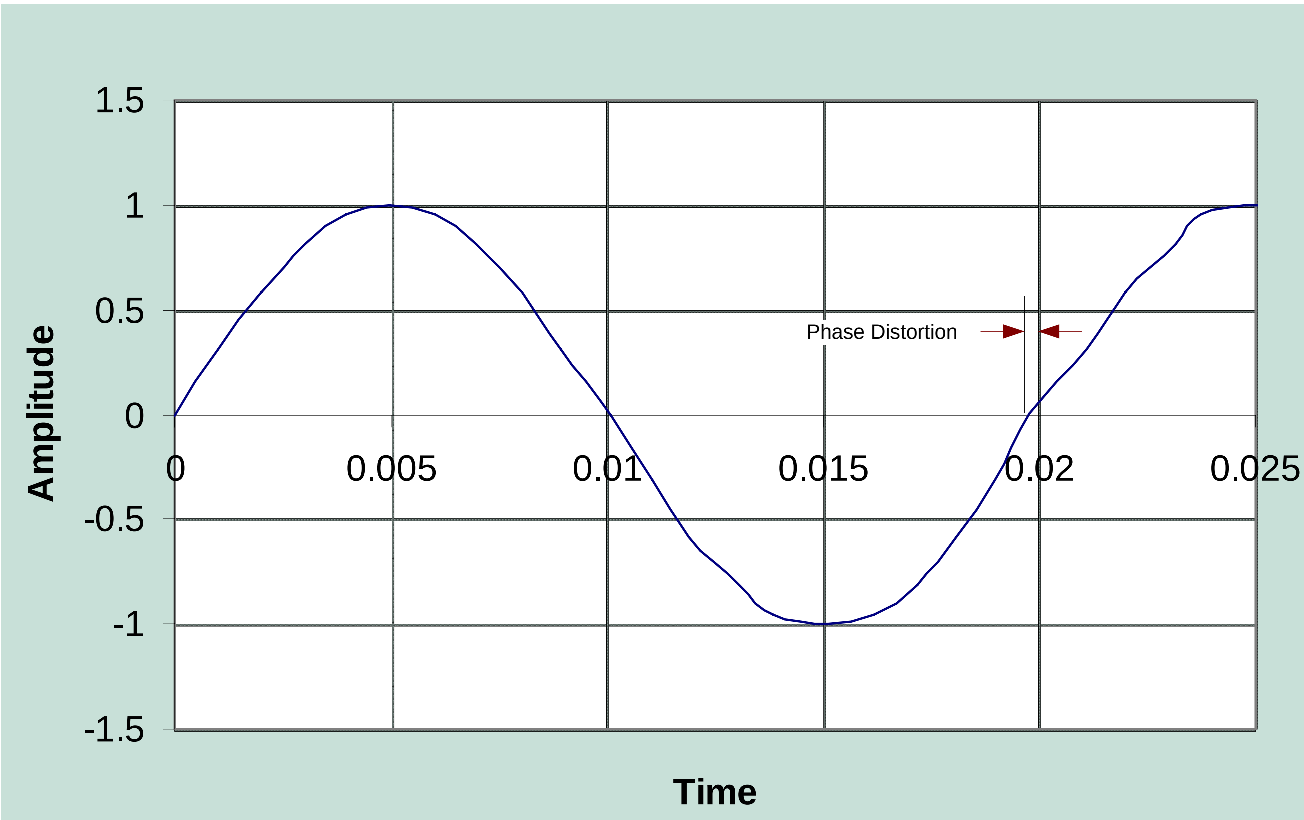

Figure 1 Sample Time Error Caused Phase Distortion

Sample timing errors can also introduce amplitude noise on relatively slowly varying measurement amplitudes. This is interpreted as sample uncertainty and directly impacts measurement uncertainty, as illustrated in figure 2.

[10] For the sake of illustration, a 2% (max) timing error was used. This is much larger than even the least accurate sample clocks, and is intended for illustration only.

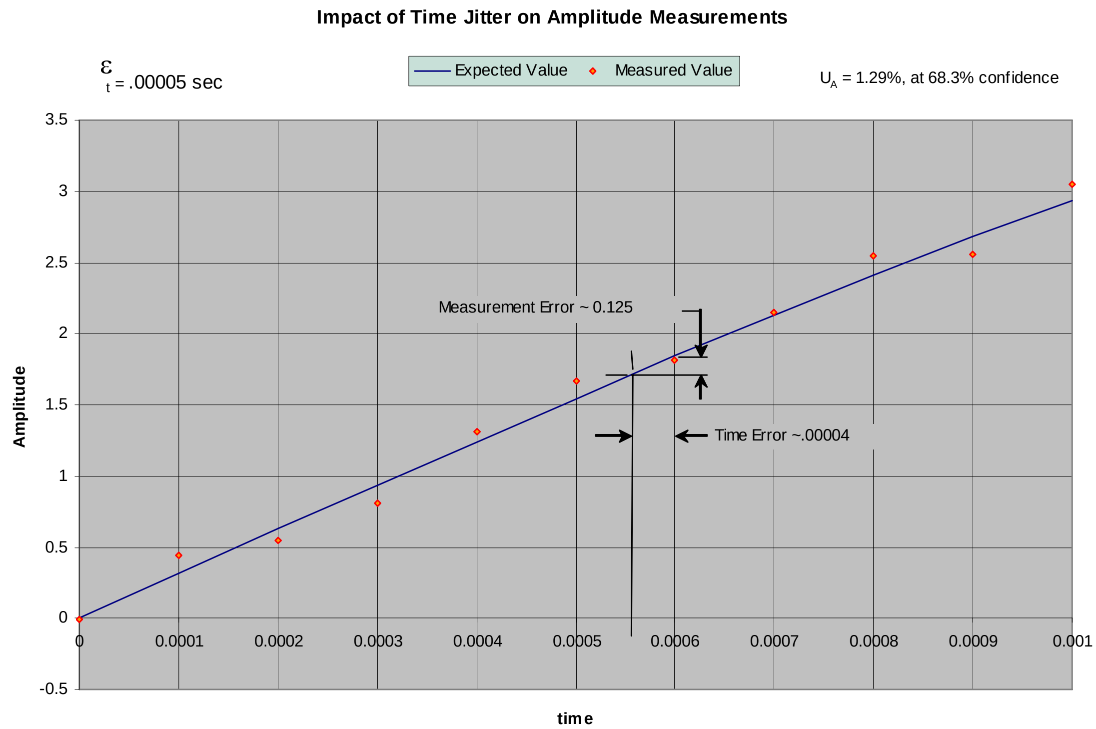

Figure 2 Effect of Time Jitter on Amplitude Measurements

What is the future of Time Measurement and Distribution (within Data Systems)?

Traditional measurement and control systems have been implemented using a centralized (treed) architecture. In such systems, timing requirements are met by programming to a predefined formatting combined with deterministic communication technologies (i.g. traditional IRIG 106 PCM). With the growing application of distributed data system architecture and the increasing use of commercial-off-the-shelf (COTS) networks such as Ethernet, a method of distributing time to the most remote acquisition element within the data acquisition chain will become increasingly important. Because distributed systems encourage autonomous operation of data sampling processes, sampling schedules need to be synchronized to ensure determinism among different sampling elements. In addition, data driven acquisition elements need to be able to time stamp the acquired data with time synchronized throughout the various parts of the data system.

Time can be distributed to the various system acquisition elements via a variety of distribution systems such as IRIG B, NTP and IEEE 1588. IRIG timing signals require a separate pair of wires, negating one of the most significant advantage of the more modern bus architectures i.e. the ability to reduce the number cables and connectors.

Network Time Protocol (NTP) was developed to synchronize the computer clock over a network. It represented a big step forward in synchronizing the activities of different networked processors and data acquisition elements. Its major drawback is that the various network components introduce variable[11] delays that cause inaccuracies in the time synchronization.

One approach to dealing with these delays conceived by Boeing to allow time stamping of data acquired by a device we called a Wireless Network Capable Application Processor (WiNCAP). This implementation was intended to use a clock sync pulse sent out on the power wires to the NCAP. The NCAP would receive its time of day information via NTP. The sync pulse would be transmitted simultaneously with the initiation of the NTP clock message. The WiNCAP programming would then adjust its time to match the NTP time of day to the sync pulse. Timing signals were to be transmitted every second. While this approach appeared reasonable, it was never tried. Instead, when we first powered up the WiNCAP we synchronized its system clock to airplane IRIG B time to an agreement of at least one second using a simple linux 'rdate' function (NTP works very well also, but 'rdate' was more efficient). Next the WiNCAP clock was synchronized to a pulse-per-second signal generated from the Airplane system reference clock using a phase-lock-loop circuit. This signal was transmitted over a fiber optic link that was also used to furnish a teat data stream to the WiNCAP. A clock jitter of around 10 nanosecond jitter was observed after a brief disciplining of the WiNCAP clock.

The IEEE 1588 standard was developed to address this shortcoming. The IEEE 1588™-2002 Standard for A Precision Clock Synchronization Protocol for Networked Measurement and Control Systems provides an approach to accurate time distribution of time across an Ethernet network. This is the approach that Boeing Commercial Airplane Company BCA is using in the design of a new distributed architecture data system for BCA Flight Testing. A method of synchronizing devices on an IEEE802.11b wireless LAN has been developed by Afshaneh Pakdaman and Todor Cooklev of San Francisco State University and John Eidson of Agilent Technologies (See reference 6). They claim to have achieved PHY jitter of 500 to 600 ns with an average offset is 7.35 microseconds. These numbers are well within the requirements for many flight test applications.

Another technology that holds promise for future wireless transducer systems is the Chip-Scale Atomic Clock. Research being conducted at the NIST Physics Laboratory and the University of California at Berkley is intended to provide an accurate, low power local time source that could be used in a smart transducer capable of time stamping its own data.

CONCLUSION

Precise and accurate time measurement plays a vital role in our understanding of the meaning of data and its interpretation leading to understanding of physical systems in the test environment. Complex physical systems make understanding the relationships of events in time an essential element of interpreting cause and effect relationships between events. In addition, precise and accurate timing of measurement sampling is essential to measuring and understanding a variety physical phenomenon.

[11] These delays depend on the bus loading which, for most non-deterministic networks, are themselves variable.

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REFERENCES

1. Timeline of Time Measurement Technology – Wikipedia (http://www.answers.com/topic/timeline-of-time-measurement-technology)
2. Nyquist frequency (http://en.wikipedia.org/wiki/Nyquist_frequency)
3. Brannon, Brad, Analog Devices Inc. "Understand the effects of clock jitter and phase noise on sampled systems" Electronics Design News (EDN), www.edn.com, 12/7/2004
4. Knappe, Svenja; Shah,Vishal; Schwindt, Peter D. D.; Hollberg, Leo and Kitching, John (Time and Frequency Division, National Institute of Standards and Technology, Boulder, Colorado) and Liew, Li-Anne and Moreland, John (Electromagnetics Division, National Institute of Standards and Technology, Boulder, Colorado) "A microfabricated atomic clock" APPLIED PHYSICS LETTERS - VOLUME 85, NUMBER 9, 30 August 2004
5. Myers, Paul "Time Synchronization Protocols for Distributed Sensor Networks" Spectracom Corporation, Sensors Expo Spring 2004, Paper Number NC8
6. Pakdaman, NodesAfshaneh and Cooklev, Todor (San Francisco State University) and Eidson, John (Agilent Technologiesafshan) "IEEE 1588 over IEEE 802.11b for Synchronization of Wireless Local Area Network Nodes", http://ieee1588.nist.gov/Presentation%20PDFs/4_IEEE%20802.11b_afshaneh.pdf