TDEV and MTIE Wander Measurements
Using the BI220 Time Interval Analyzer and Stable32

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• Introduction

This paper describes how to use the Brilliant Instruments BI220 Time Interval Analyzer/Counter [2] along with the Stable32 software [3] to make TDEV and MTIE wander measurements on a frequency source.

• Wander

Wander means to move about without a fixed course. In the telecommunications industry, wander refers to long-term timing variations with a frequency below 10 Hz, while variations above 10 Hz are called jitter. In the frequency control field, wander relates to the medium and long-term stability of the timing source. Wander is therefore a time-domain measure of clock stability at observation times of (say) 0.1 second and longer [1].

Wander is caused by three main factors:

1. Frequency offset and aging in the timing source.
2. Noise mechanisms in the timing source and distribution network.
3. Environmental sensitivity (e.g., temperature, EMI, etc.) affecting the system.

Wander is characterized by several statistical measures [8]. The fundamental parameter is the time interval error (TIE), the difference between the actual and ideal clock readings. Several statistics have been devised to characterize TIE in the time domain. Some of these are similar to the familiar standard or rms deviation but tailored to gracefully handle the more divergent that occur in frequency sources. Others are based on peak values are specifically intended to characterize telecommunications timing systems. The statistics of particular interest here are as follows:

1.	TIE	Time interval error is the data type used for these statistics.
2.	ADEV	Allan deviation is the most common measure of frequency stability.
3.	MDEV	Modified Allan deviation using phase averaging is the basis for the TDEV statistic.
4.	TDEV	Time deviation is the most common measure of time stability.
5.	TIE rms	TIE rms is simply the rms value of the time fluctuations.
6.	MTIE	MTIE is a peak measure of time error.

TDEV and MTIE are the most commonly-used measures of wander. TDEV is closely related to the underlying noise mechanisms of a frequency source. In particular, TDEV is based on the MDEV statistic which is directly related to the power law noise types used to characterize a frequency source [8]. The relationship between MTIE and these noise types is more complex because of the peak nature of the MTIE statistic that depends on the amplitude distribution of the noise process [9, 10]. One must, in principle, limit the time span that the clock is observed to prevent the MTIE value from becoming infinite.

Wander in a telecommunication system is often measured with a specialized instrument, and the results generally include all aspects of the system. The measured time interval error is what it is. Specifying and measuring the wander of a frequency source by itself is somewhat different because one must make assumptions about the way it is utilized in the host system. In particular, the host system may provide initial and/or periodic synchronization and syntonization (phase and frequency adjustments), environmental compensation and other disciplining of the source. The fundamental wander contribution by the source is due to its noise, and that is the main thrust of the measurements described herein. Thus it is reasonable to operate the device under test in a well-controlled environment and to remove any systematic frequency offset before analyzing the source performance. The effect of frequency aging is relatively minor unless the measurements extend over a long period of time.

A significant phase transient is rare for a frequency source, and would cause a corresponding flat MTIE value until it is exceeded by another larger effect. Frequency offset causes a linear increase in MITE versus observation time, τ. Source noise mechanisms cause the MTIE to increase with a slope depending on the noise type (e.g., flat for white PM noise, increasing as √τ for white FM noise). Some examples of those MTIE effects are shown below:

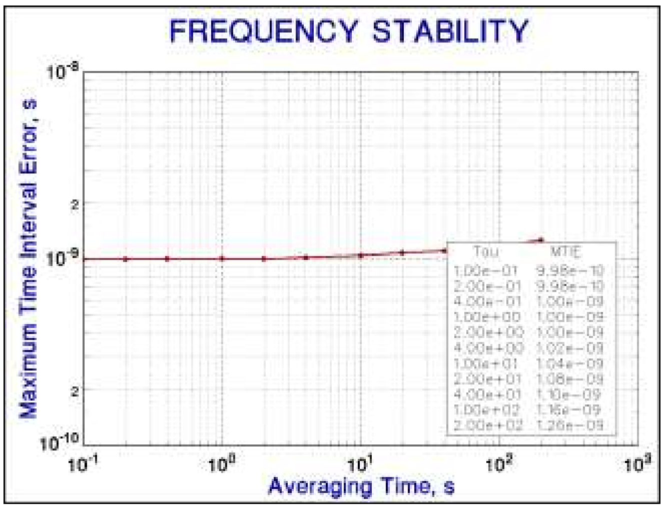

Figure 1. 1 ns Phase Step

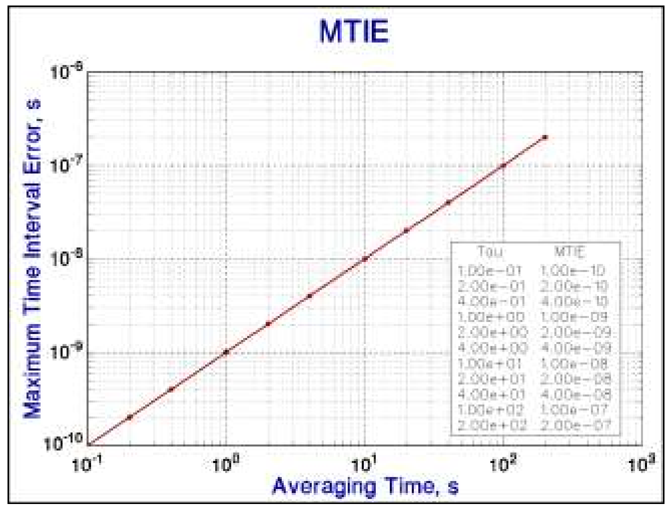

Figure 2. $1x10^{-9}$ Frequency Offset

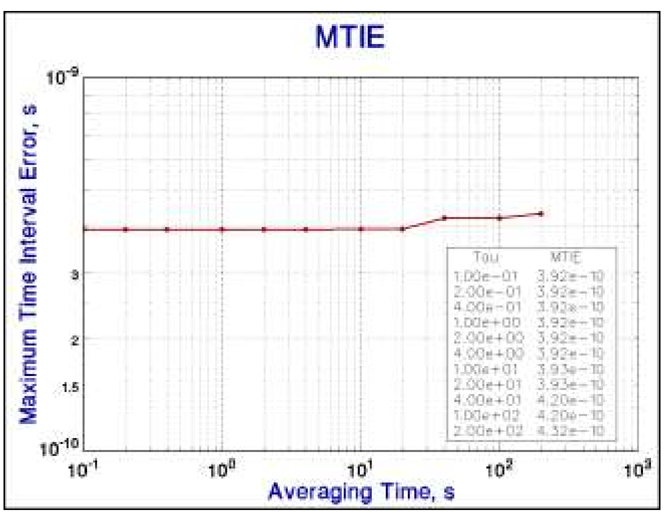

Figure 3. White PM Noise $1x10^{-10}$ at 1 Second

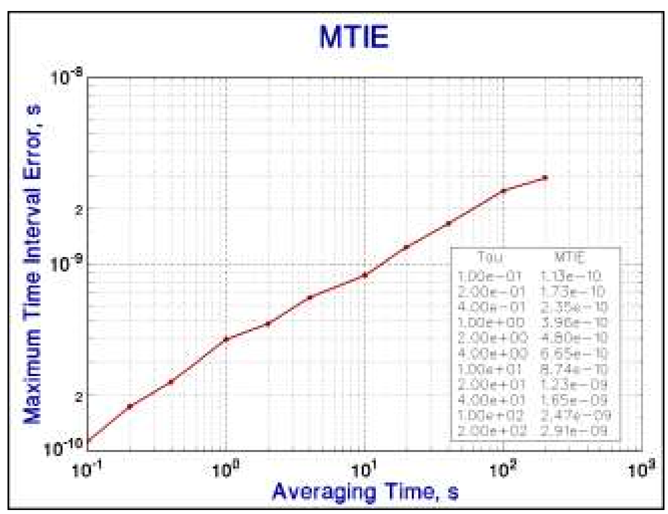

Figure 4. White FM noise $1x10^{-10}$ at 1 Second

Because MTIE is a peak measure of time interval error, it tends to increase as the number of samples becomes larger. Figure 5 shows this effect for a 100,000-point, 0.1 second set of simulated white PM noise having a $\sigma_y(1s)=1x10^{-10}$ and no frequency offset or drift for averaging factors of 1, 10 and 100 corresponding to 100k, 10k and 1k data points.

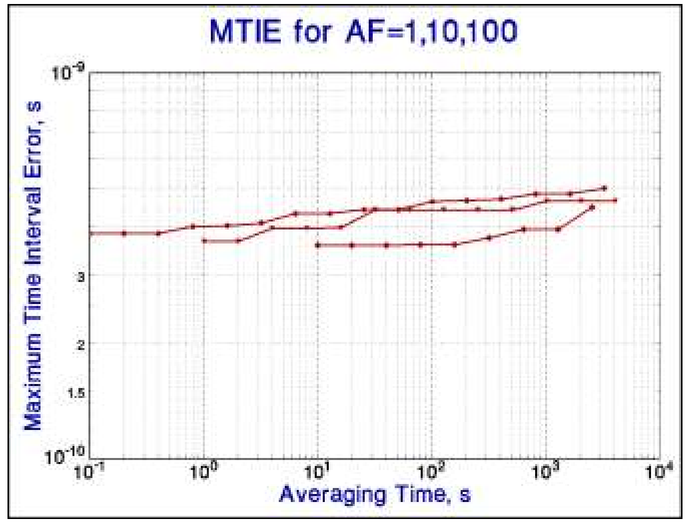

Figure 5. MITE versus # Samples Analyzed

• Measurement System

The Brilliant Instruments BI220 Time Interval Analyzer/Counter [2] was used for the measurements described below along with a GPS-calibrated Efratom LPRO rubidium frequency standard as a reference source.

• Measurement Methodology

The measurement methodology was simply to set up the BI220 for an externally-referenced channel A TIE measurement, capture the resulting data stream to a file, and analyze those data for TDEV and MTIE with Stable32.

• Test Setup

The setup for the BI220 TDEV and MTIE measurements is shown in Figure 6.

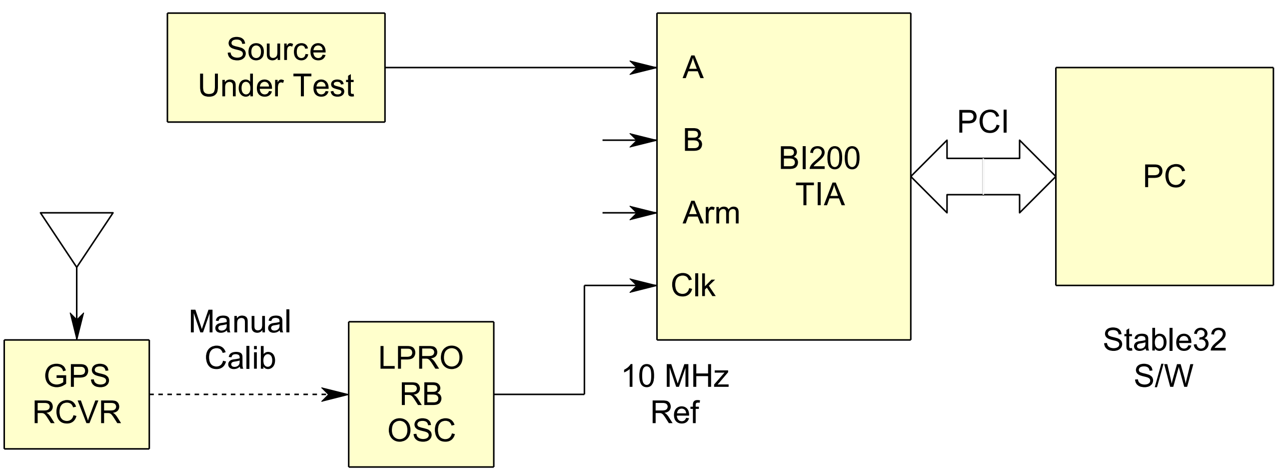

Figure 6. Test Setup

• Bi220 Virtual Instrument Panel

The BI220 TIA/Counter comes with a Windows virtual front panel application called BiVirt which can be used to set up and control its measurements. See Figure 7 and Page 2 of Appendix I for pictures of the main BiVirt screen with data table, statistics and plot displays.

The preferred way to use the Bi220 and BiVirt to acquire TIE data for a TDEV and/or MTIE analysis is to select the TIE measurement option and enter the nominal frequency of the source under test. But it is also acceptable to make average frequency measurements over each measurement interval, scale them to fractional frequency and convert those to phase data by numerical integration. Those latter steps can be performed with Stable32, and the frequency-to-phase integration is correct because the frequency data are obtained with zero dead time.

The BiVirt setups are divided into three groups of screens:

1. Instrument – Set up the Bi220 timebase and external clock input impedance.
2. Measurement – Set up the measurement function, inputs, blocks, block size, inputs and arming.
3. Displays – Set up one or more displays, including plots, statistics and data streaming to a file.

These measurement setup screens are shown in the table below for a 10,000-point, 0.1 second, channel A 100 MHz TIE measurement using an external 10 MHz reference clock. Note that not all options are shown. See Reference 8 for more details about these setup screens and Bi220/BiVirt usage.

Table I. Typical Bi220 Virtual Instrument Setup

Group	Section/Type	Item	Setting
Instrument		Timebase	Ext 10 MHz
		Ext Clk Impedance	50 Ω
Measurement	General	Function	TIA 1C1E
		Channel	A
		Polarity	↑
		# Blocks	1
		Meas/Block	10,000
	Inputs	Ch A Impedance	50 Ω
		Ch A Threshold	0 Volts
	Arming	Block Arm	Immediate
		Start Arm	Every 0.1 second
Display 1 (Plot)	General	Function	TIE
	Graph	Scaling, Colors, Labels, etc.	Defaults
Display 2 (Statistics)	General	Function	TIE
		TIE Reference	100 MHz
	Digital	Items to Show	All
Display 3 (Streaming)	General	Function	TIE
		Math	None
	Table	Columns to Show	Meas Point (only)
	Streaming	Enable Streaming	Yes
		Save to File	Yes
		Filename	Enter

In addition, the Bi220 has several calibration functions that should be used occasionally as described in its User Guide [7].

• Bi220 Command Line Interface

The BI220 TIA/Counter also comes with several command line interface sample programs, including Sample06CPP.exe which can be used as a convenient way to perform a streaming measurement. The best way to use this program seems to be to make a zero dead time high resolution frequency measurement and integrate those results to obtain phase data for a TIErms and MTIE analysis. An example of that program's command line usage is as follows:

```
Sample06CPP freq_avg 1000 bt 0.1 0 0 C:\Data\BiData 1 1 0
```

This command invokes the Sample06CPP program to perform 1000 tau=0.1 second "by-time" frequency average measurements with 0 volt input signal thresholds, streaming the results to a base filename called BiData in the folder C:\Data\ using a 10 MHz external clock and showing the data as it is acquired. Thus method apparently does not directly support TIE measurements.

• Noise Floor

The noise floor of the Bi220 measuring system was evaluated by applying a coherent 100 MHz input signal from a phase locked oscillator multiplier (PLOM) and making both zero dead time frequency and time interval error measurements as shown in Appendix III. The instrument has white PM noise that corresponds to a TDEV of about 10 ps at 1 second and an MTIE level slightly below 0.2 ns at 1 second. A longer 100,000-point 0.1 second run was also performed with essentially identical results, as shown in Figures 7 and 8.

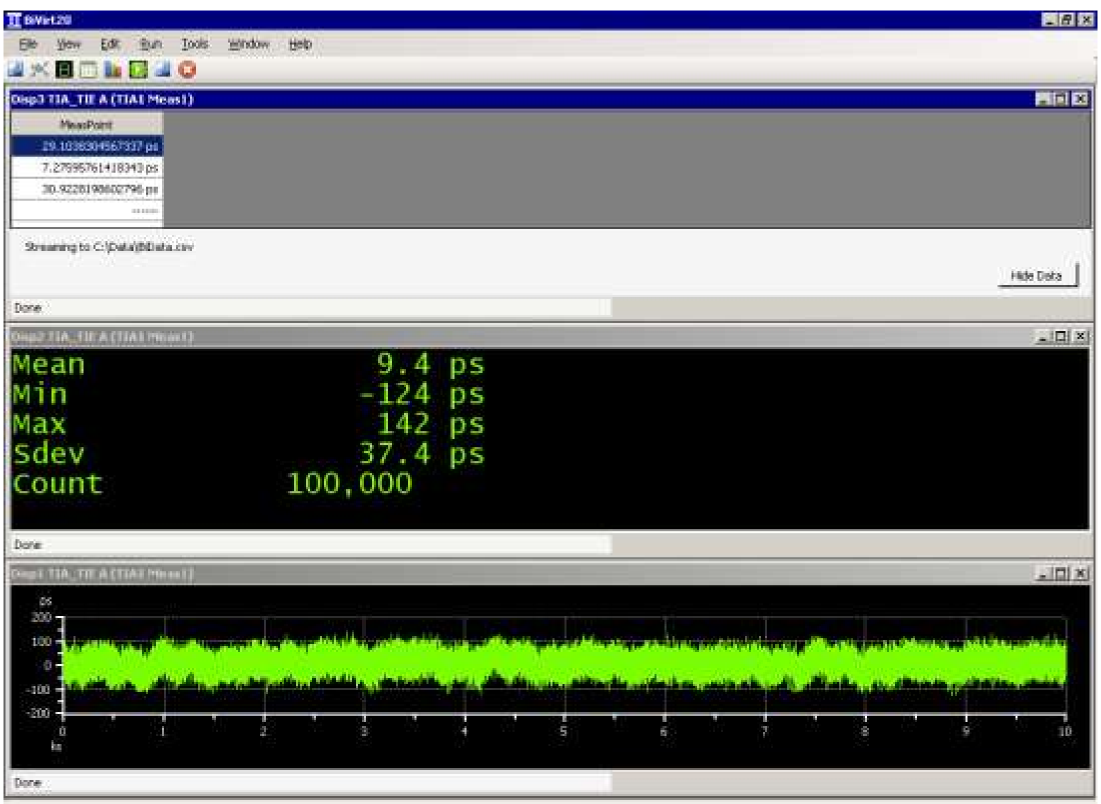

Figure 7. BiVirt Screen for 100,000-Point 0.1 Second Coherent Noise Test

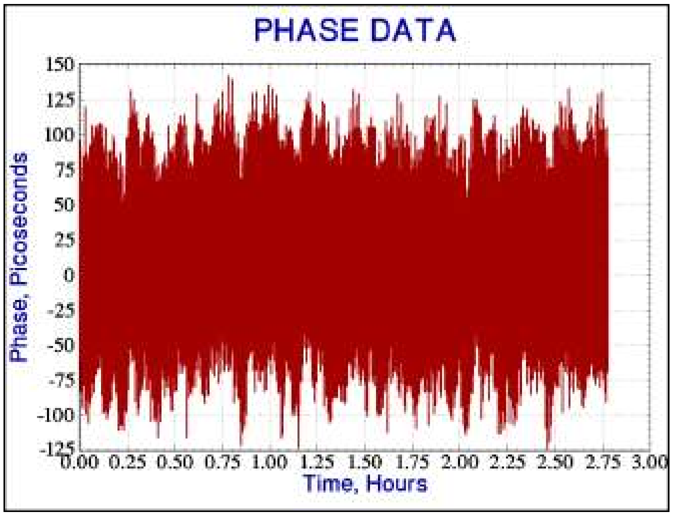

Figure 8a. TIE Data

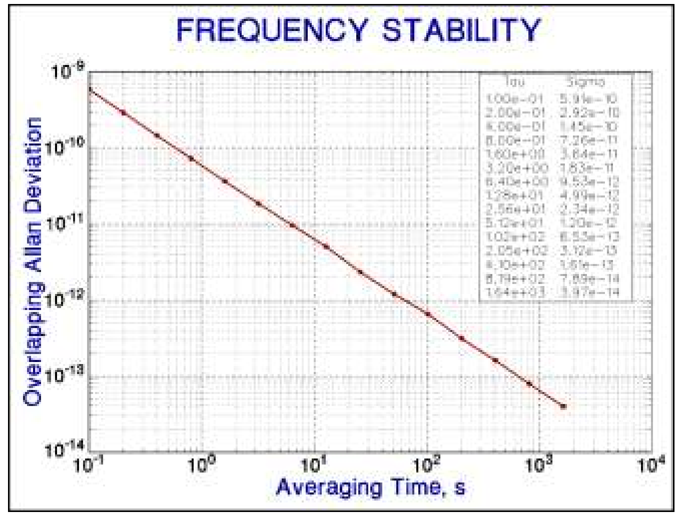

Figure 8b. Allan Deviation Plot

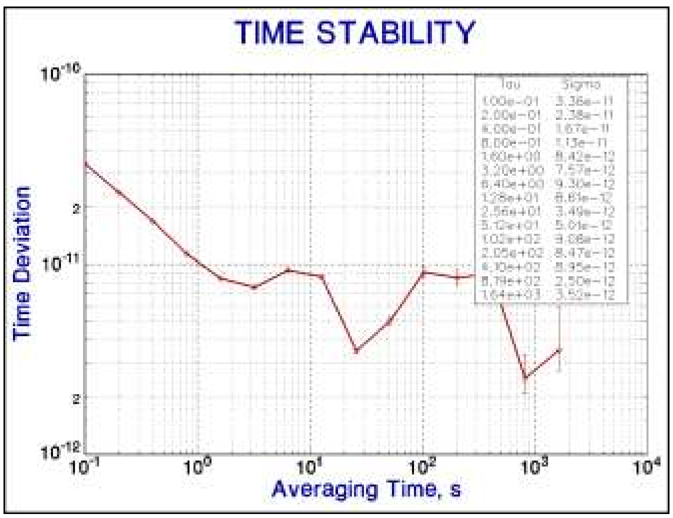

Figure 8c. TDEV Plot

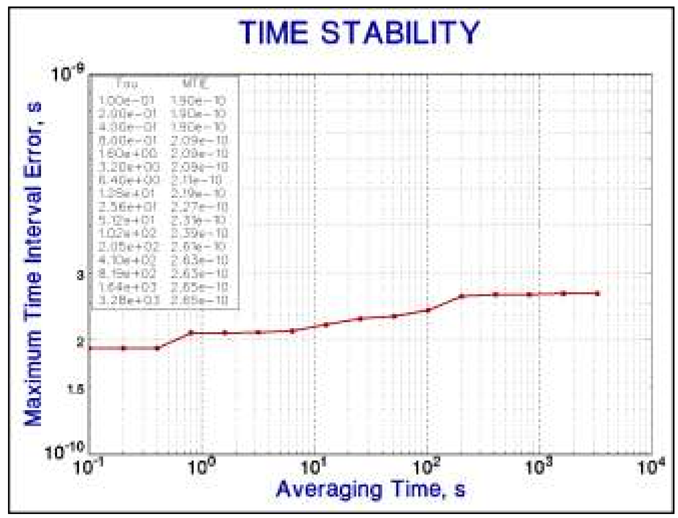

Figure 8d. MTIE Plot

Bi220 100 MHz Coherent Noise Floor Measurements

• Other Measurement Instruments

Wander measurements can be made with three basic types of instrument:

1. General purpose counters. In this context, *counter* refers to an interpolating reciprocal electronic frequency counter or similar event time tagging instrument that can make relatively high resolution zero dead time frequency and/or time interval measurements. The more sophisticated of those instruments are called time interval analyzers (TIA). These may be stand-alone instruments or boards that plug into a personal computer. An example of the former is the Stanford Research Model SR620, while an example of the latter is the Brilliant Instruments BI220 TIA/Counter used for these measurements. Those instruments generally require that their data be captured for subsequent analysis by specialized software like Stable32.

2. High resolution clock measuring systems. This category refers mainly to heterodyne type arrangements such as a dual mixer time difference (DMTD) system that provide very high resolution

and low noise. They may use analog mixers and zero crossing detectors or high speed analog to digital conversion followed by digital signal processing. Examples of those instruments are the Symmetricom 5110A and 5125A respectively. Those instruments may include internal firmware and displays for showing their results, but probably need to be supplemented by specialized analysis software for TDEV and MTIE.

3. Specialized telecom instruments. Specialized instruments are available to directly measure telecom-specific stability statistics like jitter and wander, and they often include performance masks for specific telecom requirements. They may handle only certain telecom signal formats, or include more general input capabilities. An example of this type of instrument is the Spectracom STA-61.

The utility of the Brilliant Instruments BI220 has been demonstrated in this report and in Reference [6]. It accepts signals up to 2.5 GHz (400 MHz direct without prescaler), and requires that its (e.g., TIE) data be captured and analyzed externally for TDEV and MTIE results.

The Symmetricom 5125A [4] is the top-of-the line of a family of superb clock measurement instruments with excellent resolution, noise floor and general measurement capabilities, including phase noise data that can be converted to time jitter. It is often used along with Stable32 for in-depth analysis. The 5125A can measure signals up to 400 MHz.

My knowledge of the STA-61 [5] is limited to the information on its data sheet. The 0.2 ns resolution sounds adequate but one should verify its noise floor. Its TDEV and MTIE displays seem nice, and it can export data to Stable32.

The BI220 is obviously the most economical choice even though it requires a PC to operate. All of these instruments also require a suitable frequency reference, either a low-noise ovenized crystal oscillator or a rubidium frequency standard. The Spectracom STA-61 has an internal rubidium oscillator and is available with an optional GPS receiver. The other instruments require an external reference. TDEV and MTIE analysis functions are integral to the STA-61, but all of the instruments either need or would benefit from the Stable32 software.

Regarding the frequency reference, while a frequency standard grade ovenized crystal oscillator could serve as an adequate reference for relatively short observation times, a small commercial rubidium oscillator such as the ones made by Symmetricom and Stanford Research is recommended for this application. Absolute frequency calibration is not necessary for an independent wander measurement where the frequency offset is removed, but can be accomplished by means of a GPS time and frequency receiver. Those devices are often combined with a rubidium oscillator to form a traceable laboratory time and frequency standard.

• Conclusion

The Brilliant Instruments BI220 is recommended, along with the Stable32 software and a suitable frequency reference, as a simple, reasonably convenient, low cost and effective way to make TDEV and MTIE wander measurements.

• References

1. *Understanding Jitter and Wander Measurements and Standards*, Agilent Technologies, February 2003.
2. Data Sheet, BI220 Time Interval Analyzer/Counter, Brilliant Instruments, November 2011.
3. Data Sheet, Stable32 Software for Frequency Stability Analysis, Hamilton Technical Services, August 2008.
4. Data Sheet, 5125A Phase Noise and Allan Deviation Test Set, Symmetricom, Inc, 2009.
5. Data Sheet, STA-61 Sync Tester/Analyzer, Spectracom, Inc., December 2011.
6. W.J. Riley, "Clock Measurements Using the BI220 Time Interval Analyzer/Counter and Stable32", Hamilton Technical Services, February 2012.
7. *Bi220 User Guide*, Brilliant Instruments, October 2011.
8. W.J. Riley, *Handbook of Frequency Stability Analysis*, NIST Special Publication 1065, July 2008.
9. P. Tavella and D. Meo, "The Range Covered by a Clock Error in the Case of White FM", *Proceedings of the 30th Precise Time and Time Interval Systems and Applications Meeting*, pp. 49-60, December 1998.
10. P. Tavella, A. Godone and S. Leschiutta, "The Range Covered by a Random Process and the New Definition of MTIE", *Proceedings of the 28th Precise Time and Time Interval Systems and Applications Meeting*, pp. 119-124, December 1996.

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Appendix I Data Sheet for BI220

Brilliant Instruments

BI220

Time Interval Analyzer / Counter

FEATURES

- Direct Time Measurement of Pulse Trains
- Measure Jitter, Frequency, Time Interval (Skew), Pulse Width, Risetime, Event Timing, Time Interval Error (TIE), and More
- 8 ps Single-Shot Resolution (12 Digits/s Frequency)
- DC to 400 MHz Frequency Range for all Measurement Functions Including Pulsewidth, Plus a Prescaler for Frequency and TIE Measurements to 2.5 GHz
- Up to 1 Million Continuous Zero Dead Time Measurements Per Second
- 1 ns Minimum Pulse Width
- Highly Sophisticated and Flexible Arming (Triggering)
- PCI Interface for Super High Throughput
- On-board Memory for 8 Million Measurement Points – Can Be Read While Measurements are Taking Place

More Tests in Less Time

The BI220 is a high performance time and frequency measurement instrument. Its high resolution and throughput, combined with continuous measurement capability, allow you to make measurements that are not possible with traditional time-interval counters. For example, it can timetag events (edges of an input pulse train) at a rate of 1 million per second continuously to on-board memory, while each of the edges is measured with 8 ps resolution. This provides it with the capability to analyze the dynamic variations in pulse timing, pulsewidth, or frequency. In other words, the difference between the BI220 and a traditional counter/timer is analogous to the difference between a voltmeter and a scope. Measurements can also be streamed continuously over the PCI interface allowing unlimited acquisition at high rates.

Full-Featured Instrument

The BI220 is a full instrument-on-a-card with all the features and capabilities you would expect in a bench-top instrument including high quality inputs, built-in NIST traceable calibration, and software and hardware that deliver fully computed results. The instrument has 10 measurement functions such as Frequency, Time Interval and Pulsewidth. All functions work directly on the input signal at frequencies up to 400 MHz without any prescaling. This means that you can measure pulses as narrow as 1 ns, occurring at frequencies up to 400 MHz, or the skew between two signals at 400 MHz. There is also a prescaler for each input channel which allows frequency and period measurements to 2.5 GHz.

The inputs of the instrument include programmable termination voltages. This feature is seldom found even in the best of the bench-top instruments. You can select by software control either a 1M Ohm impedance to ground, or a 50 ohm load which is terminated to an accurately programmable voltage between -3 V and +3 V. This allows you to connect ECL, PECL, or CML sources directly to the instrument with the proper loading. The input comparators have a fixed hysteresis of 25 mV which is useful for signals with slow risetime or high noise levels. It sets different threshold levels for the rising edge and the falling edge which prevents false triggering.

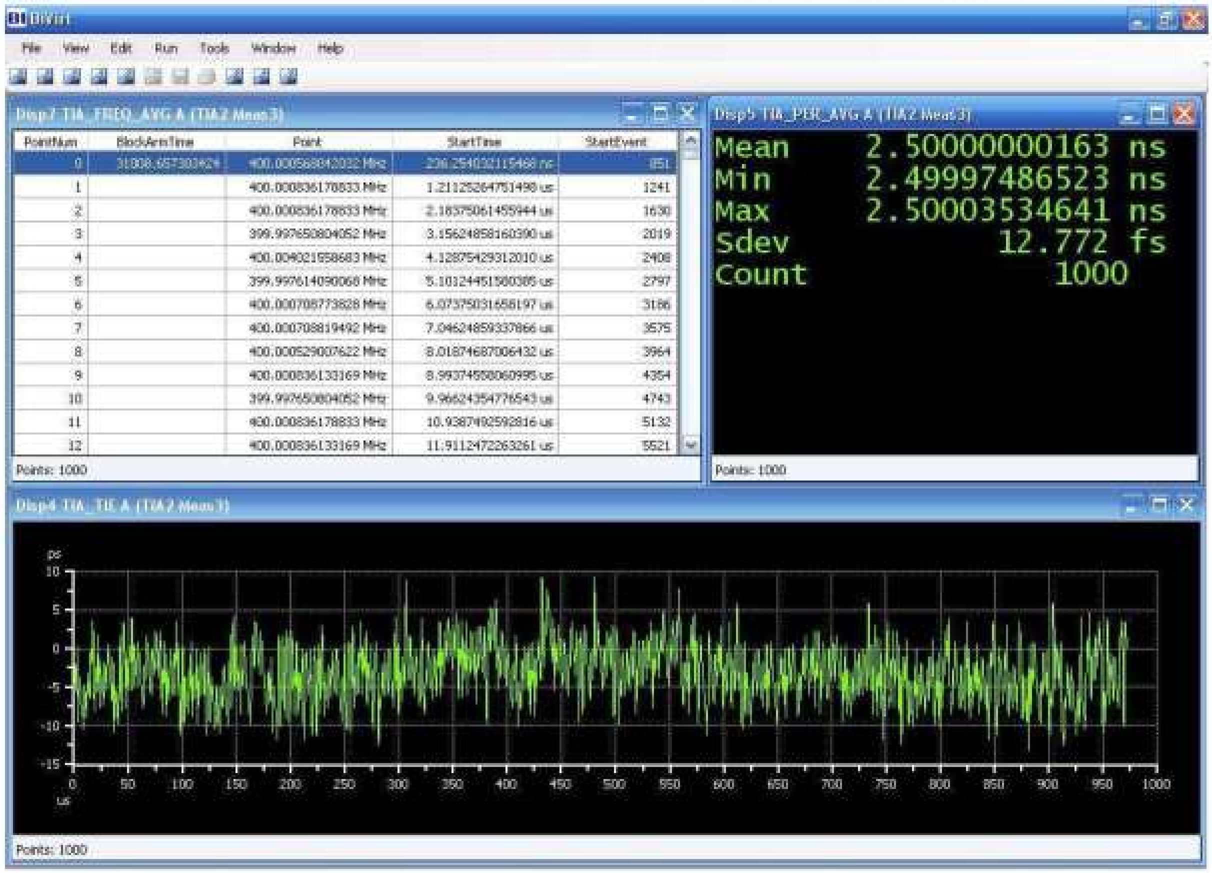
APPLICATIONS

- PLLs and frequency modulation – measure jitter, time interval error and settling time
- Ultrasonic and radar pulse timing
- Optical and magnetic disk drive – measure jitter, risetime, and bit timing directly
- Oscillators and crystals – measure frequency, start-up time and time interval error
- Pulse width modulated signals – measure variations over time
- Time stamping of events in real time
- Nuclear physics

Easy to Use Software

The software for the BI220 is designed for ease of use and extremely high performance. The driver software (Windows and Linux) automatically manages the streaming of measurements at the high rates which are possible with the PCI interface. The front panel software for Windows allows you to easily set up multiple simultaneous displays of the measurements. This gives multiple views of the same data, or different functions from the same data. For example, you can set up the display to show a graph of the frequency of the signal vs. time, plus a tabular display of the same results, plus a graph of the time deviation of the signal vs. time, all from the same measurement acquisition run. The front panel can also run multiple instruments simultaneously. All instrument models use the same driver for easy migration between models.

The screen image below is from an actual measurement of a 400 MHz clock. One thousand single channel measurements were taken. The tabular display shows 1000 frequency measurements and the times and event numbers when they were taken. The digital display shows the statistics on period calculations of the same data. The graph display shows the TIE (Time Interval Error) calculations vs. time. Note that all 1000 measurements were taken in less than 1 ms. In addition, the resolution of the instrument is clearly evident with the Y axis of the graph at 5 ps per division.



HOW DOES IT WORK?

The simplified block diagram on the right shows the key components of the instrument from the user's point of view. The input signal is terminated by 1M ohm to ground or 50 ohms to a user-programmable voltage (Vt) and fed to a comparator. The comparator output goes high when the signal crosses a user-programmable threshold voltage (Vth). At this point the signal is a digital waveform whose rising or falling edges are considered to be "events". These events are continuously counted by the Event Counter, while the Arming System selects the edges which are to be timetagged according to the user configuration. For example, you can set up the instrument to timetag every N events, or every T seconds.

When an event is timetagged, the event count (pulse number) and the time of the occurrence are logged to memory. The Timetag Circuits require a recovery time of 1 µs to be ready for another timetag. Note, however, that the signal is still counted by the Event Counter, so no information is lost. This recovery time means that up to 1 million timetags (or pairs of timetags) can be logged per second. From this timetag data, the instrument calculates the measurement results.

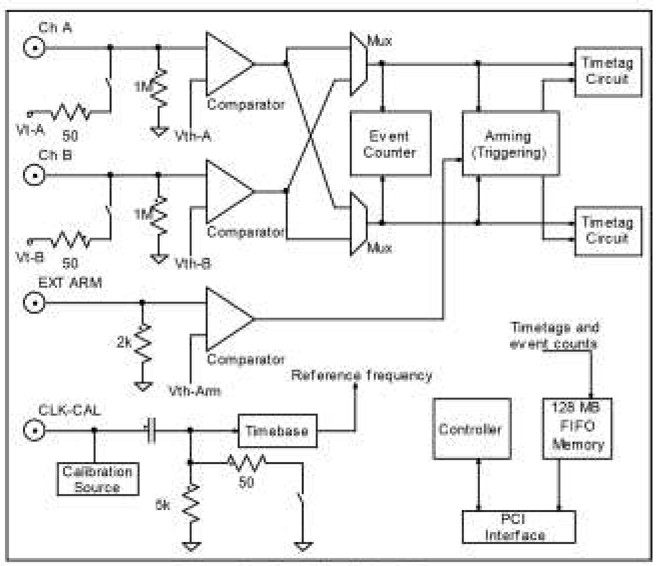


Figure 1: Simplified block diagram

There are three groups of measurement functions – 1C1E, 1C2E, and 2C2E. The timing diagrams below illustrate the operation of the instrument for each group.

One-Channel-One-Edge Functions

The 1C1E functions (one-channel-one-edge) operate on a single channel (either A or B) and use only one timetagging circuit. That is, each timetag contains only one edge time and one event count. The recovery time of 1 µs is the minimum time between timetags. That is, for frequencies below 1MHz it is possible to measure every rising or falling edge. The equations for the first measurement point in the timing diagram are shown in the table below. For example, in the equation for Frequency Average E1 and E2 are event counts while T1 and T2 are the time information from the first two timetags. Note that you can make up to 1 million frequency measurements per second on a continuous zero-dead-time basis. The measurement points are back to back since the end of one point is the start of the next one.

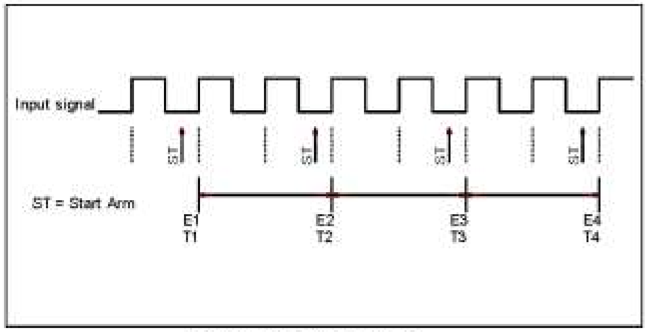


Figure 2: 1C1E functions

Function	Calculation	Notes
Frequency Average	$FreqAvg = \frac{\Delta E}{\Delta T} = \frac{E2-E1}{T2-T1}$	Average frequency of the input signal
Period Average	$PeriodAvg = \frac{\Delta T}{\Delta E} = \frac{T2-T1}{E2-E1}$	Average period of the input signal
Continuous Time Interval	$CTI = \Delta T = T2 - T1$	The actual time between pairs of timetags
Time Interval Error	$TIE = T1 - ExpectedTime$	The deviation in time of each of the timetags from an expected value. The user supplies the reference period of the signal

One-Channel-Two-Edge Functions

The 1C2E functions (one-channel-two-edge) operate on a single channel (either A or B) and use both timetagging circuits. That is, each timetag contains two edge times and one event count. The recovery time of 1 µs is the minimum time between the stop timetag and the next start timetag. For all these functions the result is the difference in time from the start to the stop. The associated event count is for the start event. The arming that the user specifies is for the Start Arm, while the Stop Arm is dictated by the function.

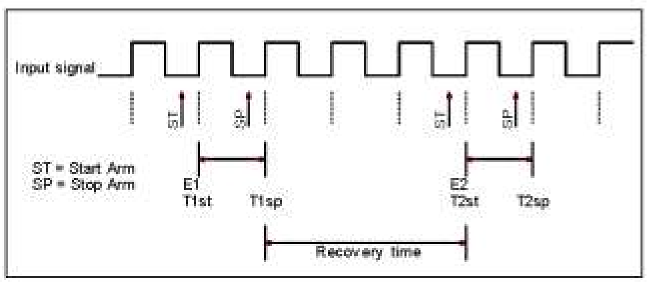


Figure 3: 1C2E functions

Function	Stop Arm	Notes
Period	Next same edge	Measures single periods of the input signal
Pulsewidth	Next opposite edge	Measures individual pulsewidths of the input signal
One-Channel Time Interval	Next signal edge	The polarity of the start and stop edges is specified by the user
Risetime, Falltime	Same signal edge	Measures a single edge with two thresholds, usually 20% and 80%

Two-Channel-Two-Edge Functions

The 2C2E functions (two-channel-two-edge) operate on both channels (A to B or B to A) and use both timetagging circuits. That is, each timetag contains two edge times and one event count. The recovery time of 1 µs is the minimum time between the stop timetag and the next start timetag. For the 2-Ch Time Interval function the result is the difference in time from the start to the stop. The associated event count is for the start event. The user can specify the polarity of the start edge and the stop edge and a delay for the Stop Arm. The delay provides for the selection of the stop edge. For example, when the Stop Arm Delay is set to 0, the instrument will measure down to a 0 time interval (zero skew between channel A and B).

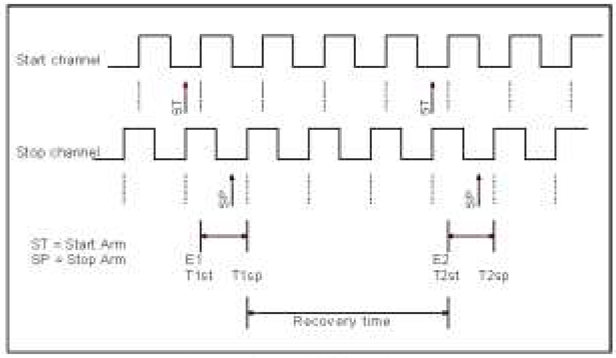


Figure 4: 2C2E functions

SPECIFICATIONS

General

- See "Definitions" below for explanation of the terms in the specifications
- Warranty: 1 year

Measurement Functions

- Fully symmetrical operation – all functions are the same for channel A or B
- One-Channel One-Edge (1C1E) Functions:
  - Frequency Average
  - Period Average
  - Continuous Time Interval (CTI)
  - Time Interval Error (TIE)
- One-Channel Two-Edge (1C2E) Functions:
  - Period (Per)
  - Pulsewidth (PW)
  - 1-Ch Time Interval (TI1)
  - Risetime
  - Falltime
- Two-Channel Two-Edge (2C2E) Functions:
  - 2-Ch Time Interval (TI2)
- In addition to the measurement results, all functions provide the actual timetag in absolute time and the event count for each measurement (using the Table display)

Frequency Average A or B

- Measures the average frequency between pairs of events on a zero-dead-time basis (measurements are back to back)
- Type: 1C1E (One-Channel One-Edge)
- Frequency range (direct): 0.15 Hz to 400 MHz
- Frequency range (prescaled): 50 MHz to 2.5 GHz
- Measurement time ("gate time"): 1 µs to 6.8 s
- Number of events per measurement point: 1 to 4.29 billion
- Number of significant digits: 12 digits/s (9 digits in 1 ms, or 5 digits in 1 µs) regardless of input frequency
- Resolution (in Hz rms):
  $$\pm\frac{Freq\times(8\,ps(rms)+1.4\times TriggerError)}{Meastime}$$
- Accuracy (in Hz): ±Resolution ± TimebaseErr

Period Average A or B

- Measures the average period between pairs of events on a zero-dead-time basis (measurements are back to back)
- Type: 1C1E (One-Channel One-Edge)
- Range (direct): 2.5 ns to 6.8 s
- Range (prescaled): 400 ps to 20 ns
- See Frequency Average function for measurement time, number of events, and significant digits
- Resolution (in seconds rms):
  $$\pm\frac{Period\times(8\,ps(rms)+1.4\times TriggerError)}{Meastime}$$
- Accuracy (in seconds): ±Resolution ± TimebaseErr

Continuous Time Interval (CTI) A or B

- Measures the time between pairs of events on a zero-dead-time basis (measurements are back to back)
- Type: 1C1E (One-Channel One-Edge)
- Frequency range (direct): 0.15 Hz to 400 MHz
- Frequency range (prescaled): 50 MHz to 2.5 GHz
- Range: 1 µs to 6.8 s
- Measurement time: 1 µs to 6.8 s (can comprise multiple periods of the input signal)
- Number of events per measurement point: 1 to 4.29 billion
- Resolution:
  ± 8 ps(rms) ± 1.4 x TriggerErr
- Accuracy: ±Resolution ± TimebaseErr ± 50 ps

Time Interval Error (TIE) A or B

- Measures the time of occurrence of events, then calculates the deviation from the expected period of the signal
- Type: 1C1E (One-Channel One-Edge)
- Frequency range (direct): 0.15 Hz to 400 MHz
- Frequency range (prescaled): 50 MHz to 2.5 GHz
- Measurement repetition rate: 1 µs to 6.8 s

- Number of events per measurement point: 1 to 4.29 billion
- Resolution:
  ± 8 ps(rms) ± 1.4 x TriggerErr
- Accuracy: ±Resolution ± TimebaseErr ± 50 ps

Period A or B

- Measures single periods of the signal
- Type: 1C2E (One-Channel Two-Edge)
- Range: 2.5 ns to 6.8 s
- Frequency range: 0.15 Hz to 400 MHz
- Time between measurements: 1 µs to 6.8 s
- Resolution: ± 8 ps(rms) ± 1.4 x TriggerErr
- Accuracy: ±Resolution ± TimebaseErr ± 100 ps

Pulsewidth A or B

- Measures pulse widths of the signal
- Type: 1C2E (One-Channel Two-Edge)
- Range: 1 ns to 6.8 s
- Frequency range: 0.15 Hz to 400 MHz
- Time between measurements: 1 µs to 6.8 s
- Resolution: ± 8 ps(rms) ± 1.4 x TriggerErr
- Accuracy:
  ±Resolution ± TimebaseErr ± TriggerLevelTimeErr ± 100 ps

1-Ch Time Interval A or B

- Measures time intervals between edges of the input signal, with selectable polarity
- Type: 1C2E (One-Channel Two-Edge)
- Range: 1.25 ns to 6.8 s
- Frequency range: 0.15 Hz to 400 MHz
- Time between measurements: 1 µs to 6.8 s
- Resolution: ± 8 ps(rms) ± 1.4 x TriggerErr
- Accuracy:
  ±Resolution ± TimebaseErr ± TriggerLevelTimeErr ± 100 ps

Risetime A or B, Falltime A or B

- Measures risetime or falltime of the input signal
- Type: 1C2E (One-Channel Two-Edge)
- Two thresholds (trigger) levels are set
- Range: 0 ps to 6.8 s
- Frequency range: DC to 400 MHz
- Time between measurements: 1 µs to 6.8 s
- Resolution: ± 8 ps(rms) ± 1.4 x TriggerErr
- Accuracy:
  ±Resolution ± TimebaseErr ± TriggerLevelTimeErr ± 100ps

2-Ch Time Interval (TI2) A-to-B or B-to-A

- Measures the time between edges of signals from two channels
- Type: 2C2E (Two-Channel Two-Edge)
- Range: -500 ps to 6.8 s
- Frequency range: 0.15 Hz to 400 MHz
- Time between measurements: 1 µs to 6.8 s
- Resolution:
  ± 8 ps(rms) ± StartTriggerErr ± StopTriggerErr
- Accuracy:
  ±Resolution ± TimebaseErr ± TriggerLevelTimeErr ± 100 ps

Inputs and Outputs

Ch A and B

- Direct input (no prescaler):
  - Frequency range: DC to 400 MHz
  - Minimum pulse width: 1 ns
  - Coupling: DC
  - Input impedance: 1 MΩ to ground or 50 Ω into a user programmable termination voltage
  - Sensitivity: 50 mV rms sine, 50 mVp-p pulse
- Prescaled input:
  - Frequency range: 50 MHz to 2.5 GHz
  - Minimum pulse width: 200 ps
  - Coupling: AC
  - Input impedance: 50 Ω into a user programmable termination voltage
  - Sensitivity: 30 mV rms sine, 30 mVp-p pulse
- Connector: SMA
- Termination voltage (Vt): -3 V to +3 V
  - Resolution: 100 µV
  - Accuracy: 10 mV
- Trigger Threshold voltage (Vth): -5 V to +5 V
  - Resolution: 200 µV
  - Accuracy: 10 mV
- Input voltage range:
  - Operating: -5 V to +5 V
  - Maximum (1 MΩ): -30 V to +30 V
  - Maximum (50 Ω): -5 V to 5 V DC, 5 Vrms AC (+27 dBm)
- Slope: Positive or negative
- Hysteresis – prevents false triggering by having separate threshold levels for rising and falling edges: 25 mV

EXTARM Input

- Connector: SMA
- Frequency range: DC to 400 MHz
- Minimum pulse width: 1 ns
- Hysteresis: 40 mV typical, fixed
- Setup time: 5 ns
- Impedance: 2 kΩ to ground (no programmable termination)
- Coupling: DC
- Trigger Threshold voltage (Vth): -5 V to +5 V
  - Resolution: 200 µV
  - Accuracy: 10 mV
- Input voltage range:
  - Operating: -5 V to +5 V
  - Maximum: -10 V to +10 V
- Slope: Positive or negative

EXTCLK Input / CAL Output

- Connector: SMA
- Input for external timebase reference
  - Coupling: AC
  - Impedance: Programmable to 50 Ω or 5 kΩ
  - Amplitude:
    - Square wave – 400 mVp-p to 4 Vp-p
    - Sine wave – 1 Vp-p to 4 Vp-p
- Output for calibration signal (see manual for instructions)

Definitions

- TriggerErr or StartTriggerErr or StopTriggerErr
  - Error due to noise superimposed on the input signal from both internal and external sources
  - $TriggerErr = \frac{\sqrt{300\mu V^2 + E_n^2}}{InputSignalSlewRate}$ s rms
  - En = RMS noise of input signal (1GHz bandwidth)
  - InputSignalSlewRate = Slew rate of input signal (V/s) at the threshold point
- TriggerLevelTimeErr
  - Time error due to threshold uncertainty
  - $TriggerLevelTimeErr = \frac{< 10mV}{InputSignalSlewRate}$ s rms
  - Example: For input signal slew rate = 100V/µs TriggerLevelTimeErr = 100 ps
- TimeBaseErr
  - Fractional Frequency error of timebase reference, times the measurement result

Arming

Each measurement run is composed of multiple blocks with multiple "points" in each block. For example, 1000 blocks of 1000 pulsewidth points can be taken, for a total of 1 million points. Statistical results are provided for each block, and for the whole set of blocks.

Arming is the enabling of measurement points or blocks. There is separate arming for blocks and for points.

Block Arm

- Mode
  - On Channel A edge (same polarity as measured edge)
  - On Channel B edge (same polarity as measured edge)
  - On EXT ARM rising or falling edge
  - By Time – every 1µs to 3.43 s, 12.8 ns resolution
  - Immediate – run as quickly as possible
  - By software command
- Number of blocks: 1 to 16,777,215 or "endless"

Start Arm

Arms the start of each measurement point.

- Mode
  - By events – every set number of edges of the input signal
    - Number of events: 1 to 4,294,967,295
  - On Channel A edge (1C2E functions on Ch A only)
  - On Channel B edge (1C2E functions on Ch B only)
  - On EXT ARM rising or falling edge
  - By Time – every 1µs to 3.43s, 12.8 ns resolution
  - Immediate – run as quickly as possible
  - By software command
- Number of measurements per block: 1 to 16,777,214 or "endless"

Stop Arm

- 1C1E functions: Not used
- 1C2E functions: Automatically configured for the specific function
- 2C2E functions: Stop Arm can be selected to occur either before or after the start edge of the signal

Timebase

- Standard internal oscillator:
  - Over full temperature range: ±2 ppm
  - Aging: ±2 ppm/year
- Optional NIST traceable internal 10 MHz oven oscillator:
  - Over full temperature range: ±0.02 ppm
  - Aging: ±0.001 ppm/day, ±0.3 ppm/year
  - Warm-up time: 5 minutes
- External 10 MHz reference input
  - Frequency: 10 MHz ±50 ppm (±500Hz)
  - See "Inputs and Outputs" section above for signal characteristics

Memory

- 128 MB on-board
  - Up to 11 million measurements in 1C1E functions
  - Up to 8 million measurements in 1C2E, 2C2E functions
- Memory can be read out while measurements are accumulating, allowing unlimited continuous measurements

Math and Statistics

- Performs additional mathematical operations on the measurement results
  - Scaling and normalizing
  - Calculating relative error
- Calculates statistics on blocks of measurements and on the total set of blocks
  - Mean, Min, Max, and Standard Deviation

Software

- Windows® and Linux driver
  - Provides a powerful set of functions for controlling the instrument and for data analysis
  - Includes tools for high speed reading of the instrument which take advantage of the PCI interface without burdening the user with the details
  - Windows® NT/95/98/2000/XP/Vista/7, 32/64-bit
  - Linux with 2.4/2.6 kernels (e.g. Redhat 3, Redhat 5)
  - Written in plain C++ for easy porting to other environments

- Virtual Front Panel (Windows® based)
  - Provides multiple simultaneous displays for the same measurement. The displays can even be different functions, as long as they are from the same group (1C1E, 1C2E, or 2C2E)
    - Graphs of results vs. time
    - Histogram
    - Numerical results (digital display)
    - Table of results and internal data
    - Streaming of results to a file
  - Can run multiple instruments of any model simultaneously
  - Compatible with Windows® XP/Vista/Win7 32/64-bit
  - Requires .NET Framework 3.5 (available free from Microsoft™)

Computer Requirements

- One 32-bit 33 or 66 MHz PCI slot
- Size: 4.0"x6.8" (10.2x17.3cm) excluding bracket
- 256 MB RAM, 100 MB disk space
- 800x600 minimum display resolution

Calibration

- Traceable calibration once a year
  - Requires a voltmeter and a frequency reference
- Internal calibration automatically calibrates the instrument against the internal voltage and frequency references

Power, Cooling and Physical

- Power supply requirements from PCI bus (typical):
  - 3.3 V @ 4.8 A 5 V @ 0.6 A 12 V @ 0.3 A
- Total power consumption: 22 W typical
- Operating temperature range: 0°C to 45°C
- Good ventilation of slots in PC is recommended
- Weight: 5 Oz (140 g)

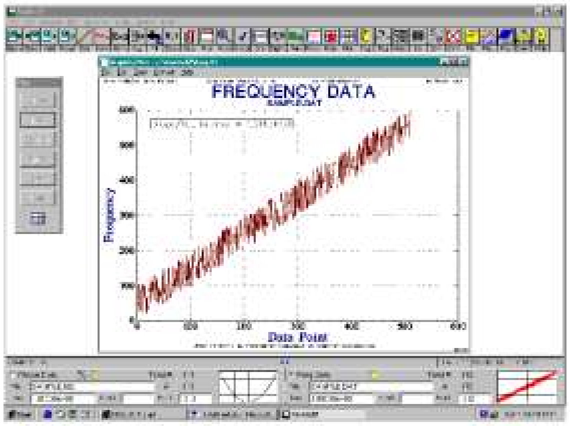
*Specifications are subject to change without notice

11/25/11

Appendix II Data Sheet for Stable32

Stable32 Frequency Stability Analysis

Stable32 is a 32-bit Microsoft Windows® program for the analysis of frequency stability. It includes all the functions necessary to manipulate, analyze and plot time and frequency stability data.



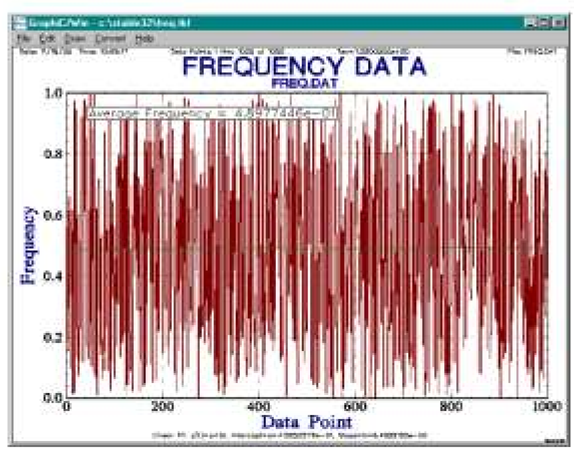
Features Stable32 file operations include opening phase and frequency data files, combining data, and storing all or a portion of the data. Data is stored in ASCII format, with gaps indicated by a value of zero, and may be input from any source that generates up to 32 columns of comma, tab, bar or space-delimited data, with or w/o timetags. Stable32 can also read and process data from several Timing Solutions Corporation clock measurement systems. All storage and calculations are performed with double precision for a virtually unlimited number of data points. Editing functions include displaying, editing, inserting, deleting, and filling gaps in phase and frequency data. Conversion between phase and frequency data is supported, as is outlier detection and removal. Timetags may be generated for indexing, or used to locate and fill gaps in the data. Plotting and printing can be done for all or a portion of the data, with drift fits and automatic or user-defined scales and titles. Analysis functions include basic statistics (max, min, avg, median and std dev), drift, drift removal, normalization, scaling, gap and outlier detection and removal, as well as several stability variances, dynamic stability, histograms, filtering, autocorrelation and power spectrum, all over selectable limits with gaps ignored. Stability analysis includes point and automatic calculation and plotting of normal and overlapping Allan deviation, modified Allan deviation, time deviation, total deviation, modified and Hadamard total deviation, modified time total deviation, and normal and overlapping Hadamard deviation, as well as Thêo1, ThêoH, MTIE and TIE rms. The PSD can be expressed as $S_y(f)$, $S_x(f)$, $S_\phi(f)$ or $\mathcal{L}(f)$. Means are available to estimate the noise type and to set selectable confidence intervals. Stability data can be saved, edited, read and re-plotted. Simulated power-law clock noise may be generated and time-frequency domain conversions may be done for power-law noise processes. A calendar is provided for date, day-of-year, GPS Week # and MJD.

Functions All Stable32 functions are accessed by menus and toolbars as shown below:

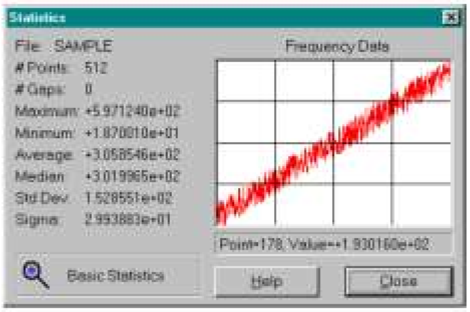
- **Open/Add/Save** Open, merge or save a data file
- **Drift** Calculate drift for x(t) and y(t) data
- **Sigma/Run** Calculate Allan or other deviations
- **DAVAR** Calculate dynamic stability
- **Read** Read a stability data file
- **Power** Calculate and plot power spectrum
- **Plot/Print** Plot or print phase or freq data
- **Histogram** Plot histogram
- **ACF** Calculate and plot autocorrelation function
- **Filter** Filter phase or frequency data
- **Phase** Plot phase data
- **Edit** Edit current data
- **Frequency** Plot frequency data
- **Convert** Convert between x(t) & y(t) data
- **Noise** Generate simulated clock noise
- **Normalize** Remove mean value from data
- **Timetags** Generate timetag data
- **Average** Combine data into longer tau
- **Calendar** Display a DOY/MJD calendar
- **Fill** Fill gaps in data
- **Domain** Time-freq domain conversions
- **Regularize** Insert gaps using timetags
- **Notepad** Invoke the Notepad text editor
- **Scale** Scale data (+,*, slope)
- **Play** Replay a *.TKF plot file
- **Part** Delete part of data
- **Configure** Set configuration options
- **File** Set filenames
- **Clear** Clear data array
- **About** Display Stable32 information
- **Statistics** Calculate basic statistics
- **Index** Display Help index
- **Check** Check frequency data for outliers
- **Auto** Perform an automated stability analysis
- **Database** Open TSC SQL database file
- **Tab** Cache phase or frequency data
- **Vibra** Calc vibration or modulation sidebands
- **Help** Display help information

The top rows of the screen contain the menu and toolbar, and the bottom lines display the status of the phase and frequency data currently in memory, including zoomable plots of the data. The usual Windows® user interface conventions are used.

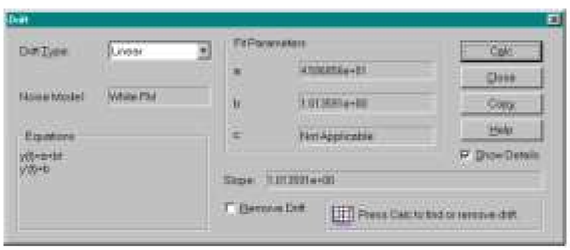
Data Plotting Stable32 includes functions for high-resolution phase and frequency data plotting, with optional title, subtitle, annotations and drift lines. The data and time axes may be scaled to other units. The plot scales may be automatically determined or manually chosen. The plots include time and date, file name, data point range, averaging time and line parameters. A number of line options are available. The plotting routines use the GraphiC® library for on-screen and publication-quality hard copy graphic printouts. The screen plots may be zoomed, stored in a file for replay by the included Play/Win program, or converted to other formats for import into other programs.



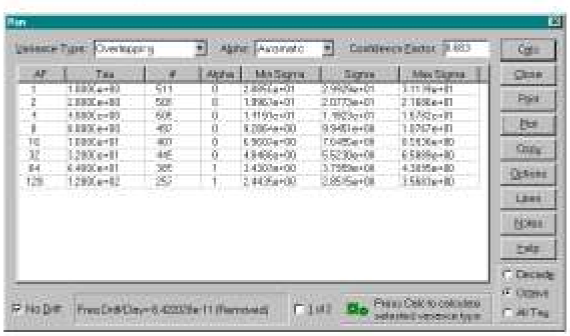
Data Analysis Stable32 includes functions for basic statistics, drift, variance, histograms, autocorrelation, and power spectrum analysis. The basic statistics are # data points and gaps, maximum, minimum, average, plot scales and standard deviation.



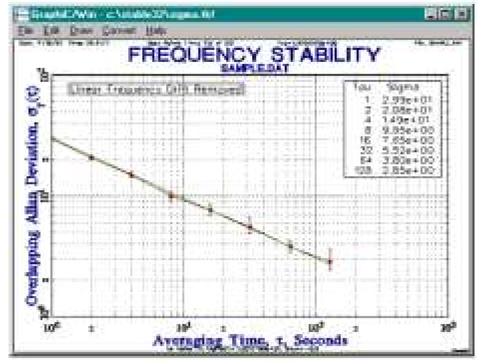
Frequency drift analysis includes 2nd difference, 3-point and quadratic fits to phase data, and linear, bisection, logarithmic and diffusion fits to frequency data. Frequency drift may be removed from the phase or frequency data. Variance analysis includes normal, overlapping, modified and time Allan deviations, Total, and Hadamard deviations for phase and frequency data. The averaging time may be chosen as any multiple of the basic data up to the maximum permitted for the particular calculation. Confidence limits are given, and single or double confidence intervals can be established for overlapping data using X^2 statistics and the estimated noise type. An example of a Stable32 drift analysis screen is shown below. This screen is typical of those for all Stable32 functions, including analysis choices and numerical results. The Stable32 drift analysis methods include linear, log, diffusion, bisection, quadratic, 3-point and 2nd difference. Linear fitting and endpoint matching is available to calculate and remove frequency offset from phase data.



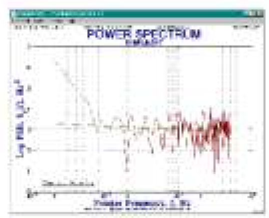
Stability Analysis Stable32 stability analysis methods include normal, overlapping, modified and time Allan deviations, total, modified, time and Hadamard total deviation, and normal and overlapping Hadamard deviation, Thêo1 & ThêoH, as well as MTIE and TIE rms. These statistics are available either at a single averaging time with the Sigma function, or over a range of averaging times with the Run function, with automatic bias corrections and error bars

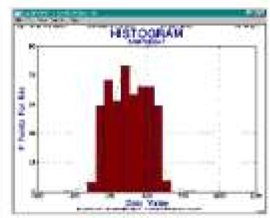


The results of the latter operation can be printed in tabular form or plotted as shown below. Automatic or user-defined noise typing is available, and decade, octave or all tau increments may be selected. The stability plot can include noise lines, specification limits and masks, and a variety of titles, sub-titles, messages and annotations.



Other Functions Other Stable32 analysis functions include dynamic stability, power spectra, $S_y(f)$, $\mathcal{L}(f)$, $S_\phi(f)$ and $S_x(f)$, autocorrelation, noise ID, histograms, LP, HP, BP & BS filtering, time-frequency domain conversions, frequency jump and spurious analysis. Simulated power law clock noise may be generated and analyzed.





Documentation Stable32 is supported by a 340 page User Manual that fully describes the installation and operation of the program. Examples are included that show the use of the major features and functions. Stable32 can be used for both routine data analysis of frequency stability measurements and as an educational tool. The ability to generate and analyze simulated clock noise is an effective way to learn the techniques of frequency stability analysis. The Stable32 program also includes on-line help.

Ordering Information The single-quantity price of Stable32 (inc. US shipping via priority mail) is $395. Copies of Stable32 may be purchased directly from Hamilton Technical Services. A check or purchase order should accompany your order. Stable32 is supplied on a CD-ROM with an installation program and is not copy protected. Backup copies may be made and may be installed on any number of computers within the immediate user group that purchased it, but only one copy of each unit purchased may be used at any time. Additional copies of the software or its documentation may not be distributed to others. Stable32 is sold with a 30-day refund policy to insure your satisfaction. Free support/updates are provided for 1 year.

Software for Frequency Stability Analysis

Hamilton Technical Services
650 Distant Island Drive
Beaufort, SC 29907-1580 USA
Telephone: +1-843-525-6495
Fax: +1-843-525-0251
E-Mail: stable32@wriley.com
Web: http://www.wriley.com

Appendix III

Coherent 100 MHz Noise Floor Test of a Brilliant Instruments BI220 Time Interval Analyzer

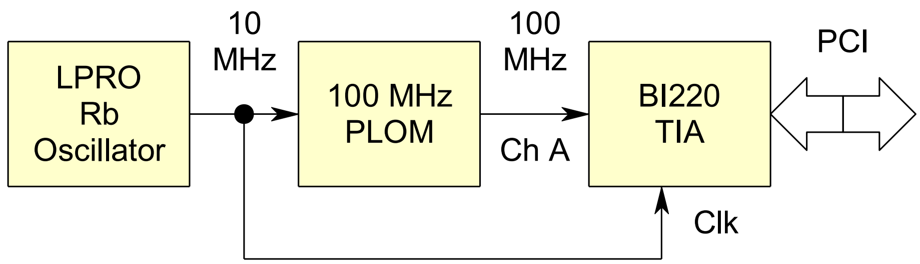


Figure 1. Test Setup – Coherent 100 MHz Phase-Locked Oscillator Multiplier
This coherent arrangement measures the noise floor of the measurement system.

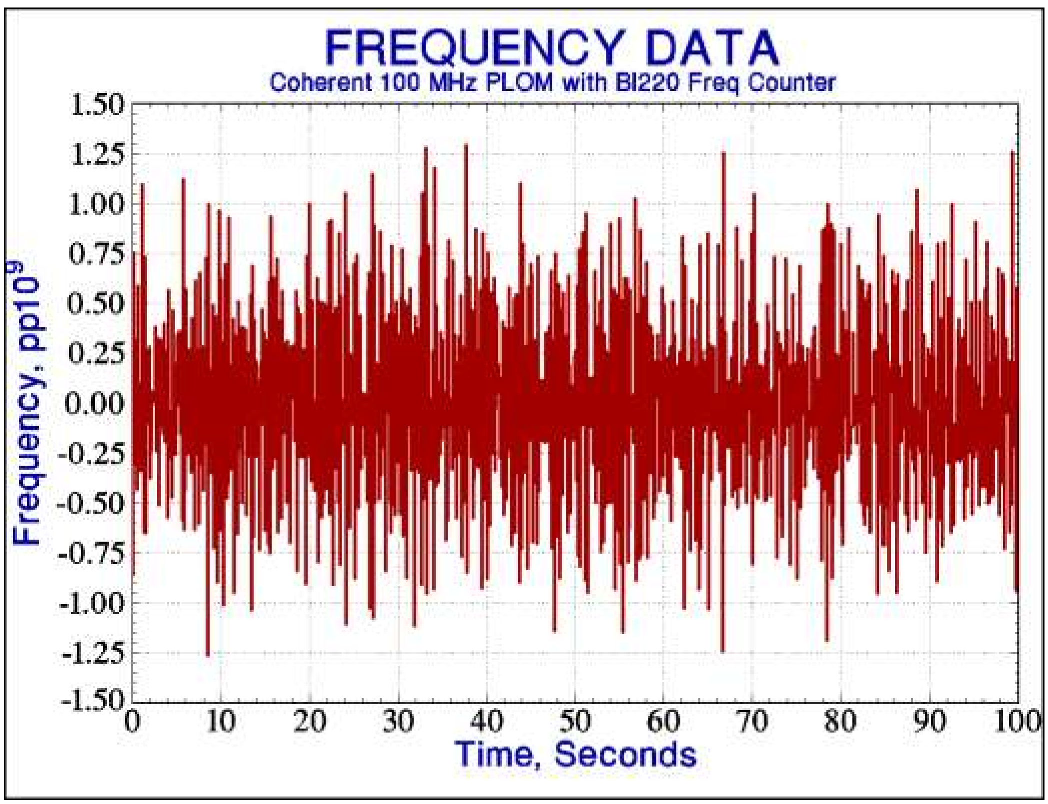


Figure 2. Tau=0.1 Second Frequency Data
The average frequency is exactly 100 MHz thus verifying the instrument accuracy.

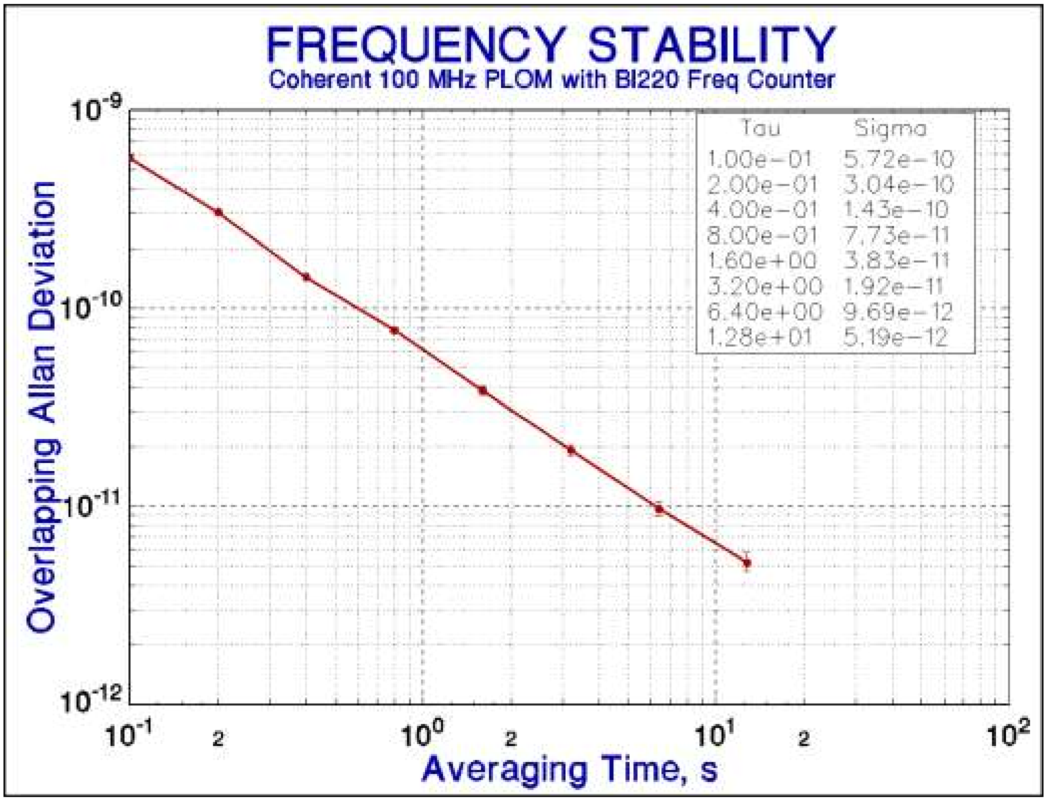


Figure 3. Frequency Stability – White PM Instrument Noise Floor
White PM noise is expected from the BI220 analog interpolation circuits.

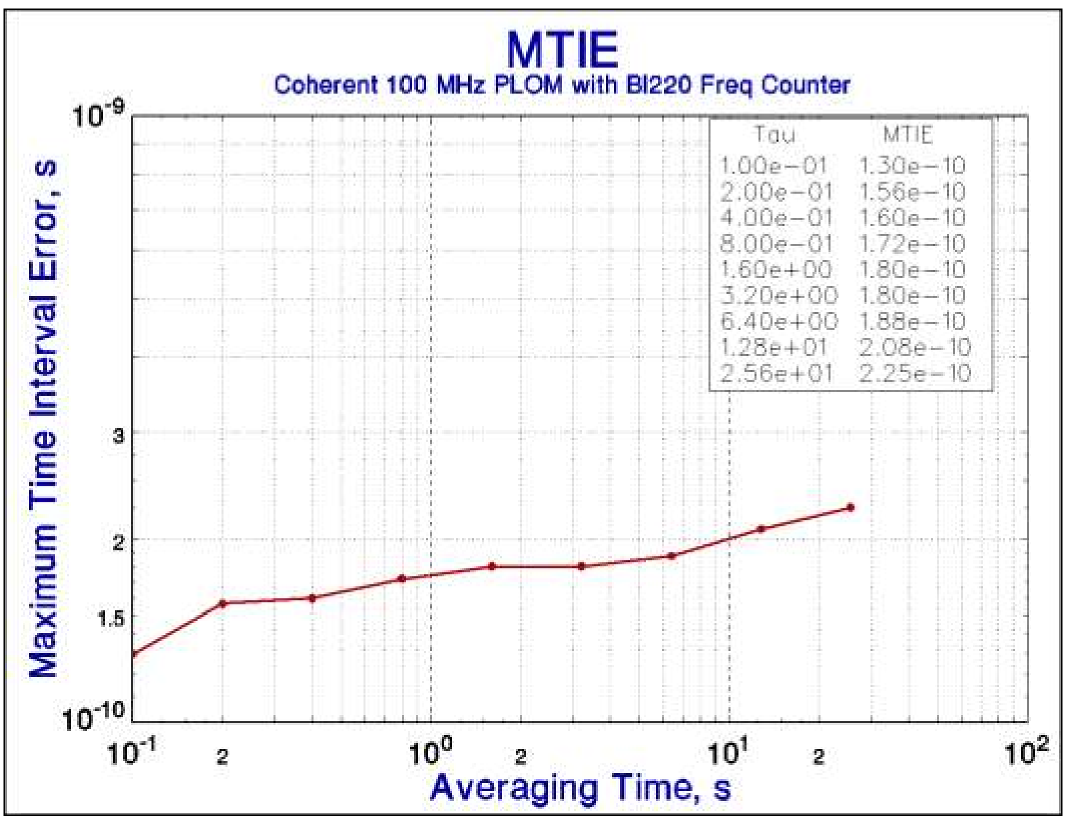


Figure 4. MTIE of Integrated Frequency Data
The frequency data has zero dead time so it can be used in this way.

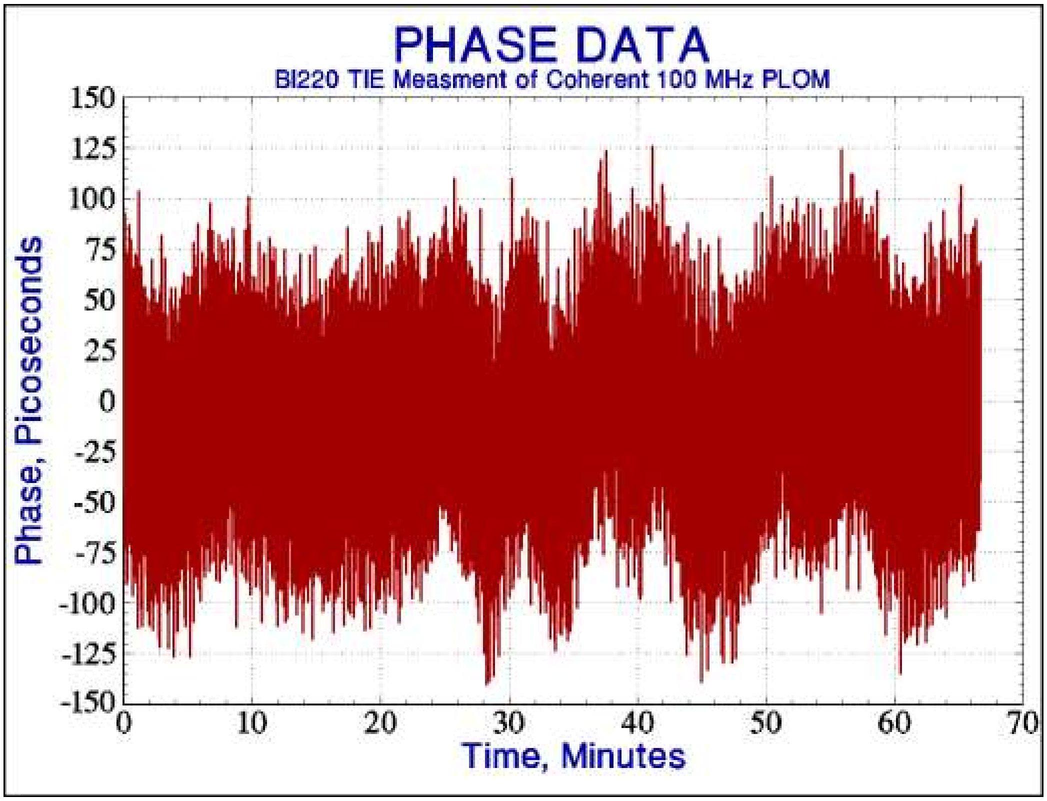


Figure 5. Tau=0.1 Second TIE Data
TIE data is preferred for an MTIE measurement

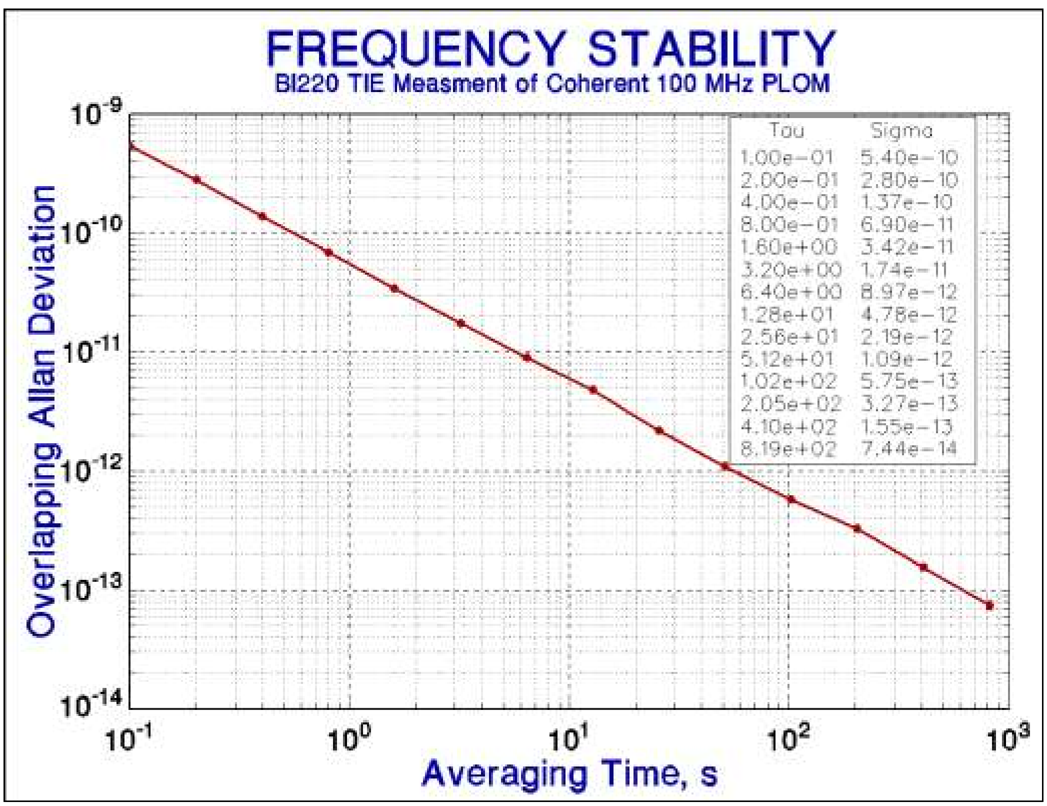


Figure 6. Frequency Stability: 5.5×10^{-11} 1-Second White PM Instrument Noise Floor
Consistent with that of the Figure 3 frequency measurement.

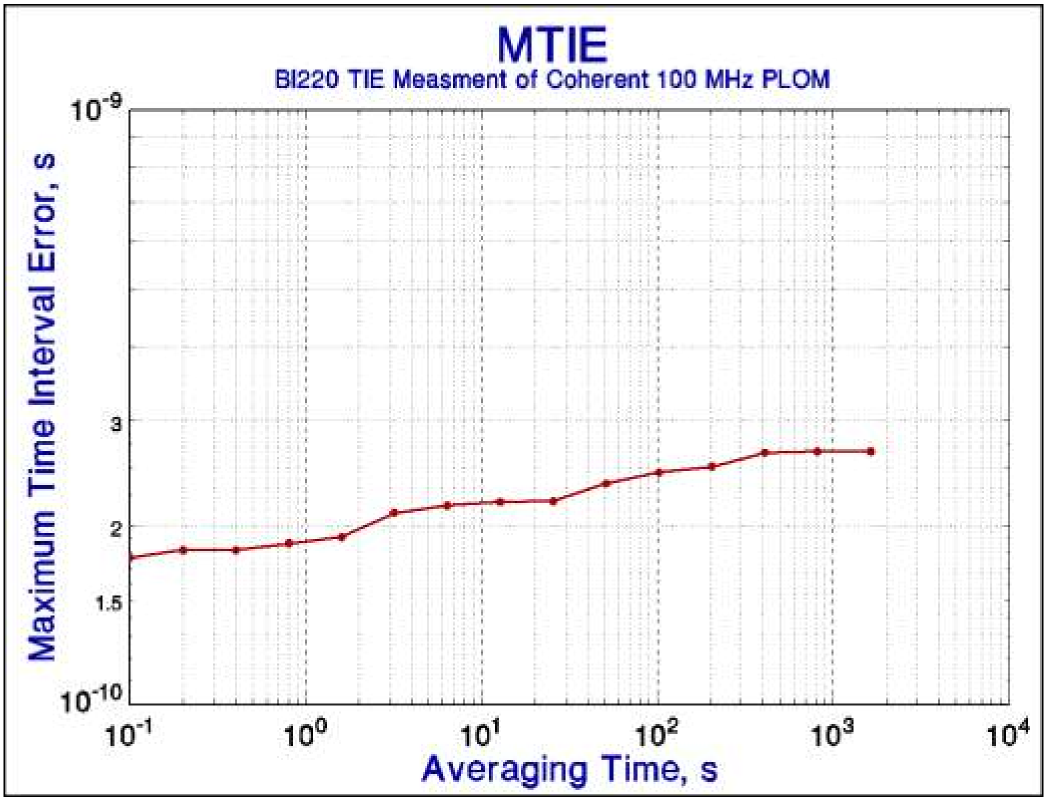


Figure 4. MTIE of TIE Data: 0.19 ns at 1-Second Instrument Noise Floor

File: Coherent 100 MHz Noise Floor Test.doc
W.J. Riley
Hamilton Technical Services
February 11-12, 2012