Accurate time stamping based on GPS brings great benefits to dynamic signal measurement applications

By James Zhuge, Ph.D.
August 2023

Crystal Instruments Corporation

Est. 1996 - Crystal Instruments designs, produces, sells, and services hardware and software for machine vibration monitoring, dynamic measurement and environmental testing.

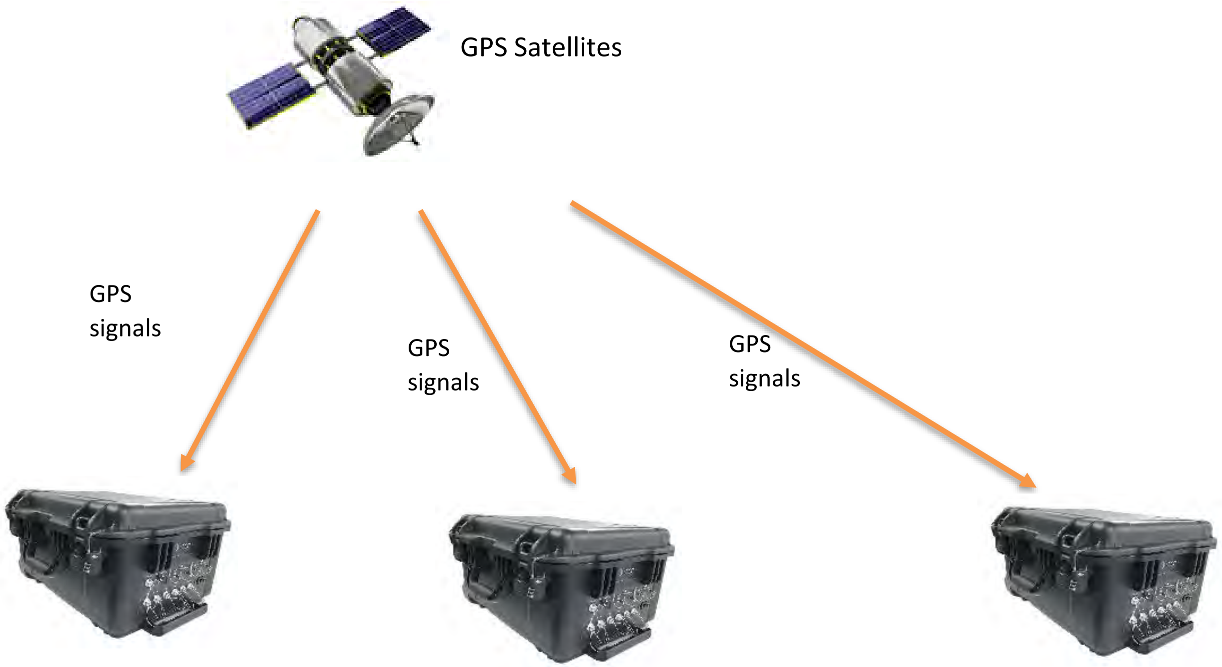
Headquarters in Santa Clara, CA and Testing Facility in Kannapolis, NC. Facilities total to approximately 40,000 square feet in size.

Background

- In existing testing labs for structural, acoustic or environmental testing, IRIG-B is often used as time source to time stamp all acquired data. IRIG-B requires dedicated wiring
- If the time stamps are implemented at the software and firmware level in the data acquisition system, the time error is in the range of 100us or worse
- The recent development at Crystal Instruments using GPS signal and time stamping at the hardware level can achieve time accuracy of 100ns
- The accuracy improvement of timing at multiple magnitude level can bring in great benefits for shock, vibration or acoustic measurement, in both indoor or outdoor applications

GPS Technology

Global Positioning System, GPS, consists of 24 satellites revolving around the earth every 12 hours. Each of these satellites has an atomic clock onboard with extremely good accuracy. The GPS satellites continuously transmit their coordinates in space along with a time message on a 1.575 GHz carrier frequency. The commercial-grade GPS receiver used in the GRS/CoCo claims to achieve ±60 ns time accuracy at 99% of time.



GPS Antenna and Connector

The longest antenna cable we tested is 150 feet. If longer distance is needed, consider the GPS repeater

Accurate GPS Time Stamping has been realized on both CoCo-80X and CI-GRS

CoCo-80X

Handheld Dynamic Signal Analyzer

8 inputs, 1 out

102.4 kHz fs

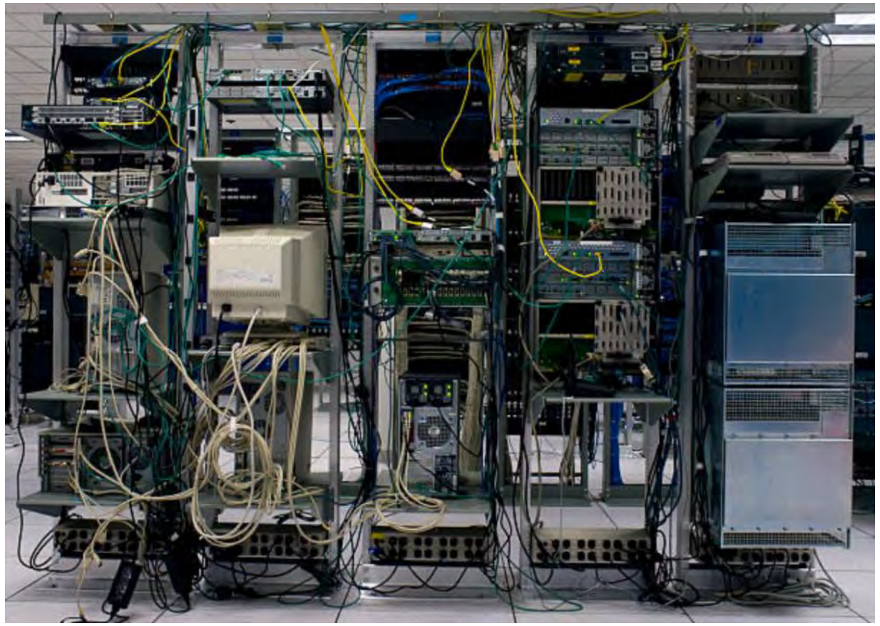
CI-GRS

Rugged Data Recorder

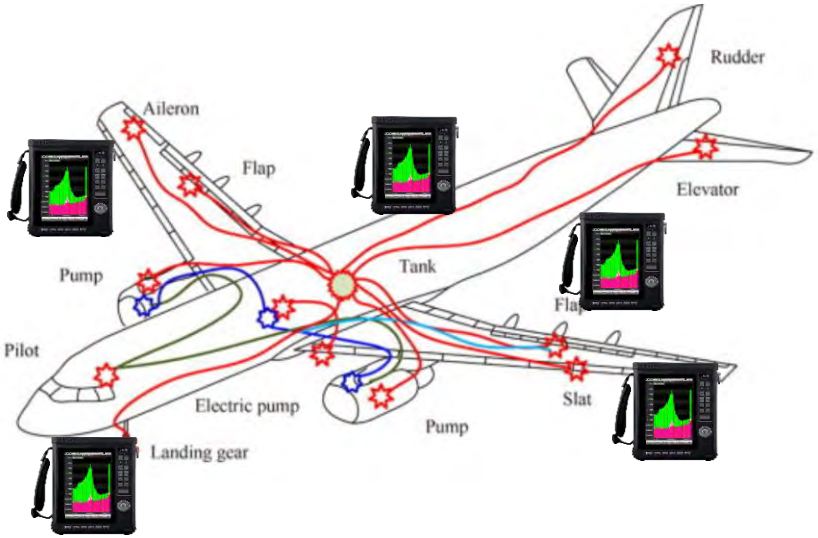
- □ Recording
- □ Transient Capture
- □ Power Spectrum
- □ Frequency Response
- □ Octave Filters
- □ Sound Level Meter
- □ Order Tracking
- □ Real-time digital filters
- □ Real-time math operations
- □ Swept sine test
- □ Remote Monitoring
- □ Limit Testing
- □ Arbitrary Waveform Output

- Designed according to requirement of NASA for the application of measuring low/high sound boom effect of next generation supersonic aircraft, X59
- 4 measurement inputs, 1 audio output
- Dual-ADC per channel, dual channel recording
- Measurement frequency range: 0.5Hz to 45 kHz
- Supports up to 2TB SD Card with encryption
- Time and location synchronization with GPS
- Integrated ADS-B Receiver
- Built-in LCD, Keypad for quick access

Using GPS is a game changer in dynamic measurement



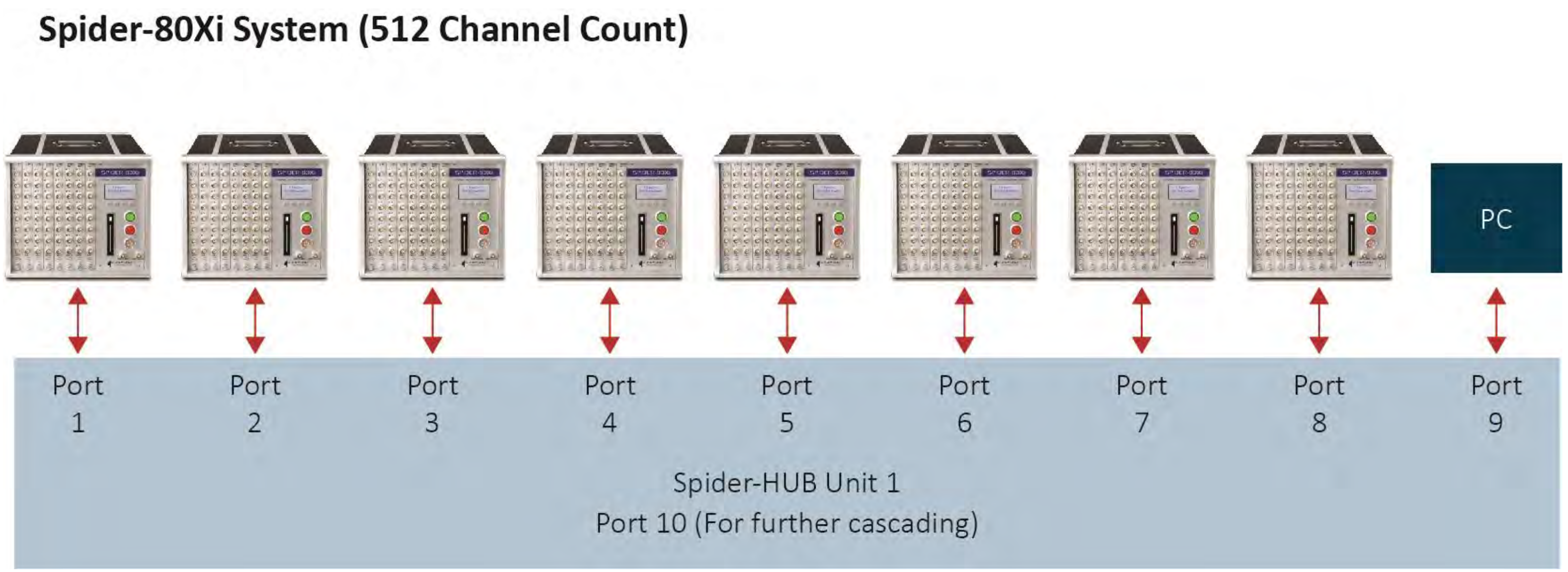
Cabling is the biggest problem of a centralized configuration. Some cables of sensors can be hundred-foot long with risk of performance reduction



Using GPS time stamping technology, measurement systems can be divided into multiple sub-systems. Length of sensor cables can be greatly reduced.

Limitation of Wired Time Synchronization

Traditionally, measuring the FRF (Frequency Response Function) between any two sensors requires that all ADC (Analog to Digital Converters) are accurately synchronized through a hardware connection. Crystal Instruments has developed Ethernet-based IEEE 1588 PTP time synchronization technology that can extend the cable length up to 300 feet. The ADC clock synchronization will become difficult and unreliable beyond 300 feet.



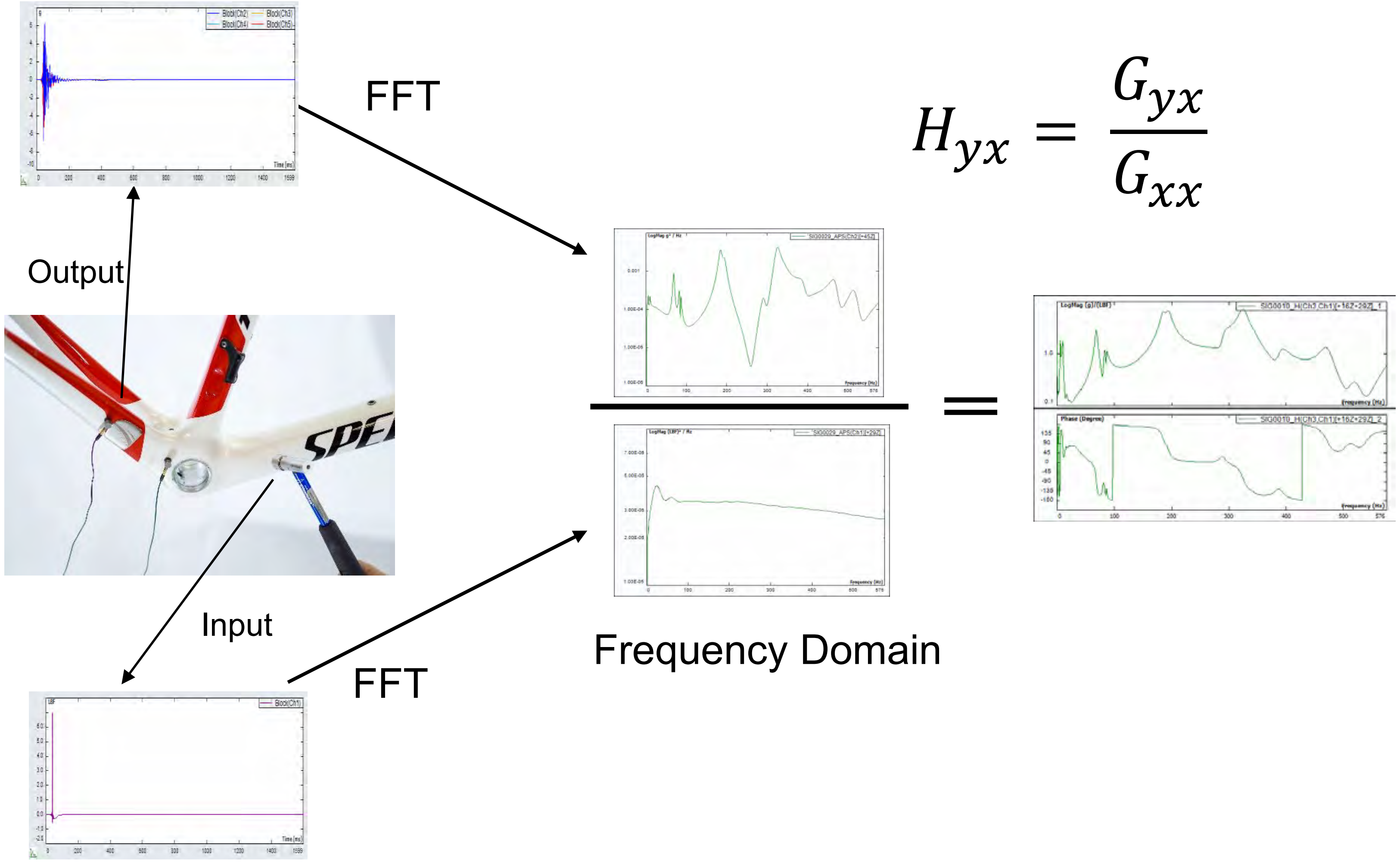
Compare IRIG-B, IEEE 1588 and GPS as time source

	IRIG-B	IEEE 1588 PTP	GPS
Market acceptance	Old technology. Most widely used	Widely used in industrial control. A few companies in dynamic measurement use it	New technology, more and more companies start to use it
Wired?	Dedicated wiring	Yes. Shared with Ethernet cable	Wireless
Time stamp accuracy	100us to 1ms typical for IRIG-B (122)	50ns to 100ns	50ns to 100ns
Hardware cost for this function	A few hundred US dollars	Shared with Ethernet PHY/MAC	Less than $100
Drawback	Has to be wired with dedicated IRIG-B source, need to handle signal jitter, cable signal delay	Wired together with Ethernet	Devices have to be exposed to GPS signal. For indoor application GPS repeater is needed
Distance between devices	1000 meter or less	100 meter or less	No limitation (can be across the earth)

Computing cross-spectrum G_{yx} between dual channels is essential in our application

Once the auto power spectra and cross-spectrum of a pair of channels are computed, other signals such as FRF, coherence can be derived. The auto-power spectra computation is very simple. The challenge is to compute the cross-spectrum of any pair of channels accurately.

$$H_{yx} = \frac{G_{yx}}{G_{xx}}$$



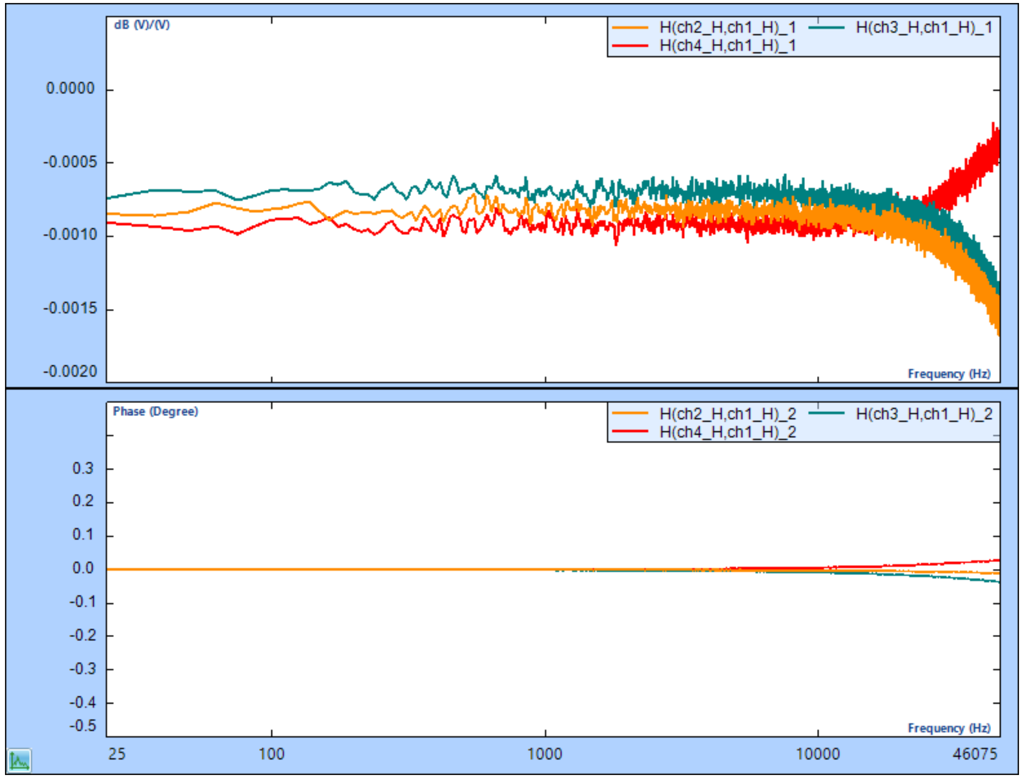
Channel match involves two parameters: amplitude and phase match

- Amplitude match is represented by the FRF amplitude in the concerned frequency range. In general the deviation is required to be less than +/- 0.1dB

- Phase match is represented by the cross-phase in the concerned frequency range. In general the deviation is required to be less than +/- 5 degree

- Before this invention, the only known hardware technology to maintain good channel match is to use wired synchronized ADC sampling clocks that is similar to that of Spider from CI

- Now GPS time stamping provided an alternative approach that comes with the same accuracy



The same accuracy of channel match can be reached by the GPS time stamping

The GRS/CoCo with GPS time stamps can achieve the following channel match which is at the same level as that of wired ADC synchronization:

Phase match between two GRS/CoCo units:	±2°(degree) at 40 kHz ±1°(degree) at 20 kHz ±0.5°(degree) at 2 kHz
Amplitude match	Less than ±0.05 dB

It is quite amazing to see that the channel match between two "independent devices" is at the same level as that of wired instruments

50ns to 200ns is a desired time accuracy in dynamic signal measurement

We believe that a time accuracy of time stamping in the range of 50ns to 200ns is the best for dynamic signal measurement.

If the accuracy is worse than 200ns, then the phase measurement between channels will not suffice the applications

If the required accuracy is better than 50ns, other factors such as consistency of ADC chips or front-end circuitry may become dominant factors. There is no need to achieve better than 50ns time accuracy in dynamic signal data acquisition system.

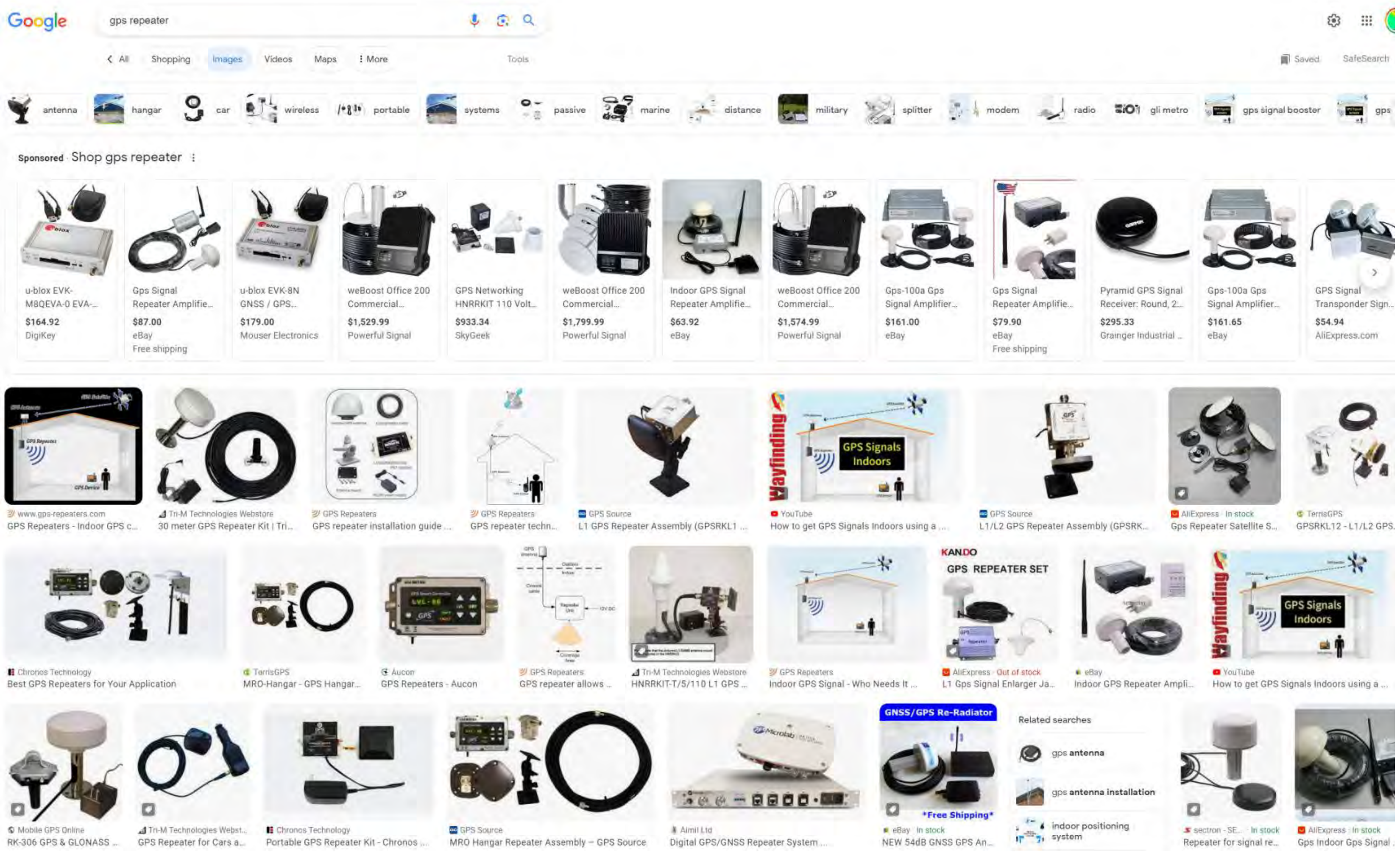
Upgrading IRIG-B to GPS in a testing lab allows cross-spectrum computation between any pair of measurement input channels.

People can use the GPS signal repeater for indoor application

A GPS repeater can be used for indoor applications.

Many brands are available in the market

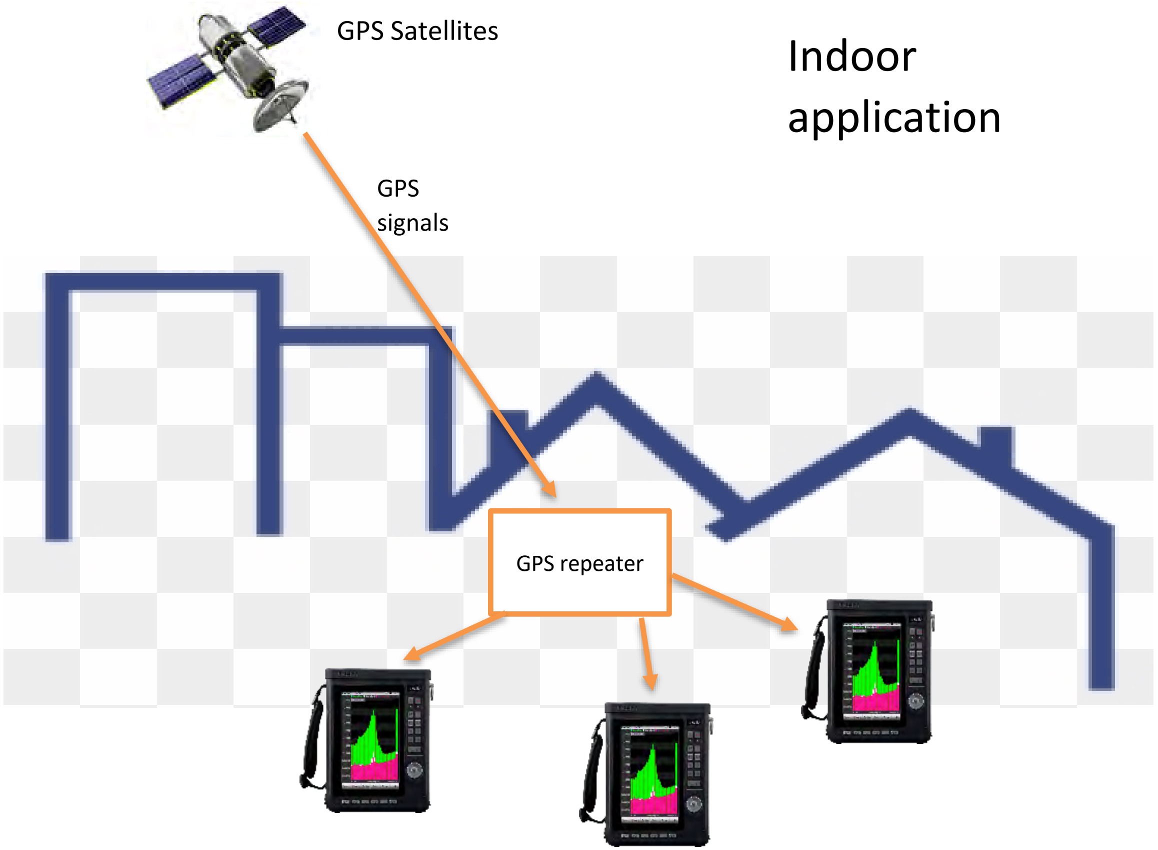
A typical indoor GPS repeater can cover the area of a few thousands of square feet



GPS signal repeater for indoor application

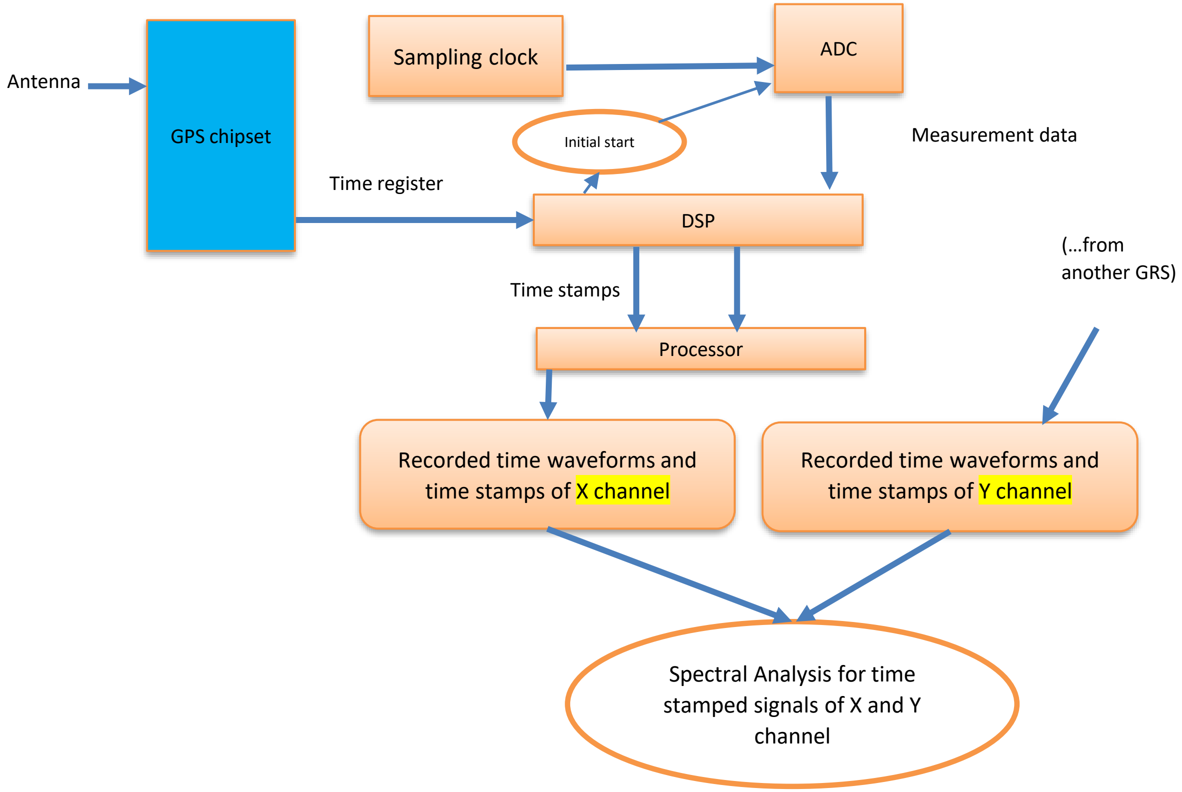
For indoor applications, one of multiple GPS repeaters can be used to transmit the GPS signal and rebroadcast it inside of the building.

Our tests indicated that there are no performance degradation of channel match by using GPS repeater comparing to using original satellite GPS signals.



Time Stamped Analysis | Flowchart of Data Processing

- The merged signals will have corrected sampling rates, calculated using the GPS timestamps that were captured alongside the timestreams.
- Once the signals have been adjusted, classic signal processing methods such as FFT, FRF (Frequency Response Function), Coherence Function, and more can be applied in the post-processing software.
- A diagram is included to illustrate the entire process.



Recording a Stream of GPS Time Stamping

Time stamp will not be only one number attached to the starting point of time data. It will be a stream of data corresponding to the recordings.

Time stamps must be recorded together with input signals.

Here is a sample of time stamping recording.

	Nominal Time(REC0078.ts)	Actual Time(REC0078.ts)
0	00:00:00.000.000.000	00:00:0
1	00:00:03.000.000.000	00:00:02.999.606.7...
2	00:00:06.000.000.000	00:00:05.999.213.5...
3	00:00:09.000.000.000	00:00:08.998.885.8...
4	00:00:12.000.000.000	00:00:11.998.492.6...
5	00:00:18.000.000.000	00:00:17.997.706.2...
6	00:00:24.000.000.000	00:00:23.996.985.3...
7	00:00:30.000.000.000	00:00:29.996.198.9...
8	00:00:48.000.000.000	00:00:47.993.905.1...
9	00:00:57.000.000.000	00:00:56.992.791.0...
10	00:01:03.000.000.000	00:01:02.992.004.6

Nominal Time, is the time of acquired signal samples calculated based on a starting time, number of samples and sampling rate

Actual Time, or Measured Time, is the time stamps taken from the GPS clocks corresponding to the samples of acquired signals. Time format: yyyy/mm/dd/hh:mm:ss.mmm.uuu.nnn

Measured signals can be lined up in time domain based on time stamps

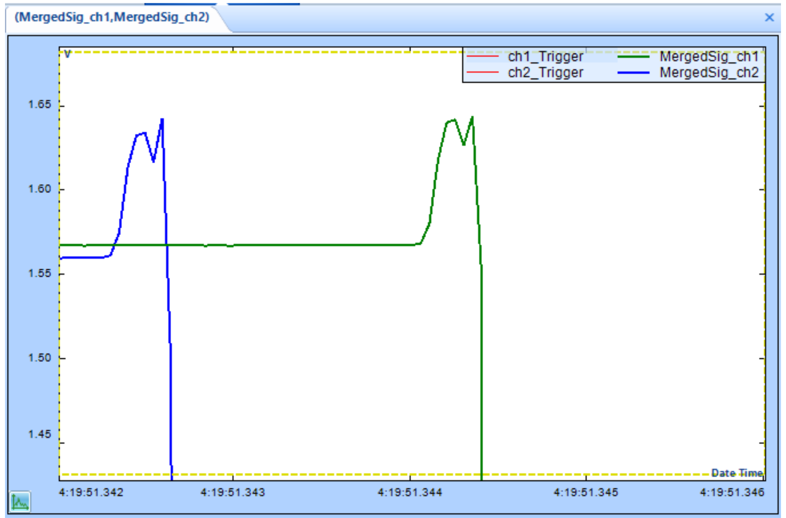
Original file name: REC0058, REC0131. They are recorded on two GRS units. When they are recorded, a source signal is fed into the input ends of both units using a T-splitter port. Both GRS units have installed the GPS receivers to communication with the GPS satellites. The recording duration is about 40 minutes.

Nominal sampling rate:

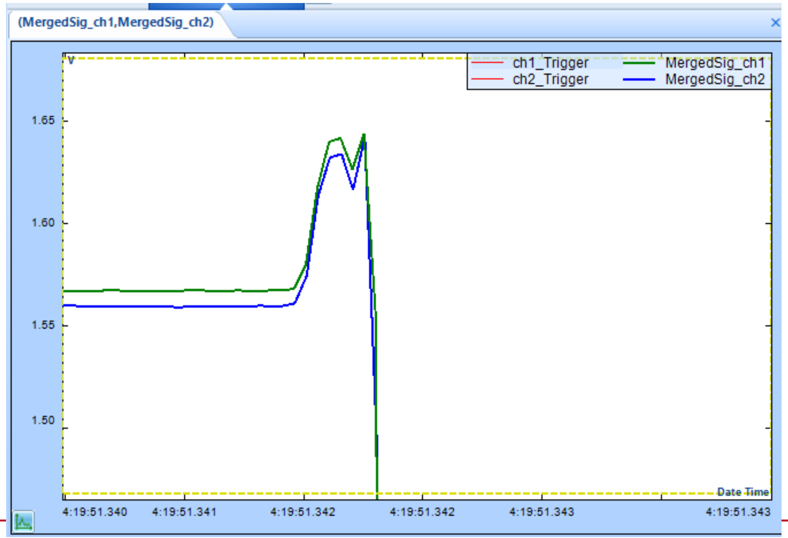
- REC0058: 20,480Hz
- REC0131: 20,480Hz

Sampling rate after the lined-up:

- REC0058: 20,480.026214158832 Hz
- REC0131: 20,480.011221929413 Hz



Due to sampling clock drift, the time difference between the two signals from two separate devices after 40 minutes of recording was approximately 36 sampling points.



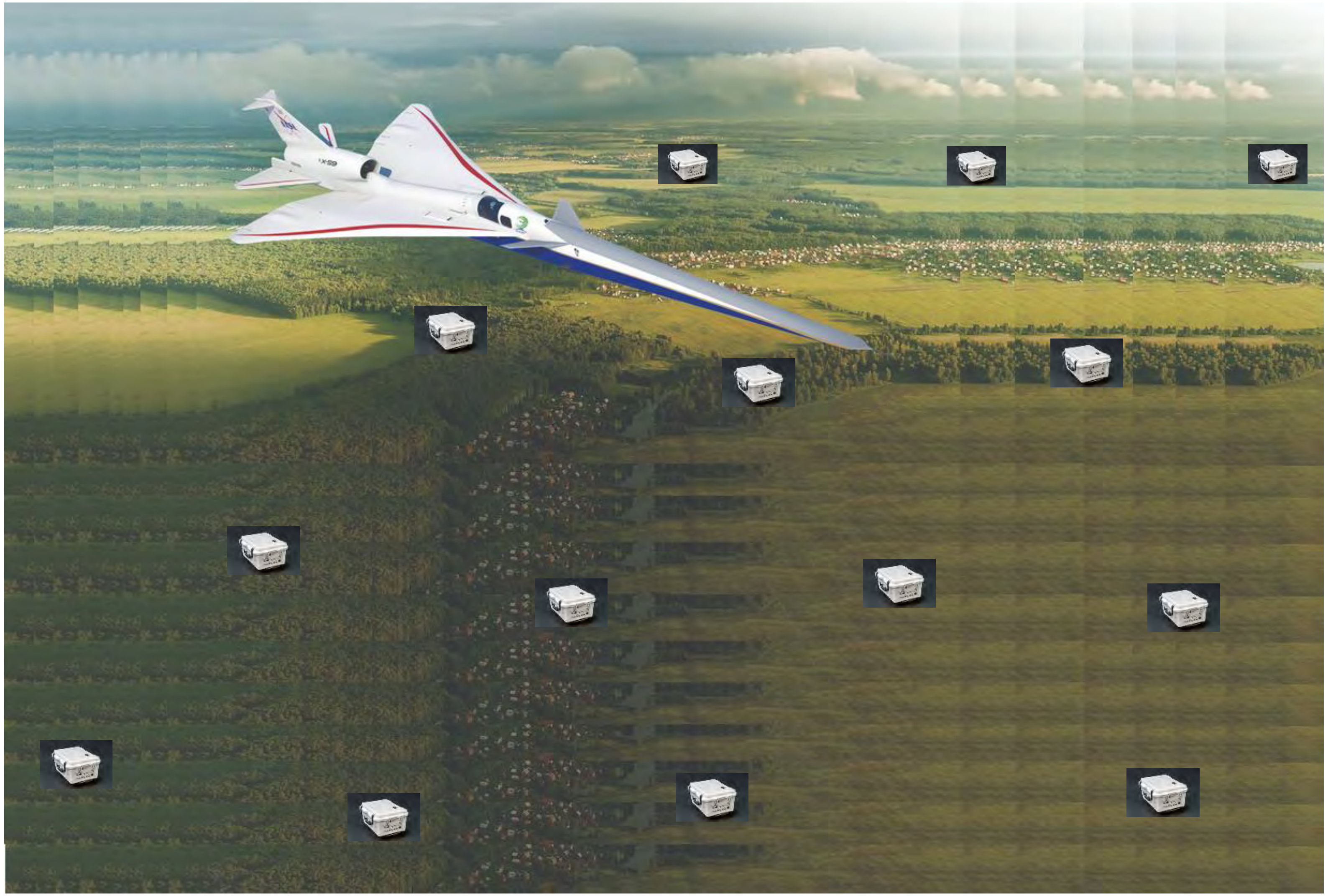
The signals were successfully aligned horizontally after being adjusted using GPS timestamps.

Example of application: Sound Boom Measurement for Aircraft

70+ units of GRS will be deployed to an area of 100 miles * 100 miles to measure the transient sound boom effect of X59, the prototype of the next generation supersonic aircraft from NASA

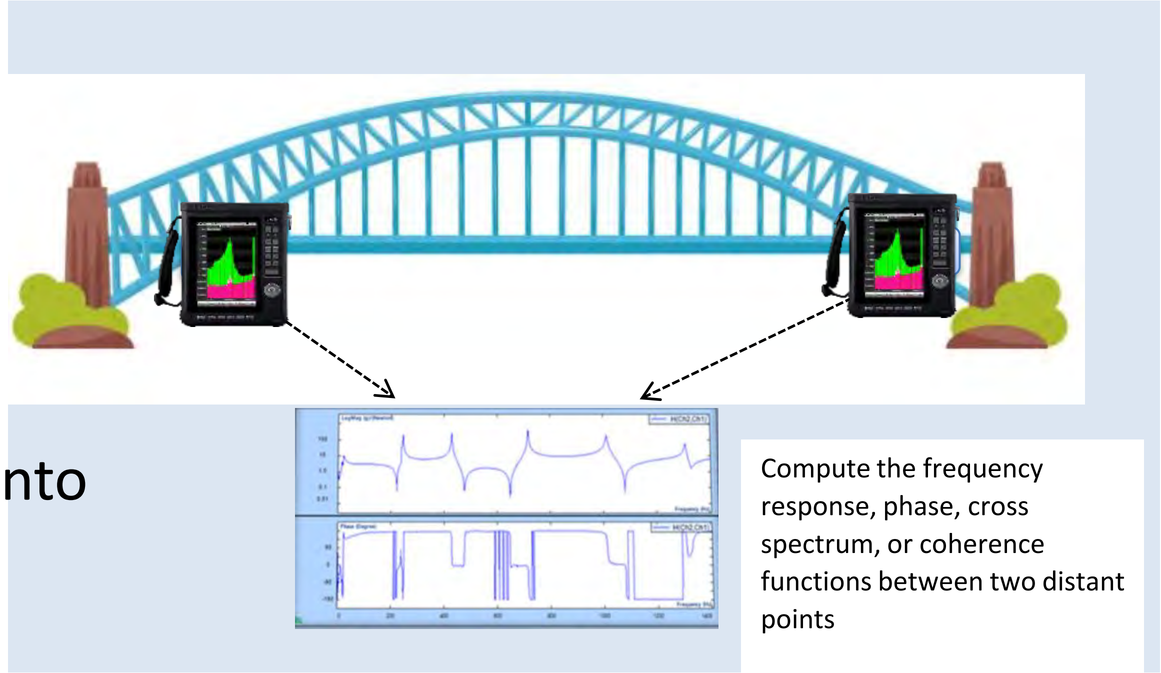
All recorded data will be accurately time stamped

Recording are triggered by ADS-B signal



Example of application: Modal Testing for Large Structure

Using only two instruments by roving the measurement points, it is possible to measure the operating deflection shape of a very large bridge. All we need is a sequence of FRF measurements in pairs.

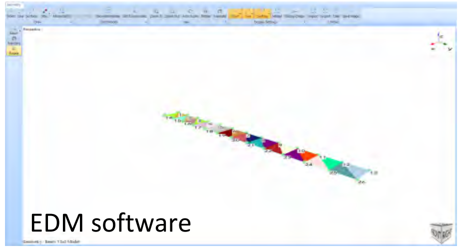


Compute the frequency response, phase, cross spectrum, or coherence functions between two distant points

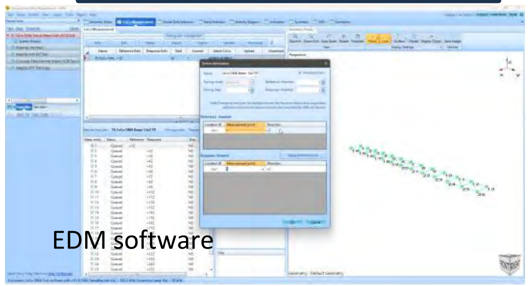
CI recently integrated this technology into the EDM Modal software. OMA (Operating Modal Analysis) function is also implemented. OMA uses ambient noise as excitation for modal testing.

OMA (Operating Modal Analysis) process using time stamped technology

Create Geometry



Create Testing Plan

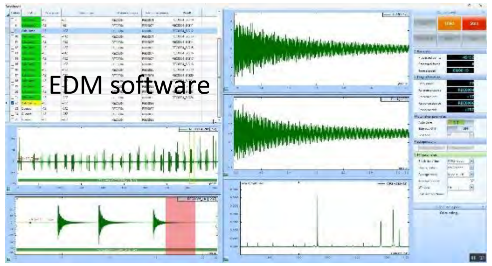


Upload the testing plans to CoCo-80X

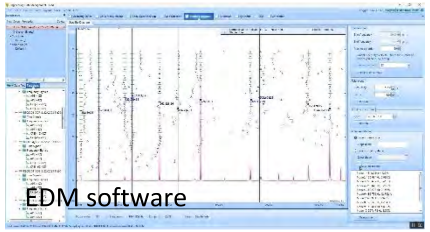
Execute Measurements on structure

Upload measurement to EDM Modal

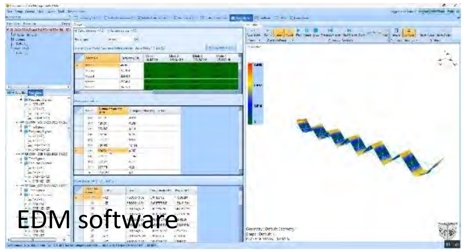
Post-Process Measurements to Calculate all spectra



Perform Curve-Fitting to Obtain Modal Parameters



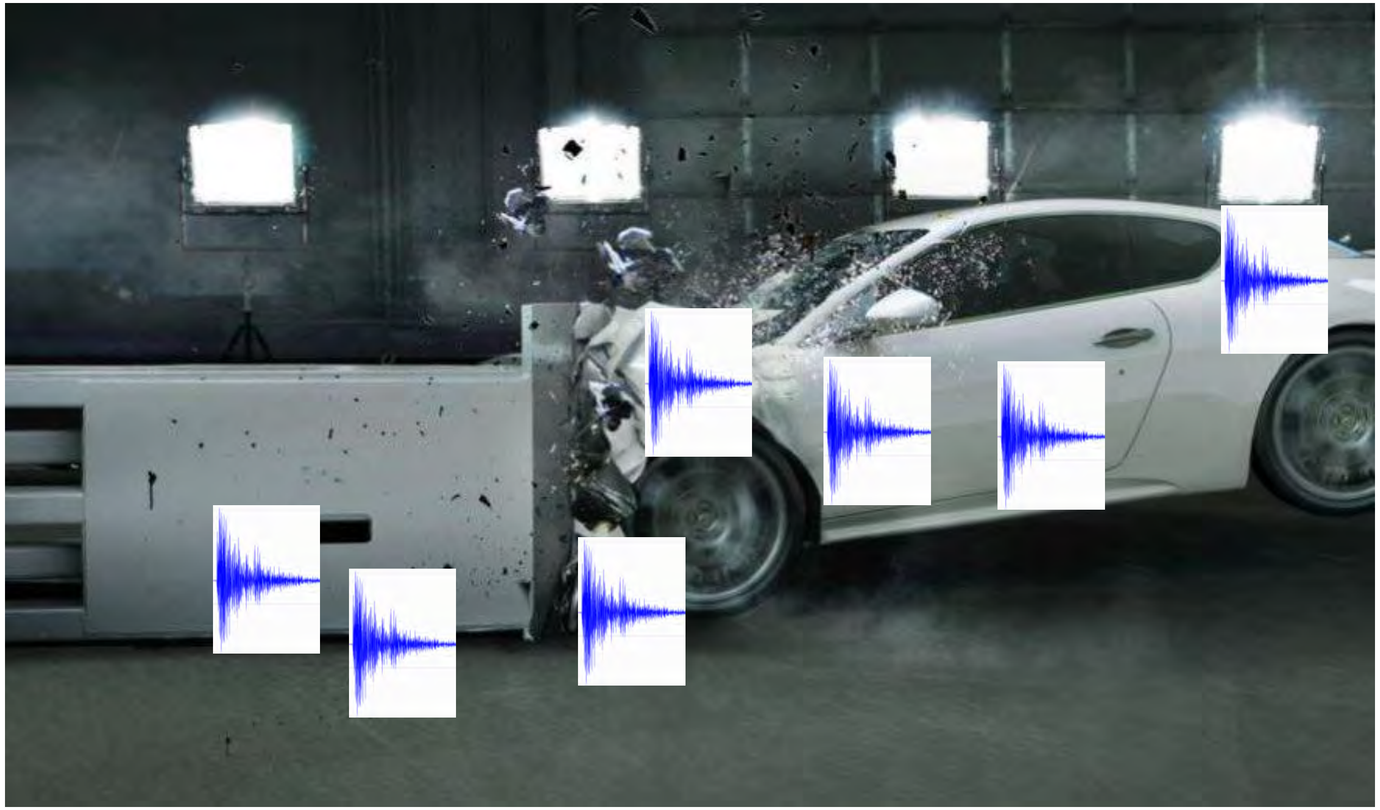
Analyze modal results



Example of application: Measure the dynamic response of a moving object

During the crash testing, many signals on multiple objects must be acquired simultaneously. A technology of synchronization without wire will be highly beneficial.

The technology described in this PPT is perfect for this type of application.



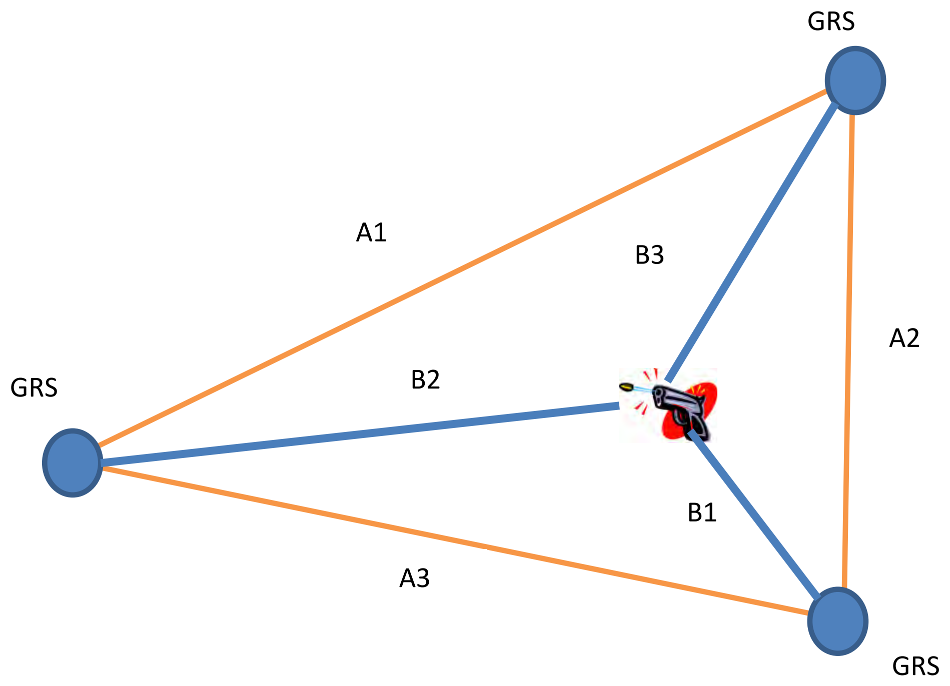
Example of application: Locating Sound Source

Known: locations of A1, A2, A3 (GPS on GRS can provide very accurate location information)

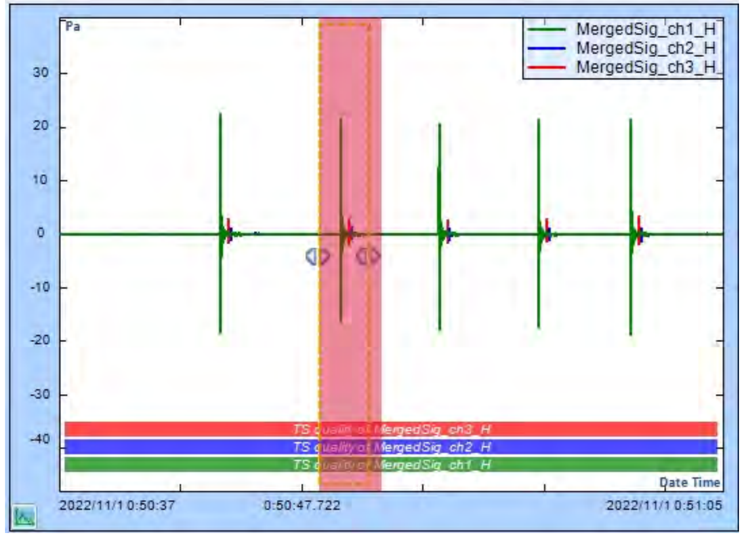
Known: distance of B2-B1, B3-B2, B3-B1 (the difference between any pair). These can be measured using correlation functions of any pair of sound pulses. These distances can be estimated by following method:

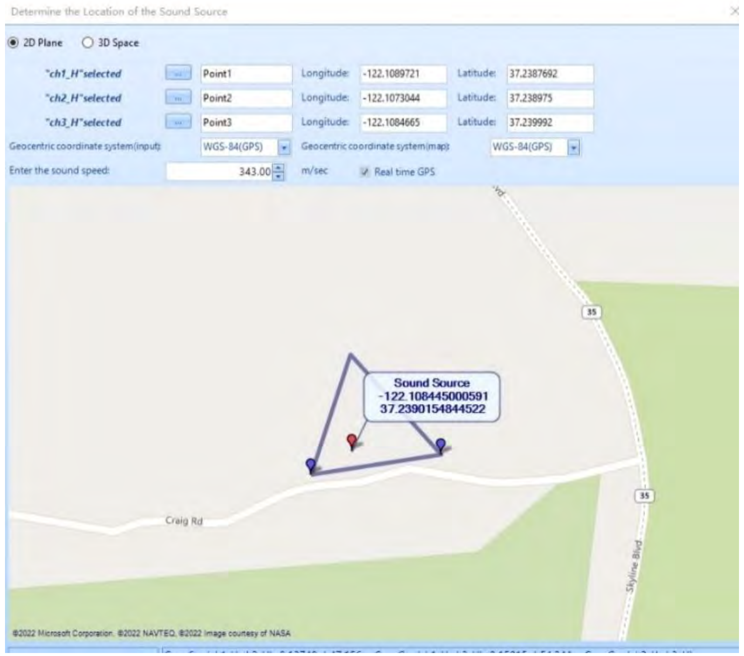
1. Use any pair of time domain signals, with time stamps, calculate the cross-correlation.
2. Using cross-correlation, detect the peak location.
3. Based on peak location, determine the time delay between two signals.
4. Based on time delay and the speed of sound, determine the distance.

Then the position of origin of the sound can be calculated.



Example of application: Locating Gunfire Sound Source (Continued)





Using the recorded signals on three separated GRS, we used the cross-correlation methods to calculate the location of the gun-fire source. In the summer of 2022, CI conducted multiple successful tests at the Los Altos Rod and Gun Range in Los Gatos, California.

Example of application: Locating Gunfire Sound Source (Continued)

- Cross-correlation method is very effective to reduce the interference of noise
- Accuracy of location estimation is about 1 meter.

Example of application: Using Seismic Sensors to Detect the Explosion

From NY Times dated Aug 30, 2023:

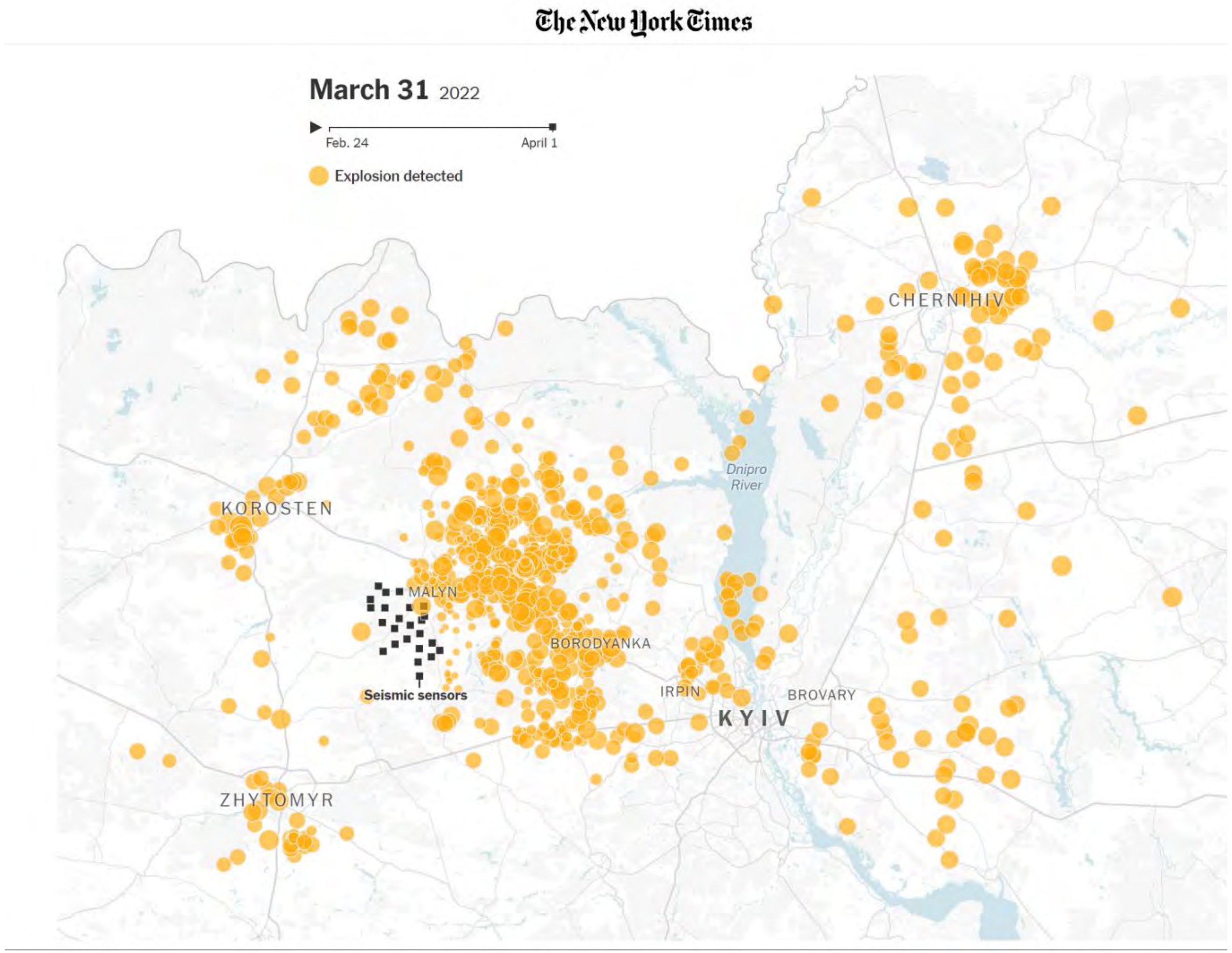
https://www.nytimes.com/interactive/2023/08/30/world/europe/ukraine-war-russia-attacks-seismic-waves.html?unlocked_article_code=U624Bir1beACiq5b9sHLnAqegnRSXX6Ico00J45MJreiN_zcW_Q63HoQhmHIoW8OPtYt-B7OzTD6NM2v260O4-mPNDN6f_xLs8N1gQfJeRrYz1YNTLwj4TGsVJdx9xVi4CIyEDUOLX6ntvsQTKNL2ijAkN8yAKajpeOQV-D0xaXwv_Ay6yjGHns_NSW5_dg9vdYhBw0oSP8wen0EQf_WIghKQk0BBi7XDE5oTb2wea2PX2sFzedUftlJPHaxoblGSk0pA6t4wNKZ7tYzU-AsG7tRDNmCMuwxIyD5__E7sFJe4VM4WTJgm-JvPaINnSn4lOipC8q4e20m2WxkshZztBg8etCfAQUc8KZR_3N1S4Gl3AlDwRIXD9tpiHVRnrio0eRyhR8i0A&smid=url-share

The explosions came one after another, a relentless series of bombings that echoed across Kyiv in the first weeks of the war. Residents at the center of Russia's invasion of Ukraine were forced underground into makeshift shelters.

While the fight for Ukraine's capital is well known, researchers have developed a way to better understand the battle by capturing subtle tremors beneath the earth's surface, a method that could improve our understanding of future conflicts.
Seismic waves were generated when Russia fired artillery, airstrikes and missiles across northern Ukraine. For the first time, researchers in Norway and Ukraine studied data from dozens of earthquake sensors around Kyiv, estimating the position and strength of each explosion to see the full extent of the Russian barrage.

There is no perfect way to chronicle a war, and the seismic record has gaps. Attacks farther from the sensors are most likely to be missed. A few of the explosions may have been set off by Ukraine. And the unique geology of the city of Kyiv, built on wetlands and floodplains, deadens signals from explosions, researchers say.

Data from multiple seismic instruments can provide accurate location of each explosion in the Russia/Ukraine war. We are speculating that the technology described in this PPT can be used.



The technology presented in this PPT are protected by several invention patents

US Patent, 17,501,302, Sampling Synchronization through GPS Signals, granted on 3/21/2023

(12) **United States Patent**
Zhuge et al.

(10) **Patent No.: US 11,611,946 B2**
(45) **Date of Patent: Mar. 21, 2023**

(54) **SAMPLING SYNCHRONIZATION THROUGH GPS SIGNALS**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **17/501,302**

(22) Filed: **Oct. 14, 2021**

(65) **Prior Publication Data**

US 2022/0322260 A1 Oct. 6, 2022

Related U.S. Application Data

(60) Provisional application No. 63/167,785, filed on Mar. 30, 2021.

(51) **Int. Cl.**
H04L 12/26 (2006.01)
H04W 56/00 (2009.01)
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(52) **U.S. Cl.**
CPC ***H04W 56/002*** (2013.01); ***H03L 7/24*** (2013.01); ***H03M 1/0624*** (2013.01);
(Continued)

(58) **Field of Classification Search**
CPC .. H04W 56/002; H04W 56/005; H04L 7/0087
See application file for complete search history.

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(57) **ABSTRACT**

A method uses a distributed data acquisition system with multiple, physically unconnected, data acquisition units, that can be in wireless communication with a remote host, to timestamp measurement data with sub-microsecond time base accuracy of sampling clock relative to an absolute timeframe. A current absolute time is derived from messages received from a satellite radio beacon positioning system (GPS). Measurement data is sampled by each unit at a specified sampling rate. Using hardware logic, batches of sampled data are associated with corresponding timestamps representing the absolute time at which the data was sampled. Data and timestamps may be transmitted to the host. A time offset bias is compensated by comparing timestamps against a nominal time based on start time and nominal sampling rate. The sampling clock rate may be disciplined using time pulses from the GPS receiver. An initial start of data sampling by all units can also be synchronized.

16 Claims, 10 Drawing Sheets

US Patent, 11,754,724, Cross Spectrum Analysis for Time Stamped Signals, granted on 9/12/2023

US 20230204791A1

(19) **United States**
(12) **Patent Application Publication**
Zhuge

(10) **Pub. No.: US 2023/0204791 A1**
(43) **Pub. Date: Jun. 29, 2023**

(54) **CROSS SPECTRUM ANALYSIS FOR TIME STAMPED SIGNALS**

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(21) Appl. No.: **17/564,654**

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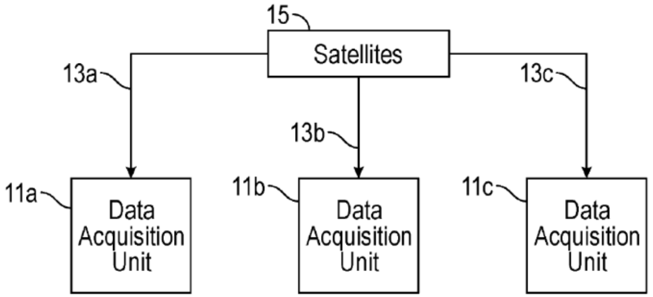
G01D 3/02 (2006.01)
G01D 18/00 (2006.01)
G01S 19/25 (2006.01)

(52) **U.S. Cl.**
CPC ***G01S 19/23*** (2013.01); ***G01D 3/02*** (2013.01); ***G01D 18/00*** (2013.01); ***G01S 19/25*** (2013.01)

(57) **ABSTRACT**

For cross-channel spectral analysis of measurement data from multiple recording units with independent sampling clocks, a processing method corrects phase mismatch between the data received over the different channels. Blocks of sampled measurement data are buffered in a hardware logic circuit and timestamps are associated with successive blocks through a hardware interrupt to a GPS receiver of each recording unit. For each first channel data block, the block's starting point, a closest point in time in a data block of the second channel, and the starting point of that second channel data block are determined, using GPS timestamps associated with those data blocks, nominal sampling rate and block size. Phase correction based on the time offset between starting points of the pairs of data blocks and the interval between starting points of successive blocks is applied in the frequency domain after a time-to-frequency domain transformation. Multiple frames of phase-corrected spectra may then be averaged. Only a subset of samples in each data block need be used based upon a specified overlap ratio.

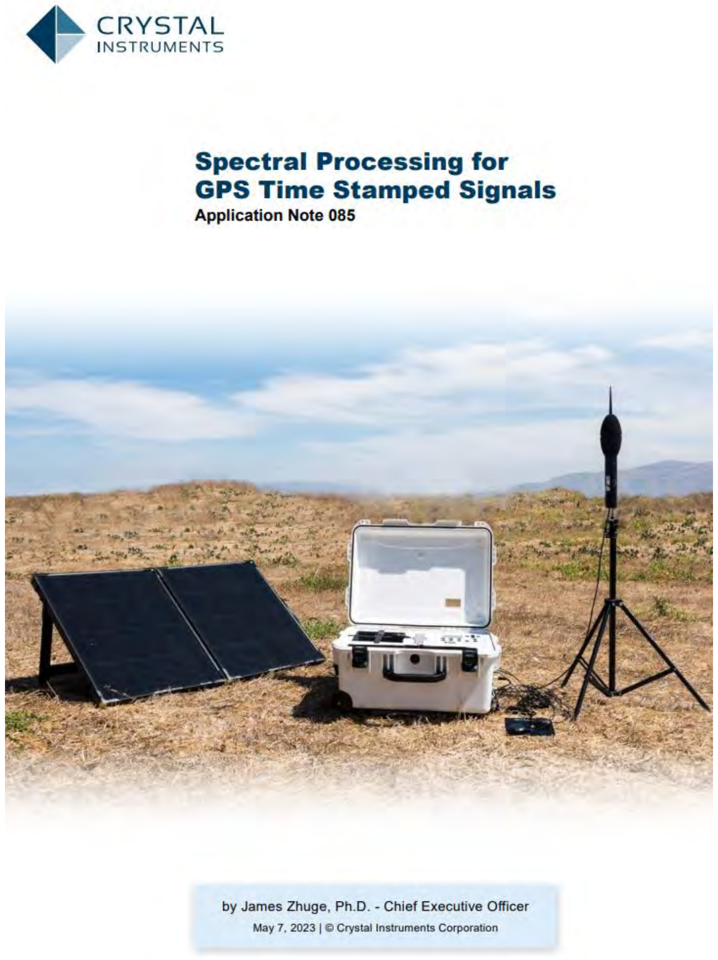


For further reading…….

Please download following white paper from Crystal Instruments website:

Spectral Processing for GPS Time Stamped Signals
by James Zhuge, Ph.D.

https://static1.squarespace.com/static/5230e9f8e4b06ab69d1d8068/t/6462c004ae7dc80869f99d62/1684193288526/Spectral+Processing+for+GPS+Time+Stamped+Signals.pdf



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