Traceability and Legal Metrology

4 Parts of a Measurement

- Device Under Test
  (quartz, rubidium, and cesium)
- Reference
  (cesium oscillator or transfer standard)
- Method
  (measurement system and procedure)
- Uncertainty Analysis
  (statistics and data reduction)

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ISO definition of *traceability*

The property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties.

The Traceability Chain

- The traceability chain is a series of comparisons between the device under test to a reference. The final comparison in the chain is made using the International System (SI) units as a reference.
- Each comparison is a link in the chain.
- The uncertainty of each comparison (link) must be known and documented.

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The Traceability Chain (cont.)

- National metrology institutes (NMIs) like NIST provide the ultimate measurement references for their countries. The intent of all NMIs is to realize the SI units as closely as possible.
- Although the goal is to establish traceability to the SI, this is often done by comparing to an NMI that in turn compares its references to the SI.

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Time and Frequency SI Units

- Second (s)
  - standard unit for time interval
  - intrinsic, defined using cesium 133 atom
  - one of 7 base SI units
- Hertz (Hz)
  - standard unit for frequency (s^{-1})
  - events per second
  - one of 21 SI units derived from base units

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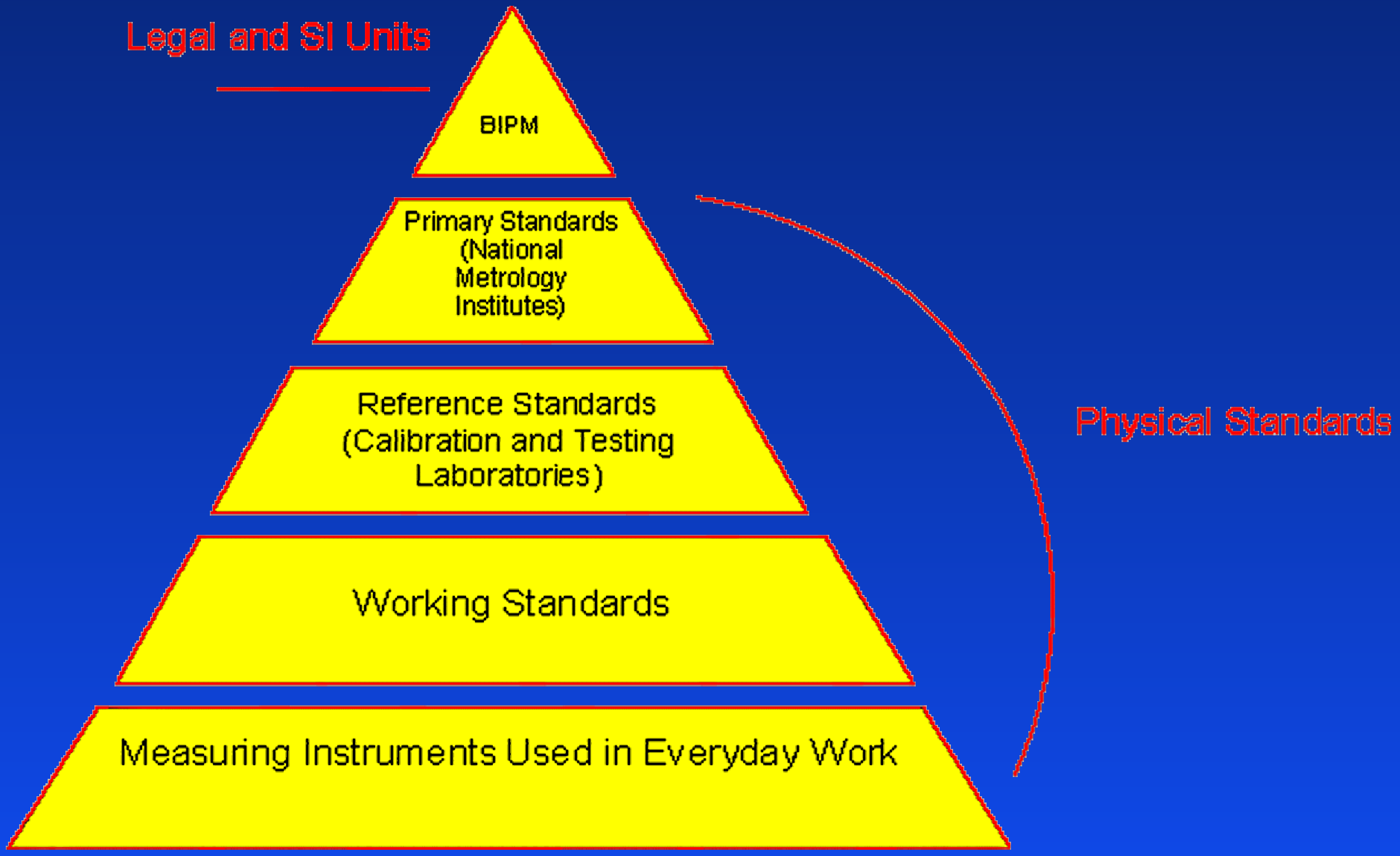
The Traceability Pyramid



The Importance of Traceability

- Establishing *traceability* to national and international standards provides evidence that measurements are being made correctly
- Traceable measurements are essential elements of:
  - quality control systems
  - trade agreements
  - allowing compatible products to be manufactured all over the world

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The Traceability Problem

- Technical
  - usually not a difficult technical problem, especially if requirements are modest
- Legal
  - requires repeatable, reliable procedures
  - requires documentation of traceability chain for quality control systems
  - may be contractual requirement or a prerequisite for doing business

ISO Guide 17025 - 5.6.2.1

For calibration laboratories, the program for calibration of equipment shall be designed and operated so as to ensure that calibrations and measurements made by the laboratory are traceable to the SI (Systeme International) units of measurement.

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Laboratory Accreditation

Calibration laboratories that seek accreditation through a program such as NVLAP must comply with ISO 17025 and document the traceability chain for each measurement. The traceability chain must link the measurement back to the SI unit, and the documentation must include the uncertainty of each link of the chain.

Types of Time and Frequency Information

- Date and Time-of-Day
  - records when an event happened
- Time Interval
  - duration between two events
- Frequency
  - rate of a repetitive event

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Everything Relates to the Second

- By counting seconds, we can determine date and time-of-day
- By counting events per second, we can measure frequency

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SI Definition of the Second

The duration of 9,192,631,770 periods of the radiation corresponding to the transition between two hyperfine levels of the ground state of the cesium-133 atom.

Uncertainties of physical realizations of the base SI units

SI Base Unit	Physical Quantity	Uncertainty
candela	luminous intensity	1×10^{-4}
mole	amount of substance	8×10^{-8}
kelvin	thermodynamic temperature	3×10^{-7}
ampere	electric current	4×10^{-8}
kilogram	mass	1×10^{-8}
meter	length	1×10^{-12}
second	time interval	1.3×10^{-15}

Coordinated Universal Time (UTC)

- About 50 NMIs do a continuous comparison of their standards (over 200 atomic oscillators are involved). The average value of these standards is used to create the UTC time scale. The BIPM in France handles the data and computes the uncertainties.
- BIPM Circular T shows difference between UTC and UTC(k), or the UTC maintained by each NMI.

BIPM Circular T (www.bipm.fr)

Circular T 171 (2002 April 12)
Circulaire T 171

1 - Coordinated Universal Time UTC. Computed values of [UTC-UTC(k)].

(From 1999 January 1, 0h UTC, TAI-UTC = 32 s)

Date 2002 0h UTC	Feb 24	Mar 1	Mar 6	Mar 11
MJD	52329	52334	52339	52344
Laboratory k	[UTC-UTC(k)]/ns			
AOS (Borowiec)	-374	-374	-370	-362
AUS (Sydney)	-82	-77	-99	-92
BEV (Wien)	-265	-259	-233	-243
BIRM (Beijing)	-	-	-	-
CAO (Cagliari)	-2784	-2776	-2778	-2770
CH (Bern)	37	32	19	2
CNM (Queretaro)	-14	-10	-11	-8
CRL (Tokyo)	74	75	78	82
CSIR (Pretoria)	2529	2458	2392	2302
DLR (Oberpfaffenhofen)	-	-	-	-
DTAG (Darmstadt)	78	88	101	95
IEN (Torino)	-3	-11	-9	-4
IFAG (Wettzell)	-1138	-1155	-1184	-1216
IGMA (Buenos Aires) (1)	44	-27	-28	-40
INPL (Jerusalem)	-3311	-3344	-3383	-3422
IPQ (Monte de Caparica)	-	-	-	-
JATC (Lintong)	-8978	-9026	-9073	-9116

Low accuracy measurements that require traceability

Type of Measurement	Link to NMI	Required Uncertainty
Calibration of radar devices used in law enforcement	Audio time announcements (HF radio or telephone)	1×10^{-3}
Calibration of stopwatches and interval timers	Audio time announcements (HF radio or telephone)	2×10^{-4}
Calibration of transmitted frequencies used by commercial broadcast stations	HF or LF radio signals	1×10^{-5}
Calibration of low cost crystal oscillators used in electronic circuits	HF or LF radio signals	1×10^{-6}
Time synchronization of computers used in financial transactions	Telephone and Internet time setting signals, LF radio signals	1 s

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High accuracy measurements that require traceability

Type of Measurement	Link to NMI	Required Uncertainty
Calibration of electronic test equipment	LF signal or GPS signal monitored by NMI	10^{-6} to 10^{-10}
Distribution of frequency for measurement and calibration purposes	LF signal or GPS signal monitored by NMI	10^{-8} to 10^{-12}
Primary reference frequency for synchronous digital networks	LF signal or GPS signal monitored by NMI	$< 1 \times 10^{-11}$
Fault location on electrical transmission lines	GPS signal monitored by NMI	1 μs
Comparisons between national laboratories, control of broadcast services, defense and space applications	Direct comparison to NMI through common view GPS measurements, two-way satellite measurements, or carrier phase GPS measurements	$< 1 \times 10^{-13}$

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Other Areas of Metrology that require Traceable Frequency

Type of Measurement	Link to NMI	Required Uncertainty
AC Electrical Measurements (1592 Hz frequency)	HF or LF signal	10^{-4}
Voltage Measurements (Josephson array intrinsic standard)	LF signal or GPS signal monitored by NMI	10^{-10}
Precision Length Measurements	LF signal or GPS signal monitored by NMI	10^{-11}

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Ways to establish traceability to the SI through NIST

- NIST controlled broadcasts
  - WWV/WWVH, WWVB, ACTS, ITS
- NIST monitored broadcasts
  - LORAN-C, GPS
- NIST controls/monitors measurements
  - Frequency Measurement Service

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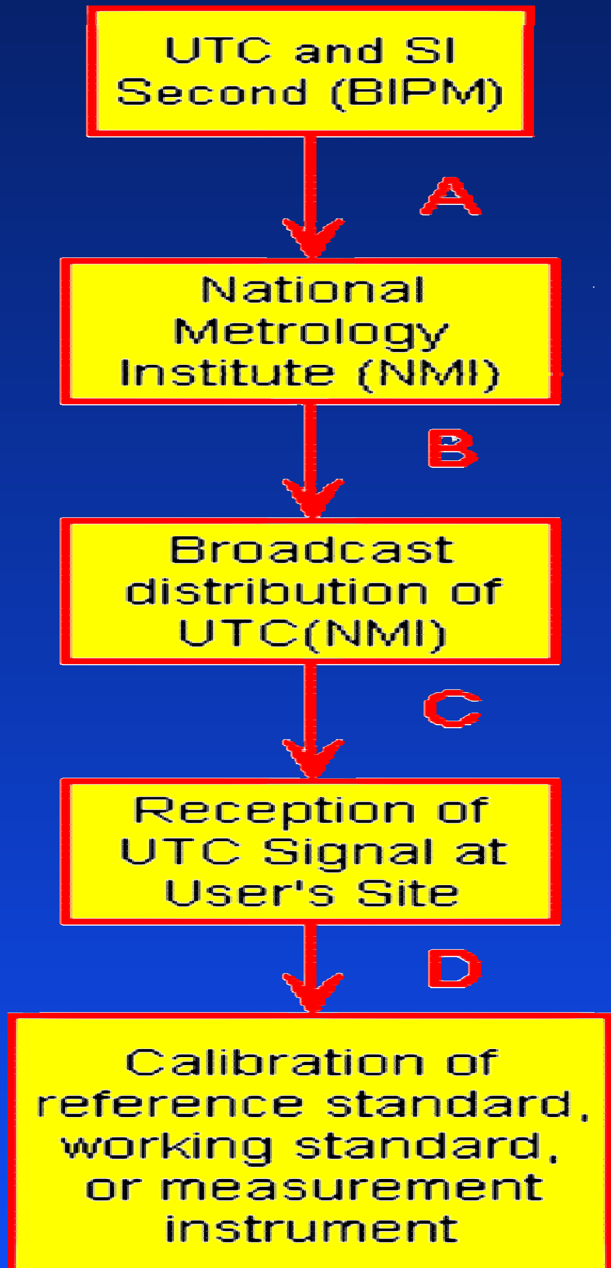
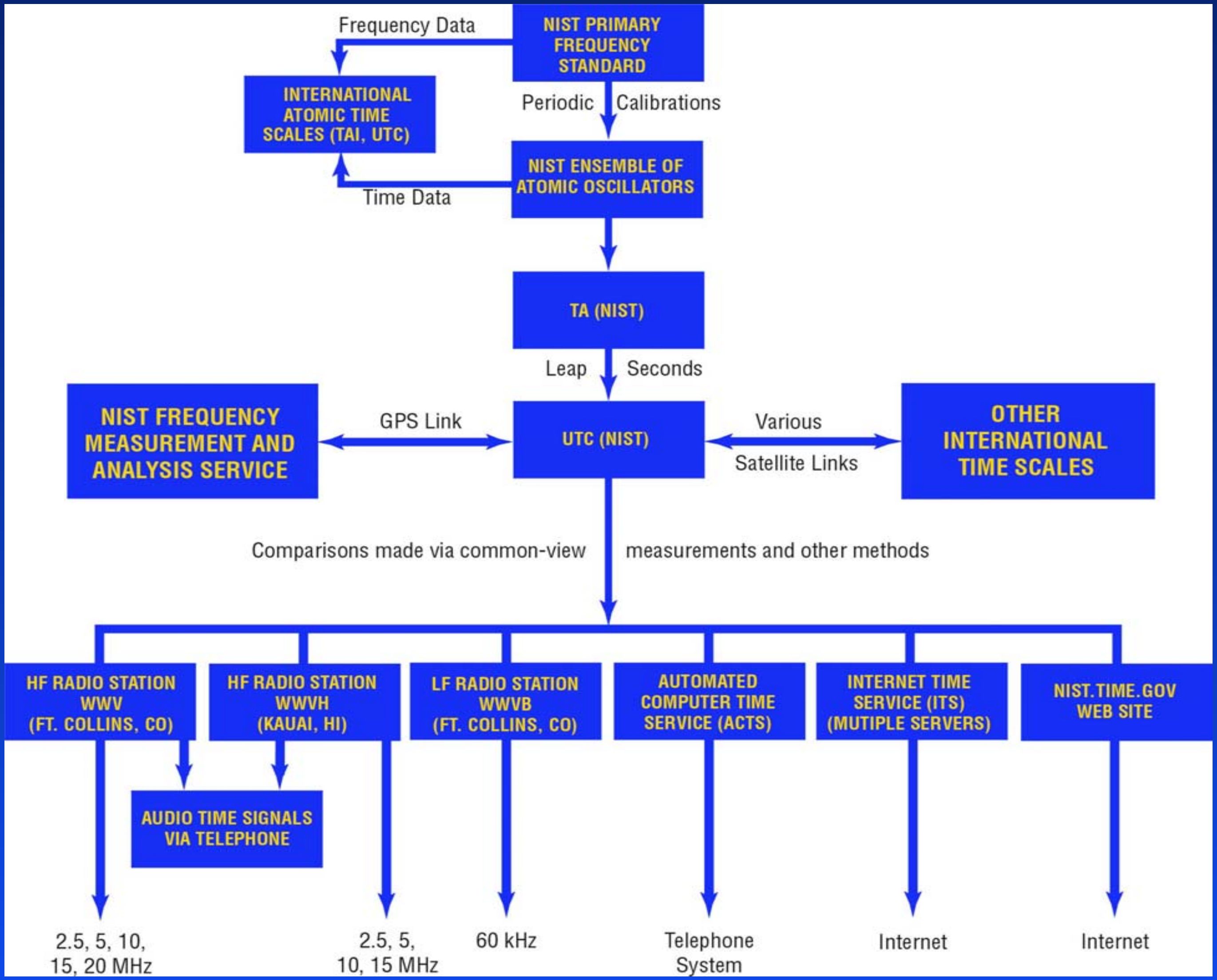
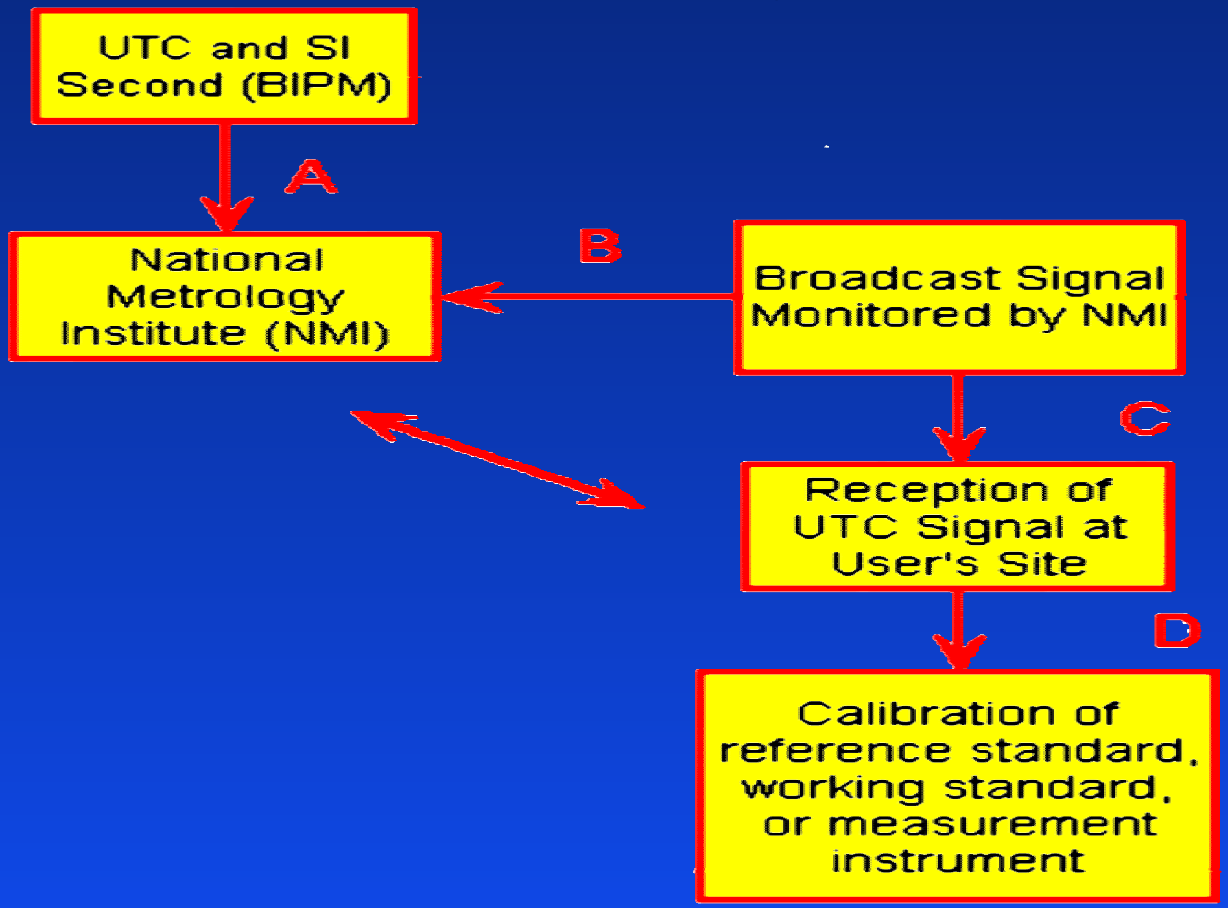
Traceability chain for signals controlled by a NMI



The Distribution of UTC(NIST)



Traceability chain for signals monitored by a NMI



GPS Monitoring

More complex than monitoring ground based signals because:

- Each orbiting satellite carries its own frequency standards
- Satellites can only be received when they fly over monitoring station

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NIST GPS Data Archive

Physics Laboratory
Time & Frequency Division

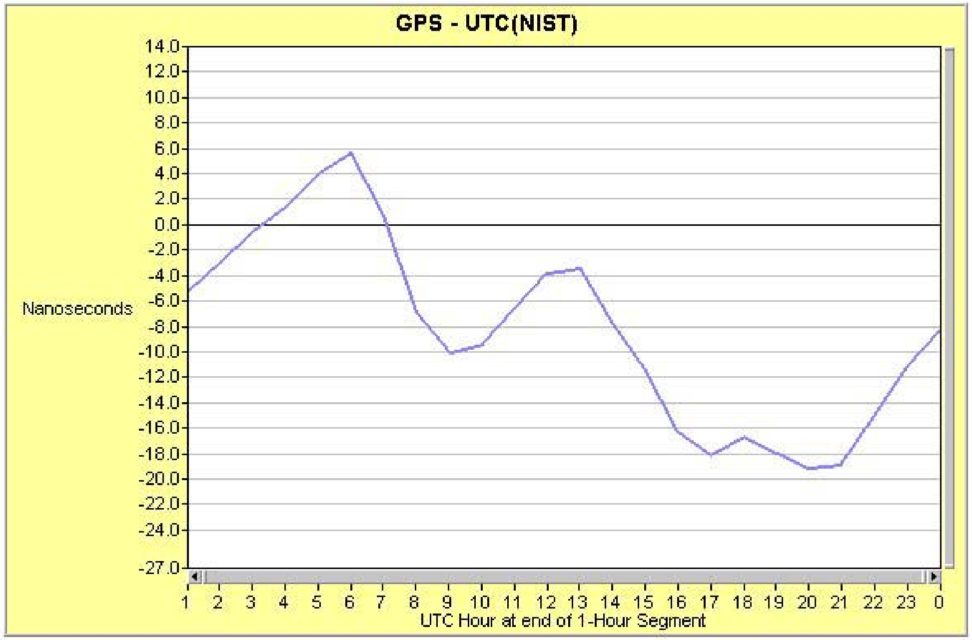
NIST
National Institute of Standards and Technology

GPS Monitoring Data for 2002-04-11
(as received at NIST in Boulder, Colorado)

Archive Home | Next Date | Last Date

GPS - UTC(NIST)
(one-hour averages using all satellites in view)

Hours	Mean Time Offset (ns)	Range (ns)	Frequency Offset	Confidence (r)
24	-8.1	24.7	-2.27×10^{-13}	-0.77



NIST GPS Data Archive

Allan Deviation

Averaging Time (τ) (seconds)	Frequency Stability
600	2.63×10^{-12}
1200	1.80×10^{-12}
2400	1.17×10^{-12}
4800	7.23×10^{-13}
9600	7.69×10^{-13}
19200	3.68×10^{-13}

Time Deviation

Averaging Time (τ) (seconds)	Time Stability (ns)
600	0.91
1200	1.00
2400	1.11
4800	1.68
9600	3.88
19200	1.88

GPS PRN - UTC(NIST)
(data from individual GPS satellites)

GPS PRN	Minutes (In-View)	Mean Time Offset	Range (ns)	Time Deviation	Frequency Offset	Confidence (r)	View Detail
1	370	+1.64	29.30	1.78	-1.1×10^{-12}	-0.72	View
2	350	-2.25	29.05	1.83	$+4.8 \times 10^{-13}$	+0.61	View
3	450	-4.79	29.75	2.19	$<1.0 \times 10^{-13}$	+0.02	View
4	330	-14.83	14.95	1.35	-2.4×10^{-13}	-0.50	View
5	380	-12.96	43.95	2.23	-4.5×10^{-13}	-0.81	View
6	340	-11.16	12.90	0.98	$+2.7 \times 10^{-13}$	+0.42	View
7	390	-17.05	37.20	1.09	-1.2×10^{-12}	-0.97	View
8	360	-18.18	19.85	1.12	-5.3×10^{-13}	-0.58	View
9	440	-11.54	33.50	1.63	-1.8×10^{-13}	-0.65	View

GPS Traceability Chain A

Link	Reference	Compared To:
A	SI units	UTC(NIST)
B	UTC(NIST)	UTC(USNO)
C	UTC(USNO)	GPS Signals
D	GPS Broadcast Signals	GPS Received Signals
E	GPS Received Signals	User's Device under Test

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GPS Traceability Chain B

Link	Reference	Compared To:
A	SI units	UTC(NIST)
B	UTC(NIST)	GPS Broadcast Signals
C	GPS Broadcast Signals	GPS Received Signals
D	GPS Received Signals	User's Device under Test

NIST traceable signals and links

Traceable Signal or Link	Receiving Equipment	Timing Offset	Timing Uncertainty	Frequency Uncertainty
Audio Time Announcement	Telephone (303-499-7111)	< 30 ms (within USA)	< 1 ms	NA
Automated Computer Time Service (ACTS)	Computer, software, modem, and phone line (303-494-4774)	1 to 150 ms (< 10 ms with loop test)	< 5 ms	NA
Network Time Service (NTS)	Computer, software, and Internet connection	< 1 s	< 100 ms	NA
WWV and WWVH	HF Receiver (2.5, 5, 10, 15, or 20 MHz)	1 to 15 ms (within USA)	< 500 µs	10^{-6} to 10^{-9}
WWVB or LORAN-C	LF Receiver (60 or 100 kHz)	< 100 µs (calibrated for path delay)	< 500 ns	10^{-10} to 10^{-12}
Global Positioning System (GPS)	GPS Receiver (1575.42 MHz)	< 100 ns (calibrated for equipment delay)	< 20 ns	10^{-12} to 10^{-13}
GPS common-view, GPS carrier phase, and Two Way Satellite Time Transfer (TWSTT)	Receiving equipment, transmitting equipment (TWSTT only), tracking schedules, and data link with NIST	< 5 ns	< 5 ns	$< 1 \times 10^{-13}$

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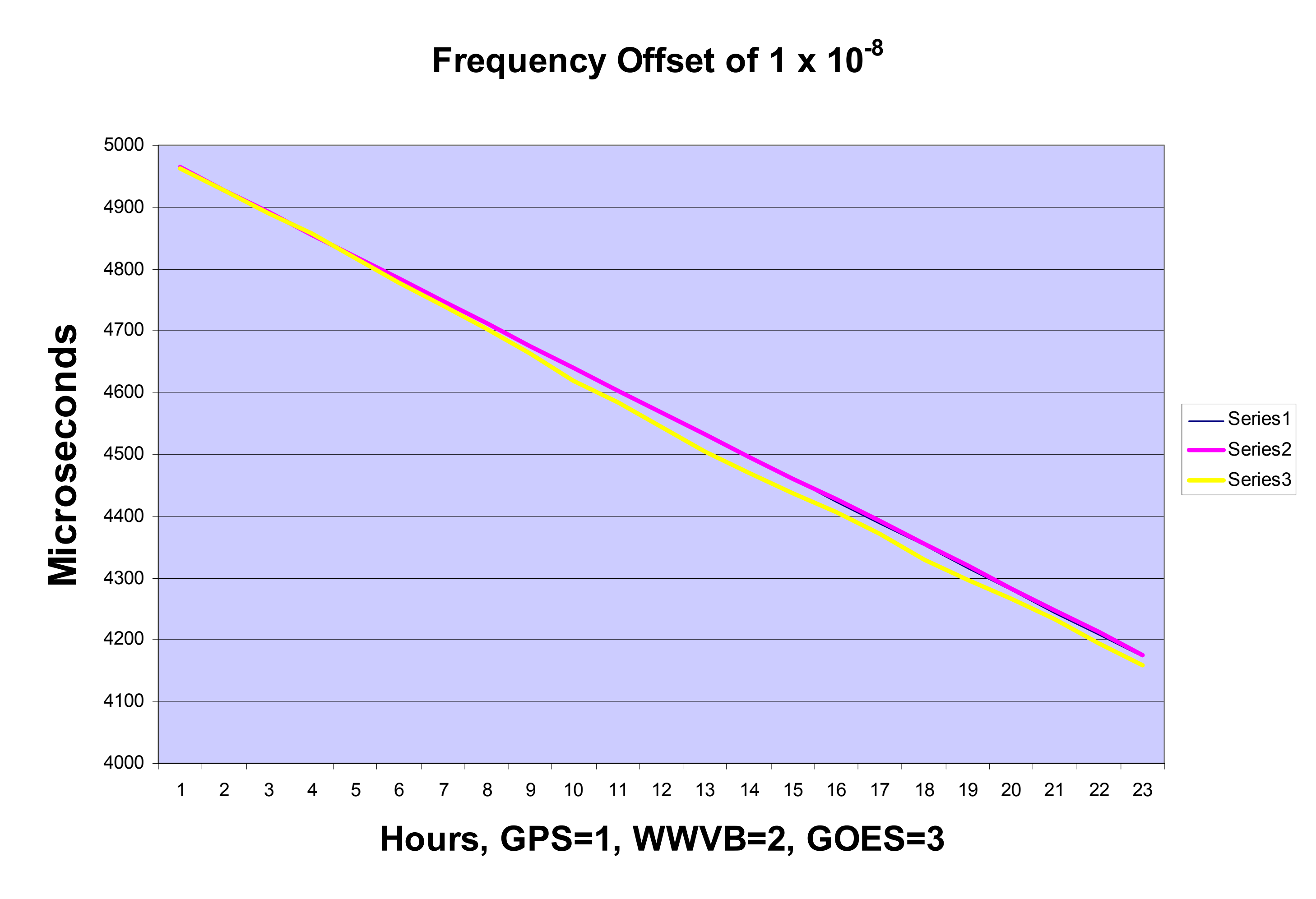
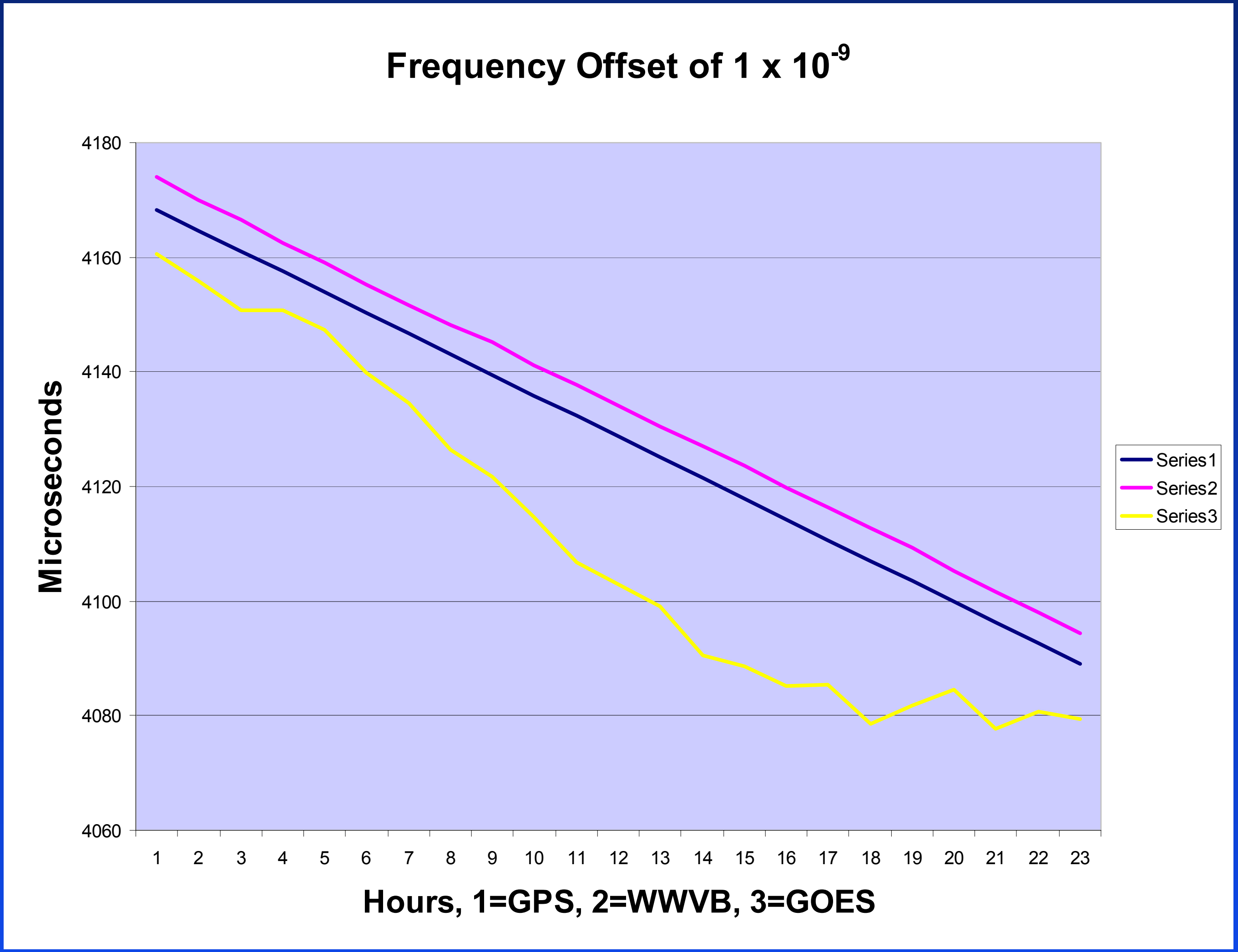
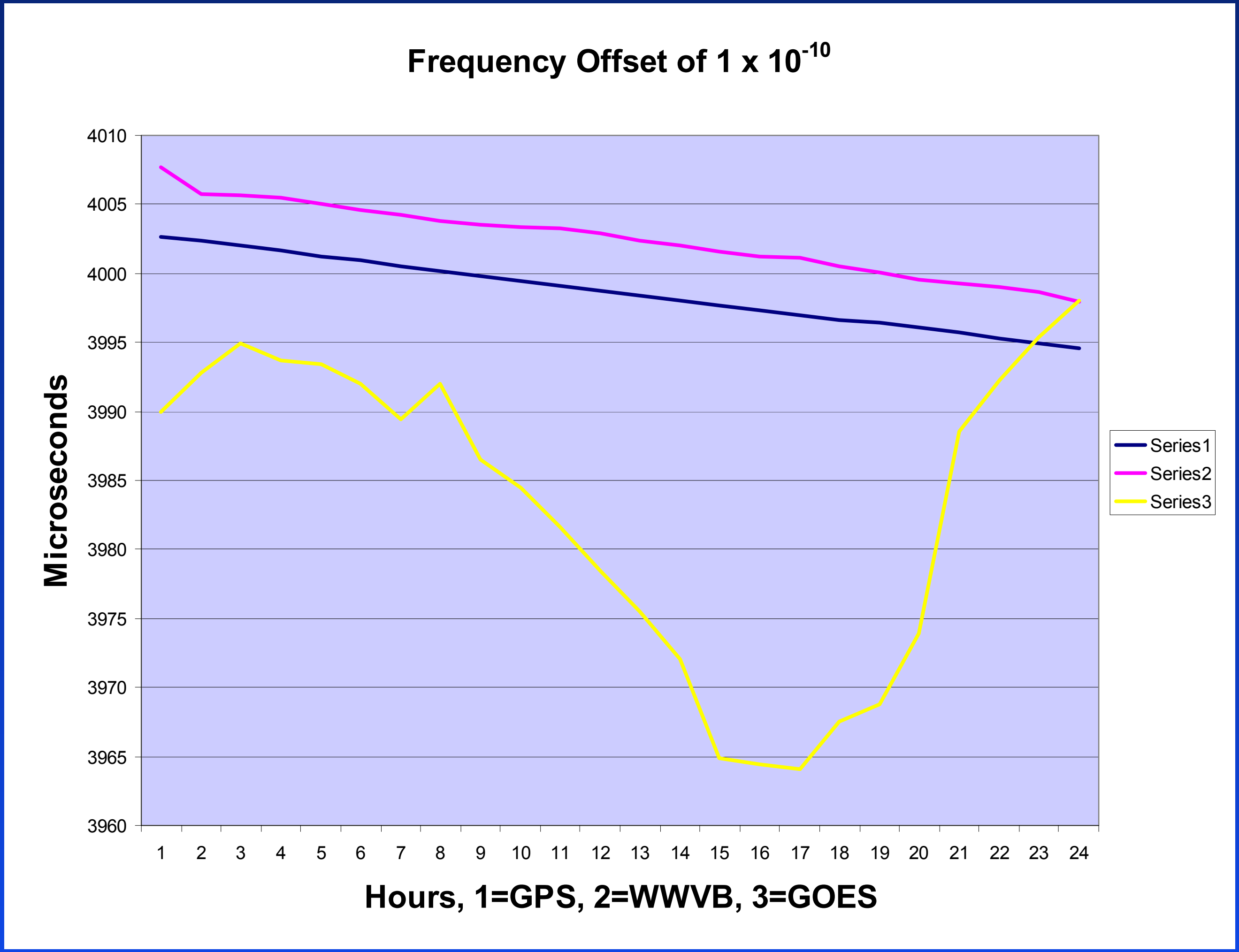
Measuring 1 x 10^{-8}



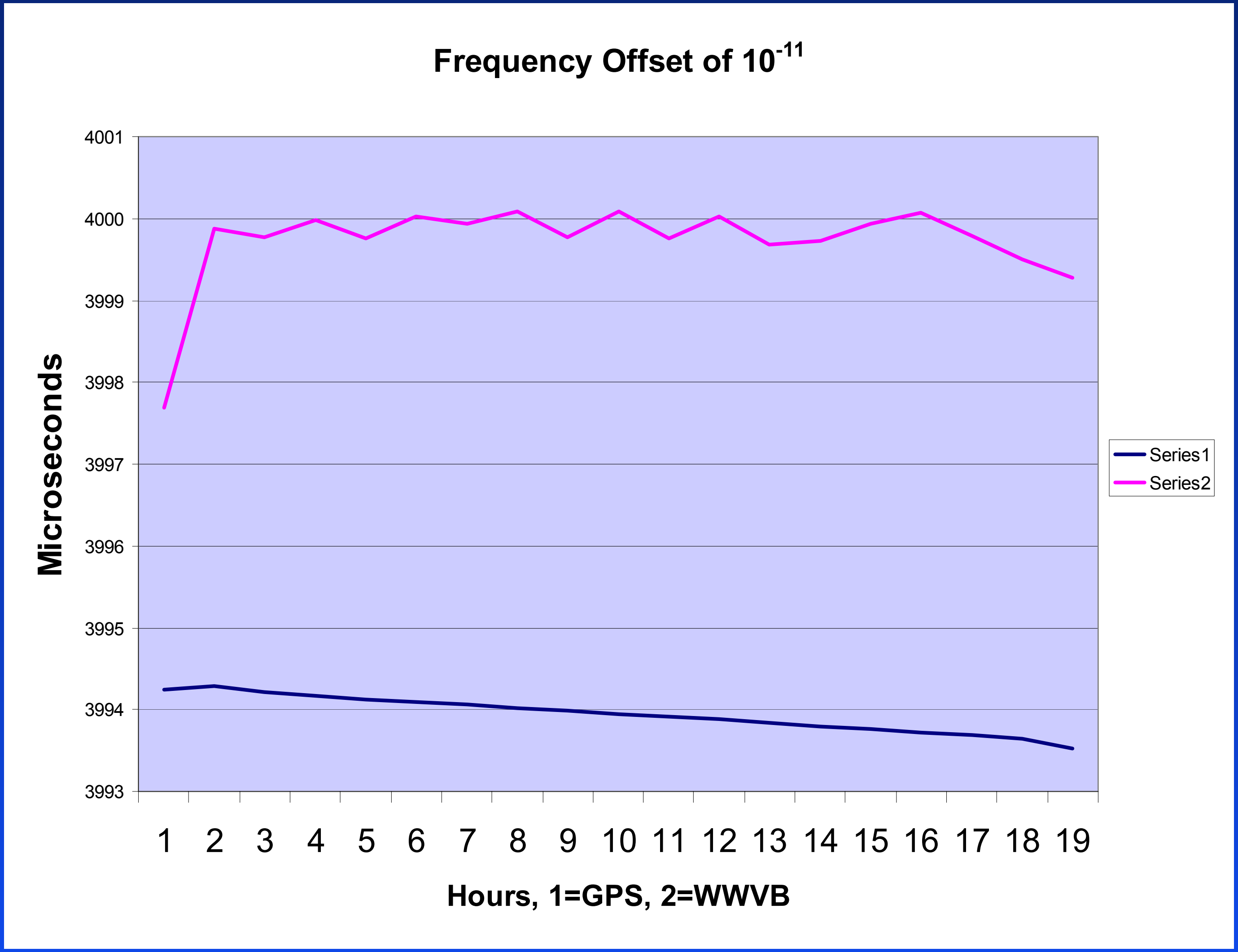
Measuring 1 x 10^{-9}



Measuring 1 x 10^{-10}



Measuring 1 x 10^{-11}



Time and Frequency is well suited for remote calibrations

- Since frequency standards are sensitive to shipment and environmental changes, calibrations are often made at the customer's site
- Radio reference (often GPS) is used as transfer standard
- Calibrations can be monitored by an NMI using a modem or Internet link

NIST Frequency Measurement and Analysis Service

- Measurements are made remotely at customer's site
  - NIST supplies everything needed
- Measurement process is automated
  - NIST downloads data by modem, performs uncertainty analysis, sends calibration reports
- Provides traceability to NIST with uncertainty of 2×10^{-13} per day

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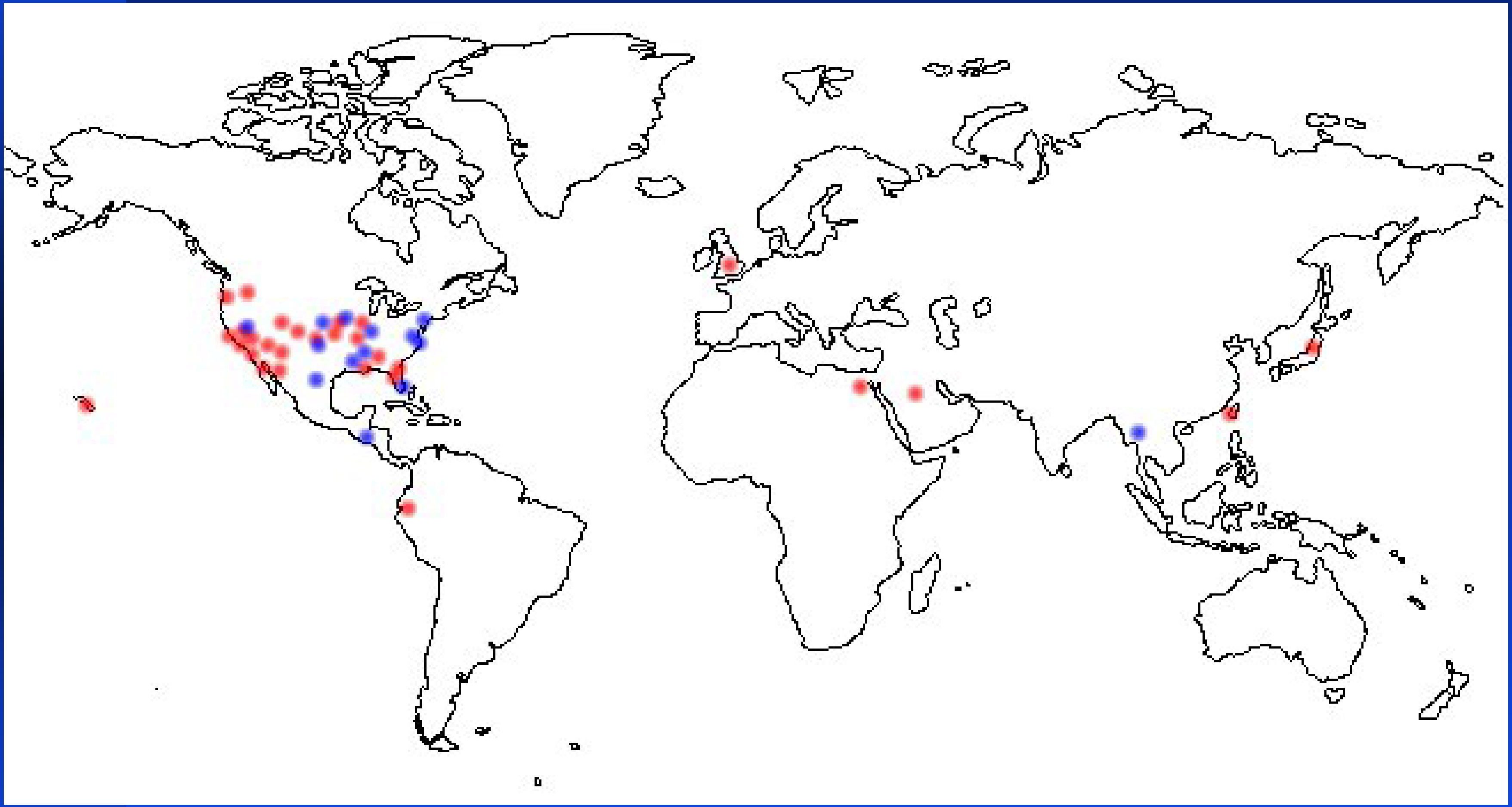
NIST Frequency Measurement and Analysis Service (cont.)

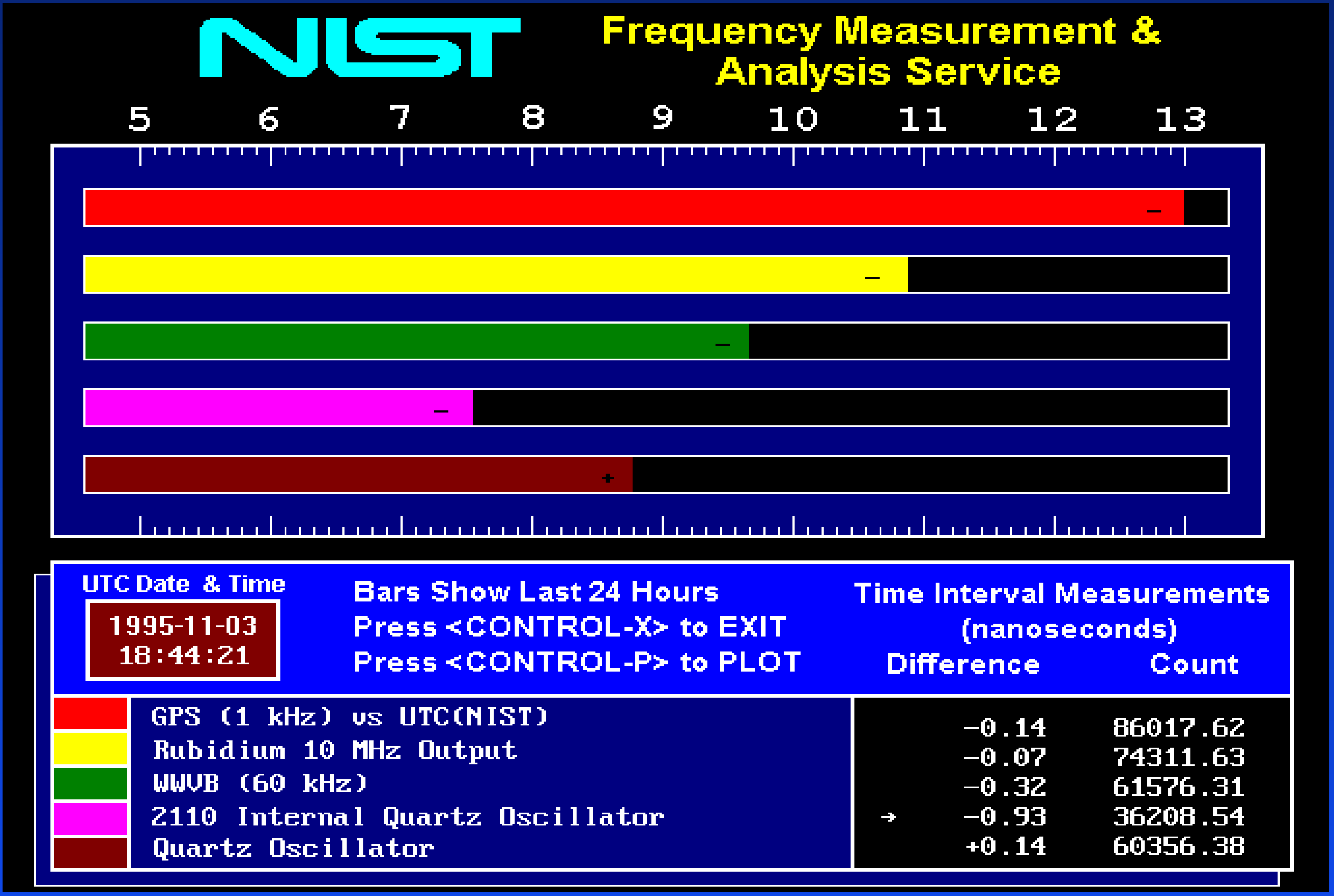
- NIST Service ID Number 76100S
- 5 oscillators can be calibrated at once
- Calibrations are automated
- Recognized by NVLAP
- Replacement parts sent when necessary using overnight delivery service

FMAS Customer Map

(labs with cesium oscillators in red)



NIST FMAS Display



Calibration Reports

- Monthly calibration reports are sent to each NIST FMAS customer.   Report is compliant with ISO Guide 25/17025 and includes a statement of uncertainty.
- The report defines the calibration period as one day (24 hours).
- The report annotates all situations where no data were recorded or where the device under test was out of tolerance.

Reporting of Measurement Errors and Outages

- The monthly calibration report annotates the following situations:
  - No data were recorded
  - GPS reception problems
  - GPS broadcast errors
  - Measurement System Errors including hardware or software failures
  - Device under Test errors
  - Device under Test substitutions/changes

FMAS Specifications

Number of Measurement Channels	5
Input Frequencies Accepted by System	1 Hz to 120 MHz in 1 Hz increments
Single Shot Resolution	< 30 ps
Measurement Uncertainty, GPS comparisons (24 hours, 2 sigma)	2×10^{-13}
Measurement Uncertainty, oscillator to oscillator comparisons (24 hours, 2 sigma)	2×10^{-15}

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NIST Policy on Traceability

- For more information about traceability, visit the NIST Traceability Web Site:

  http://nist.gov/traceability/

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