Traceability chain for Pendulum GPS-88/GPS-89 GPS Frequency Standards

White Paper from Pendulum Instruments

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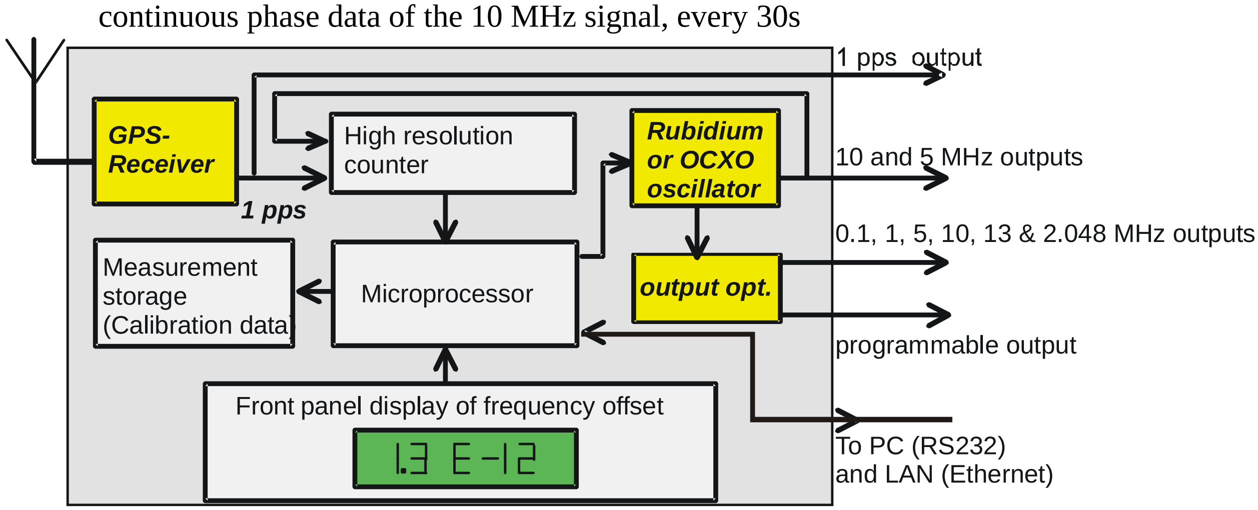
Preface

Traceability = the property of a 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.
(ISO's international vocabulary of basics and general terms in metrology – 1993)

Design of the GPS-88/89 GPS Frequency Standard

The GPS timing information is received in a multi-channel GPS timing receiver.
The output from the receiver module is the 1-pps signal which is used in two different ways inside the GPS-88/89

1. Disciplining of the local oscillator (OCXO or Rb) via a Kalman filter
2. Reference signal to an *independent* Time Interval Counter (TIC) Asic. The TIC compares the 1-pps reference to the 10 MHz output of the LO, and produces continuous phase data of the 10 MHz signal, every 30s



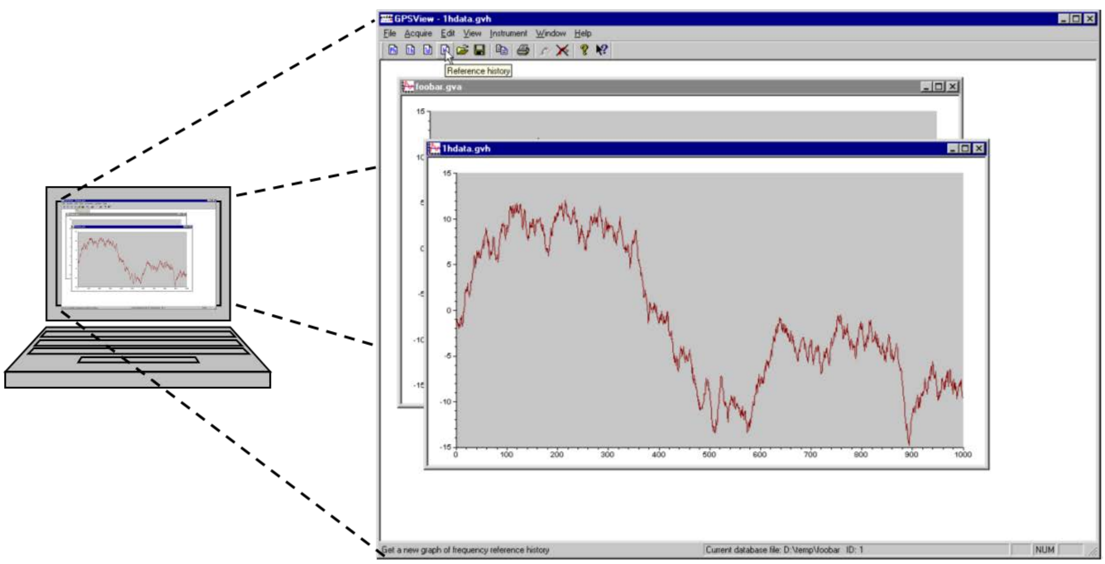
The phase comparison in the TIC is totally independent of the disciplining process, and the output is the phase calibration raw data.

Stored calibration data in RAM

The phase calibration data is converted to frequency data via regression line fitting (least squares method), since the slope of phase vs time ($\Delta\phi/t$) equals the relative frequency offset ($\Delta f/f$).

Inside the GPS-reference, four different types of data is continuously recorded in a cyclic RAM memory:
- TIE (phase raw data) every 30s, data is overwritten after approx. 2 days
- TIE (phase raw data) every 1 hour, data is overwritten after approx. 40 days
- Average frequency over 1 hour (calculated and updated every 15 min)
- Average frequency over 24 hour (calculated and updated every 15 min)

All these data can be downloaded as files via the GPSView SW.



Stored calibration data in Non-volatile memory

In addition to the RAM data, the 24h average frequency is stored at midnight UTC time in a non-volatile memory, together with the change of adjustment (expressed as frequency compensation) during the day.
This memory stores >4 years of data and is segmented, so that during continuous operation, the 24h frequency offset and adjustment data is stored every day since start in up to 4 years. After 4 years, data for year 1 & 2 is overwritten and after 6 years, data for year 3 &4 is overwritten, etc.

The instrument's Database and Calibration protocol in GPSView

The data stored in the GPS-88/89 is used to produce a calibration report, to allow a continuous day-by-day protocol of the 24h frequency offset during that day, plus the uncertainty of that value.

Table of archived Frequency Offset values.

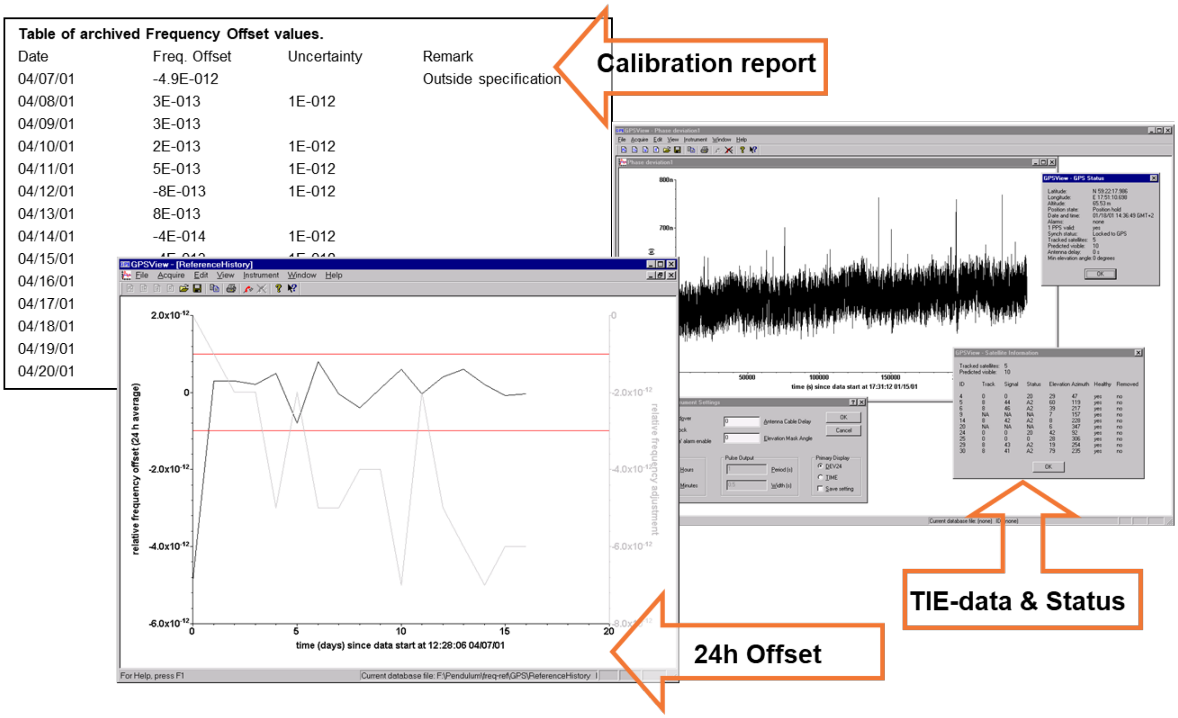
Date	Freq. Offset	Uncertainty	Remark
04/07/01	-2.9E-012		Outside specification
04/08/01	3E-013	1E-012	
04/09/01			No valid data
04/10/01	2E-013	1E-012	
04/11/01	5E-013	1E-012	
04/12/01	-8E-013	1E-012	
04/13/01	8E-013	1E-012	
04/14/01	-4E-014	1E-012	
04/15/01	-4E-013	1E-012	
04/16/01	1E-013	1E-012	
04/17/01	6E-013	1E-012	
04/18/01	-4E-014	1E-012	
04/19/01	4E-013	1E-012	
04/20/01	6E-013	1E-012	

The calibration report is managed by the accompanying SW GPSView. The procedure to generate a calibration report is the following:

1. **Create a GPS-88/89 database** for your specific instrument in the local PC running GPSView. This is a one-time action. If you have more GPS-88/89, you need to create a database for each instrument.
2. **Update the database monthly** by connecting GPS-88/89 to GPSView, and download the internally stored data.
   The database will be updated with all **Frequency offset** values stored in the instrument's non-volatile memory (the daily 24h offset plus adjustment data).
   The **uncertainty** will also be calculated and stored in the database, using the volatile phase data in RAM (30s and 1h data). The 1h phase data is overwritten in the RAM after 40 days, so if you haven't updated the database in a long time, frequency offset values older than 40 days will have no calculated uncertainty in the protocol
3. **Print the protocol from GPSView**. The database values between selectable days are used to generate the printout

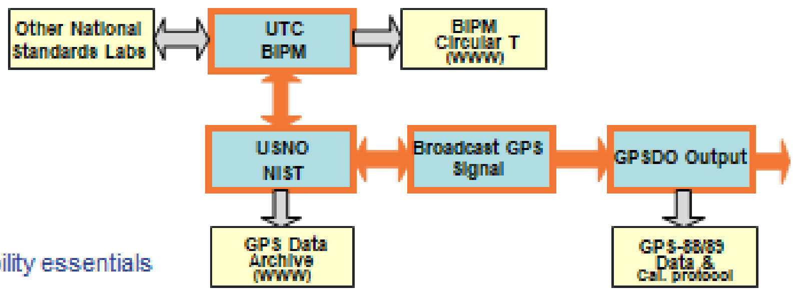
If you forget to update the database regularly, the 24h Frequency offset values stored in the non-volatile memory will anyway be printed in the protocol for the latest 2-4 years of use.

Note that GPSView can also display and print other parameters, like graphs of short-term phase and frequency variations, the long-term adjustment history, satellite status info and more. The phase raw data can be exported to other programs, like MS Excel, for further analysis.



The traceability chain for GTPS-88/89:

Traceability chain



Traceability essentials

- Comparison to national or international standards
- *Unbroken chain* of comparisons all having stated uncertainties
- Comparisons on a *continuous basis* (not ad-hoc)
- *Documented results* of each comparison

pendulum

The traceability chain, from the reference frequency output of the GPS-88/89 all the way back to NIST, consist of 4 links

1. Internal Rubidium or OCXO compared to 1-pps from the GPS receiver output.

This comparison is made in the internal calibrator and is documented via measurement data in several formats.
TIE vs t every 30 s is the basic raw data from the calibration process.
Frequency offset over last 1h or 24h is a calculated parameter and is updated every 15 minute.
The 24h frequency offset has an associated measurement uncertainty that is printed every time you generate a calibration report. This uncertainty of the comparison, to an ideal 1-pps reference, is the uncertainty of the measurement process including:

- resolution of the TIE-measurement (<500 ps rms)
- trigger noise contribution (internal noise <0.5 mV rms)
- short term stability of the used reference (OCXO or Rubidium)
- uncertainty of the frequency calculation (variance around the linear regression line of the TIE data samples). This factor depends on the number of samples used in the calculation over 24h, and the individual TIE-offsets from the regression line.

The combined rms uncertainty for frequency offset over 24h of the measurement HW is approx. 5E-14, a fixed value for all measurements. Then you need to add the uncertainty of the calculation, which can vary between measurements, depending on the number of data points, and how much the TIE values are scattered around the regression line.

2. UTC(GPS) vs 1-pps output from GPS receiver board

Here we must rely on the published specifications of the receiver manufacturer.
The receiver used has a specified uncertainty of 15 ns (rms) in the 1-pps timing accuracy

3. UTC(GPS) vs UTC(NIST)

NIST updates daily the result of yesterday's monitoring and comparison of all satellites vs UTC(NIST). It is available from https://www.nist.gov/pml/time-and-frequency-division/services/gps-data-archive.

Ideally the GPS-88/89 should automatically look up the data archive and retrieve the current frequency offset for every day from the GPS-constellation. But we did choose a pragmatic way of using a "safe value" for the frequency uncertainty of 5E-13 (1-sigma).

Since the total uncertainty in the calibration protocol is expressed as a 2-sigma value, this uncertainty factor amounts to 1E-12, and is the dominating uncertainty factor in the total calculation.

(This "safe value" is now very old. Today's satellites are more accurate and are nowadays typically in the 1E-14 range)

4. UTC(NIST) to UTC

BIPM publishes Circular-T every 2:nd week, with comparisons to all 200+ contributing labs around the world at https://www.bipm.org/en/bipm-services/timescales/time-ftp/Circular-T.html#nohref.
This also includes the comparison to NIST

THAT COMPLETES THE TRACEABILITY CHAIN!

SUMMARY:

The NIST and BIPM published data is the formally correct traceable calibration data to document the uncertainty of the transmitted frequency from the GPS-satellites.
In the GPS-88/89 calibration documents, we have chosen to use a “safe” value of <5E-13 rms (the NIST reported values are never above 1E-13, and typically some parts in E-14).

The traceability from the receiving antenna to the 1-pps output is reached via the suppliers internal type test and specification

The traceability from 1-pps to the internal OCXO or Rubidium to the frequency output of GPS-88/89 is achieved via the documented comparison results.
PLUS the fact that SP (the former Swedish national metrology institute for a.o. Time and Frequency, nowadays research institute RISE) has type tested GPS-89 and issued a report FemF016992. In this report, SP compared the internally generated data with their own external comparison with UTC(SP) and found that over several days of testing, the 24h frequency offset differed less than 5E-13 between the external measurement (SP) and the internal (GPS-89).
The report is available at https://pendulum-instruments.com/wp-content/uploads/2017/01/sp-report-gps-88-89_english.pdf