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THERMAL INFLUENCE ON THE RECEIVER CHAIN OF GPS CARRIER PHASE EQUIPMENT FOR TIME AND FREQUENCY TRANSFER

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Abstract - **In this study a temperature controlled environment is used in order to quantify the thermal influence on all major parts of state of the art geodetic GPS receiving equipment. Temperature variations, effective as time delay variations, were identified as a dominating error source that degrades the capabilities of carrier phase GPS based time and frequency transfer considerably. For purely code-based measurements with uncertainties in the *ns* range is temperature rarely an issue. In contrast carrier phase observations offer potentially a two orders of magnitude better accuracy and are therefore suitable for exploiting the characteristics of maser quality clocks. However, the stability of the environment around the receiver equipment defines the achievable accuracy.**
Four distinct parts of the receiver chain were subject to systematic measurements of the temperature-delay dependency: antenna preamplifier, antenna and clock cables, power distribution devices and geodetic receivers. A temperature controllable climate chamber was deployed with the respective component to follow a long time-constant temperature stepping. Signal through devices were mainly tested in a vector-voltmeter approach. Zero base line GPS processing was used to test receivers. With individual component temperature dependence being far above the expected accuracy of carrier phase based time and frequency transfer it underlines the necessity to include temperature as an important parameter into time/frequency solutions.

Keywords - **GPS, carrier phase, time, frequency, temperature, delay, accuracy**

I. INTRODUCTION

Dynamic delays in the receiver chain contribute to the uncertainty of GPS carrier phase based time and frequency comparisons. Temperature is presumably the main cause for short and middle term delay changes, whereas aging of the components, for instance change of the dielectric of cables, affects the delays in the long run.
A geodetic GPS setup is depicted in Figure 1. Some stations that are used for time and frequency transfer are "reused" geodetic systems, e.g. IGS (International GPS Service) stations that originally were not designed for frequency applications. Their setup is focused on the stability of the position of the antenna, a reasonable multi-path environment, the receiver type, etc. Such design decisions can have a negative effect on the capability of a system to be used for

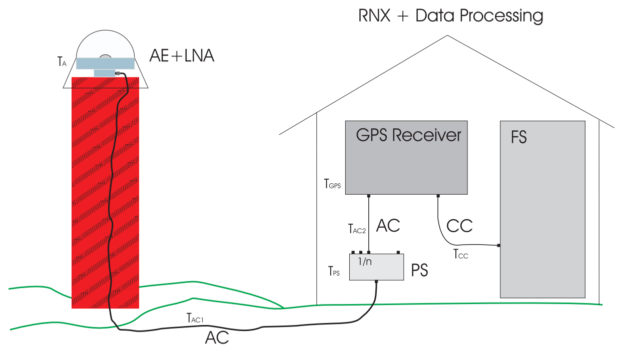

Fig. 1. A geodetic GPS station, typical for Sweden (SWEPOS). A monument is anchored in the bedrock giving the antenna (antenna element AE, low noise amplifier LNA) a stable position. The antenna cable AC runs partly outdoors and is distributed indoors by a power splitter PS to the GPS receivers. The receiver(s) are connected to a frequency of a frequency standard FS via clock cables CC.

time and frequency transfer. The usual geodetic use of carrier phase GPS for geophysical and atmospheric studies is not affected by delay variations in the receiver chain. Delay is an elevation independent parameter that accumulates in the clock parameter and therefore it is not visible in any of the position or atmospheric parameters. Thus it is important to quantify these delays since they are indistinguishable from variations in the station clock.
Carrier phase based time transfer using post processing tools such as GIPSY/OASIS have shown a potential to compare clocks on the level of 10 ps, see e.g. [1]. The limit for real time solutions is about 100 ps [2]. Uncertainties due to temperature-induced delays can accumulate up to several 100 ps or even to the ns level for a badly controlled system, see e.g. [3-5]. It is obvious that a good temperature-delay model will improve the quality/accuracy of carrier phase GPS based time and frequency transfer.

According to Figure 1 there are five components in a typical receiver chain that are important to investigate.

- Antenna element and antenna pre-amplifier (LNA) undergo temperature changes that can easily exceed a daily 50K and a seasonal 70K. Together with the antenna housing (e.g. aluminum choke ring) they form a thermal unit where temperature is easily measured. The LNA is an active component that dissipates power in the form of heat, the setup and stability of the LNA power supply has a consequent impact on the delay variations. As an outdoor component it is exposed to the elements, which affect the apparent temperature of the device (solar exposure, wind, clear sky, etc.).

- Antenna cables are easily modeled, but extensive cable lengths through varying environment make it practically difficult to make a correct estimation of the delay variations. It is not uncommon to have cable lengths of more than 150m. Measuring and modeling the actual cable temperature is difficult. Measuring round trip delays instead might be a solution to the varying temperature gradient along the cable path.
- Power splitters are passive components and are very common in systems with several receivers. They distribute the input power equally to the number of outputs while maintaining proper impedance matching. Indoor situated and compact build they are easily measured and modeled.
- Clock cables are usually indoor placed and of limited length and thus are easier handled than antenna cables. Even here round trip delay measurements and appropriated models can be used to determine an integral delay along the cable path.
- Geodetic receivers are complex active components that contain hardware and software, which both have an impact on the delay variations of the system. Temperature presumably influences the analog and the analog to digital components and further the clock paths within the receiver. This might include hardware (PLL/DDS) and/or software for internal clock generation. The pure digital parts (processing) are likely not affected by temperature variations as far as timing is concerned. Most receivers dissipate a considerable and varying amount of heat that makes modeling more difficult. But as rather compact devices it is easy to measure the case temperature, some receiver types can even deliver internal temperature values.

II. METHODOLOGY

Several methods can be used to measure the relative delay /delay variations of micro frequency components. One can distinguish between signal through devices, i.e. devices that input and output a signal without degrading its spectral density/integrity, and devices that do not output the input signal in an appropriated form to make a direct delay measurement possible. These different types require different approaches, which differ in their applicability and achievable quality.

Vector-Voltmeter Approach (VVA):
Figure 2 depicts the principle setup for measuring delay variation using a vector voltmeter VV and a signal generator SG. The signal generator, which is referenced to a stable frequency source, FS delivers a monochromatic frequency, e.g. center frequencies of L1 or L2. A power distribution device PS distributes the signal to the input of the test object in a controlled environment (climate chamber) and to the vector voltmeter at input A. The test object has to be a signal through device and its output is connected to input B of the vector voltmeter. The temperature environment around the equipment, especially the cables, has to be constant. The vector voltmeter measures the phase difference between B and A (B-A), which can be used to calculate a delay measure (inverse direction from what is seen in the diagrams). Active components might require further equipment in the signal path such as DC power supplies, DC blocking devices or attenuators. Signal level and frequency are easily adjustable. The vector voltmeter method is very easy to handle and gives in general better results than the zero-baseline method. It

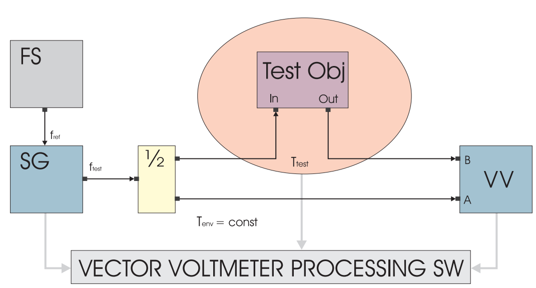

Fig. 2. The vector voltmeter approach: a signal generator (SG) generates a monochrome GPS frequency. A power splitter (PS) distributes the signal to the vector voltmeter's input A and to the test object in the climate chamber. The output signal is fed to input B of the vector voltmeter (VV). Certain test objects need external power supplies that might require additional DC blocking and / or attenuation in the signal path. The signal generator is ideally referenced with a stable frequency (FS)

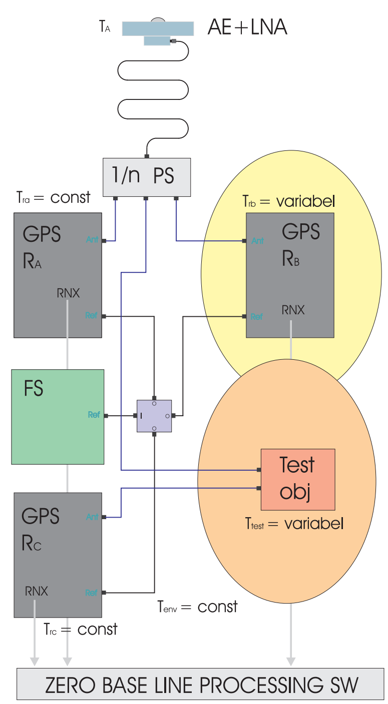

Fig. 3. A zero base line setup: receiver A is the reference receiver that is held in a constant environment. In order to test the receiver temperature dependence receiver B is placed in a climate chamber (case I). Other test objects are measured by holding receiver C at a constant temperature and varying the ambient environment of the object of interest. This can be done by connecting it either to the clock or to the antenna (depicted) cables (case II).

cannot be used for receiver testing and does not work well for low frequencies (e.g. clock cables) with small temperature/delay coefficients due to the period time based resolution of the vector voltmeter. Refer to Figure 5 for a real setup for LNA testing.

Zero-Baseline Approach (ZBA):
Figure 3 gives an overview about the used zero-baseline method. Two receivers are connected to the same antenna/antenna cable. A power splitter distributes the antenna signal to the respective receiver via antenna cables through ideally the same environment. Both receivers are connected to the same frequency normal via a power splitter close to the receivers. In case the receivers under test require different frequencies as a clock input, some sort of frequency translation device is needed. At SP a micro-phase stepper and several distribution amplifiers are used to create 5Mhz and 10Mhz sinusoidal signals of UTC(SP).
Receiver A is held at a constant temperature in a controlled environment. Receiver B is the device under test and is placed within a climate chamber. In order to test other components receiver C is placed outside the chamber and is held at constant temperature. The component of interest is placed within the chamber and an appropriated temperature stepping is applied. It is required to use the same sampling time for both receivers and to switch off a possible clock steering. The resulting phase/code data (RINEX) is fed to a simple zero base line software that subtracts the raw phase values of L1 respectively L2 from each other. C/A code information is used in order to determine the approximate sampling offset between the receivers. Together with orbit information it is possible to correct for the Doppler shift caused by satellite motion during the offset time. Finally a cycle slip and phase connection algorithm corrects the data and eliminates outliers. Clock combination and residuals can be used to determine the delay caused by the induced temperature change.
This method can be used for all mentioned components in the receiver chain, but has its limits in the receiver noise visible in the clock combination. Sensitive delay changes might be difficult to track. Components that degrade the signal level (e.g. power splitters in the antenna path) might require additional amplification.

Pulse Per Second Approach (PPSA):
This approach is quite similar to the vector voltmeter method described above, but works well with low frequencies. Figure 4 depicts a setup. An auxiliary output generator (AOG) creates a, possibly frequency corrected, one pulse per second (1pps) signal, which is directly fed to input A of a time interval counter (TIC). The same pulse is also routed to input B, this time via the test object in the climate chamber. The counter measures the absolute delay of the additional signal path through the test object. Real world square signals have a large spectrum with high power at low frequencies. With appropriated filtering one can restrict the bandwidth of the signal to a required level. Naturally this method is not limited to 1pps signals but works well for higher frequency

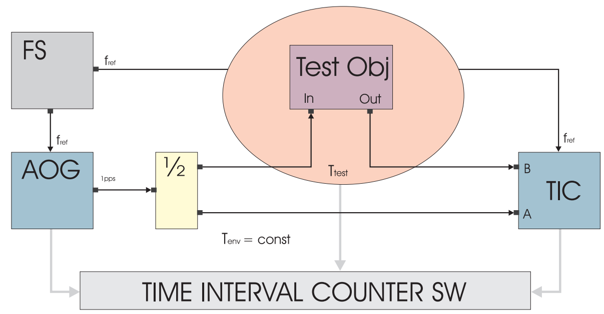

Fig. 4. Similar to the VVA the Pulse Per Second Approach uses the stable frequency of a frequency standard FS to create a synchronous test frequency, in this case a square one pulse per second signal (AOG). A time interval counter (TIC) measures the absolute delay experienced by the test object. TIC is referenced to either FS or AOG.

square signals and sinusoidal signals depending on the abilities of the time interval counter, the expected delay of the test object and the testing bandwidth. If temperature depending signal dispersion is of interest, this could be studied using an additional spectrum-analyzing device in the signal path.
This method is a good substitute for VVA for low frequencies and offers a good resolution and accuracy when VVA suffers from the period time dependent resolution problem.

General Considerations:

- Temperature has two main effects on the group delay experienced by electric/electronic devices:
  - *Thermal expansion* expands the materials of the device in question. One millimeter expansion within a system can translate into several picoseconds delay (depending on the relative propagation coefficient), expansion can be complex difficult to model.
  - A *Change of the dielectric constant* of the dielectric used in the device changes the relative propagation

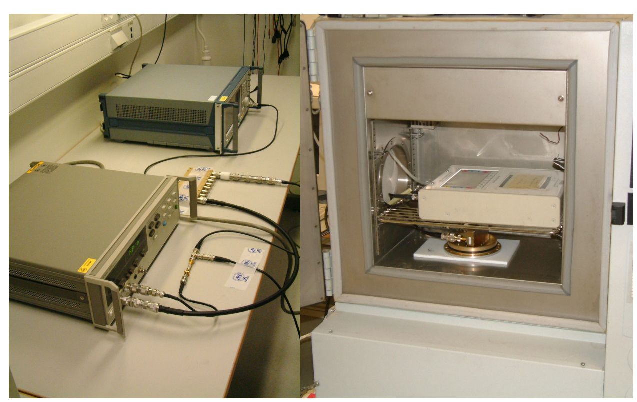

Fig. 5. left: VVA for LNA testing with a HP8505 vector voltmeter (front), a Rhode & Schwarz SME03 signal generator (back) and a Micro-Circuits ZB8PD-2 power splitter (mid)
right: open Thermotron climate chamber with a TurboRogue GPS receiver and an Ashtech LNA

coefficient. This can have an opposite effect of the length change discussed above. Even here complex devices that are build with a mix of different materials and thus they have a very complex and difficult to model temperature dependent dielectric constant.

- Other environmental quantities, such as humidity, air pressure, radiation, etc. could affect the delay variations. Aging which is a combination of radiation, temperature and time has a well know effect. None of these quantities were addressed in this study.

III. Results

Antenna:

A GPS antenna consists of three parts: antenna body, antenna element and antenna low noise amplifier (LNA). All these components are temperature dependent and have effects on GPS processing. The antenna body, e.g. a Choke Ring, has an expansion coefficient that affects the phase centers and with it the apparent position of the antenna. Cables within the antenna body are subject to delay changes. The antenna element suffers as well from expansion and change of the dielectric, which affects delay and position. Preamplifiers are active electronic devices with a complex delay function.

The LNA of an Ashtech Choke Ring antenna was tested both with VVA and ZBA. The component is very stable but nonlinear over a wide temperature range. VVA at L1 (1.57542 GHz) results in about

-0.1 ps/K above 20 ºC
+0.17 ps/K below 15 ºC.

Figure 6 shows a temperature phase delay relation for this LNA. These small coefficients obtained are drowned in receiver noise using ZBA.

Testing of the Dorne & Margolin dipole AE was not applicable with neither of the methods. Reference [4] discusses the temperature sensitivity of this type of antenna.

Antenna Cable:

Three different types of antenna cables were tested, with both mentioned phase based methods in qualitative agreement. Testing cables is straightforward and the following table illustrates results from VVA.

Cable type	Length (m)	Total delay at 23 ºC (ns)	Temperature coeff. (ps K^{-1} m^{-1})
LDF2-50	86	331.62 (19.5ps STD)	0.01
RG213U	16	81.85 (19.8ps STD)	-0.45
RG58	20	101.87 (18.7ps STD)	-0.42

Figures 7 and 8 depict the temperature/delay relations for the RG213 and RG58 cable types.

Power Splitter:

A Micro-Circuits ZB8PD-2 was tested using the ZBA. Refer to Figure 9 for the result. The temperature coefficient is in

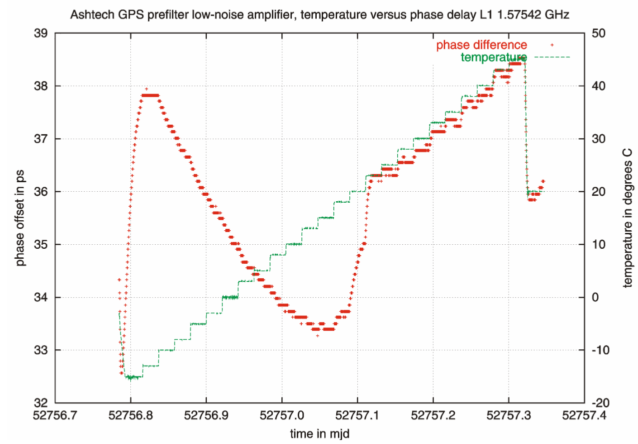

Fig. 6. Temperature induced delay on an Ashtech LNA. The linear area above 20 ºC indicates a temperature dependence of about -0.1ps/K. The measurements were done with VVA.

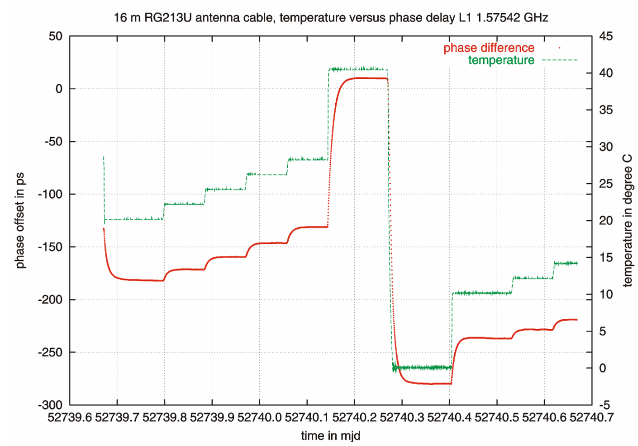

Fig. 7. Temperature induced delay on a RG213U cable. The delay is almost linear within the measured range. 0.45ps/Km for a step between 40.5 and 0 ºC. The measurements were done with VVA.

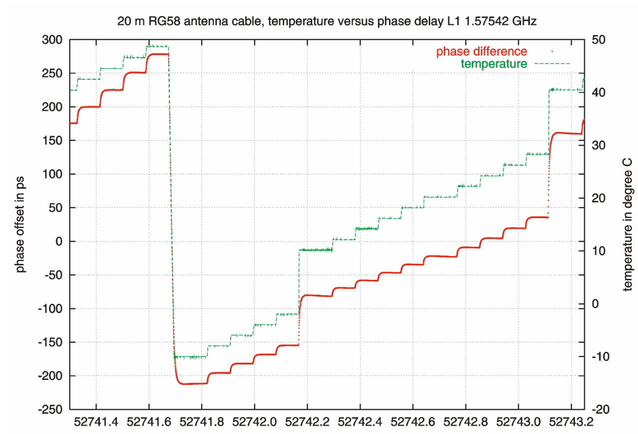

Fig. 8. Temperature induced delay on a Rg58 antenna cable at the L1 frequency. Also here one sees a linear behavior over the measured range. 0.42ps/Km for a step of 58.5K. The measurements were done with VVA.

the order of -1 to -2 ps/K. VVA based measurements give a better result, Figures 10 and 11 show temperature delay relations for L1, respectively L2. Both agree qualitative but slightly differ in the coefficients. An average of about –0.7 ps and -1ps is a good estimate. Depending on the output port used, different coefficients can be found since the signal length somewhat differs from port to port.

Clock Cable:
VVA testing was not successful, the trusted resolution of the used HP8505A (ca 27.7ps at 10MHz) was not enough to form a conclusive picture of the delay variation caused by temperature. The same holds for ZBA. Measurements using PPSA are planned for the future. In principle one can expect similar results as seen for antenna cables.

Receiver:
Several receivers were tested with the SBA. VVA is not applicable with receivers. None of the receiver is capable of true time transfer. But the Z12T version is similar to the tested receiver and even the Javad that was tested is easily upgradeable for time marker use. Following table shows some results. See also Figures 12 to 14. An Ashtech Z18 was not usable because the receiver software did not manage to use the external frequency.

Receiver Type	Estimated Temperature Coeff. (ps K^{-1})
SNR-8000	About 100
Ashtech Z12	About 700 at room temperature, -600 at -3 degree Celsius
Ashtech Z18	Not usable for time and frequency
Javad Lexon-GGD	About -160

IV. Conclusion

We systematically investigated the temperature dependence of the components of the GPS receiver chain with two independent methods. The results partly agree well with several publications in the field. Receiver, LNA and power splitting results are somewhat new and emphasize the need to include temperature delay models into post processing and real time processing for time and frequency applications. The choice of receiver type and antenna cable seems to be most important for the design of a receiver system used for time and frequency.

Acknowledgments

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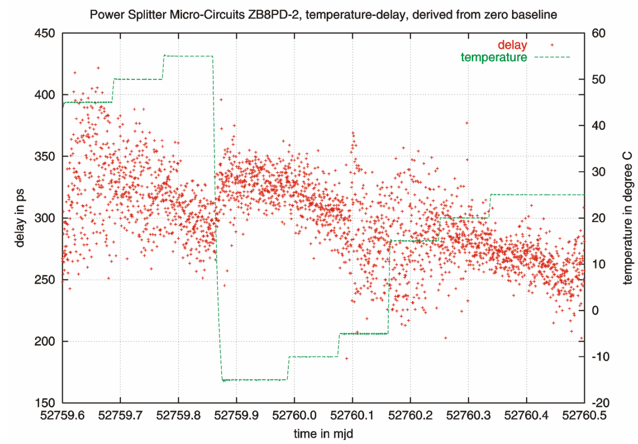

Fig. 9. Power splitter delay measurement derived from ZBA., small steps are drowned in the receiver noise. An rough estimation results in –1 to –2 ps/K as a temperature coefficient.

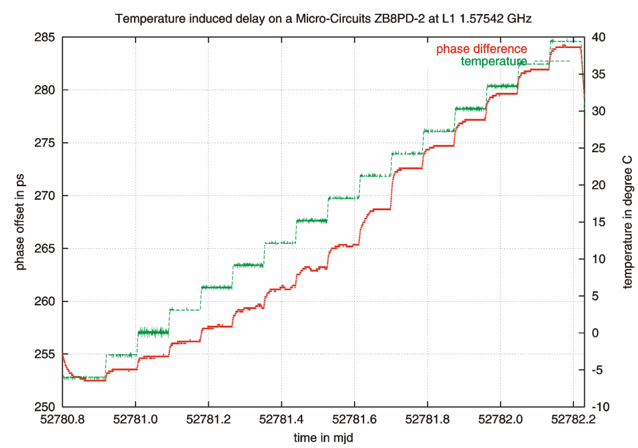

Fig. 10. Power splitter delay measurement derived from VVA at L1. Slightly nonlinear, from 0.45 ps/K around 0 ºC to about 0.7 ps/K at 30 ºC

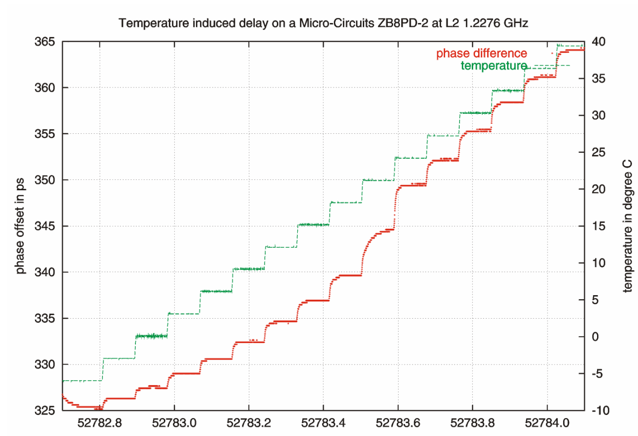

Fig. 11. Power splitter delay measurement derived from VVA at L2. Slightly nonlinear, from 0.5 ps/K around 0 ºC to about 1 ps/K at 30 ºC

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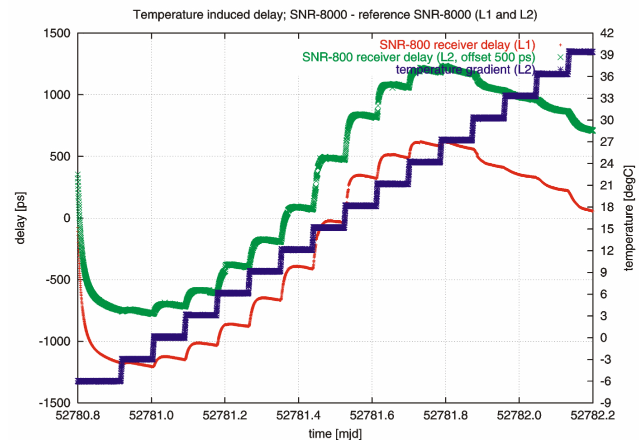

Fig. 12. A TurboRogue GPS receiver under test: The receiver does not work properly at higher temperature. Temperature delay behavior is slightly nonlinear. A mean coefficient of about 100ps/K is realistic.

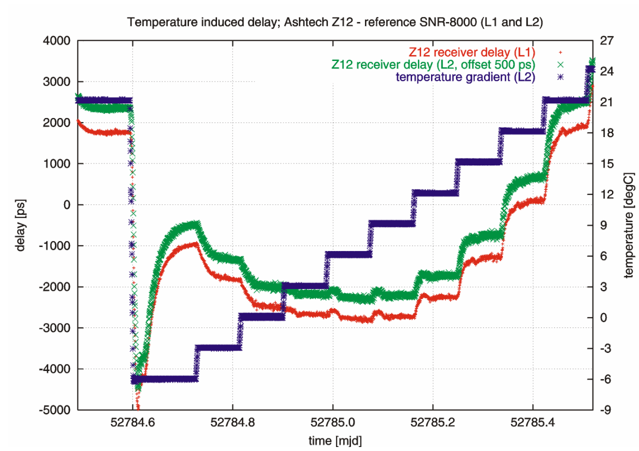

Fig. 13. An Ashtech Z12 under test: nonlinear temperature delay relation. Around room temperature one can expect around 700ps/K additional delay

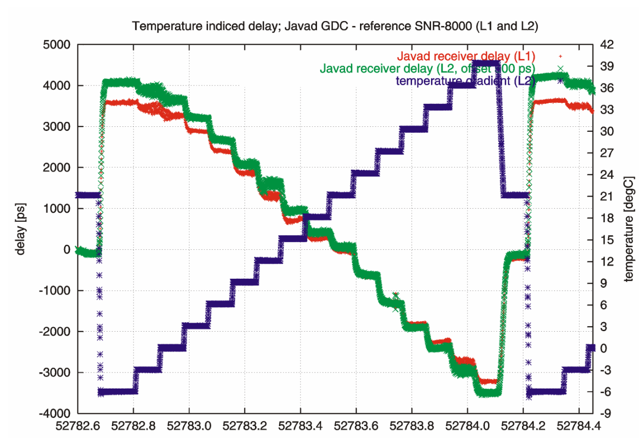

Fig. 14. A Javad Lexon –GGD receiver. In contrast to the other receiver types a negative coefficient of about –160ps/K was found. Note the slight difference between L1 and L2;