Metrolab

Performance comparison between the PT2025 and the PT2026

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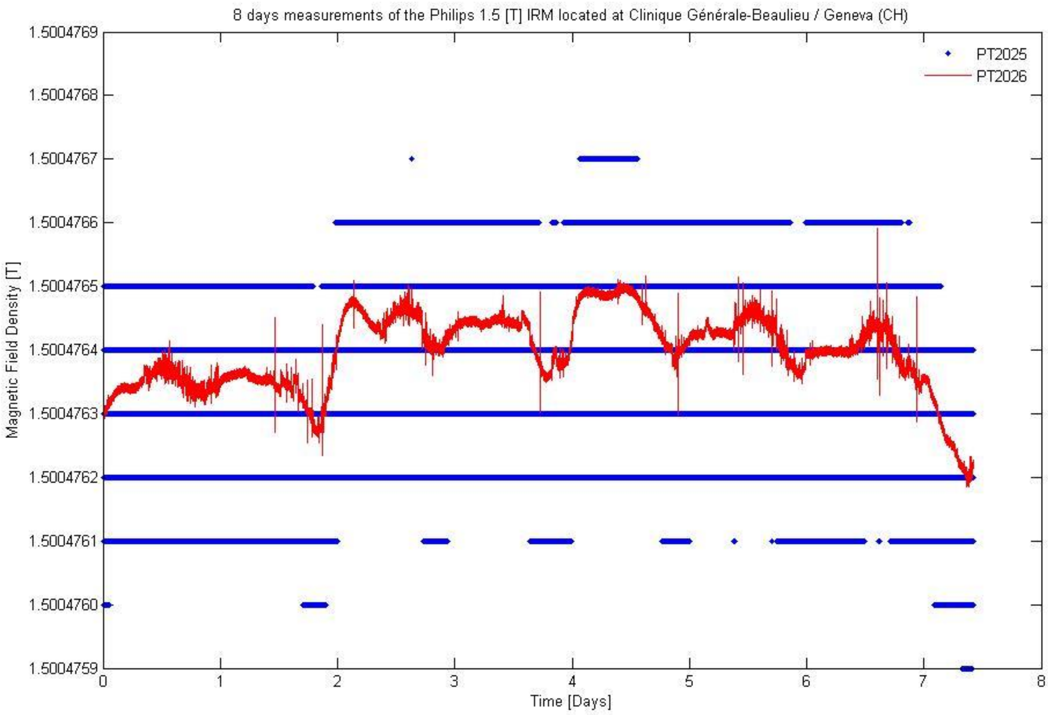
1 Foreword

Comparing the PT2025 versus the PT2026 isn't obvious. One could think that it is just a matter of comparing the measurement results from each instrument and compute some statistics, it's not. The difficulty comes from the fact that the PT2025 returns measurements as fixed-point ASCII-encoded numbers that are limited in resolution, discrete in other word, whereas the PT2026 return its results with 64-bit floating point numbers. At that resolution level, quantization occurs at some point but at a level that is so low that the measurement principle is the limiting factor, not the way we encode measurements results.

Even before giving comparison figures, the following survey of a 1.5 [T] MRI for several days shows this numerical effect and the incredible improvement offered by the PT2026.



2 NMR Measurement principle

A short description of the measurement principle of both instruments will help us understanding their measurement limits.

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2.1 Obtaining an NMR Signal

Several articles or books explain in great details how NMR works, a clear explanation is given in [1][2] and we won't enter in a deep explanation of this principle. However, three common methods exist to obtain the NMR signal. This signal can be detected when a sample immersed in the magnetic field being measured is briefly stimulated by an oscillating magnetic field perpendicular to it. If the oscillation frequency matches the resonance, the nuclei in the sample will interact with the stimulation.

The principle in use in the PT2025, commonly called continuous wave modulation, consist in stimulating a sample continuously with a radio frequency set to the value of the NMR frequency. As stated before, the stimulation must be brief, but since the sample is being stimulated continuously, to briefly stimulate the sample at the NMR frequency one must just shift the magnetic field being measured a little bit off. Using an external coil and the principle of superposition we create a total magnetic field equal to the sum of the one being measured and the perturbation one. When the total magnetic field matches the radio frequency that stimulates the sample, it is possible to detect an NMR signal.

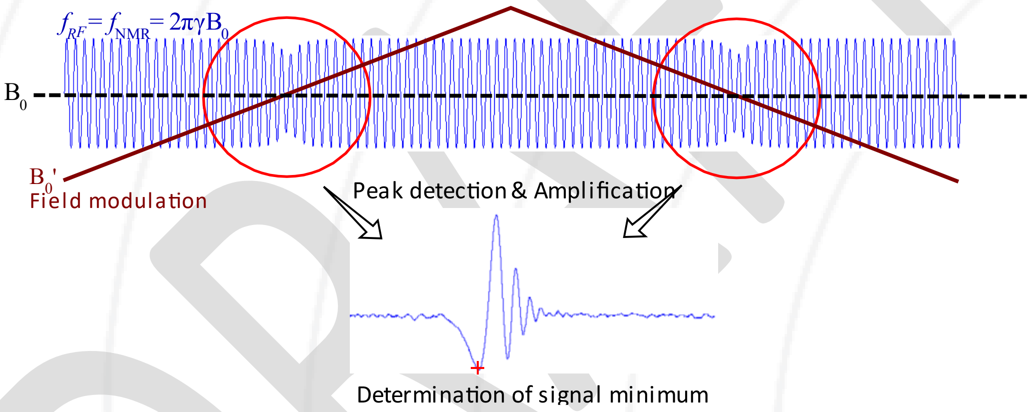


Figure 1 NMR Signal obtained with field modulation

Another way to perform a continuous wave stimulation is implemented in the MFC3046. This method consists in stimulating the sample with a radio frequency that is continuously varying around the NMR frequency. When the radio frequency matches the NMR frequency we may, again, detect an NMR signal.

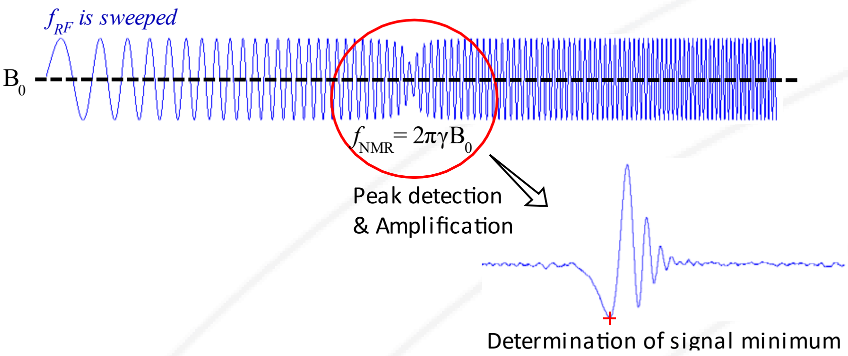


Figure 2 NMR Signal obtained with frequency sweep

Finally, the principle in use in the PT2026, called pulsed NMR, consist in stimulating the sample with a brief impulsion of radio frequency set to match the NMR frequency. When the stimulation stops, an NMR signal can be detected.

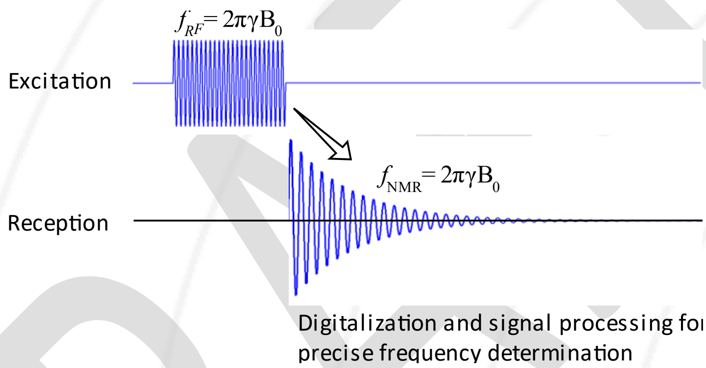


Figure 3 NMR Signal obtained with pulse modulation

2.2 *Sample shape and excitation*

When it comes to precision, a question that usually rises is: “What is the exact location of the measurement”. To answer that question, and to simplify the reasoning, one must understand that the NMR signal that is collected by any reception electronics is created by the participation of every single nucleus located in the sample according to the external magnetic field it sees locally [1][2]. The overall effect can either be constructive in presence of a homogeneous magnetic field or destructive in the case of inhomogeneous one. When the gradient is too important, the NMR signal might disappear completely. Part of the intensity at which a nucleus participate to the final signal is relative to the so-called flip-angle that the excitation coil can produce. In a perfect world, every single nucleus is flipped to the ideal 90° angle that would allow it to produce its maximum intensity. However, in a magnetometer, the coil that excite the sample doesn’t irradiate the sample volume with the same power level. The physical construct of the excitation coil is a simple wire that surround the sample. This construct creates an electromagnetic field that not only isn’t constant in power over the whole volume but also diverges, preventing the condition of perpendicularity of the oscillating magnetic field – often called **B_1** in the literature - to be fully met, hence reducing de-facto the local NMR signal emitted by the nuclei.

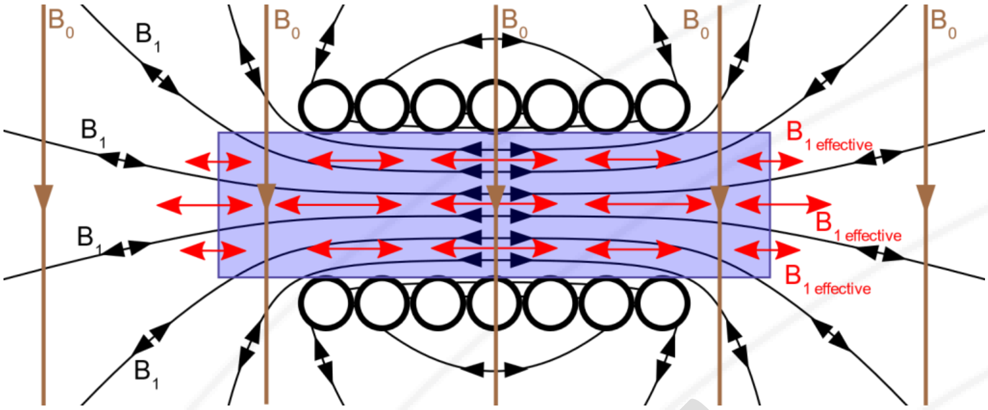


Figure 4 NMR sample and coil (adapted from [5])

If the condition of homogeneity is respected on the measured magnetic field, the exact location can clearly be considered as the center of the sample, the geometrical construct of the measuring head having been designed to achieve this specification. But when it comes to the measurement of a gradient, the shape of it, the shape of the excitation coil, the shape of the sample itself and some other intrinsic factors needs to be considered to determine the exact location of the magnetic measurement as returned by the instrument. On the other hand, inhomogeneity also leads to weaker NMR signal that results in higher noise on the final measurement blurring its exact location.

3 PT2025 Principle of operation

The PT2025 uses a continuous wave measurement scheme consisting in stimulating continuously at the NMR frequency a coil that surround the NMR sample. An envelope detector follows the amplitude of the RF signal. This amplitude signal is amplified, and its variation is used to detect the NMR absorption signal. As stated during the description of the NMR signal obtention, stimulating the sample with a fixed frequency leads to nowhere, we need a variation, either by sweeping the RF frequency around the estimated NMR frequency of by creating a local variation of the magnetic field using a modulation coil. This last is the solution implemented in the PT2025. However, since an external field is created, we must be certain that the NMR frequency is related to the magnetic field that is measured and not a shifted version of it. This problem is solved by making sure that the NMR absorption peak occurs when the current injected in the modulation coil is null.

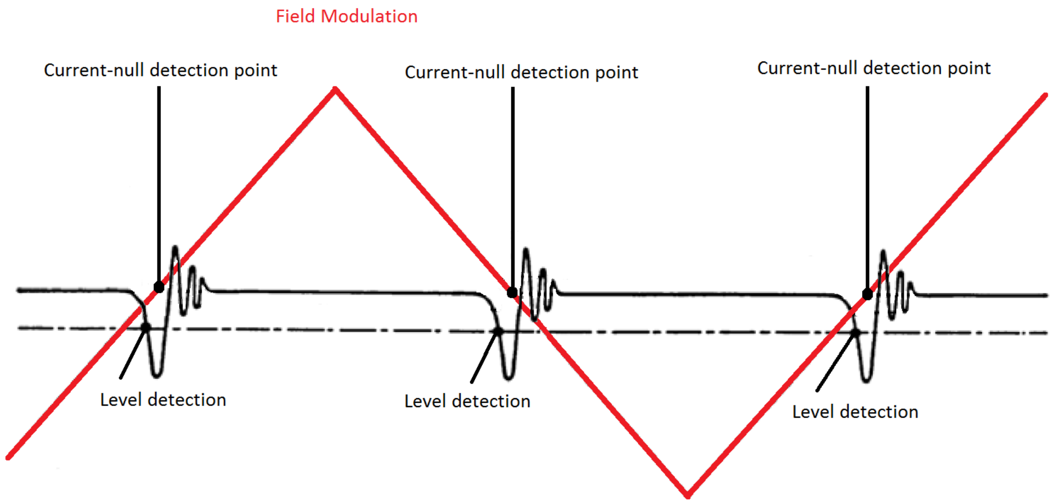


Figure 5 PT2025 field modulation

Maintaining the position of the absorption peak at the instant where the modulation coil induces no magnetic field consist in constantly adjusting the RF frequency. Another analog mechanism makes sure that the detected signal has the right amount of voltage and works as a lock detector. If the peak is detected, the RF frequency is fed to a counter gated for a duration that is related to the units in which the measurement is displayed, de-facto averaging of the frequency using a timed window.

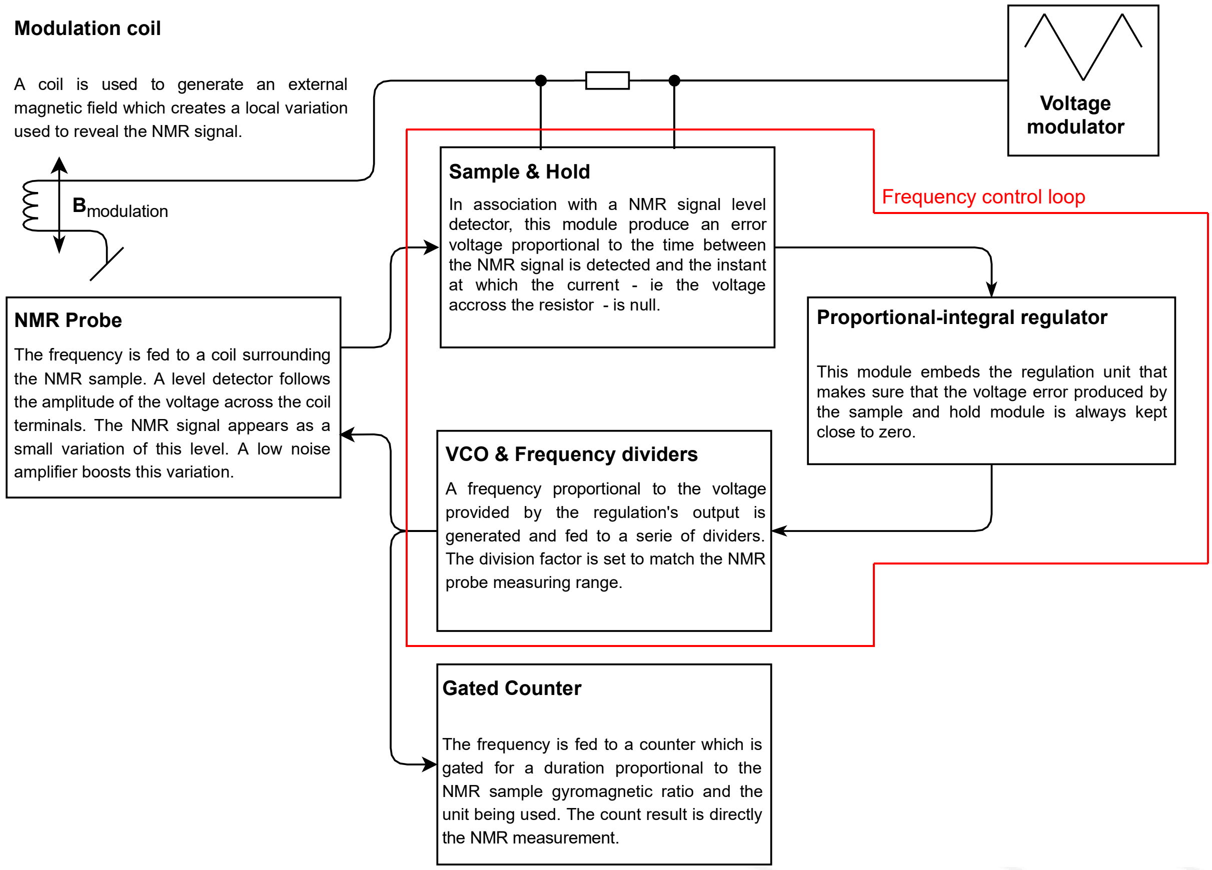


Figure 6 PT2025 simplified bloc diagram

Despites being a jewel of analog electronics, one can immediately deduce the various drawbacks of this design.

- First, and some complained about this limitation in the past, a modulation coil is needed to make a measurement creating a local perturbation that may be harmful in the customer environment. Moreover, the loop that follows the measured magnetic field dynamics is obviously affected by a time lag resulting in an absolute error if the field isn't static.
- The NMR signal is revealed by a change of the amplitude of the radio frequency voltage as it appears across the coil terminals. The noise that affects the detected signal will directly impact the error voltage fed to the proportional-integral regulator, resulting in a slight frequency shift.
- Any noise present on the VCO input immediately translate in small frequency variations.
- Another limitation comes from the fact that the gyromagnetic ratio is created using a time window gate. The clock that is used to generate that window has a granularity of 100 [ns]. As explained in [4], when the unit are set to Tesla, this windowing leads to digitization of the gyromagnetic ratios. This directly impacts the time taken between each measurement. This also impacts the resolution when using [T] units. For ^{1}H probes, the resolution is close to four time worse than when using [MHz] units.
- And finally, during the time window, the counter holding the NMR measurement acts as a fixed float registers which last digit directly determines the resolution.

Sample	Unit	Effective time window	Gyromagnetic ratio
^{1}H	Tesla	0.939 491 [s]	$\gamma''_p(eff)/2\pi$= 42.576 246 073 671 800 MHz/T
^{2}H	Tesla	1.530 060 [s]	$\gamma''_d(eff)/2\pi$= 6.535 691 410 794 350 MHz/T
^{1}H & ^{2}H	MHz	1.000 000 [s]	N.A.

4 PT2026 Principle of Operation

The PT2026 is a magnetometer based on pulsed NMR. Its operational principle consists in stimulating the NMR sample with a radio frequency send to the coil that surrounds it for a duration that leads most of the nuclei to reach a flip-angle of 90°.

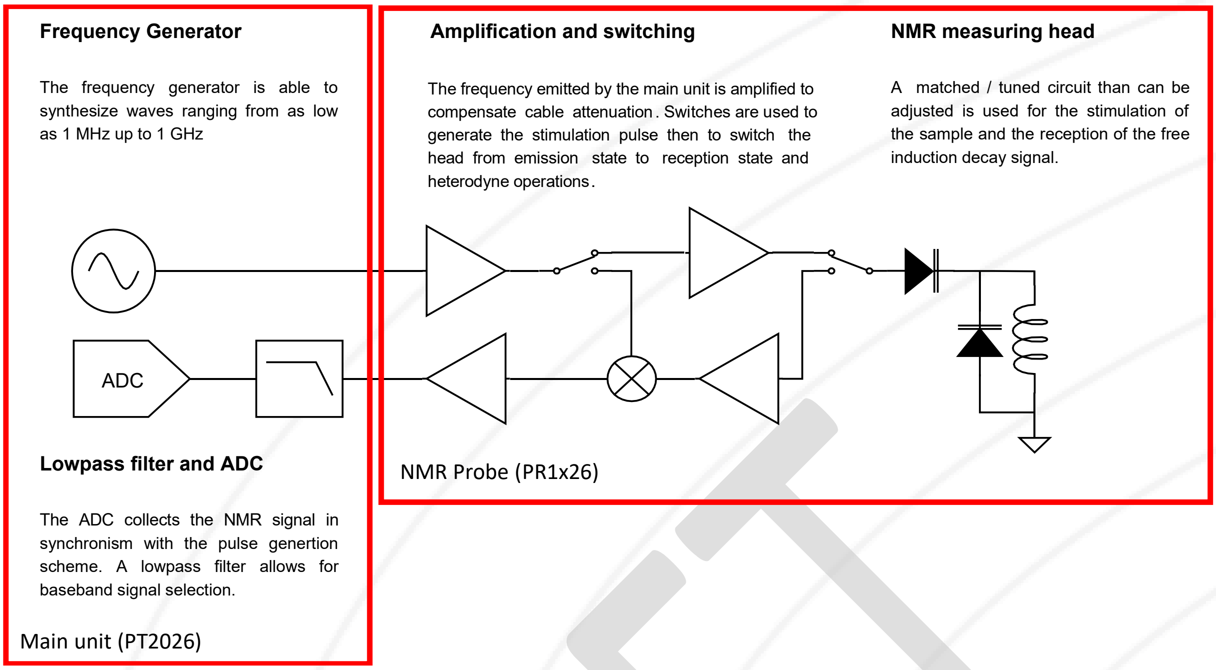
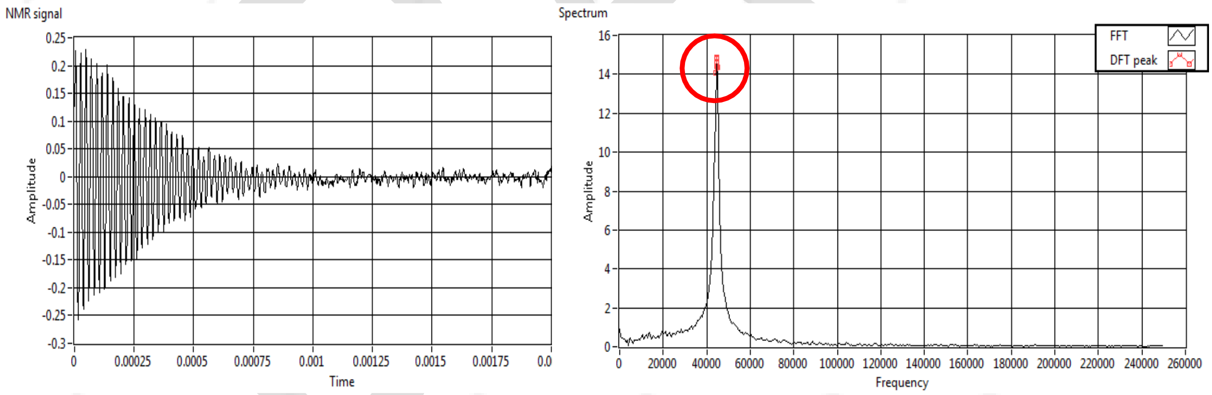


Figure 7 PT2026 simplified bloc diagram

When the stimulation is stopped, the nuclei are pulled back to their initial state by the magnetic field that we would like to measure. During this state restoration, an NMR signal can be measured using the same coil. This signal being very small, a high gain amplification is needed. An ADC collects the free induction signal which is then processed using Fourier transform techniques to determine its frequency.



Despites seeming very much simpler than the PT2025, the PT2026 embeds the latest RF integrated circuits on the market and even an ASIC developed in collaboration with EPFL / Lausanne [6]. All the measurements are made at a very precise rate which is limited mostly by the spin-lattice relaxation time. The probe's gyromagnetic ratio is stored as a 64-bit float directly in the probe allowing any NMR-prone sample usage.

5 Resolution comparison

Before performing any measurements, we used a TFM1176 to determine the distance to which the magnetic field induced by the modulation scheme of the PT2025 wouldn't affect the PT2026. We determined that at a distance of 10 [cm], the PT2026 measurements wouldn't be impacted. The probe setup in the magnet was to set the probe 10 [cm] apart, each of them being positioned 5 [cm] away from the magnet center.

We had the chance of getting access to a 1.5 [T] MRI magnet in a private facility in Geneva. They were working on a retrofit of their building during which the access to the MRI was impossible. We took this opportunity to install a PT2025 and a PT2026 to perform long term measurements in the same magnet. Out of fairness for the PT2026 and to prevent the dataset to be very huge, we configured the instrument to report a measurement based on a 1 [s] block average. As mentioned earlier, this leads to a measurement rate that is almost identical as the one of the PT2025.

And here are the results: 99.7 % of the measured values are 7.3 better than the theoretical resolution of the PT2025, not taking its noise into account.

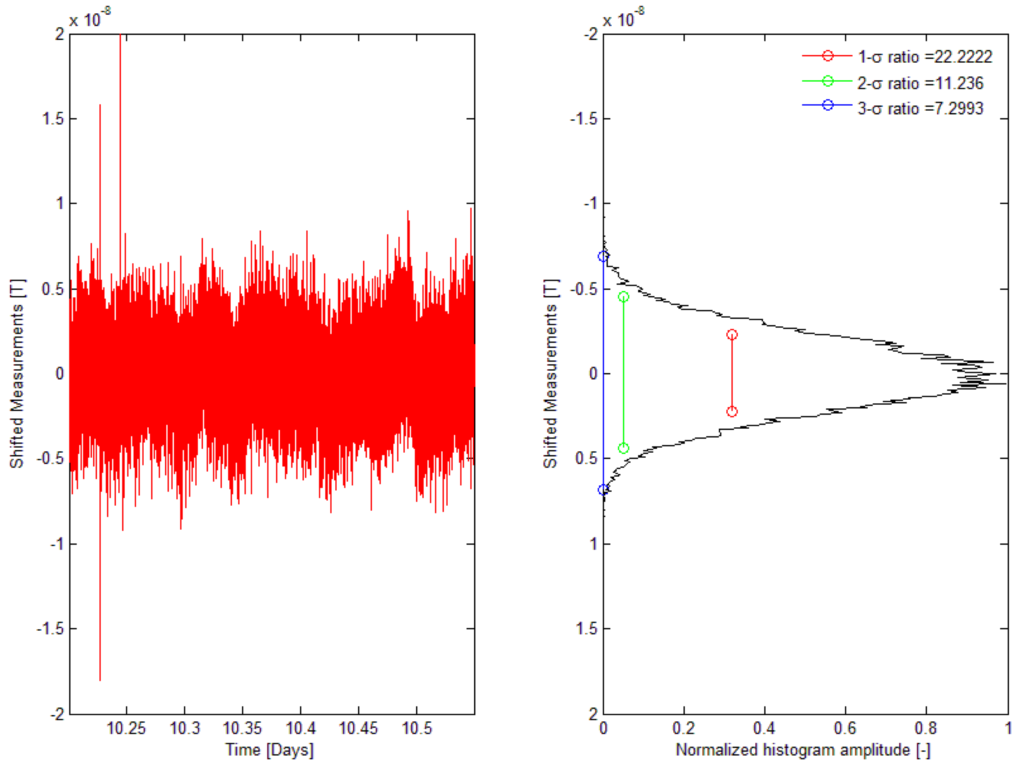


Figure 8 PT2026 histogram and standard deviations

6 Future work

The analysis of the collected data is far from being complete, the discrete value of the PT2025 tends to create a bias in the comparison results as the value are the same over a long period of time. Moreover, as it can be seen on the figure 1., the measurements provided by the PT2026 is wandering and change dramatically sometime. A correlation seems apparent between the measurements made by the PT2025 and those made by the PT2026 leading our comprehension of this phenomenon to be related to external factors, not only to the instrument. This still must be proven. We have plans for a new set of measurement campaigns during which we will use several instruments and several probes in a highly stable MRI-type magnet and compare all the results to determine which part of this variation can be affected to external phenomenon (elevators, metallic masses moving around the MRI magnet, etc) and which part is imputable to some sort of 1/f noise.

If, during the reading of this small report, it occurred to you that you have some measurements or analysis principle ideas, please share them with us, we will try to incorporate them in this report which is meant to evolve.

It will be augmented to provide actual figures determining the true resolution of our NMR magnetometer.

7 Acknowledgements

Metrolab Technology SA would like to thank the Clinique Générale Beaulieu for granting access to their 3 [T] MRI magnet during the retrofitting work of their control room.

8 References

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