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PERFIDI Filters: A Summary

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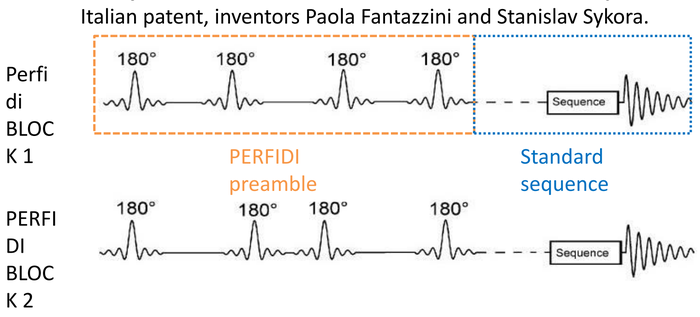
Abstract

In the field of Nuclear Magnetic Resonance, the capability to distinguish or filter the signals of different parts of a sample plays a key role in many applications. For example, in the medical field, such a possibility allows to improve the image contrast and the identification of the different tissues inside the human body. In oil and gas petrology, the characterization of different saturating reservoir fluids permits a better optimized exploitation [1, 2]. Regarding T1 filtering, literature reports many sequences dedicated to signal selection such as Short Time Inversion Recovery and Multiple Inversion Recovery [3], but usually these techniques allow the selection of only a discrete number of T1 values at which the signal is to be suppressed.
Parametrically Enabled Relaxation Filters with Double and Multiple Inversion [4, 5, 6] (PERFIDI) is an innovative technique which implements T_1 filters but, in contrast to standard selective sequences, it allows to filter the signal associated with a selected range of T_1 values. PERFIDI filters, de facto, act somewhat like electronic band-pass, low-pass and high-pass filters. They have been developed and tested in both Nuclear Magnetic Resonance Relaxometry and in Magnetic Resonance Imaging.
Here we present a summary of this innovative filter technique, up to this point of its development, describing the validation of the method and the application to different kind of samples, all characterized by a continuous T_1 distribution, such as biological tissue and oil-water saturated porous media.

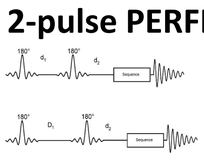
General PERFIDI Filters time scheme

Parametrically Enabled Relaxation Filters with Double and Multiple Inversion
Italian patent, inventors Paola Fantazzini and Stanislav Sykora.



Schema of a PERFIDI filter: combination of PERFIDI block 1 and PERFIDI block 2. The inversion pulses constitute the preamble to the standard sequence (4, 5).

2-pulse PERFIDI FILTERS

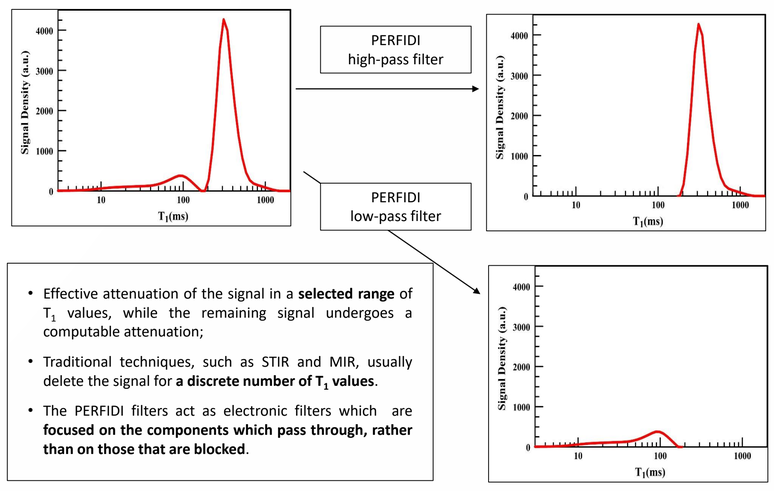


$$F(T_1;d_1,d_2)-F(T_1;D_1,d_2)=$$
$$=\eta(1+\eta)(e^{-\frac{d_1}{T_1}}-e^{-\frac{D_1}{T_1}})e^{-\frac{d_2}{T_1}}$$

- η .... Inverse pulse efficiency, typically between 0.75 and 0.95.
- d_2 .. Optional delay affecting attenuation added to the filter effect.

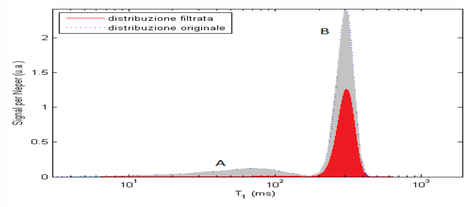
- **High-pass**: d_1 chosen depending on T_1 distribution, $D_1 = \infty$;
- **Low-pass**: $d_1 = 0$, D_1 chosen depending on T_1 distribution.

PERFIDI Filters effect



- Effective attenuation of the signal in a **selected range** of T_1 values, while the remaining signal undergoes a computable attenuation;
- Traditional techniques, such as STIR and MIR, usually delete the signal for **a discrete number of T_1 values**.
- The PERFIDI filters act as electronic filters which are **focused on the components which pass through, rather than on those that are blocked**.

FAST-PERFIDI



- Aquisition of a FID with zero-PERFIDI preamble (i.e. All delay set equal to zero). The extrapolation to zero gives the sum of the two component signal: $S_{ZP}=S_F+S_W$ (F stands for fat and W stands for water);
- High-pass PERFIDI filters: knowing the attenuation of the water peack (TA) due to the filter, the extrapolation to zero gives: $S_{HP}=S_W \cdot TA$;
- In this way it is possible to quantify: $\frac{S_F}{S_W}=\frac{S_{ZP}\cdot TA}{S_{HP}}-1$

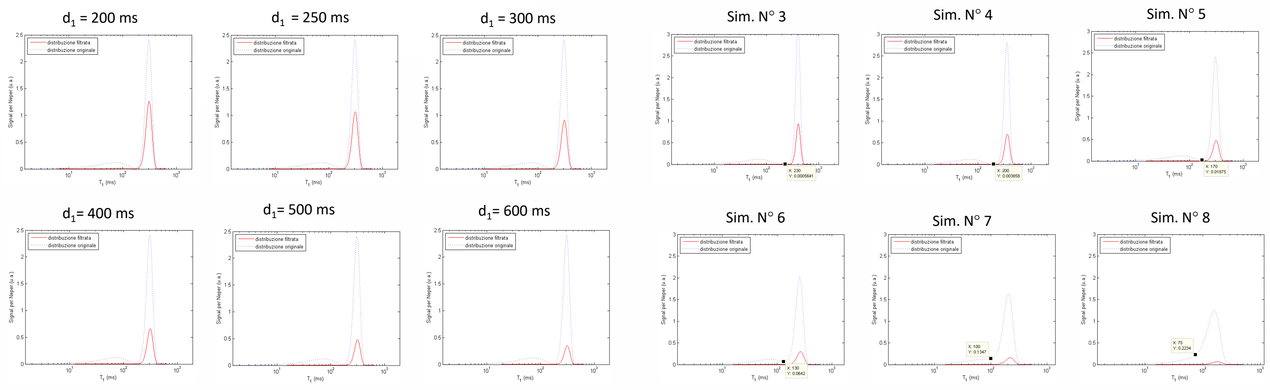
This is true only if in the High-pass PERFIDI filter:

$$d_1 >> T_{1F}$$
$$D_1 >> T_{1F}$$
$$D_1 >> T_{1W}$$

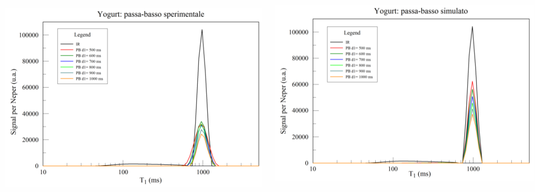
In terms of T_1 disribution:
- S_{ZP} : original distribution area (in gray);
- S_P : high-pass filtered area distribution (in red);
- TA : attenuation peck B (area after/ area ante filter application).

PERFIDI in Relaxometry: theoretical feasibility study and an experimental test

Simulation of PERFIDI effects with respect to the d_1 delay (left three columns) and T_1 peaks distance:



Experimental control:



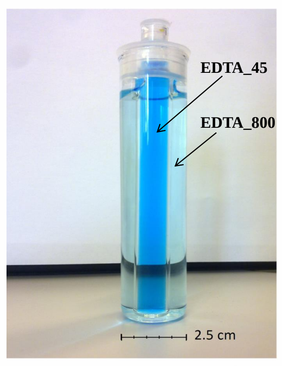
d_1 (ms)	Experimental S_p	Simulated S_p	% difference
500	0.462	0.553	17
600	0.410	0.497	18
700	0.346	0.448	19
800	0.322	0.403	20
900	0.290	0.363	20
1000	0.256	0.327	22

PERFIDI in Relaxometry. Conclusions:

- **The High-pass filter effect:** it is always possible to delete a range of T_1, representing the component 1 of the total signal, but at the same time it results in an excessive attenuation of the component 2;
- **FAST-PERFIDI:** good results as much as the T_1 distribution pecks are distinguishable;
- The difference between the simulation results and the experimental ones reach 20%.

PERFIDI in Imaging. Application on a system model and the protocol:

1. The model system and the tomograph:

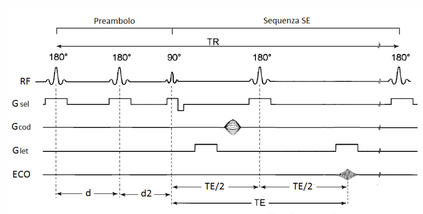


Above: Two concentric tubes filled with two aqueous solution of EDTA: EDTA_45 (T_1=45 ms, T_2= 43 ms) EDTA_800 (T_1=800 ms, T_2= 755 ms)

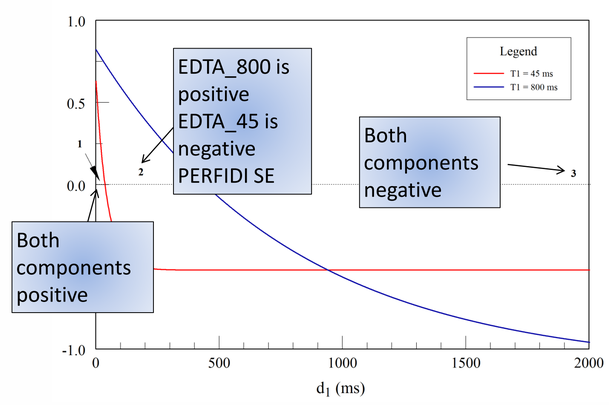
Above: the concentric tubes inside the reciever coil: transversal view.

Below: ARTOSCAN 0.2 T/8 MHz MRI tomograph (ESAOTE)

2. The sequence PERFIDI-SE and its equation:



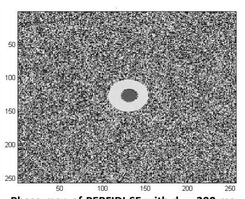
$$M_y(T_R;d;d_2;T_E)=M_\infty[1+(1-2e^{-\frac{T_E/2}{T_1}})e^{-\frac{T_R}{T_1}}+2(e^{-\frac{d}{T_1}}-1)e^{-\frac{d_2}{T_1}}]e^{-\frac{T_E}{T_2}}$$



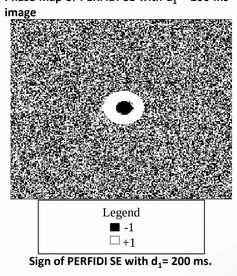
3. PERFIDI Filter procedure:

- Acquisition of PERFIDI SE and PERFIDI OFFSET images;
- Restoration of the signal sign pixel by pixel (by processing the raw data);
- Linear combination of the PERFIDI SE and of the OFFSET images:

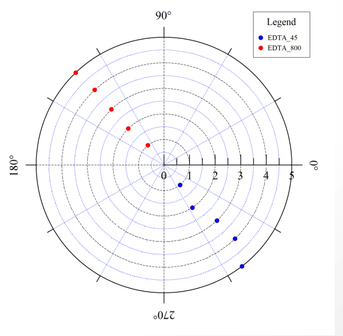
PERFIDI high-pass = PERFIDI SE image – PERFIDI OFFSET image;
PERFIDI low-pass = – (PERFIDI SE image + PERFIDI OFFSET image)



Phase map of PERFIDI SE with d_1 = 200 ms image



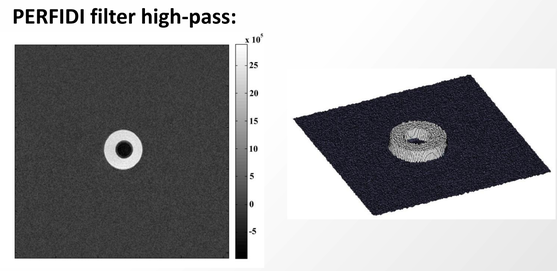
Sign of PERFIDI SE with d_1= 200 ms.



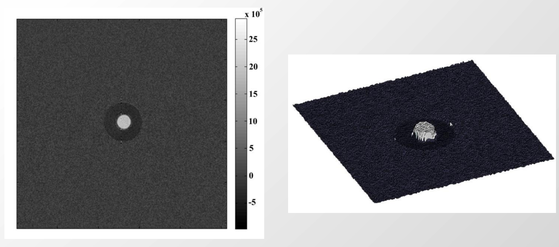
Goniometric plot of the phase being from 10 selected pixel of PERFIDI_200 phase map: 5 in correspond to EDTA_45 and 5 correspond to EDTA_800. As predicted by the model they are in phase opposition.

4. Results:

PERFIDI filter high-pass:



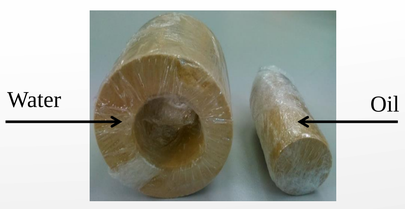
PERFIDI filter low-pass:

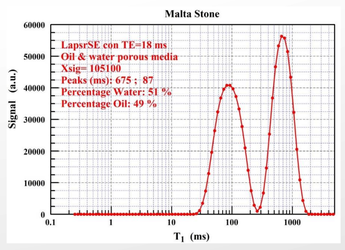


The application of PERFIDI filters on a synthetic two-component sample produced the expected results.
The PERFIDI high-pass and the low-pass filters, acting on components with given T_1 relaxation time distributions, have produced high contrast images.

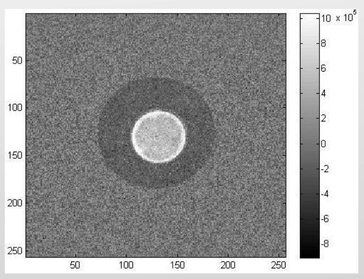
PERFIDI in Imaging: application on porous media phantoms

1. Malta stone:
Two concentric core have been obtained from a cylindrical sample. The inner core has been filled with Soltrol oil, which is characterized, inside the pore space, by a T_1 distribution centered around 700 ms. The outer core has been filled with water, which, inside the pore space, shows a T_1 distribution centered around 70-80 ms.
In this way it has been possible to obtain a wide T_1 distribution sample.

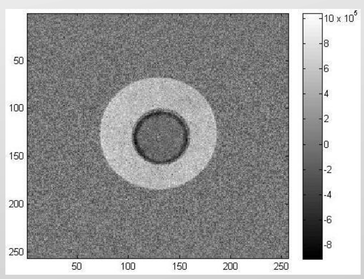




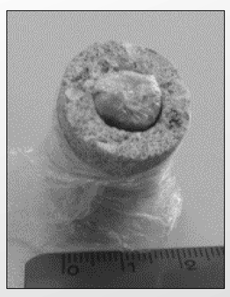
PERFIDI filter high-pass:

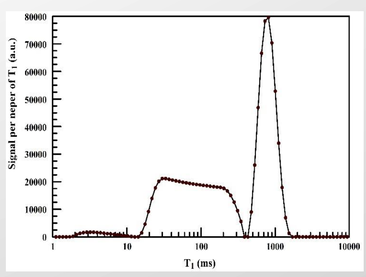


PERFIDI filter low-pass:

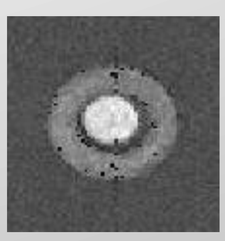


2. Vicenza stone:
Outer core: 20 mm diameter; 30 mm height, saturated with pure water, T_1= 800 ms;
Inner core: 8 mm diameter; 30 mm height, saturated with Soltrol oil 170, T_1= 70 ms.

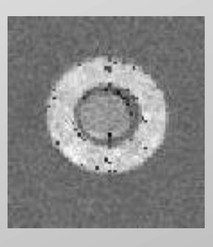




PERFIDI filter high-pass:

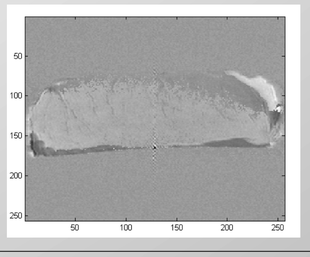


PERFIDI filter low-pass:

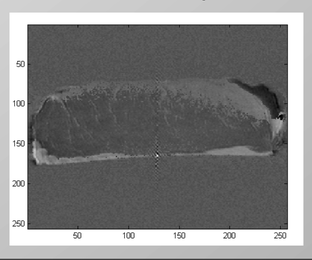


PERFIDI in Imaging: preliminary results on a biological tissue (pork loins) [7]

PERFIDI filter high-pass:



PERFIDI filter low-pass:



Conclusions:

- The application of PERFIDI filter sequences, combined with the use of the PERFIDI sequence mathematical model, on a two-component model sample, produced the expected results.
- The use of the MRI PERFIDI sequences on a sample with a wide T_1 distribution, such as an oil-water saturated porous media sample, has shown that these T_1 filtering techniques can effectively be used on samples characterized by continuous distributions of T_1 showing, for example, the spatial distribution of the fluids.
- The next steps of the research will be the reduction of the measurement time and the enhancement of the image contrast.

References

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Notes:
- Image processing made using Matlab;
- Relaxation measurement are made using a a full size coil by Stelar (Mede, Italy);
- Relaxation T_1 distribution elaborated using the UPEN algorithm [8].

Future work:

Apply PERFIDI in NMR Spectroscopy!!!