Leonardo Brizi, Physics and Astronomy Department, University of Bologna, Bologna, Italy

Low-Field Nuclear Magnetic Resonance Fingerprinting aided by Artificial Intelligence

PROOF OF CONCEPT

PON Seminars - April 21, 2023
Workshop on Food Quality Analysis with Time Domain NMR and AI-Driven Mathematical Models

Overview

- Why Nuclear Magnetic Resonance Relaxometry?
- What is Magnetic Resonance Fingerprint (MRF) technique?
- Why Artificial Intelligence?
- Low-field MRF relaxometry Framework
  - The approach
  - Proof of concept
- Conclusions

Why NMR Relaxometry?

Composition and internal structure of diary products

e.g. Quality: pH Viscosity Water holding Oxidation Matrix…

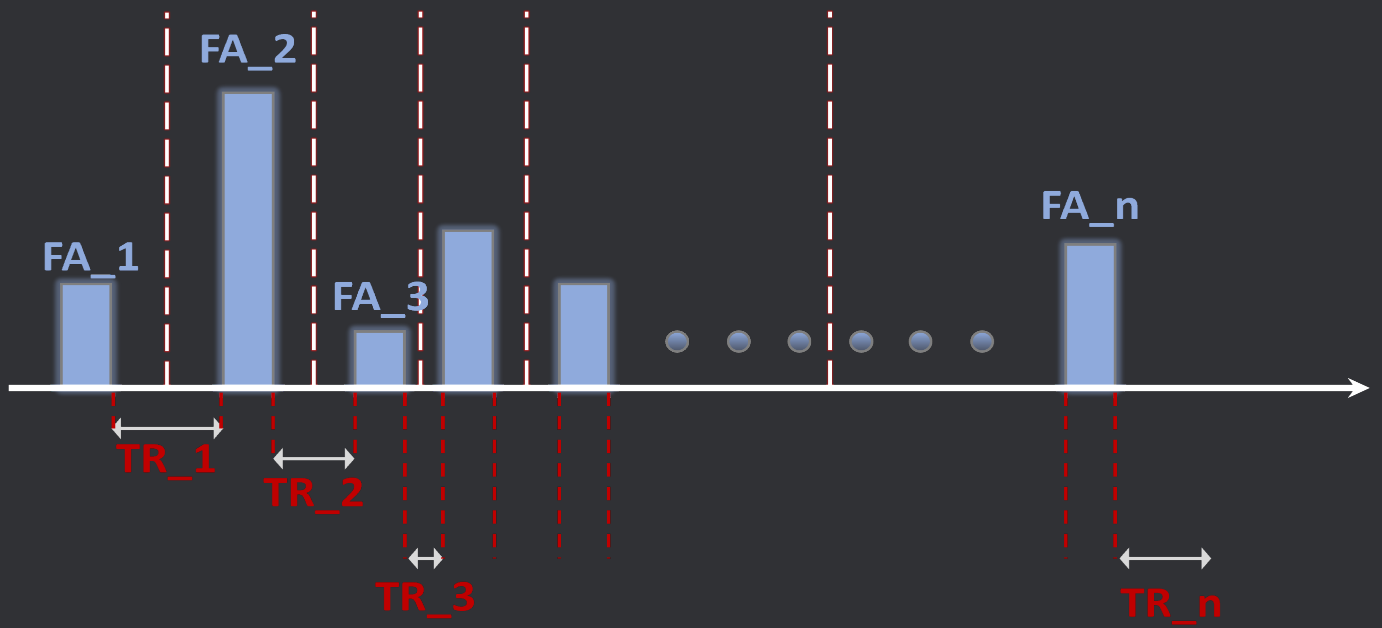
can be characterized by

NMR relaxometry parameters …

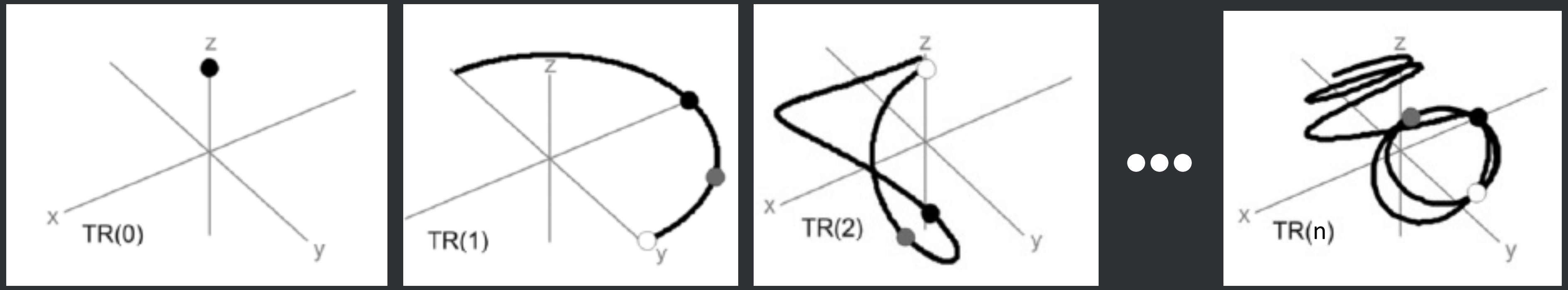
T_1 T_2 D Solid/Liquid Ratio …

What is Magnetic Resonance Fingerprint (MRF) technique?

RF Pulse Sequence

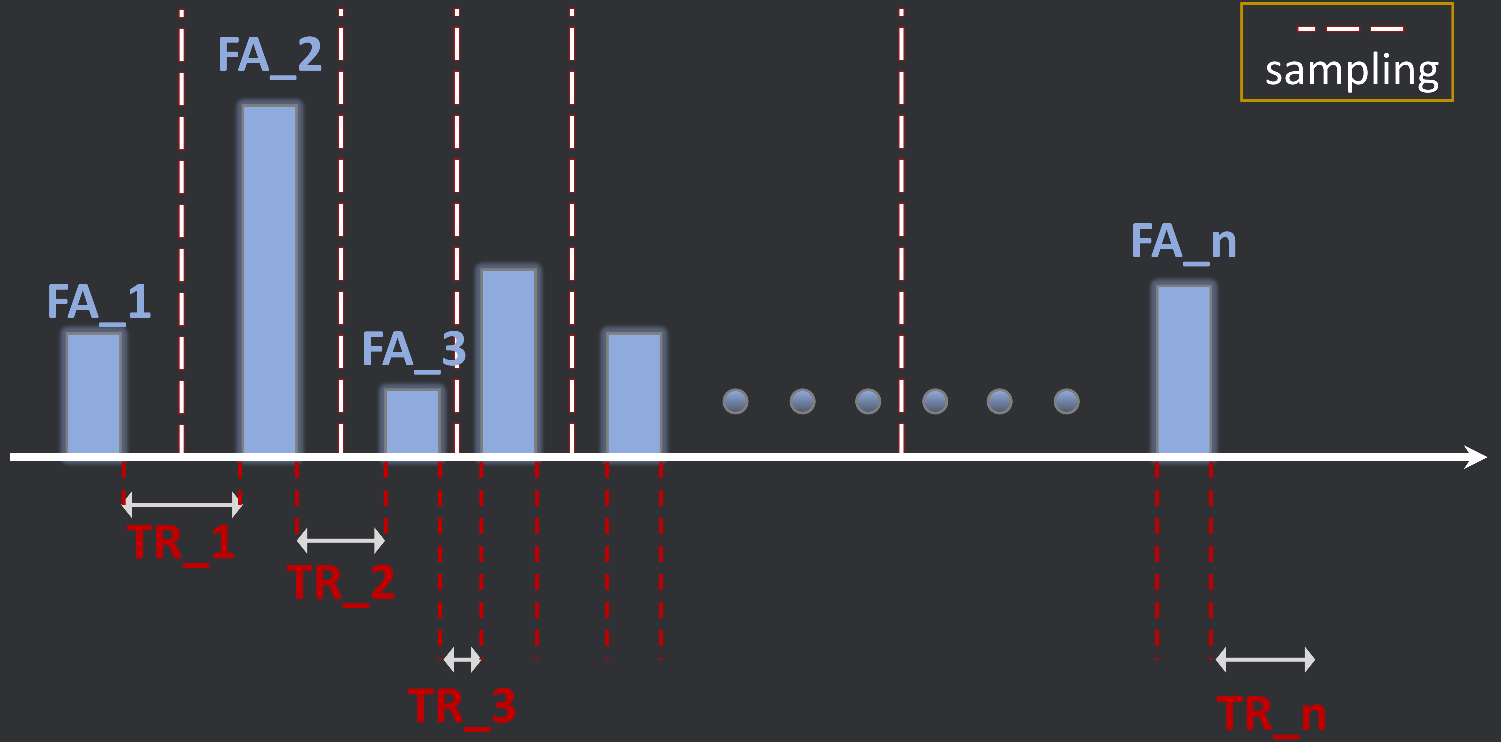


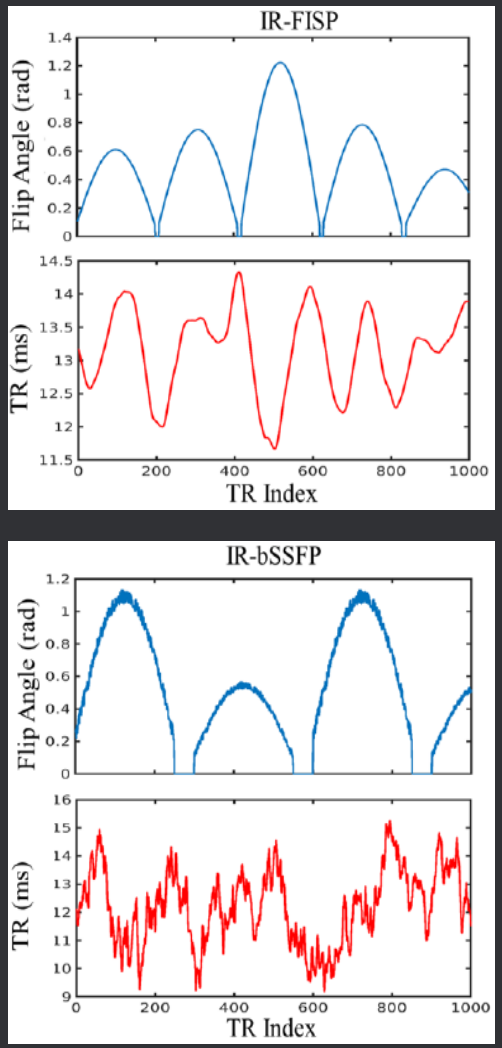
Bulk Magnetization evolution



Magnetic Resonance Fingerprinting - Sequence design

RF pulses: flip angle (FA) and repetition time (TR) vary according to a pattern designed to make the magnetization evolution sensitive to several MR parameters simultaneously.

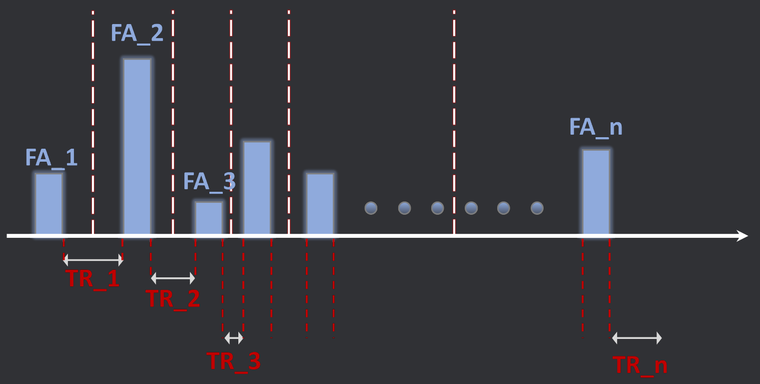




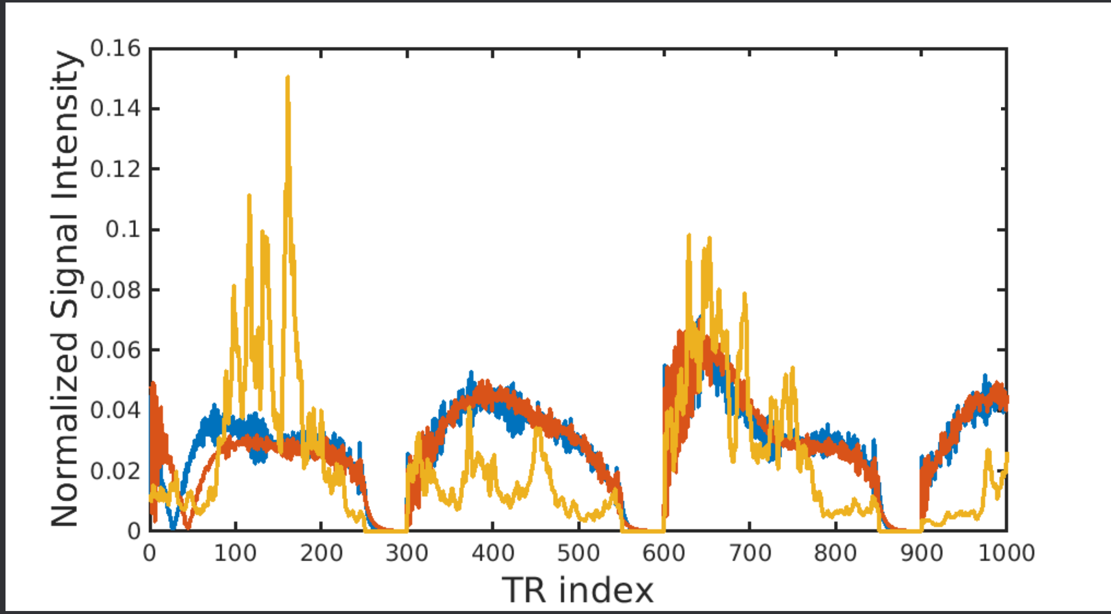
Examples of Flip Angle (FA) and Repetition Time (TR) of MR Fingerprint sequences

Magnetic Resonance Fingerprinting approach to MR parameter mapping

RF Pulse Sequence

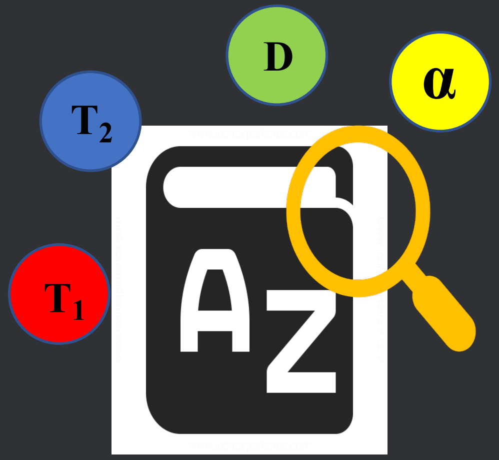


NMR Signal



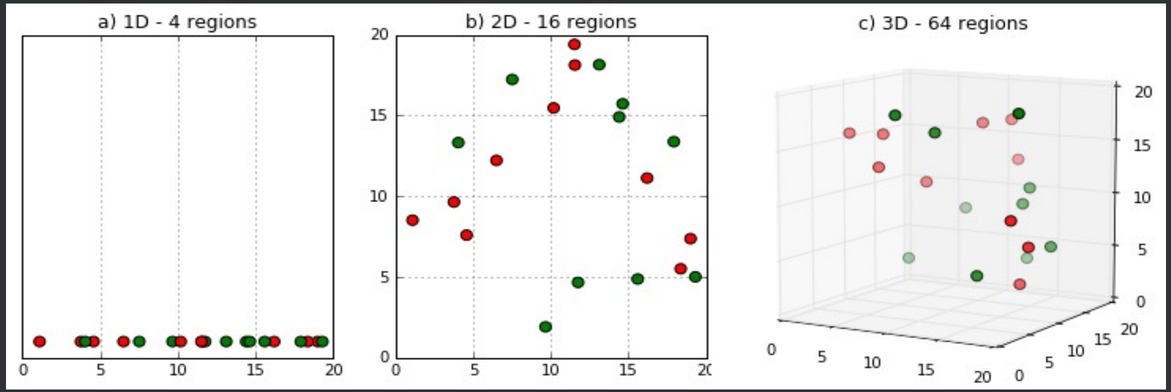
Examples of Fingerprint Signals varying T_1,T_2 parameters

Parameters estimation

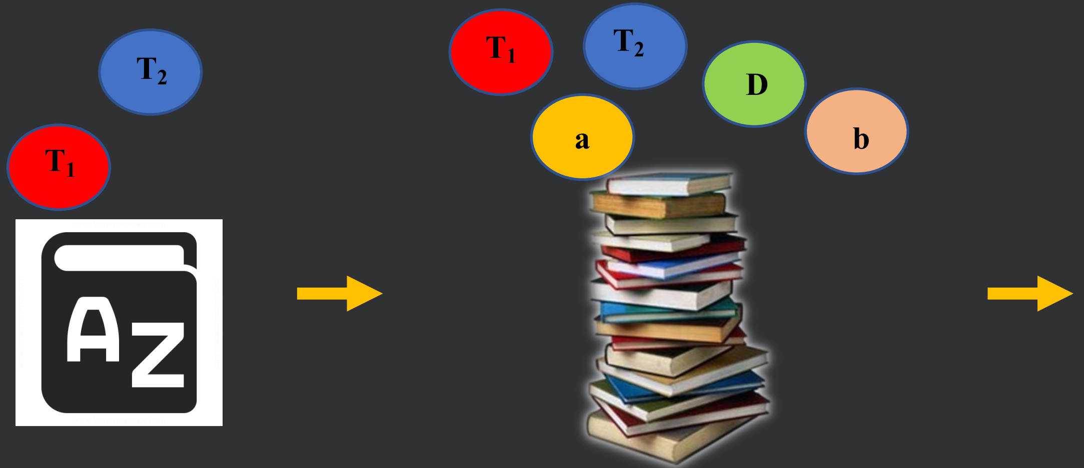


Simulating a dictionary with possible evolutions given a set of NMR parameters

Circumventing The Curse of Dimensionality in Magnetic Resonance Fingerprinting with Deep Learning

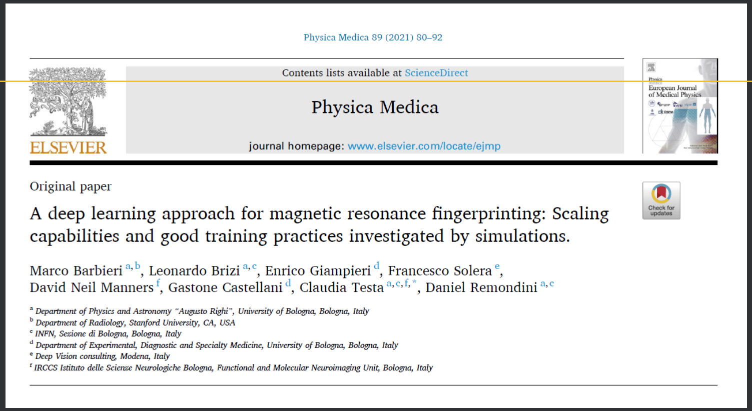


The curse of dimensionality



Memory inefficiency and computational burden limit the scalability of MRF

The more parameters are added the bigger the dictionary becomes if no drops in accuracy is wanted.



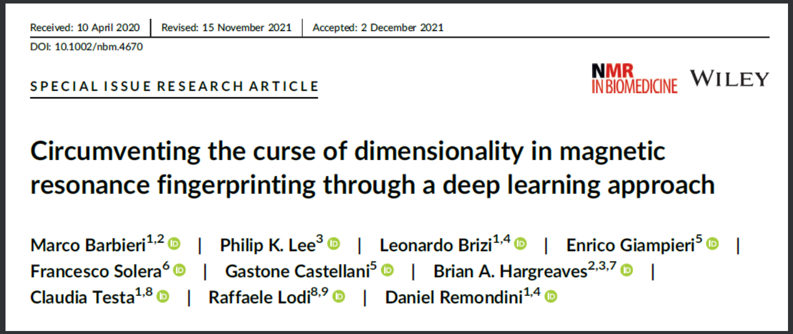
Physica Medica 89 (2021) 80–92
Contents lists available at ScienceDirect
Physica Medica
journal homepage: www.elsevier.com/locate/ejmp

Original paper

A deep learning approach for magnetic resonance fingerprinting: Scaling capabilities and good training practices investigated by simulations.

Marco Barbieri [a,b], Leonardo Brizi [a,c], Enrico Giampieri [d], Francesco Solera [e], David Neil Manners [f], Gastone Castellani [d], Claudia Testa [a,c,f,*], Daniel Remondini [a,c]

[a] Department of Physics and Astronomy "Augusto Righi", University of Bologna, Bologna, Italy
[b] Department of Radiology, Stanford University, CA, USA
[c] INFN, Sezione di Bologna, Bologna, Italy
[d] Department of Experimental, Diagnostic and Specialty Medicine, University of Bologna, Bologna, Italy
[e] Deep Vision consulting, Modena, Italy
[f] IRCCS Istituto delle Scienze Neurologiche Bologna, Functional and Molecular Neuroimaging Unit, Bologna, Italy



Received: 10 April 2020 | Revised: 15 November 2021 | Accepted: 2 December 2021
DOI: 10.1002/nbm.4670

SPECIAL ISSUE RESEARCH ARTICLE

NMR IN BIOMEDICINE WILEY

Circumventing the curse of dimensionality in magnetic resonance fingerprinting through a deep learning approach

Marco Barbieri [1,2] | Philip K. Lee [3] | Leonardo Brizi [1,4] | Enrico Giampieri [5] | Francesco Solera [6] | Gastone Castellani [5] | Brian A. Hargreaves [2,3,7] | Claudia Testa [1,8] | Raffaele Lodi [8,9] | Daniel Remondini [1,4]

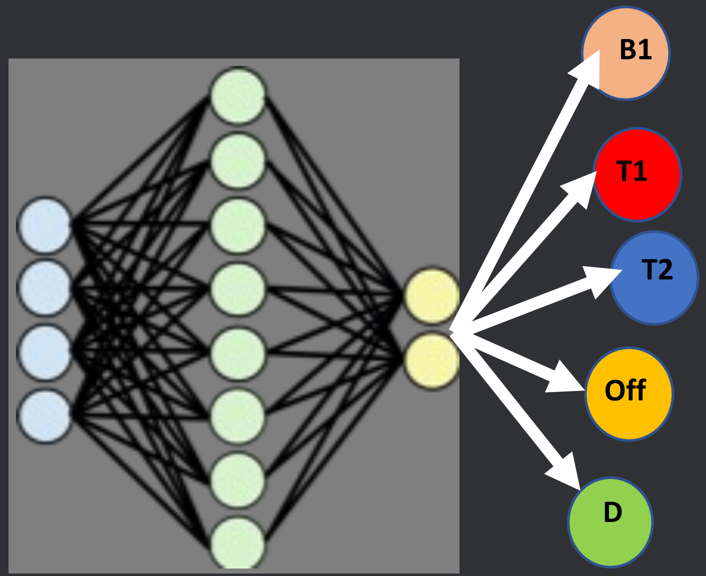
Barbieri, M., Brizi, L., ...Testa, C., Remondini, D. A deep learning approach for magnetic resonance fingerprinting: Scaling capabilities and good training practices investigated by simulations. Physica Medica, 2021, 89,80–92.
Barbieri M, Lee Philip K, Brizi L, et al. Circumventing the Curse of Dimensionality in Magnetic Resonance Fingerprinting through a Deep Learning Approach. NMR in Biomedicine, 2022, 35(4), e4670.

Circumventing The Curse of Dimensionality in Magnetic Resonance Fingerprinting with Deep Learning

Circumventing the curse of dimensionality

We can train
a Neural Network
to retrieve MR parameters
given the MRF signal as input

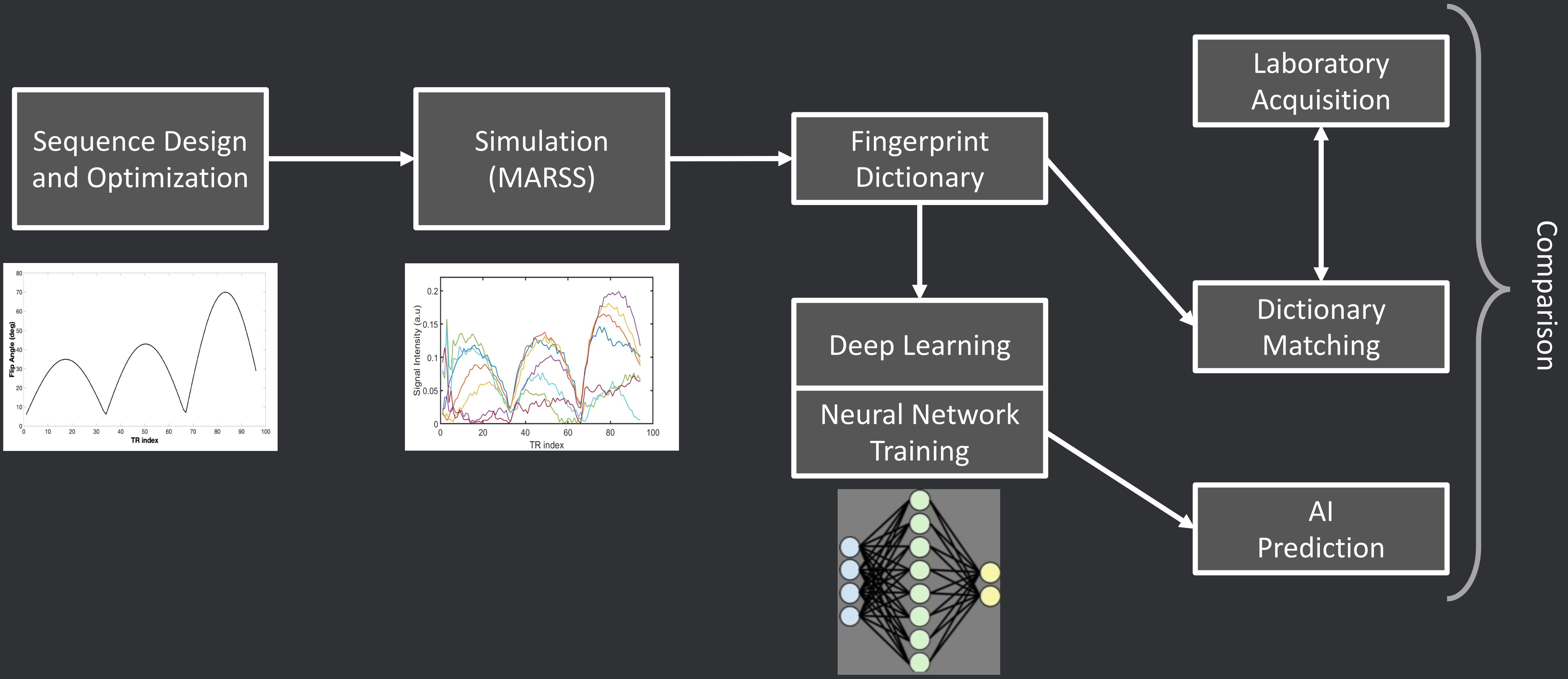
Experimental Signal →



→ **Adding parameters to be retrieved does not affect processing time.**

Barbieri, M., Brizi, L., ...Testa, C., Remondini, D. A deep learning approach for magnetic resonance fingerprinting: Scaling capabilities and good training practices investigated by simulations. Physica Medica, 2021, 89,80–92.
Barbieri M, Lee Philip K, Brizi L, et al. Circumventing the Curse of Dimensionality in Magnetic Resonance Fingerprinting through a Deep Learning Approach. NMR in Biomedicine, 2022, 35(4), e4670.

Low-Field NMR Fingerprinting aided by Artificial Intelligence



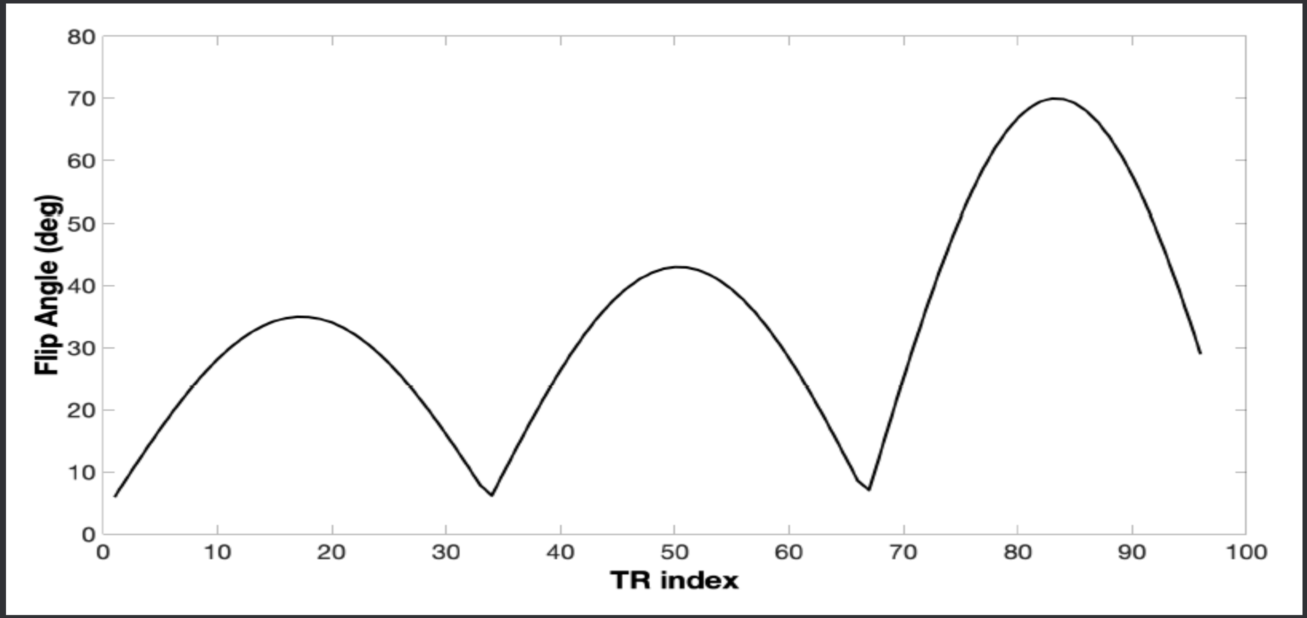
Low-Field NMR Fingerprinting aided by Artificial Intelligence

Sequence Design

Time between pulses (TR) → fixed at 1 ms

Acquisition Time → fixed at the half of TR

Filp Angle Pattern (FISP-like)



MARSS[1,2] (MAgnetic Resonance Simulation Software)

INPUT

Sample

T1

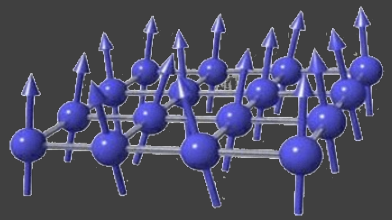
T2

Hardware

B0

B1

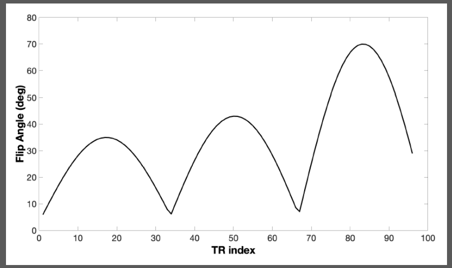
Spin system



PROCESSING

Pulse Sequence (TX)

FA	Flip Angles
TR	Timing
RD	Reptition Time



Spin system evolution → Block Equations

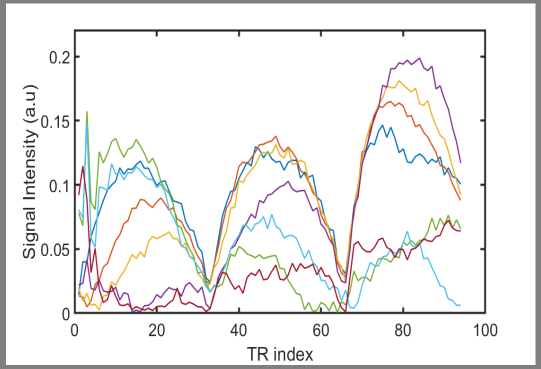
OUTPUT

Hardware (RX)

Sampling

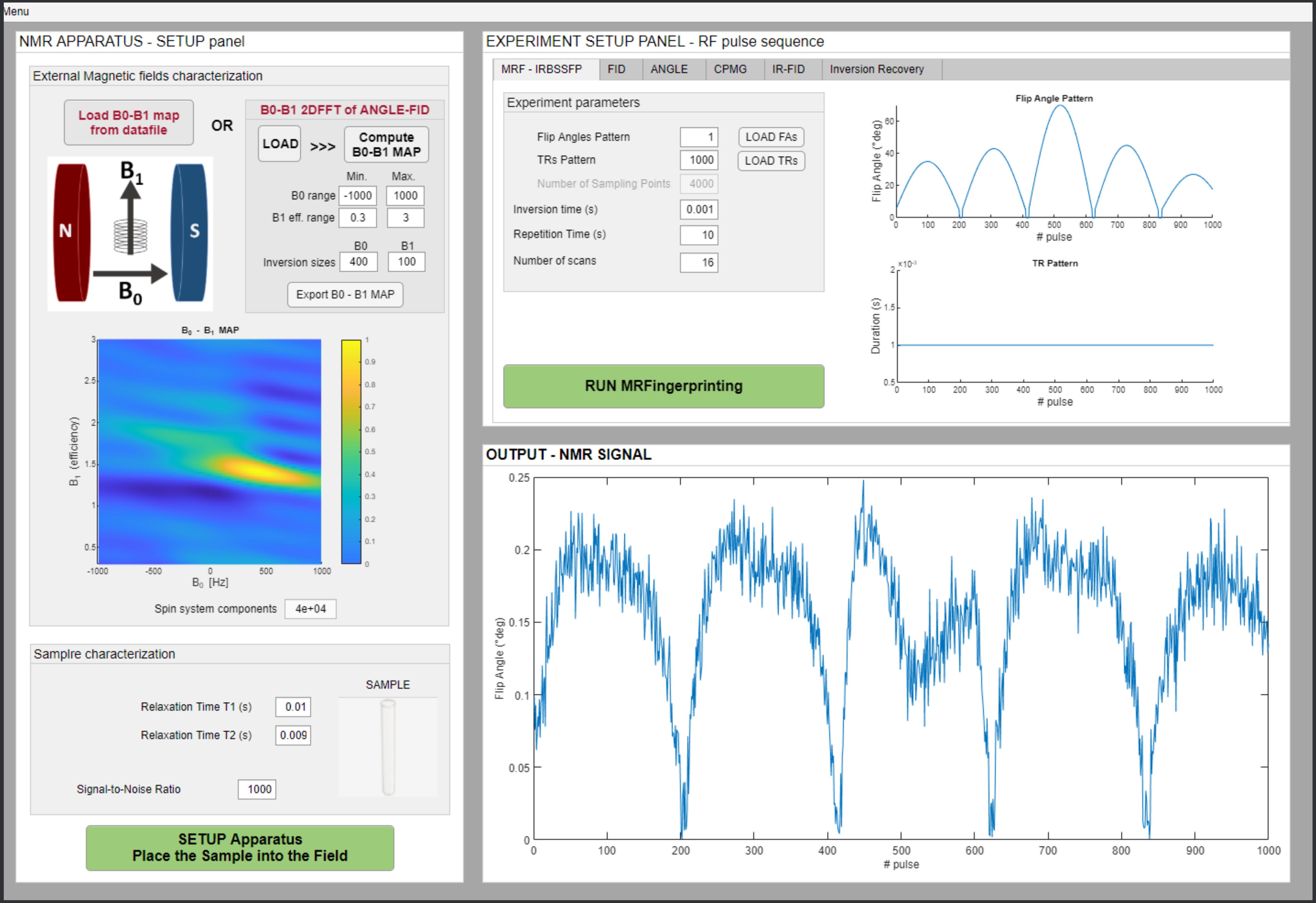
Acq. Channels

Noise



1) “MR Fingerprinting for partial volume fractions quantification: A simulation study”, 103° Congresso Nazionale SIF, Trento, 11-15 sept 2017.

2) “Quantification of partial voxel volume fraction in a two-component system with a short T2 component: a UTE-MR Fingerprinting simulation study”, 8° Congress AIRMM - Italian Chapter ISMRM, Gaeta, 8-9 june 2017.


Menu
NMR APPARATUS - SETUP panel
External Magnetic fields characterization
Load B0-B1 map from datafile
OR
B0-B1 2DFFT of ANGLE-FID
LOAD
>>>
Compute B0-B1 MAP
Min.
Max.
B0 range
-1000
1000
B1 eff. range
0.3
3
B0
B1
Inversion sizes
400
100
Export B0 - B1 MAP
N
S
B1
B0
B0 - B1 MAP
B1 (efficiency)
B0 [Hz]
Spin system components
4e+04
Samplre characterization
SAMPLE
Relaxation Time T1 (s)
0.01
Relaxation Time T2 (s)
0.009
Signal-to-Noise Ratio
1000
SETUP Apparatus
Place the Sample into the Field
EXPERIMENT SETUP PANEL - RF pulse sequence
MRF - IRBSSFP
FID
ANGLE
CPMG
IR-FID
Inversion Recovery
Experiment parameters
Flip Angles Pattern
1
LOAD FAs
TRs Pattern
1000
LOAD TRs
Number of Sampling Points
4000
Inversion time (s)
0.001
Repetition Time (s)
10
Number of scans
16
RUN MRFingerprinting
Flip Angle Pattern
Flip Angle (°deg)
pulse
TR Pattern
Duration (s)
pulse
OUTPUT - NMR SIGNAL
Flip Angle (°deg)
pulse

Low-Field NMR Fingerprinting aided by Artificial Intelligence

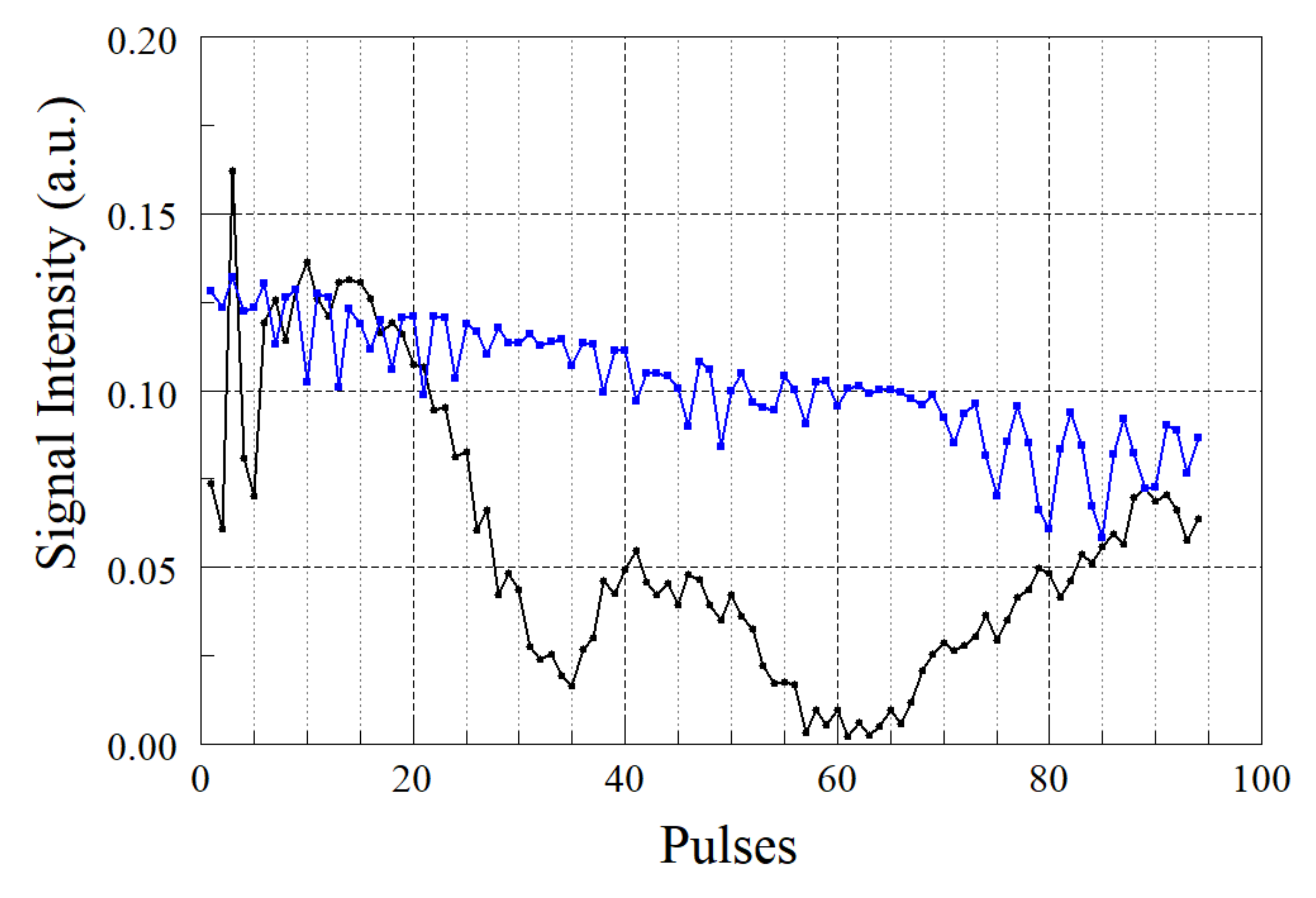
Early challenging results…

Acquired Signal

Known T1,T2

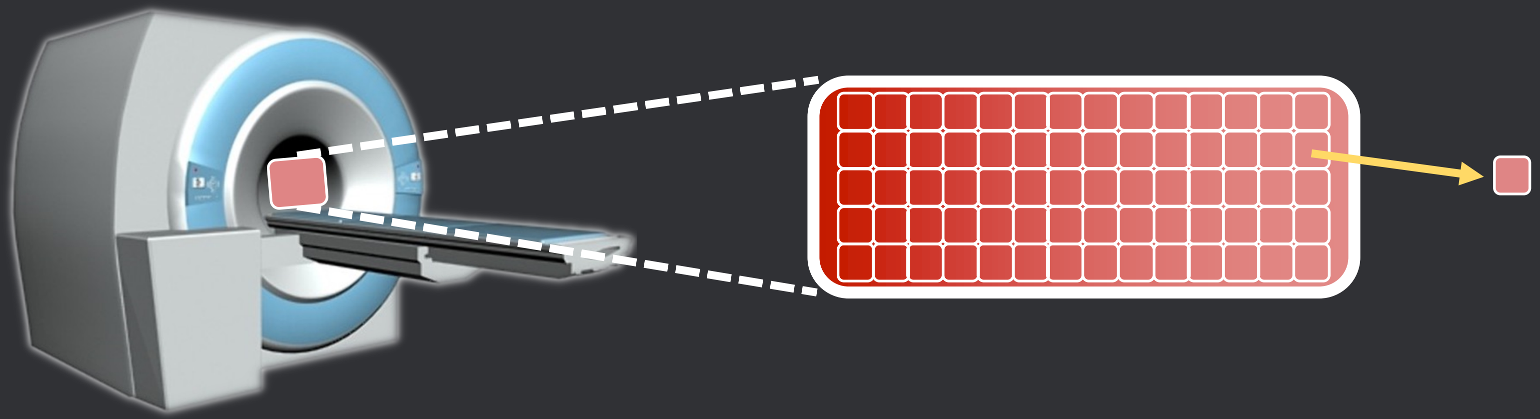
Simulated Signal with known T1,T2

(using single B_0-B_1)



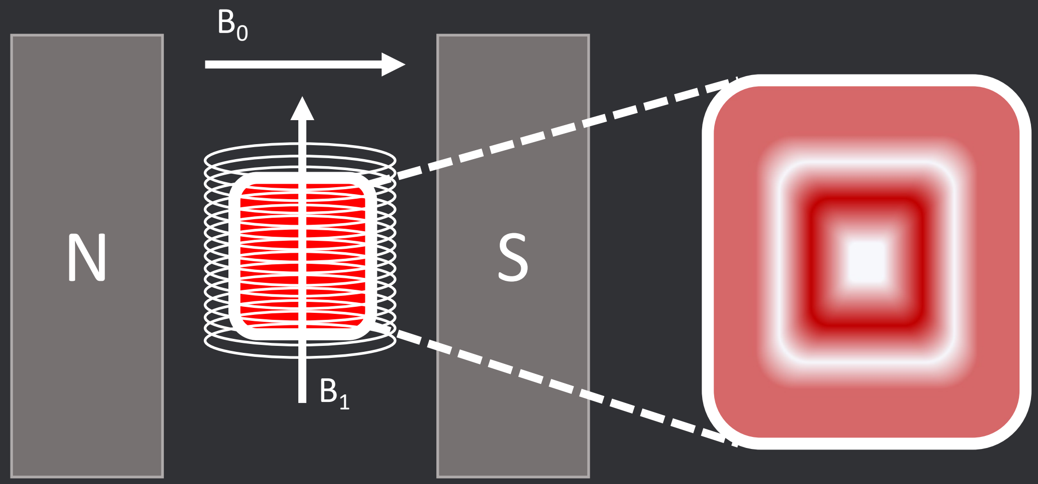
Low-Field NMR Fingerprinting aided by Artificial Intelligence

MRI APPARATUS



B_0-B_1 can be considered homogeneous within each voxel

LOW-FIELD NMR APPARATUS



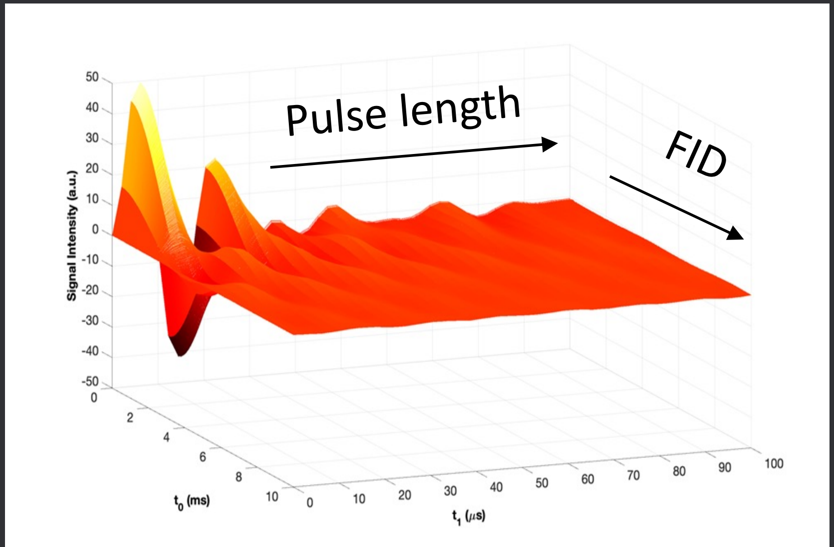
SPINS <u>DO NOT</u> EXPERIENCE HOMOGENEOUS B_0 AND B_1

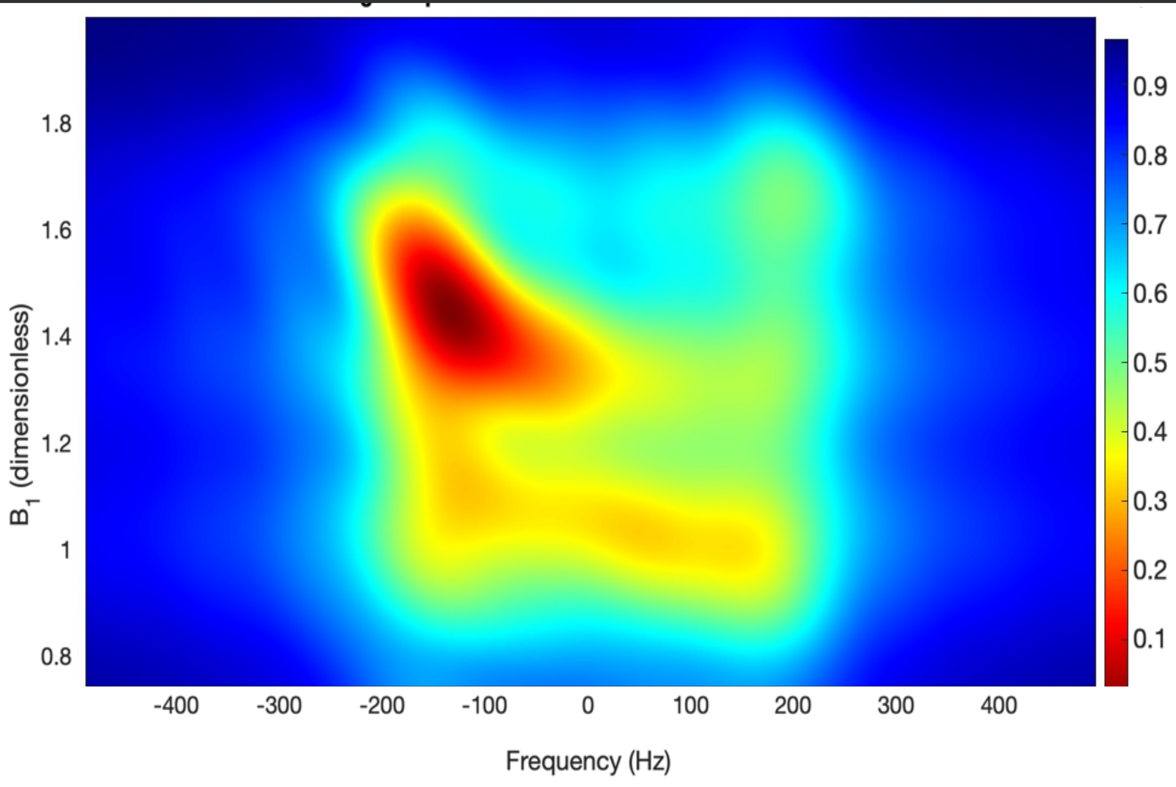
Characterization of B_0-B_1 correlation function

2D FFT

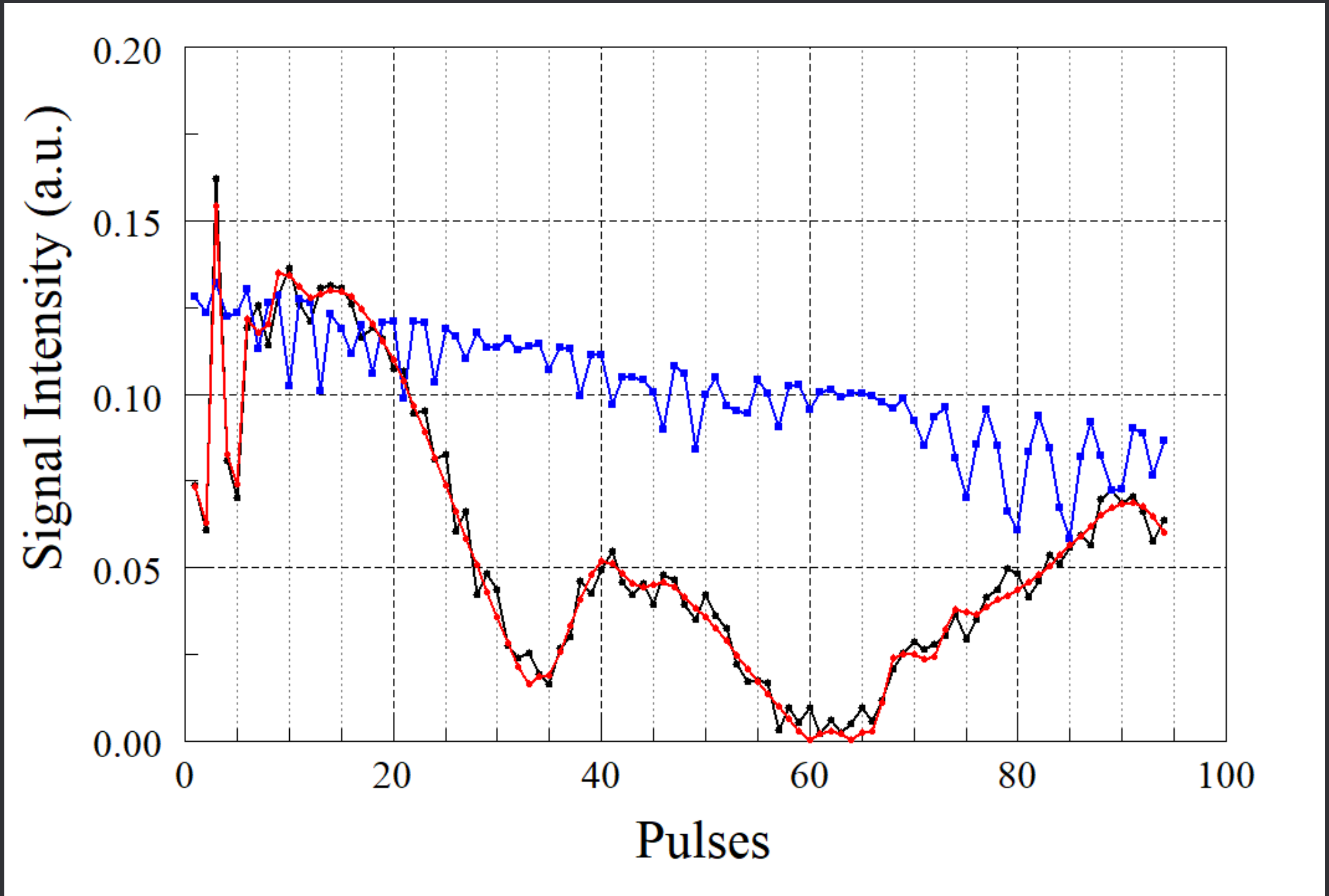
$$S(t_0, t_1) = \int \int P(\omega_0, \omega_1) \sin(\omega_1 t_1)\, e^{(i\Delta\omega_0 t_0)}\, d\omega_0 d\omega_1$$

$$P(\omega_0, \omega_1)$$





Low-Field NMR Fingerprinting aided by Artificial Intelligence



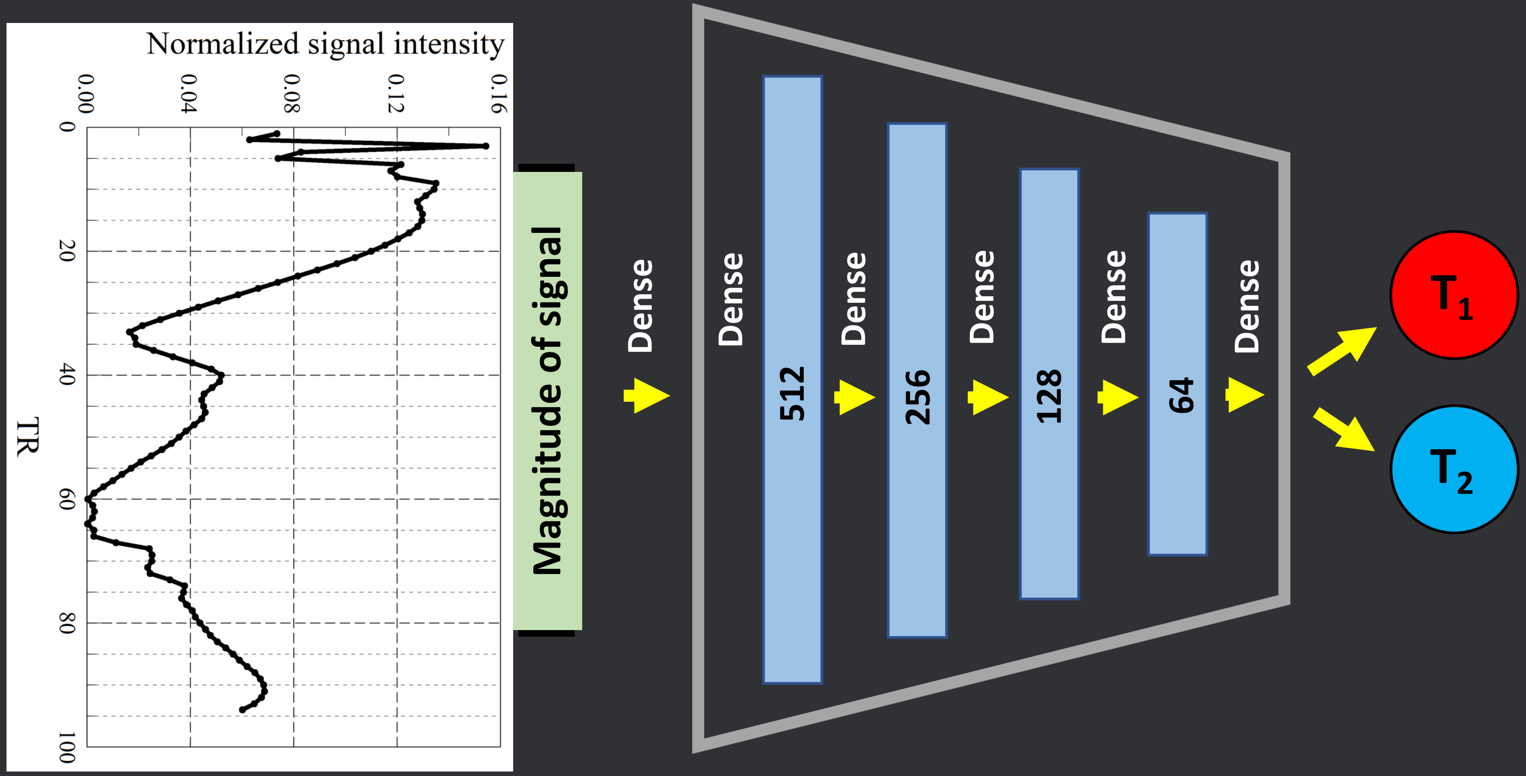
Acquired Signal

Simulated Signal (using single B_0-B_1)

Simulated Signal (using B_0-B_1 distribution)

Low-Field NMR Fingerprinting aided by Artificial Intelligence

Fully Connected Neural Network design



Feed Forward Net - 5 fully connected layers

Rectified Linear Unit (ReLU) as the activation function for the neurons in the first 4 layers

Linear activation function was chosen for the output layer

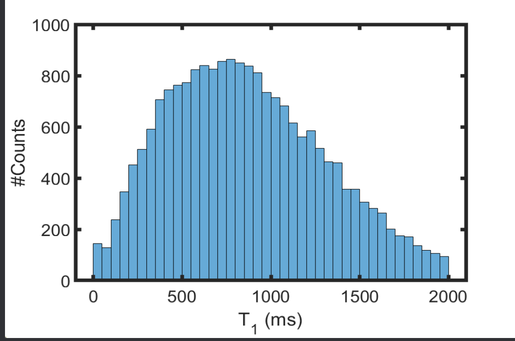
Low-Field NMR Fingerprinting aided by Artificial Intelligence

Training strategy

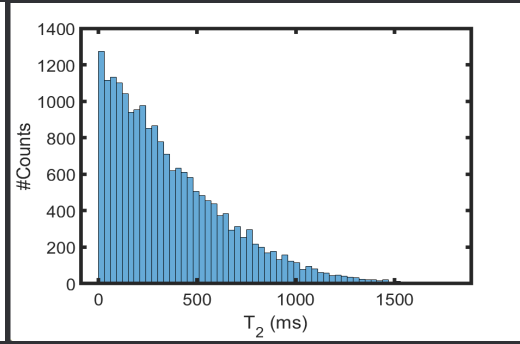
Training with MARSS synthetic data

20’000 (T1, T2) pairs

T1 (ms)

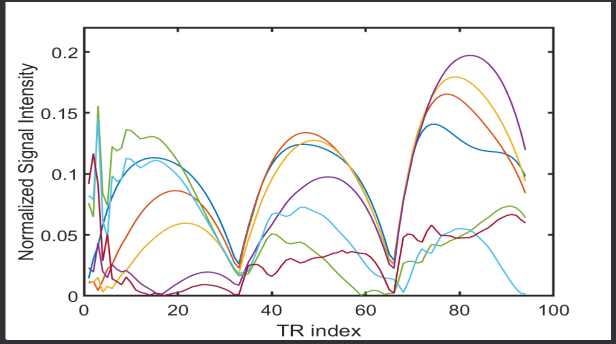


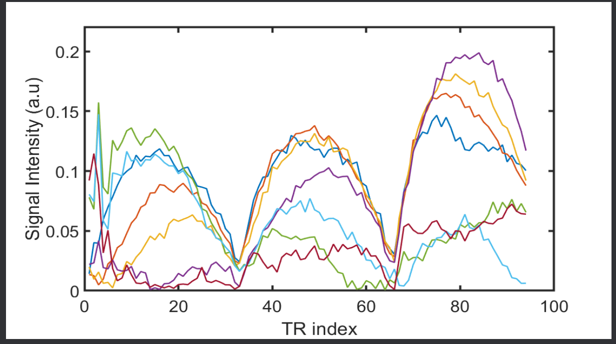
T2 (ms)



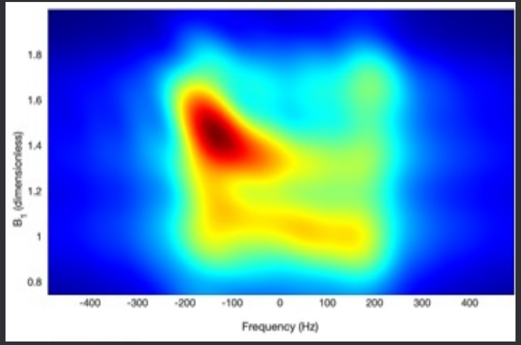
+

Noise Addition
(white additive Gaussian)





B0-B1 Correlation function (84 x 320 MAP)

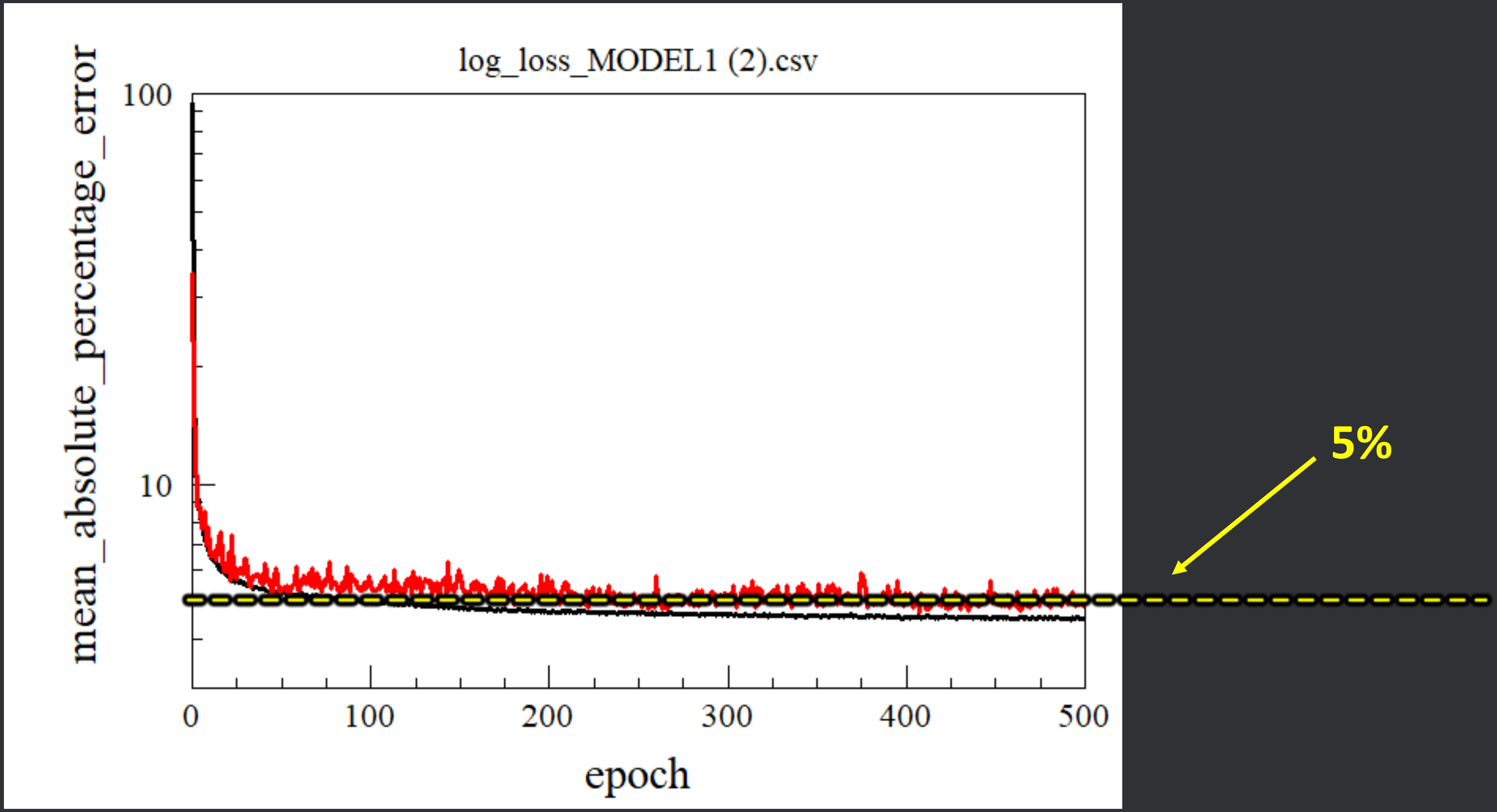


~3s for 1 simulation (standard PC)
26880 spin components

Spin System

~ 2.5 hours for whole dataset generation

training loss / validation loss



Experimental

H2O + CuEDTA

Sample	T1 (ms)	T2 (ms)
CE_1	2.2	1.9
CE_2	12.3	10.4
CE_3	24.1	20.2
CE_4	78.9	66.3
CE_5	301	251
CE_6	729	613
CE_7	1510	1270

Electromagnet JEOL C60 (B_0=500 mT)

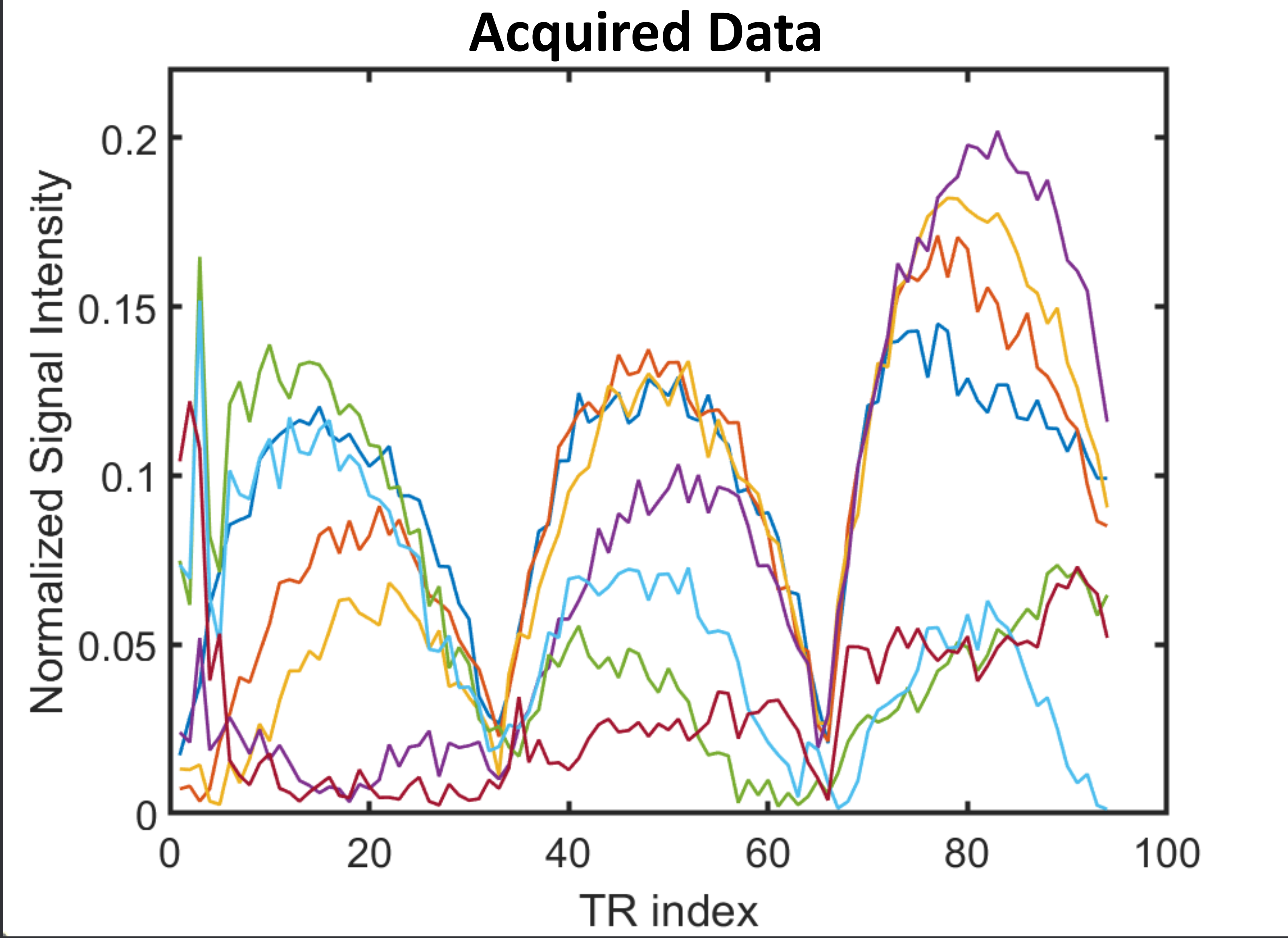
Spectrometer KEAII (Magritek, NZ)

n° of pulses = 95

64 scans

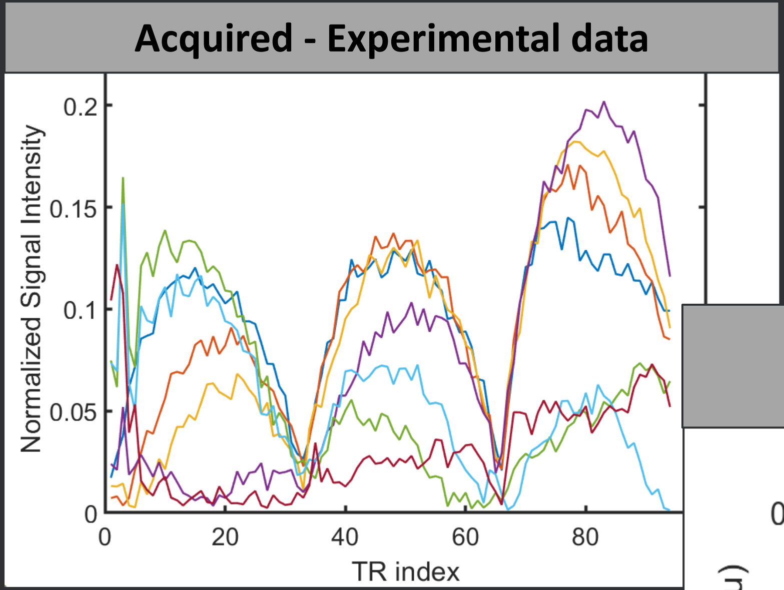
TR fixed at 1 ms

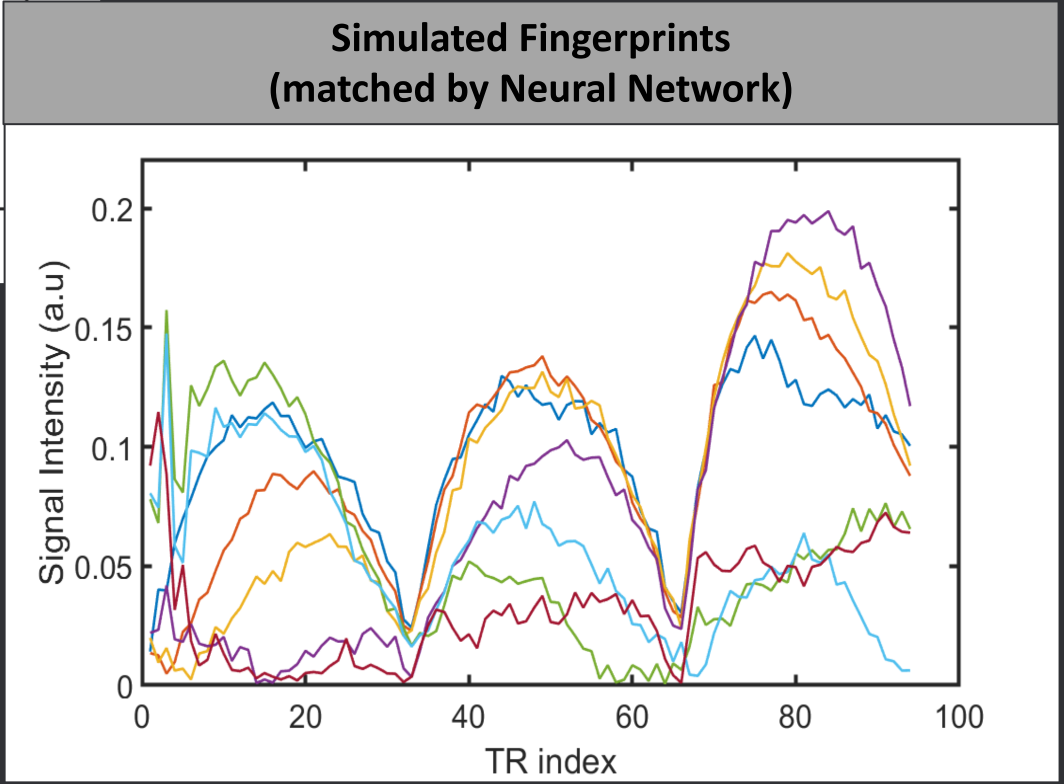
~ 2.5 minutes per fingerprint



Low-Field NMR Fingerprinting aided by Artificial Intelligence

Data Analysis: Dictionary Matching Vs Neural Network Prediction





T2 Ground	T2 Dict.	T2 NN
1.83	2.00	1.94
10.4	11.0	9.0
20.2	22.0	20.0
66.3	60.0	64.8
251	148	273
613	520	532
1270	1240	1190

T1 Ground	T1 Dict.	T1 NN
2.15	2.00	2.22
12.3	12.0	12.1
24.1	22.0	21.4
78.9	81.0	79.6
301	300	306
730	720	713
1510	1460	1476

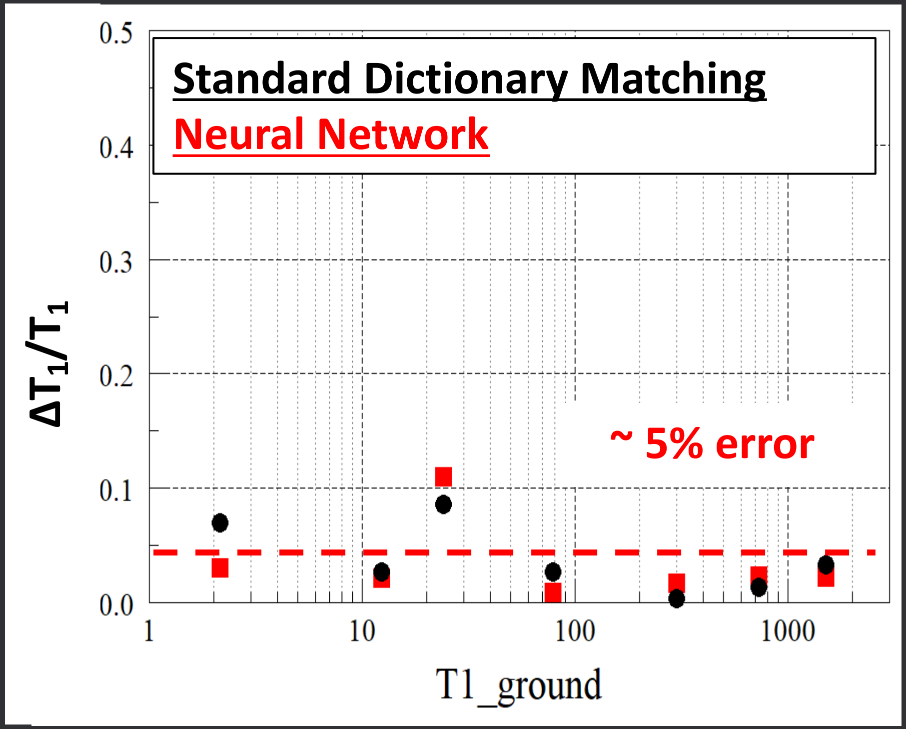
Data values in ms

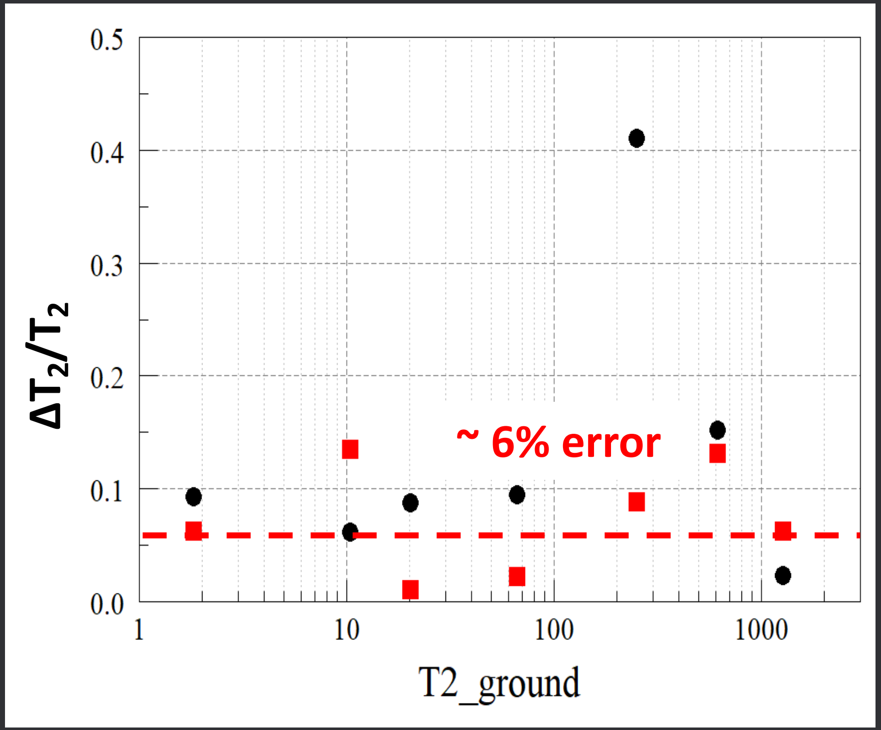
Low-Field NMR Fingerprinting aided by Artificial Intelligence

Data Analysis: Dictionary Matching Vs Neural Network Prediction

T1 Ground	T1 Dict.	T1 NN
2.15	2.00	2.22
12.3	12.0	12.1
24.1	22.0	21.4
78.9	81.0	79.6
301	300	306
730	720	713
1510	1460	1476
T2 Ground	**T2 Dict.**	**T2 NN**
1.83	2.00	1.94
10.4	11.0	9.0
20.2	22.0	20.0
66.3	60.0	64.8
251	148	273
613	520	532
1270	1240	1190

Data values in ms





CONCLUSIONS

Magnetic Resonance Fingerprinting was demonstrated for low-field Relaxometry devices

Characterization of B_0-B_1 correlation function of the system is requested

A fully connected Neural Network was establish to fasten the matching process, achiving the same performance of the standard method

Fast Relaxometry multi-parameter measurements can be performed

Low-field Magnetic Resonance Fingerprint

Further Development

Gain Sensitivity to NMR Parameters

Increase the number of encoded Parameters

Extend to multi-components

Self characterization of the hardware ($B_0 – B_1$)

Translation to

- Single-sided NMR (Compact and Portable devices)
- Fast Field Cycling (FFC)

Sequence Design and Optimization

Faster and more Accurate simulation

Neural Network

About diary products / companies

Portable, low-cost and low-maintainance devices (Low-field)

Fasten the acquisition
(real-time in the production line?)

Automatize for specific applications
(not user dependent)

Authors have collaborated to presented studies about NMR Fingerprinting

ALMA MATER STUDIORUM A.D. 1088
UNIVERSITÀ DI BOLOGNA

Claudia Testa
Paola Fantazzini
Villiam Bortolotti
Daniel Remondini
Marco Barbieri
Giovanni Spinelli
Anastasiia Nagmutinova

Stanford MEDICINE | Radiology

Marco Barbieri
Brian A. Hargreaves
Philip K. Lee

Thanks for your attention

Contacts and useful links

PERSONAL: leonardo.brizi2@unibo.it
https://www.unibo.it/sitoweb/leonardo.brizi2/en
https://www.researchgate.net/profile/Leonardo_Brizi

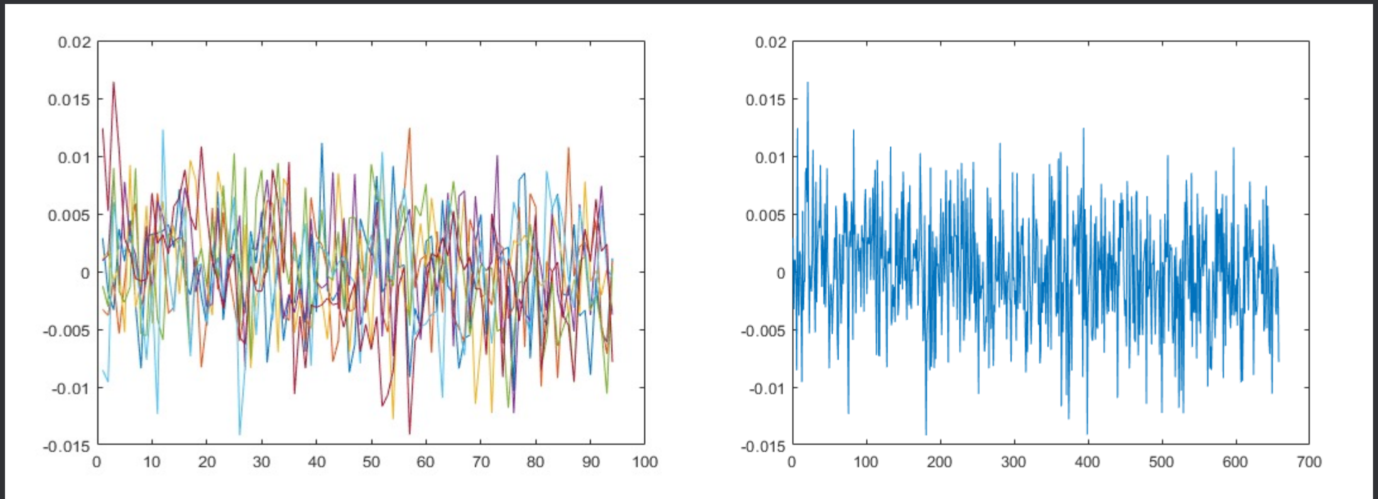
DICTIONARY

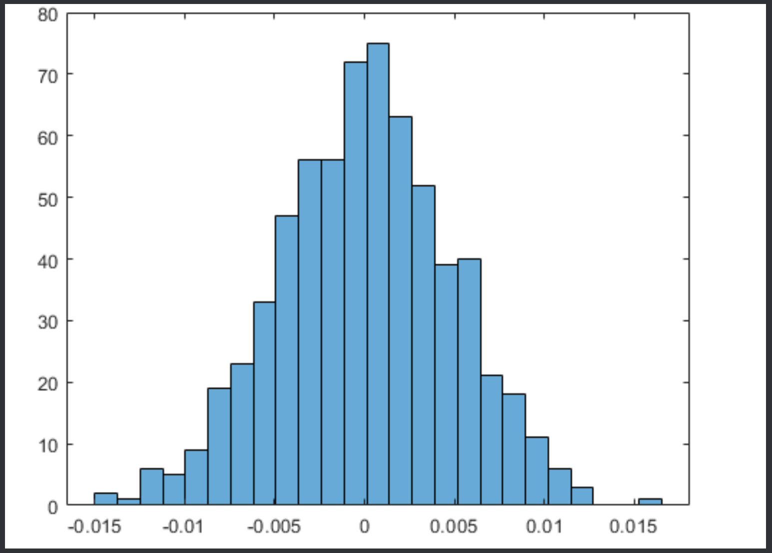
GRID sampling

	T1 (ms)	T2 (ms)	
DICTIONARY	[2 ÷ 200]* [201 ÷ 2000]**	[2 ÷ 200]* [201 ÷ 2000]**	**20000 entries**

**) T_1 and T_2 were incremented with steps of 1 ms;*
***) T_1 and T_2 were incremented with steps of 20 ms.*

Residuals ~ Noise → Single noise sequence → Noise ~Gaussian
$\mu = 0$, $\sigma = 0.005$





Physica Medica 89 (2021) 80–92

Contents lists available at ScienceDirect

Physica Medica

journal homepage: www.elsevier.com/locate/ejmp

Original paper

A deep learning approach for magnetic resonance fingerprinting: Scaling capabilities and good training practices investigated by simulations.

Marco Barbieri [a,b], Leonardo Brizi [a,c], Enrico Giampieri [d], Francesco Solera [e], David Neil Manners [f], Gastone Castellani [d], Claudia Testa [a,c,f,*], Daniel Remondini [a,c]

[a] Department of Physics and Astronomy "Augusto Righi", University of Bologna, Bologna, Italy
[b] Department of Radiology, Stanford University, CA, USA
[c] INFN, Sezione di Bologna, Bologna, Italy
[d] Department of Experimental, Diagnostic and Specialty Medicine, University of Bologna, Bologna, Italy
[e] Deep Vision consulting, Modena, Italy
[f] IRCCS Istituto delle Scienze Neurologiche Bologna, Functional and Molecular Neuroimaging Unit, Bologna, Italy

December 2021

NMR IN BIOMEDICINE WILEY

Circumventing the curse of dimensionality in magnetic resonance fingerprinting through a deep learning approach

Marco Barbieri[1,2] | Philip K. Lee[3] | Leonardo Brizi[1,4] | Enrico Giampieri[5] | Francesco Solera[6] | Gastone Castellani[5] | Brian A. Hargreaves[2,3,7] | Claudia Testa[1,8] | Raffaele Lodi[8,9] | Daniel Remondini[1,4]

Received: 18 June 2020 | Revised: 24 November 2020 | Accepted: 24 November 2020

DOI: 10.1002/mrm.28648

FULL PAPER

Magnetic Resonance in Medicine

Single-sided NMR to estimate morphological parameters of the trabecular bone structure

Marco Barbieri[1,2] | Paola Fantazzini[1] | Villiam Bortolotti[3] | Fabio Baruffaldi[4] | Anna Festa[4] | David N. Manners[5] | Claudia Testa[1,6] | Leonardo Brizi[1,6]

[1]Physics and Astronomy Department, University of Bologna, Bologna, Italy
[2]Department of Radiology, Stanford University, Stanford, CA, USA
[3]Department of Civil, Chemical, Environmental, and Materials Engineering, University of Bologna, Bologna, Italy
[4]IRCCS Istituto Ortopedico Rizzoli, Bologna, Italy
[5]Department of Biomedical and Neuromotor Sciences, University of Bologna, Bologna, Italy
[6]National Institute for Nuclear Physics Bologna, Bologna, Italy

FULL PAPER

Magnetic Resonance in Medicine 00:00–00 (2017)

Bone Volume–to–Total Volume Ratio Measured in Trabecular Bone by Single-Sided NMR Devices

Leonardo Brizi,[1,2] Marco Barbieri,[1] Fabio Baruffaldi,[3] Villiam Bortolotti,[4] Chiara Fersini,[3] Huabing Liu,[5] Marcel Nogueira d'Eurydice,[5] Sergei Obruchkov,[5] Fangrong Zong,[5] Petrik Galvosas,[5] and Paola Fantazzini[1,2]*

Purpose: Reduced bone strength is associated with a loss of bone mass, usually evaluated by dual-energy X-ray absorptiometry, although it is known that the bone microstructure also

an impoverishment in the life of elderly people, but also an increase in the costs of health care. Methods to improve the early detection of these diseases are an

ELSEVIER

journal homepage: www.elsevier.com/locate/micromeso

Single-sided NMR for the diagnosis of osteoporosis: Diffusion weighted pulse sequences for the estimation of trabecular bone volume fraction in the presence of muscle tissue

M. Barbieri [a,*], L. Brizi [a,b], V. Bortolotti [c], P. Fantazzini [a,b], M. Nogueira d'Eurydice [d], S. Obruchkov [d], H. Liu [d], P. Galvosas [d]

[a] Department of Physics and Astronomy, University of Bologna, Italy
[b] Centro Fermi-Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi", Roma, Italy
[c] Department DICAM, University of Bologna, Italy
[d] MacDiarmid Institute for Advanced Materials and Nanotechnology, School of Chemical and Physical Sciences, Victoria University of Wellington, New Zealand