User Manual for the TF Measurement System in Curved Trajectory

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User Manual for the TF Measurement System in Curved Trajectory

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Table of Content

This document provides the details of the components and set up of the transfer function (TF) measurement system in curved trajectory [1]-[4]. The goodness of the measurement system in curved trajectory is compared to the typical TF measurement in straight line configuration and the deviation is quantified as the average relative error (ARE) as detailed in the document further below.

The system comprises the following components:

1. A robotic arm with six degrees of freedom - model XArm 6 from UFACTORY (Shenzhen, China)
2. A current sensing probe - model 7713-03, from Pearson Electronics (Palo Alto, CA, USA)
3. A vector network analyzer - model TR1300/1, from Copper Mountain Technologies (Indianapolis, IN, USA)
4. Tank filled with tissue simulant medium – tank size 115 cm x 53 cm x 15 cm: liquid saline with the conductivity level of 0.47 S/m with permittivity ~78 per recommendation by ISO/TS 10974
5. 3D printed lead supports for curved trajectories – 2 mm diameter lead supports printed with PLA filament.
6. A computer system that runs the python code that controls the robotic arm and collects the data for TF measurement.

Measurement Uncertainty of the System:

To quantify the differences in magnitude between the TFs in different trajectories versus the one in a straight configuration, the ARE were evaluated, which is defined as:

$$E_r = \frac{1}{N}\sum_{1}^{N}\frac{|TF_S(i) - TF_C(i)|}{|TF_S(i)|} \times 100,$$

where N is the number of measurement points along the lead trajectory, $TF_c(i)$ and $TF_s(i)$ are the measured magnitudes of TFs from curved trajectories configuration and from the straight configuration, respectively [2].

Averaged Relative Error in measurement (%)			
	Arc	Sinusoidal	U-shape
1.5T	6.69	11.61	9.28
3T	13.26	13.66	16.47

Table 1. Average relative errors (ARE) between measured TFs obtained from three simplified curved trajectories and the measured TF obtained from a straight configuration for a commercial AIMD lead.

Averaged Relative Error in measurement (%)			
	Path 1	Path 2	Path 3
1.5T	9.65	14.56	15.18
3T	11.01	8.84	6.83

Table 2. Averaged relative errors (ARE) between measured TFs obtained from three clinically relevant trajectories and the measured TF obtained from a straight configuration for a commercial lead.

The worst ARE based on the measurements we conducted on a commercial lead was ~16.5% and ~15% for a U-shaped trajectory with 2.5 cm bending radius at 128 MHz and for a clinically relevant trajectory developed by a surgeon at 64 MHz, respectively. The ARE values are less than the % of uncertainty in measuring the TF in straight line configuration which is ~23%. Appendix A below describes the uncertainty calculation of the TF in straight line configuration.

Tool Reference

1. Z. Zuo, Q. Wang, C.Z. Xu, J. Zheng, A. Kumar, W. Kainz, J. Chen, “The Independence of Active Implantable Medical Device (AIMD) Lead Transfer Functions on the Trajectory Shapes”, URSI GASS 2023, Sapporo, Japan, August 2023.
2. Z. Zuo, L. Yang, J. Zheng, Q. Wang, H. Jeong, S. Long, A. Kumar, J. Chen, **“**On the Validity of the AIMD Transfer Function Model Over Different Implantation Trajectories”, IEEE Transactions on Instrumentation and Measurements (August 2024, accepted).

Standard Operating Procedures (SOP) for the Transfer Function Measurement System in Curved Trajectory

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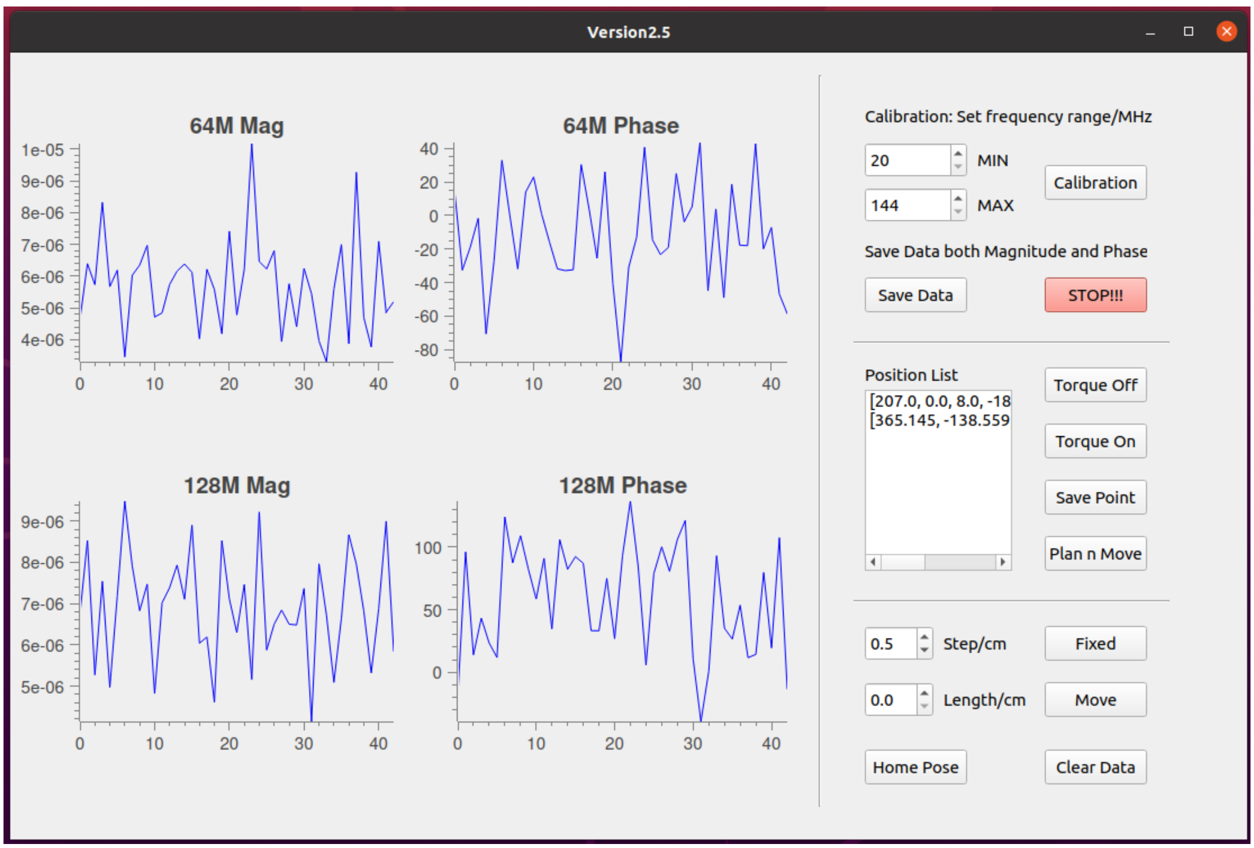
Abbreviations used: VNA – vector network analyzer; AIMD – active implantable medical device; TF- transfer function; SMA – subminiature version A radio frequency (RF) connector; CAD – computer aided design; GUI – graphical user interface.

In this SOP, a step-by-step guide to measure TF for AIMD in arbitrary curved trajectory is presented. Prior to starting the measurement, please follow the installation instructions and install the application. Some buttons are allocated for other functions, so the arbitrary trajectory measurement won't need or cover all the buttons shown in the application's GUI window (version 2.5) below.



Preparation: The whole system setup is described in the manual of the TF measurement system in curved trajectory.

Step 1: VNA calibration. The default measurement range is from 20 MHz to 144 MHz, and the TF data at 64 MHz (1.5T) and 128 MHz (3T) are collected. Connect the automatic calibration kit for copper mountain VNA to the computer while the VNA is connected on the calibration kit in the scattering (S) parameter mode, click the 'calibration' button on the application GUI (version 2.5), then the calibration process is done. After that, reconnect the VNA to the computer.

Step 2: Trajectory preparation. Extract the trajectory coordinates from the CAD modeling software. The input coordinates are relative coordinates, which means the (x,y,z) coordinates start from 0 position.

For example:

#x = [0.00, -0.12, -0.23, -0.35]; #y = [0.00, 4.99, 9.98, 14.97]; #z = [0.00, 0.00, 0.00, 0.00]

These coordinates are from a roughly 15 mm line with a measurement step size of 5 mm. Once you have the coordinates, edit function 'measuretrajectoryide()', and replace the coordinates there with your trajectory data.

To make sure the AIMD lead aligned along the arbitrary trajectory, a 3D printed fixture is often needed. Tie the lead on the fixture and submerge it in the tissue simulant liquid phantom.

Step 3: Robotic arm preparation. The current measurement probe should be fixed at the tip end of the robotic arm and moved near the distal end of the lead. The reciprocity transfer function method is used in the testing environment, thus an excitation from the monopole antenna connected to an SMA connector from port 1 of VNA should be placed at ~2mm distance away from the distal electrode end of the lead; and the distance between the monopole antenna tip and lead electrode won't change during the measurement. Note that antenna tip and lead electrode tip shall not directly contact.

Step 4: Preparation for measurement. Now the system has been setup: the coordinates have been input to the application, the arm is positioned at the tip of the lead, the excitation is placed near the tip of the lead, the AIMD to be tested is submerged in the testing phantom. CLICK the 'plan n move' button to start the measurement process.

Step 5: Measurement. Maintain the position of the AIMD. If any movement unexpectedly happened, click the 'STOP!' button to abort the action.

Step 6: Data collection. After a successful measurement, the data will be plotted on the GUI. You can save the data by clicking 'Save Data' button. Then, the TF data will be named after the time stamp now and saved in the same folder as where the code is.

Step 7: Home position. Click the 'Home pose' button then the arm will return to its predefined home position.

Installation instructions for the Curved Trajectory TF Measurement System Application GUI (version 2.5)

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This document provides installation instructions for the application that provides a graphical interface (GUI) for controlling an XArm robotic system and visualizing data using a PyQt5-based GUI. The application allows you to manage, analyze, and plot data from connected instruments using libraries like NumPy, pandas, and qwt.

The python code and installation instructions can be found at the GitHub page link given below:

GitHub - UHEMCLAB/Robotic-Arm-TF-Measurement-System: Source code and instruction to robotic arm transfer function measurement system developed by Dr. Ji Chen's lab at University of Houston

This code (python code – see 'armsystem.py') has only been tested under ubuntu 20.04 LTS version, it is not guaranteed to operate on any other environment.

Features

- GUI Interface: Built using PyQt5 for intuitive user interaction.

- Data Visualization: Uses Qwt for plotting data (e.g., magnitude and phase plots).

- Robotic Arm Control: Supports control of an XArm robotic system via the `xarm` Python wrapper.

- Instrument Communication: Interacts with instruments through pyVISA.

- Data Handling: Processes and stores data using NumPy and pandas.

Requirements

- A compatible robotic arm, this code is tested on model XArm 6 from UFactory. (https://www.ufactory.cc/product-page/ufactory-xarm-6/)

- A visa-compatible vector network analyzer (VNA), this code is tested on Copper Mountain TR1300 VNA. (https://coppermountaintech.com/vna/tr1300-1-2-port-1-3-ghz-analyzer/)

- Python 3.x. (https://www.python.org/downloads/)

- PyQt5: PyQt5 is a set of Python bindings for the Qt application framework, used for creating graphical user interfaces (GUIs). In this code, PyQt5 is utilized to build the main interface for controlling the robotic arm and visualizing data. It handles the window layouts, buttons, and other user interaction elements. (https://pypi.org/project/PyQt5/)

- Qwt: Qwt (Qt Widgets for Technical Applications) provides widgets for plotting and other scientific purposes. In this code, Qwt is used to create visualizations of TF plots for magnitude, phase. (https://pypi.org/project/PythonQwt/)

- XArm Python SDK: This library is the Python SDK provided by UFactory for controlling their XArm robotic arms. In this code, it provides the necessary functions and interfaces to communicate with and control the XArm 6 robotic arm. It handles tasks like sending commands to move the arm, and monitoring the status of the robot. (https://github.com/xArm-Developer/xArm-Python-SDK)

- pyVISA: pyVISA is a Python library used for communicating with instruments like oscilloscopes, spectrum analyzers, and in this case, vector network analyzers (VNAs). It provides a high-level API to control instruments over various interfaces such as USB, Ethernet, and GPIB. In this project, pyVISA facilitates communication with the Copper Mountain TR1300 VNA, allowing you to send commands and retrieve measurement data. (https://pyvisa.readthedocs.io/en/latest/)

- NumPy: NumPy is a powerful library for numerical computing. It provides support for arrays and matrices, along with a collection of mathematical functions to operate on these data structures. In this code, NumPy is used to handle the numerical data retrieved from the VNA and other instruments, enabling mathematical operations and data processing. (https://numpy.org/install/)

- pandas: pandas is a data manipulation library designed to handle and analyze structured data. It is particularly well-suited for operations on tabular data (e.g., CSV files). In this code, pandas is used to manage data logs, process the measured data from the instruments, and organize it for further analysis and visualization. (https://pandas.pydata.org/getting_started.html)

Installation

Step 1: Set up the linux environment and python running environment. Connect both VNA and robotic arm to linux environment. Note that, in the testing environment, VNA is connected via USB, and robotic arm is connected via LAN. Extra permission on mounted devices may be needed to allow the code read and write data to Devices. The devices' name or address in this code may need yo change to allow the code find the devices.

Step 2: install the dependencies, like PyQt5, qwt, xarm sdk, pyvisa, numpy, pandas.

Step 3: Use any python compiler, VS code is recommended for it's easy to use. import this code to VS code. Once all dependencies are installed, you can run the application. This will launch the graphical interface, allowing you to interact with the robotic system and visualize the data.

Troubleshooting

If you encounter issues related to dependencies, ensure that all required libraries are installed and that your environment is properly configured. You can also try reinstalling the dependencies. You can also refer to the devices' programming guides.

Appendix A
Uncertainty assessment for heating TF development

1. Introduction

This document provides the uncertainty assessment for the heating transfer function development. The uncertainty process evaluation follows ISO/TS 10974 Ed. 1 Annex R. According to this document, the result of a measurement *y* is a function of *N* parameters x_1, x_2, …,x_N,. The combined standard uncertainty $u_c(y)$ can be derived from individual uncertainty components $u(x_i)$. The total uncertainty can be calculated from root sum square of the uncertainty of the individual components

$$u_c(y) = \sqrt{\sum_{i=0}^{N} c_i^2 \cdot u^2(x_i)} \quad (1)$$

In this formula c_i is the sensitivity coefficient calculated by $\partial y/\partial x$. $u(x_i)$ is the standard deviation of each term and $u_c(y)$ is the combined uncertainty.

The uncertainty sources in our test case can be categorized into two parts:

A. Uncertainty from the transfer function development

The uncertainty of the TF development comes from simulation or measurement errors in a) TF shape measurement, b) electromagnetic modeling of incident field, and c) TF scaling factor estimation from phantom measurement. Therefore, it comes from the following parts:

1. Uncertainty of TF shape measurement
2. Uncertainty of Modeling
3. Uncertainty of Electrical equipment readout
4. Uncertainty of measurement in RF coil

B. Uncertainty from validation measurement

The error of validation measurements comes from the tests of induced heating of different device-lead combination along different lead paths. Therefore, the error comes from the following:

1. Uncertainty of Modeling
2. Uncertainty of Electrical equipment readout
3. Uncertainty of measurement in RF coil

2. Individual uncertainty evaluation

The individual uncertainty can be evaluated in two steps:

A. the calculation of the sensitivity coefficient c_i
B. The evaluation of the standard deviation of each individual term $u(x_i)$.

A. The evaluation of the sensitivity coefficient c_i

The sensitivity coefficients of the phantom position, lead path, phantom medium conductivity and permittivity, grid resolution and transfer function coefficient estimation are estimated. And the result of the target value *T* is the temperature rise in our situation. Incident field of a lead in length of 44 cm is extracted in the simulations to calculate the temperature rise. Therefore, we have

$$T = \left| \iint TF \cdot E_{tan} dl \right|^2 \tag{2}$$

The uncertainty of E-field should be independent from the transfer function of a device. Therefore, it is set to a constant of 10^{-4} without any phase change. The temperature rise at lead tip is the square of the sum of the tangential component of the electric field along the lead. It is assumed the temperature rise during the measurement is a function of the phantom position, lead path, phantom medium conductivity and permittivity and grid resolution. And it is a linear equation when the variation of these parameters is small. The sensitivity coefficient can be written as $\Delta y/\Delta x_i$.

1. To calculate the sensitivity coefficients regarding to the phantom position, the phantom position is moved $\pm 5\ mm$ in the x, y, z direction from the standard position (at the middle of the coil in x, z direction and the center of the gel is at 6 cm below the center of the coil in y direction) and the lead locates at the position in the middle of the gel and 2 cm away from the left side wall of the phantom. The CAD model of the RF coil and phantom is shown below:

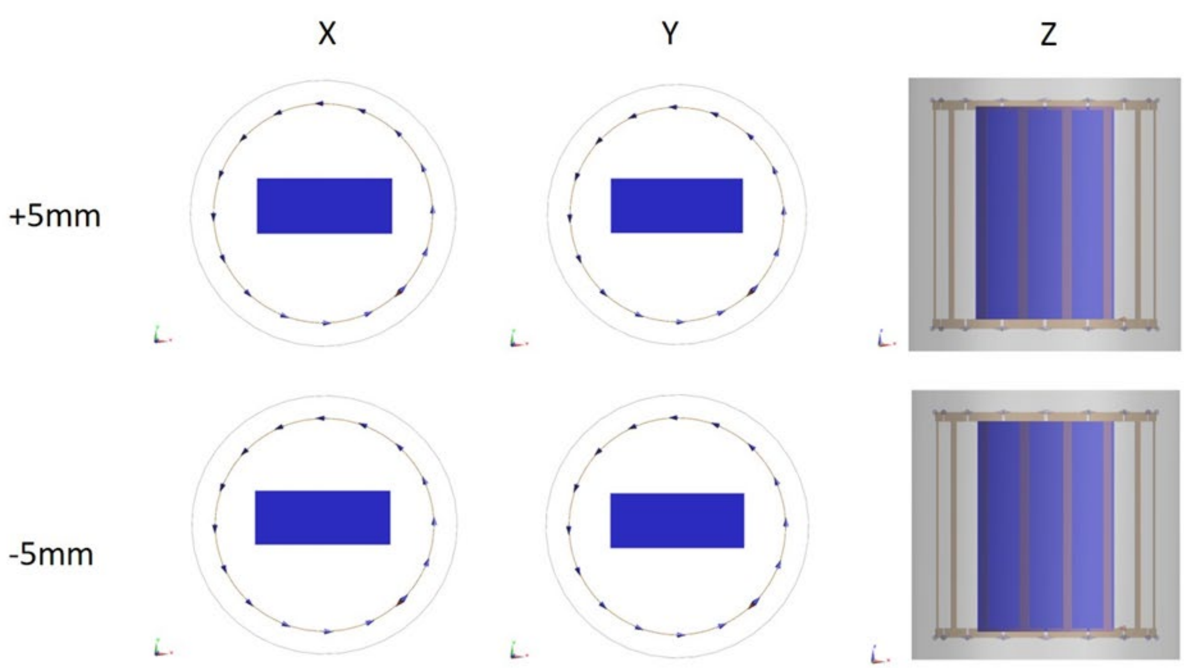

Figure 1 Shift of phantom CAD model in SEMCAD.

The sensitivity coefficient is calculated for each direction. The relative percentage is obtained by dividing the sensitivity coefficient by the calculated temperature rise *y* when the phantom is at the standard position.

Table 1 Sensitivity coefficient of phantom position.

1.5 T	ΔT	T standard	Δx (mm)	$\Delta T/\Delta x$	$\Delta T/\Delta x$ / $T_{standard}$ (%)
X direction	5.44E+06	3.50E+09	10	5.44E+05	0.0156
Y direction	1.52E+06	3.50E+09	10	1.52E+05	0.0043
Z direction	8.00E+05	3.50E+09	10	8.00E+04	0.0023
Combination					0.0163

2. To calculate the sensitivity coefficient regarding to the lead path, the phantom is placed at the standard position and the lead is moved ± 5 mm in the x, y, z direction from the standard lead position as shown below:

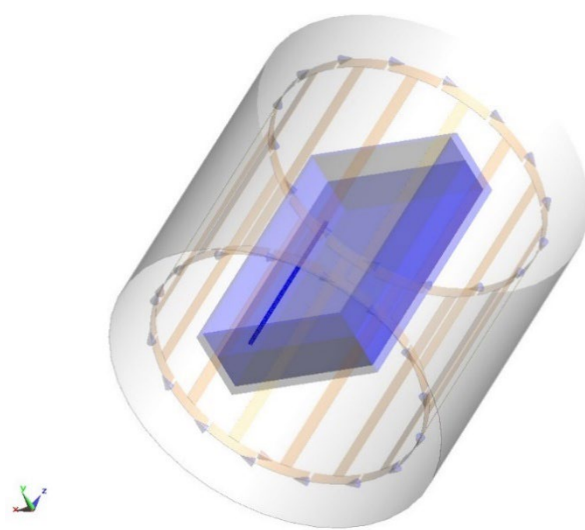

Figure 2 lead position inside phantom.

The sensitivity coefficient of lead path is calculated for each direction. The relative percentage is obtained by dividing the sensitivity coefficient by the calculated temperature rise *y* when the lead is at the standard position.

Table 2 Sensitivity coefficient of lead path.

1.5 T	ΔT	T standard	Δx (mm)	$\Delta T/\Delta x$	$\Delta T/\Delta x$ / $T_{standard}$ (%)
X direction	3.24E+08	3.49E+09	10	3.24E+07	0.9263
Y direction	2.09E+08	3.49E+09	10	2.09E+07	0.5976
Z direction	2.34E+06	3.49E+09	10	2.34E+05	0.0067
Combination					1.1023

3. To calculate the sensitivity coefficient regarding to the gel medium (conductivity and permittivity), the value of gel conductivity and relative permittivity are set to be 0.47(1 ± 5%) and 80.38(1 ± 5%) separately. The relative percentage is obtained by dividing the sensitivity coefficient by the temperature calculated when the conductivity and relative permittivity are 0.47 S/m and 80.38 individually.

Table 3 Sensitivity coefficient of medium conductivity and permittivity.

1.5 T	ΔT	T standard	Δx	$\Delta T/\Delta x$	$\Delta T/\Delta x$ / $T_{standard}$ (%)
conductivity	3.21E+08	3.49E+09	0.047	6.84E+09	195.7702
permittivity	3.39E+07	3.49E+09	8.038	4.21E+06	0.1206

4. To calculate the sensitivity coefficient regarding to the grid resolution, the max step of the mesh is set to be 2 mm and 3 mm.

Table 4 Sensitivity coefficient of the grid resolution.

1.5 T	ΔT	T standard	Δx (mm)	$\Delta T/\Delta x$	$\Delta T/\Delta x$ / $T_{standard}$ (%)
Grid resolution	4.04E+07	3.49E+09	1	4.04E+07	1.1562

Table 5 Sensitivity coefficients of each individual term.

Source of sensitivity coefficient	1.5T (%)
Phantom position	0.0163
Lead path	1.1023
Liquid conductivity	195.7702
Liquid permittivity	0.1206
Grid resolution	1.1562

B. The evaluation of the individual uncertainty components $u(x_i)$

The individual uncertainty components $u(x_i)$ is calculated regarding to the phantom position, lead path, liquid conductivity and permittivity and grid resolution.

1. Based on the measurements, the estimated individual uncertainty of the phantom position and lead path is 10 mm.
2. The uncertainty of the liquid permittivity

The relative permittivity of the water over the range of 0.1ºC to 99 ºC can be calculated using the following equation [1]:

$$\varepsilon = 87.740 - 0.4008t + 9.398(10^{-4})t^2 - 1.410(10^{-6})t^3$$

The measurement temperature usually ranges from 18 ºC to 45 ºC. The relative permittivity of the liquid gel under various temperature is estimated by the above equation:

Table 6 Relative permittivity of liquid gel under various temperature.

	18 ºC	19 ºC	20 ºC	21 ºC	22 ºC	23 ºC	24 ºC	25 ºC	26 ºC	27 ºC
Permittivity	80.82	80.45	80.01	79.72	79.36	79.00	78.64	78.29	77.93	77.58
	28 ºC	29 ºC	30 ºC	31 ºC	32 ºC	33 ºC	34 ºC	35 ºC	36 ºC	37 ºC
Permittivity	77.22	76.87	76.52	76.18	75.83	75.49	75.14	74.80	74.46	74.13
	38 ºC	39 ºC	40 ºC	41 ºC	42 ºC	43 ºC	44 ºC	45 ºC		
Permittivity	73.79	73.45	73.12	72.79	72.46	72.13	71.80	71.48		

Hence the uncertainty of the permittivity is the standard deviation of 2.85.

3. The uncertainty of the liquid conductivity

The uncertainty of gel conductivity is assessed by mixing the gel according to document ASTM F-2182 10 times and using a conductivity meter to measure liquid conductivity. The measured results are (0.47 0.48 0.52 0.50 0.42 0.41 0.48 0.46 0.45 0.50 S/m). The standard deviation of these observations is 0.033 S/m.

4. The uncertainty of the grid resolution is estimated to be 1 mm

Table 7 Individual uncertainty component.

	Uncertainty $u(x_i)$
Phantom position	10 mm
Lead path	10 mm
Liquid conductivity	0.033 S/m
Liquid permittivity	2.85
Grid resolution	1 mm

Combine Table 5 and Table 7, the uncertainties introduced by each source ($c_i u(x_i)$) are shown in Table 8.

Table 8 Uncertainty caused by each source ($c_i u(x_i)$).

Source of uncertainty	1.5T (%)
Phantom position	0.163
Lead path	11.023
Liquid conductivity	6.52
Liquid permittivity	0.344
Grid resolution	1.15

3. Combined uncertainty evaluation

The uncertainty from the transfer function development can be calculated from Table A-1 to Table A-4. Uncertainty from the validation measurement can be calculated from Table A-2 to Table A-4.

Table A-1 Uncertainty of TF shape measurement system.

Source of uncertainty	1.5T Uncertainty in %	Source of Numerical Value
Mutual coupling between VNA ports	0	Experimental analysis performed by UH
Detection limits	0	Negligible. Signal strength significantly exceeds VNA noise floor.
VNA drift	1.16	Manufacturer's specification (NI network analyzer)
Liquid conductivity and permittivity	6.52	Table 8
Combined Std. Uncertainty	6.63	

Mutual coupling: The mutual coupling of the two port of the VNA is negligible after calibration.

VNA drift: From NI PXle-1082 User Manual.

Table A-2 Uncertainty of numerical modeling.

Source of Uncertainty	1.5T Uncertainty in %	Source of Numerical Value
Grid resolution	1.15	Table 8
Liquid conductivity and permittivity	6.52	Table 8
Leads path uncertainty	11.02	Table 8
Combined Std. Uncertainty	12.86	

Table A-3 Uncertainty of electrical equipment readout.

Source of Uncertainty	1.5T Uncertainty in %	Source of Numerical Value
Readout Electronics	± 0.8°C	Optical Fiber probe

Table A-4 Uncertainty of measurement in RF coil.

Source of Uncertainty	1.5T Uncertainty in %	Source of Numerical Value
B1 RMS	4.1	Estimation of center B1 field
Drift of B1 RMS	2.33	Manufacturer's specification. MITS1.5 SN BC1006
Phantom position uncertainty	0.16	Table 8
Coil length variation	3.5	Numerical analysis performed by UH
Coil diameter variation	7.1	Numerical analysis performed by UH
Combined Std. Uncertainty	9.21	

Table A-5 Combined uncertainty of transfer function development.

Source of Uncertainty	1.5T Uncertainty in %	Source of Numerical Value
Transfer function shape measurement	6.63	Table A-1
Numerical modeling	12.86	Table A-2
Electrical equipment readout	± 0.8℃	Table A-3
Measurement in RF coil	9.21	Table A-4
Combined Std.	17.15 ± 0.8℃	

Table A-6 Combined uncertainty of the validation tests.

Source of Uncertainty	1.5T Uncertainty in %	Source of Numerical Value
Numerical modeling	12.86	Table A-2
Measurement in RF coil	9.21	Table A-4
Combined Std. Uncertainty	15.81	

Table A-7 Overall uncertainty of the TF development.

Source of Uncertainty	1.5T Uncertainty in %	Source of Numerical Value
Combined uncertainty of transfer function development	17.15 ± 0.8℃	Table A-5
Combined uncertainty of validation test	15.81	Table A-6
Combined Std. Uncertainty	23.32 ± 0.8℃	

The combined uncertainties of 1.5T is 23.32% ± 0.8℃ according to Table A-7.

References

[1] Maryott, C. G. (1956). Dielectric Constant of Water from 0 to 100 C. *Research of the National Bureau of Standards, 56 No.1*.