MRI homogeneity:
Introduction and vendor-specific evaluation

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Learning objectives

- Understand what B_0 homogeneity is, why it matters, and the challenges of this measurement
- Understand methods for measuring B_0 homogeneity
  - General and specific
- Identify resources for background and step-by-step instructions on homogeneity testing

What we'll cover

- Homogeneity **OVERVIEW**
- An introduction to the main **METHODS** of measuring B_0 homogeneity
- Step-by-step **PROCEDURES** for B_0 homogeneity measurement on different vendor platforms
- **RESOURCES** for more information about theory and implementation of different B_0 homogeneity testing methods

Contributors

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TG325 MRI Resources website accessible to AAPM members:
https://w3.aapm.org/pubs/MRIResources/

B_0 inhomogeneity (ΔB_0)

- Measure of static magnetic field strength uniformity

- Influenced by
  - Magnet design & manufacturing
  - External ferromagnetic structures
  - Shim compensation
  - Phantom or patient in magnet

- Influences
  - Chemical shift techniques: fat suppression (SPIR, SPAIR)
  - Spectroscopy techniques
  - Geometric distortion
  - Signal uniformity
  - Banding artifacts

For diagnostic physicists…

- Annual evaluation of B_0 homogeneity required by **The Joint Commission** and for **American College of Radiology (ACR)** accreditation.

- Challenge:
  - Vendor phantoms, software tools, access level
  - Vendor accepted methods and tolerance levels
  - Quick on-site evaluation

For therapy physicists…

- Contributes to geometric distortion, especially near edges of FOV
- Extensive and frequent QA procedures

→ need quick, easy, meaningful B_0 homogeneity evaluation approach

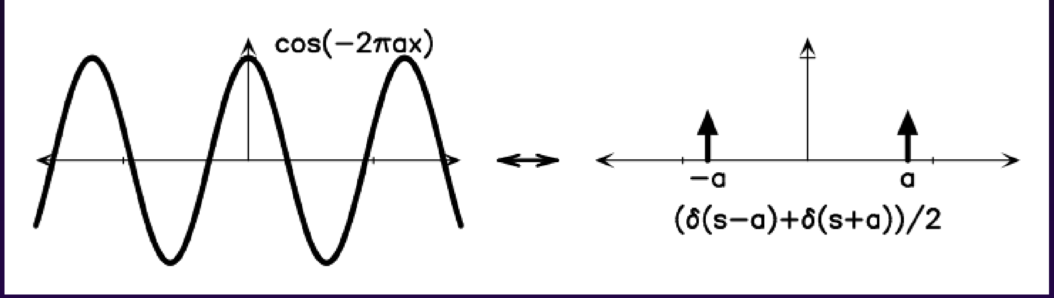
Further considerations

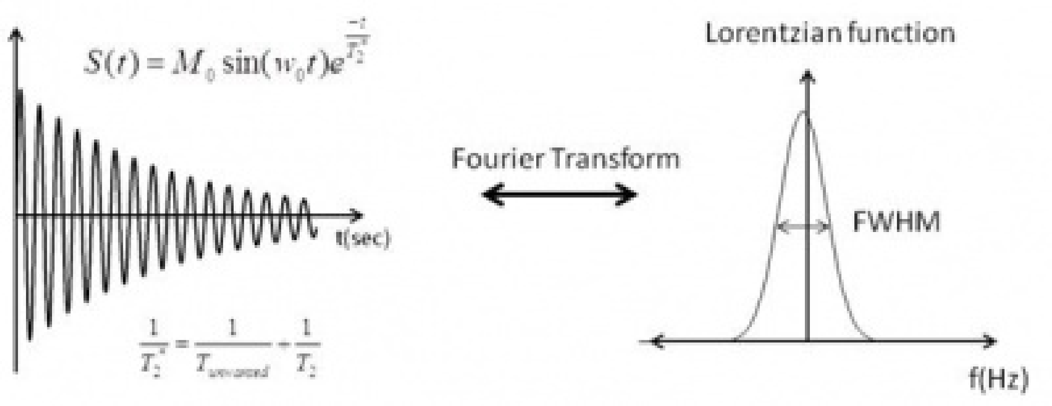
- How to choose a method
  - Accessibility
  - Compatibility with vendor action limits
  - Output characteristics: 1D vs. 2D vs. 3D
  - Quick results at workstation

GE	Availability and accessibility	Immediately actionable by vendor	Provides spatial information	Quick results at workstation
Spectral peak	+	-	-	+
Phase difference	-	-	+	+
Field mapping	+	+	~ (multiple DSVs)	+
Bandwidth difference	+	-	-	+

- How to establish tolerances

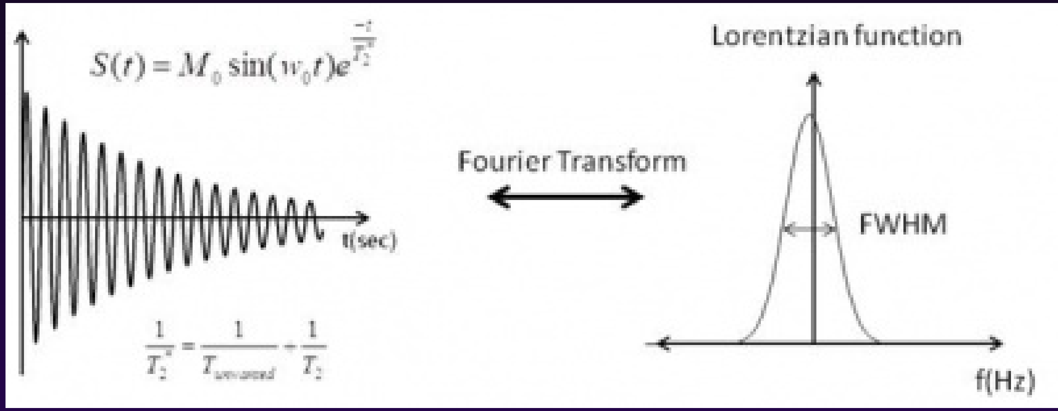
B_0 inhomogeneity (ΔB_0)

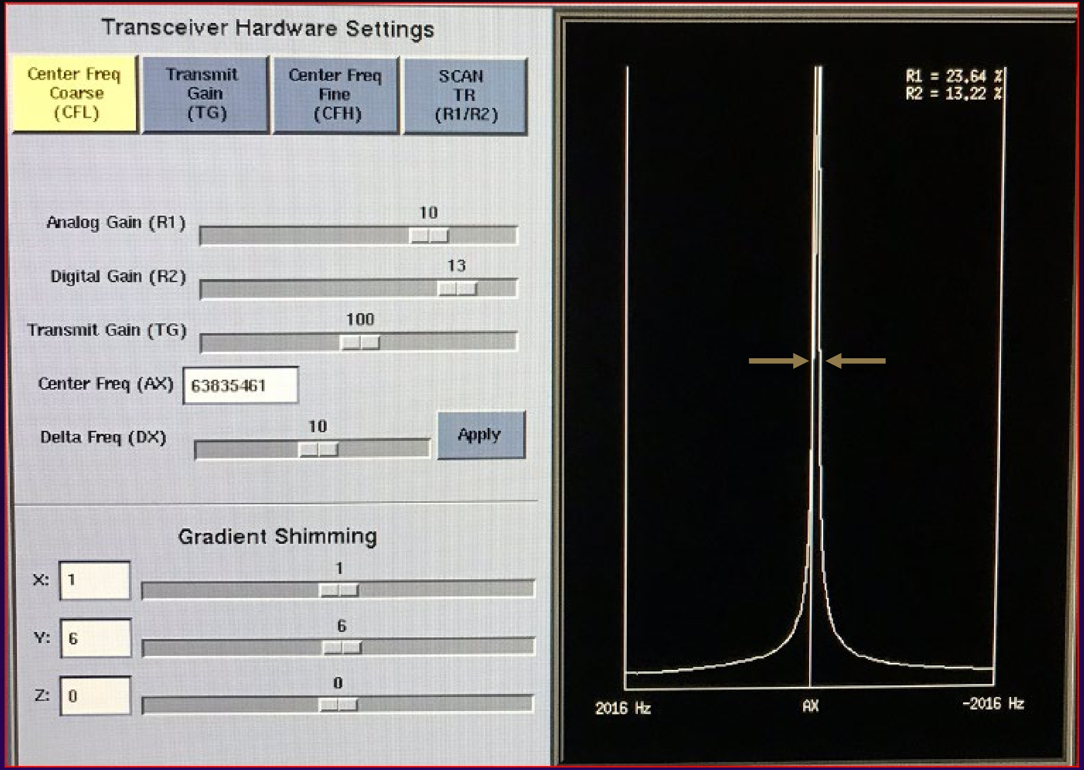




- Measure of static magnetic field strength uniformity
  - Variation over a specified volume (DSV)
  - Expressed in ppm or Hz
  - **RMS** measurement of B_0 inhomogeneity is volume-averaged
  - **Peak-to-peak** requires a spatial measurement of variations

Spectral peak





Notes

\+ quick and simple

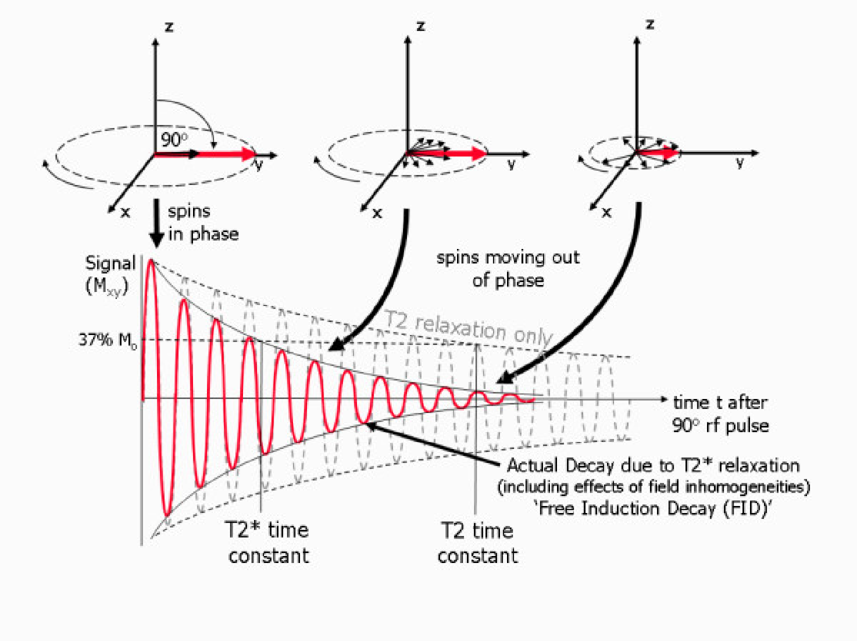
\- no spatial information

- Global measure: $B_{0,rms}$ only, not $B_{0,pp}$
- DSV determined by phantom

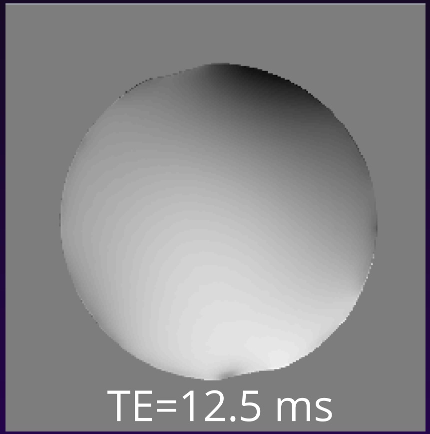
$$\Delta B_{0,rms}\,(ppm) = \frac{FWHM\ (Hz)}{\gamma\left(\frac{MHz}{T}\right) \times B_0(T)}$$

$$\gamma = 42.56\ MHz/T$$

Phase difference & phase map



Ridgway JP. *J Cardivasc Magn Reson* 2010. 12(1):71.



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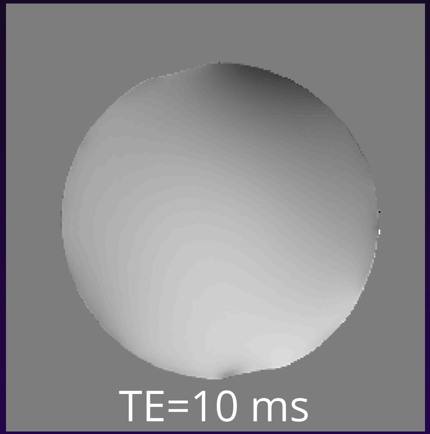

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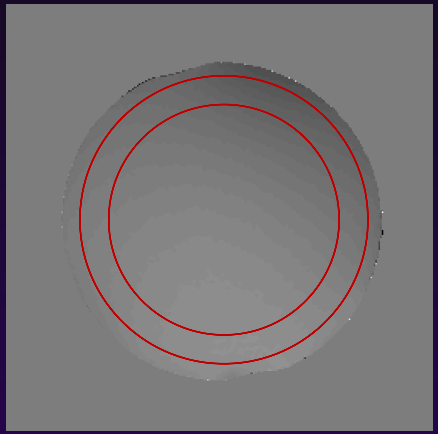


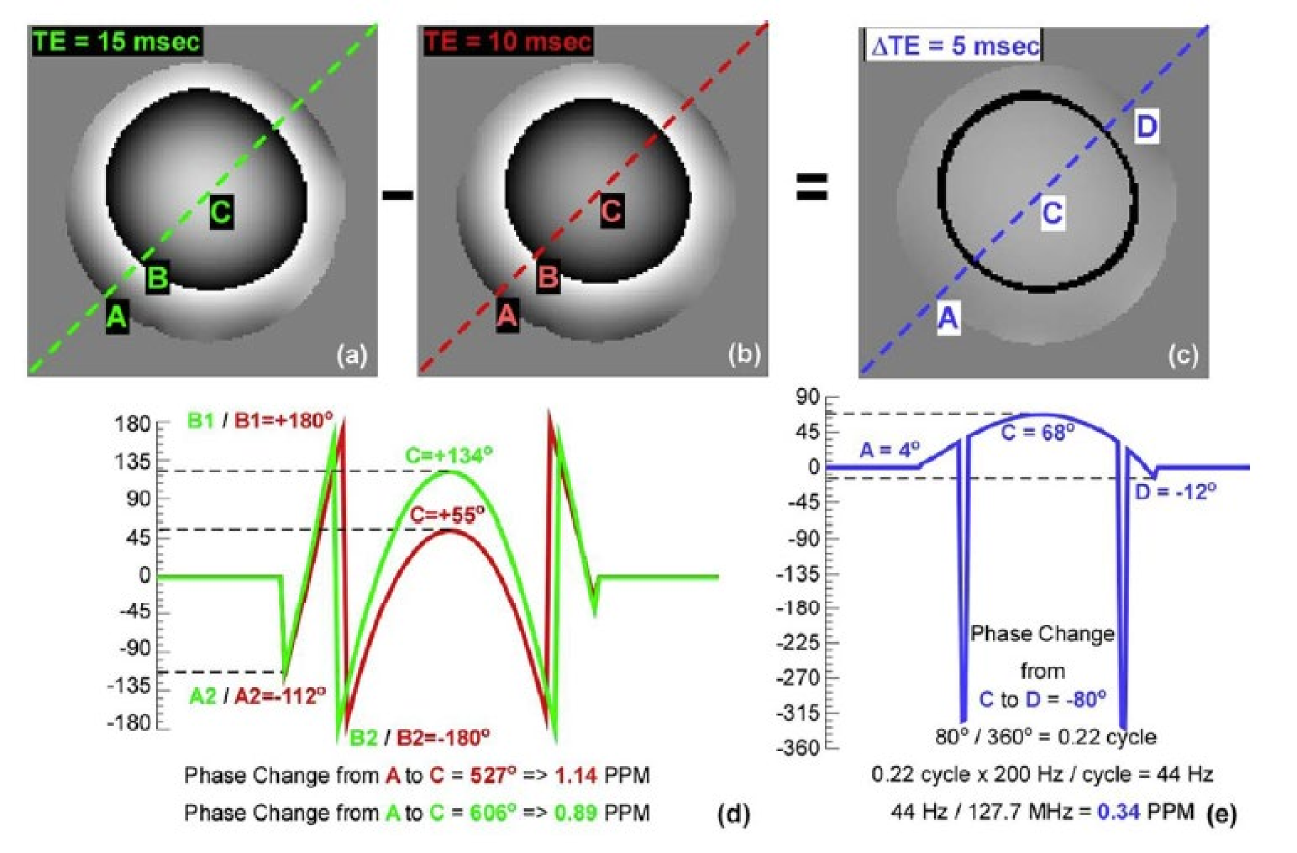
$$\Delta\varphi_{pp} = \frac{ROI_{max} - ROI_{min}}{DR_{ADC}} \qquad \Delta\varphi_{rms} = \frac{\sqrt{ROI_{mean}^2 + ROI_{stdev}^2}}{DR_{ADC}}$$

$$\Delta B_0\ (ppm) = \frac{\Delta\varphi}{\gamma B_0 \times \Delta TE}$$

Phase difference & phase map

Notes
+ can perform in 3D (or 3 orthogonal planes)
+ includes spatial information
- phase image accessibility
- phase wraps
- analysis on scanner can be difficult

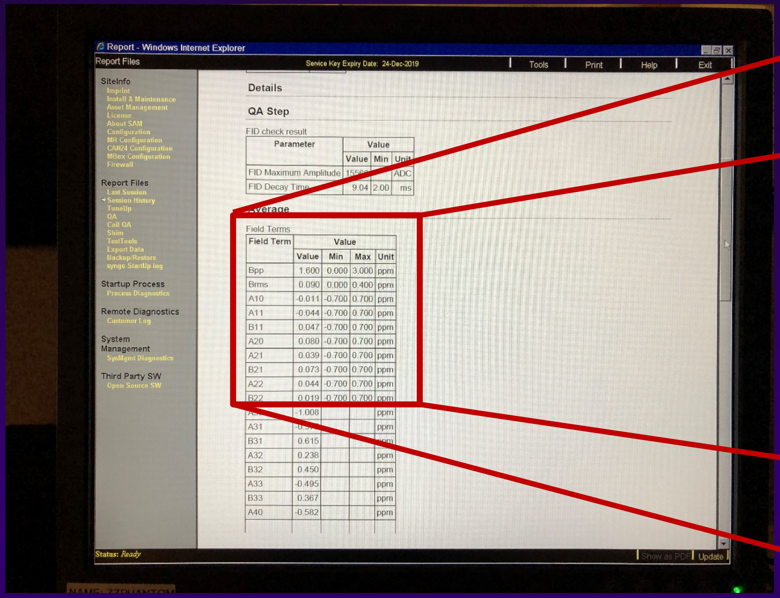
- $B_{0,rms}$ or $B_{0,pp}$
- DSV determined by ROI (user-selectable within phantom)
- A single phase map can also be used to estimate upper bound of ΔB_0

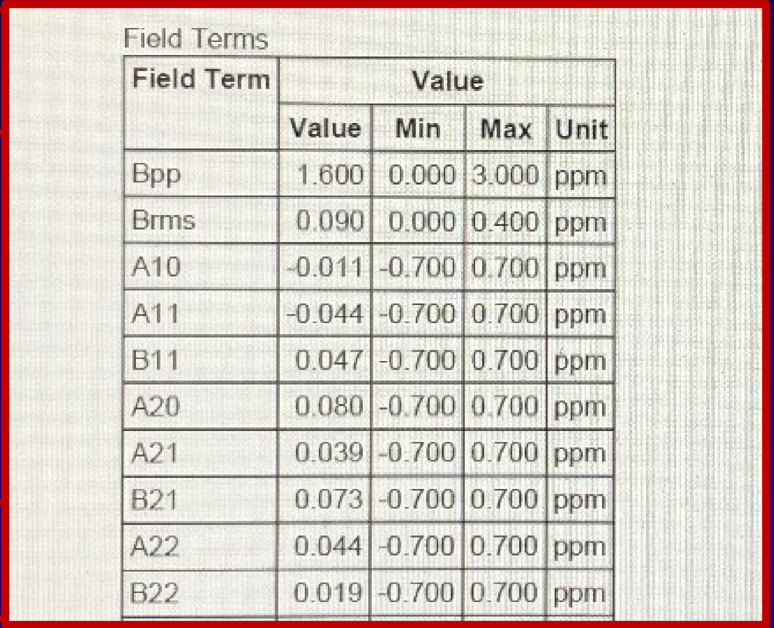


ACR 2015 MRI Quality Control Manual

Field map

- If available, this is a straightforward vendor-provided capability
- 3D map acquired or created from 2D maps
- Comparable results to phase difference mapping



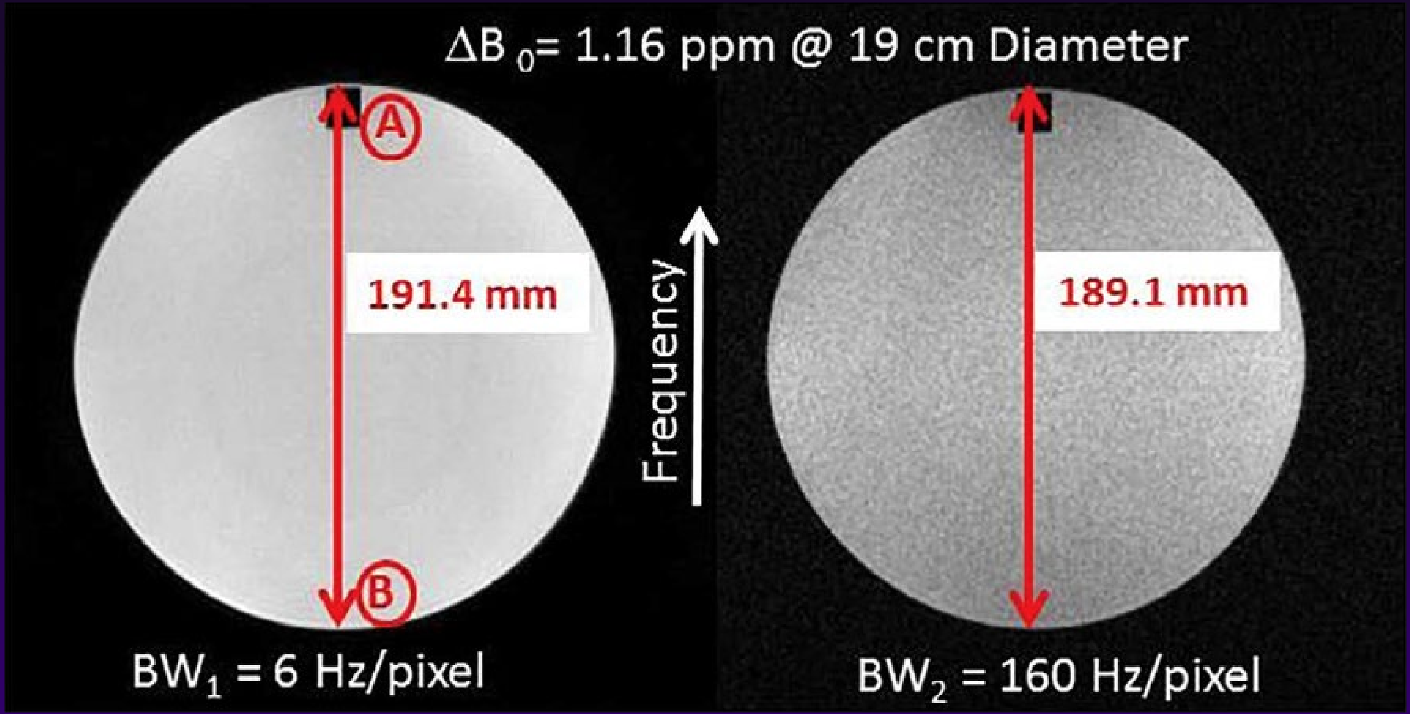


Field Terms

Field Term	Value			
	Value	Min	Max	Unit
Bpp	1.600	0.000	3.000	ppm
Brms	0.090	0.000	0.400	ppm
A10	-0.011	-0.700	0.700	ppm
A11	-0.044	-0.700	0.700	ppm
B11	0.047	-0.700	0.700	ppm
A20	0.080	-0.700	0.700	ppm
A21	0.039	-0.700	0.700	ppm
B21	0.073	-0.700	0.700	ppm
A22	0.044	-0.700	0.700	ppm
B22	0.019	-0.700	0.700	ppm

Chen HH, Boykin RD, Clarke GD, Gao JHT, Roby JW.
Med Phys 2006 33(11)

Bandwidth difference



ACR 2015 MRI Quality Control Manual

$$\Delta B_o\ (ppm) = \frac{BW_1 \times BW_2 \times (x_1 - x_2)}{\gamma B_0 \times FOV \times (BW_2 - BW_2)}$$

(BW in Hz)

Notes

+ accessible on all platforms
- many acquisitions & measurements for 3D evaluation
- assumes proper gradient calibration

- DSV determined by phantom or internal markers

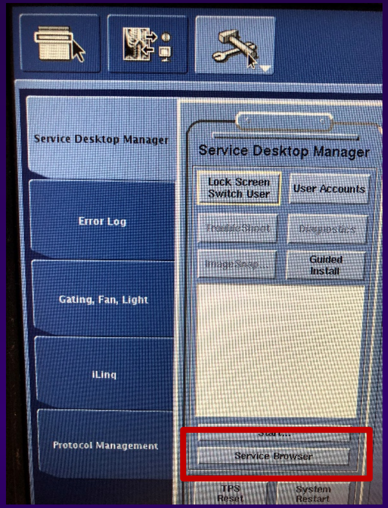
Procedures by vendor

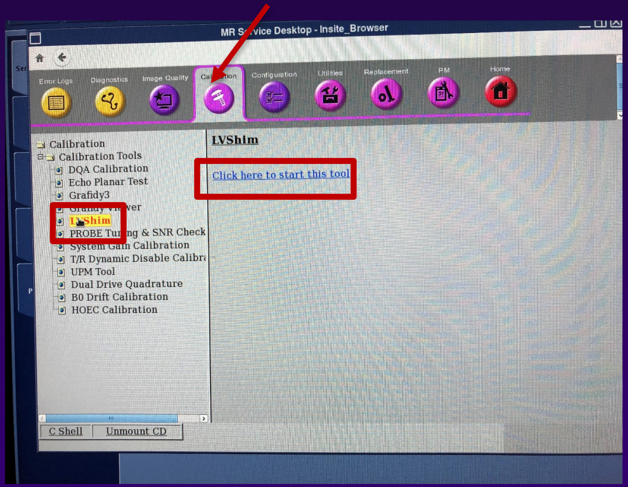
- Step-by-step instructions/button-ology
- Variation by software version, but this should provide a solid starting point
- Talk to vendor field engineer if you need guidance on your specific system

GE: LV shim procedure

- Accessible field map function: Large Volume (LV) shim
- Phantom: 45 cm diameter LV shim phantom*
- Coil: body coil

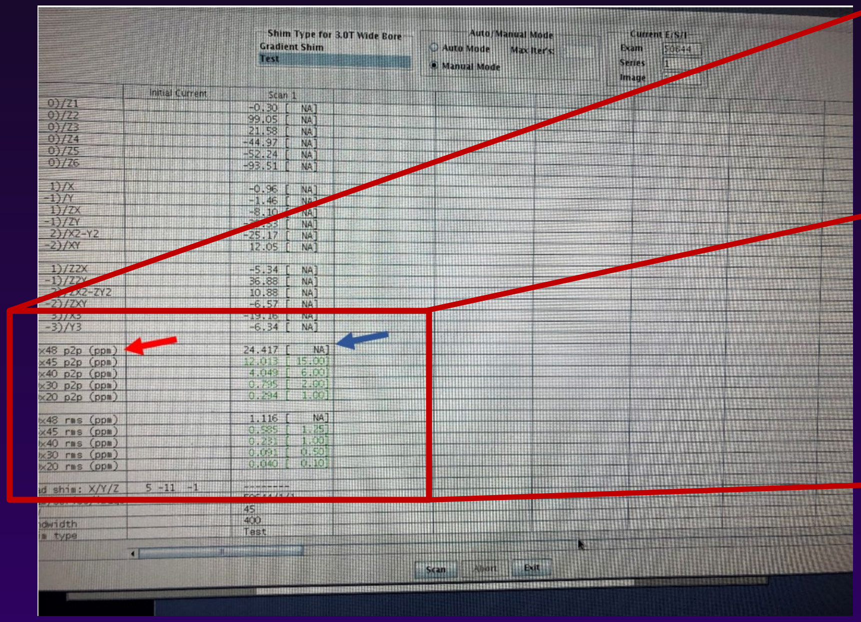
Calibration→Calibration tools→LV shim
→"Click here to start this tool"
→Test
→Scan

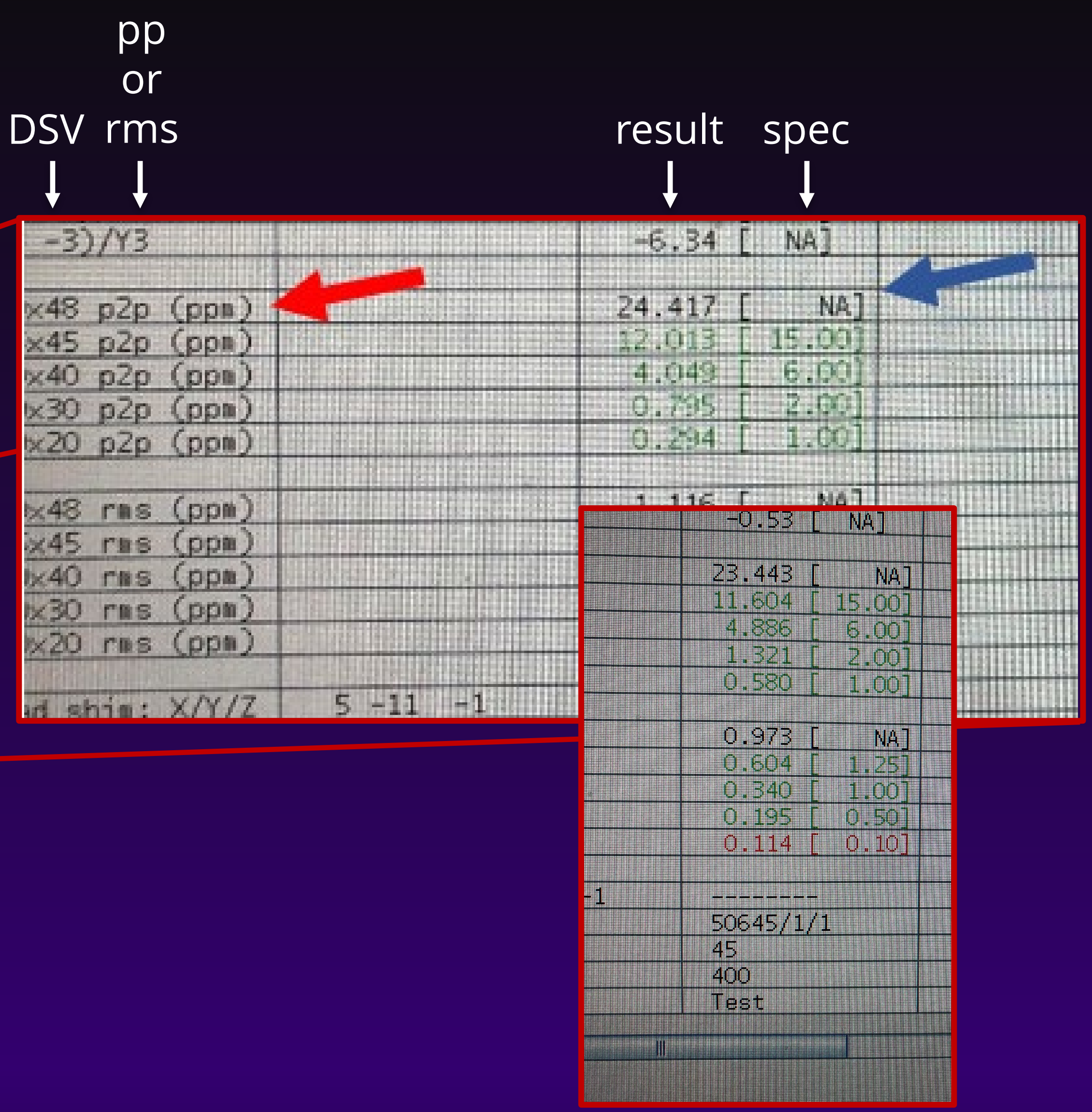




*no matter the phantom or procedure, let it rest a few minutes so fluid can settle

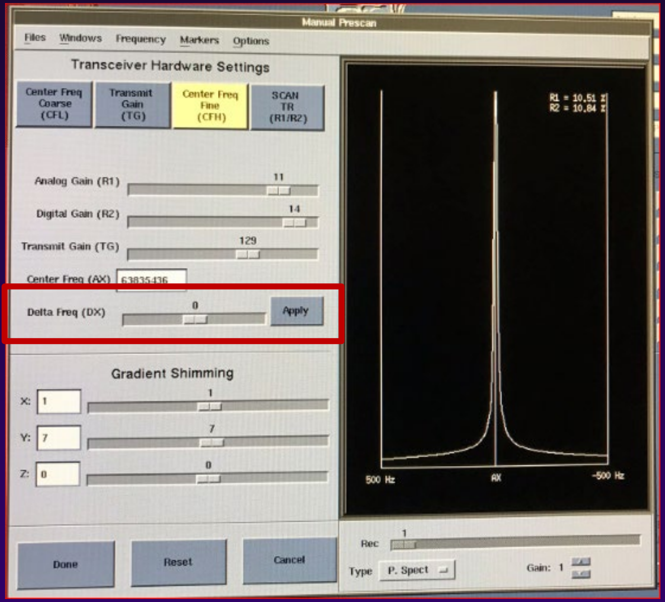
GE: LV shim results



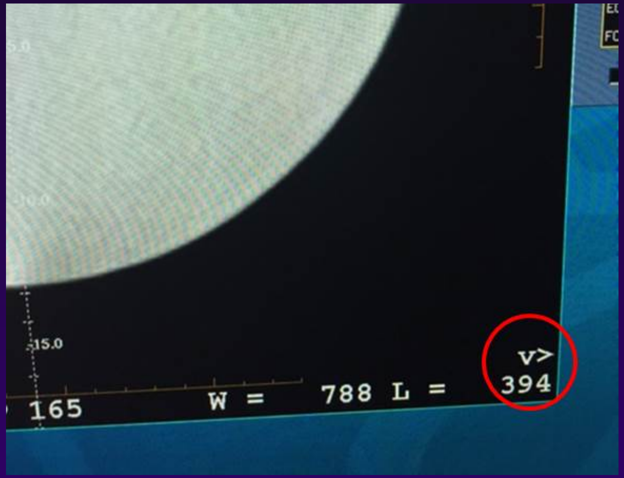


GE: Other options

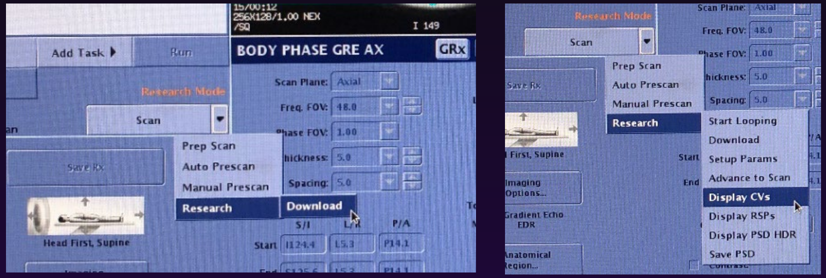
Spectral peak in manual pre-scan

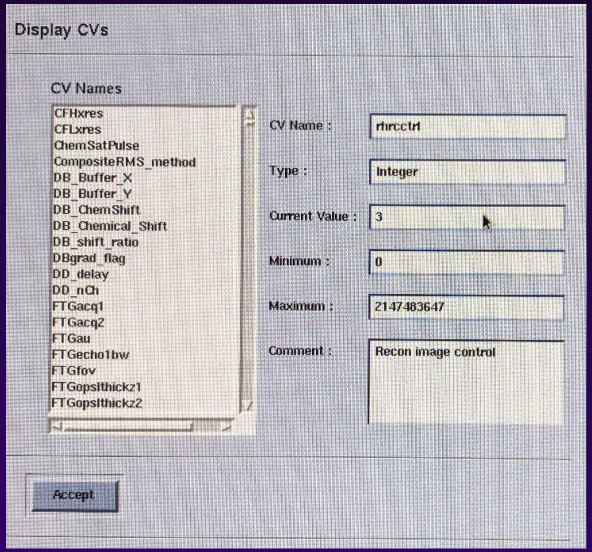


Bandwidth difference



Phase difference





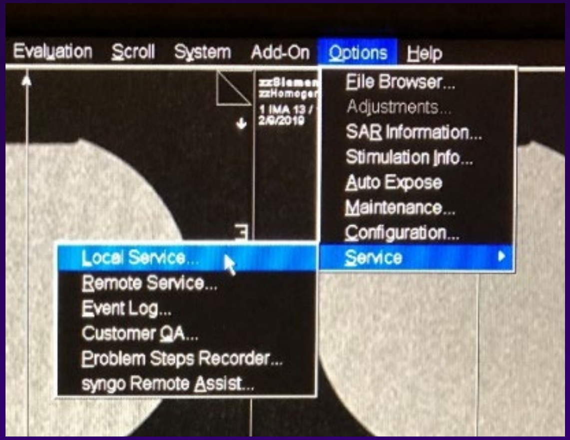
CV rhrcctrl = 3 for magnitude and phase (31 for magnitude, phase, real, imaginary)

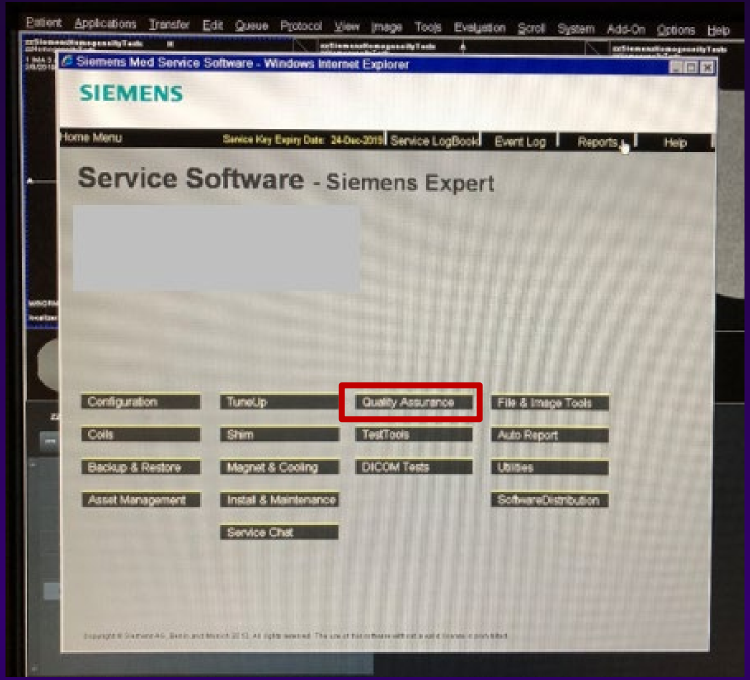
GE: Comparing methods

GE	Availability and accessibility	Immediately actionable by vendor	Provides spatial information	Quick results at workstation
Spectral peak	+	-	-	+
Phase difference	-	-	+	+
Field mapping	+	+	~ (multiple DSVs)	+
Bandwidth difference	+	-	-	+

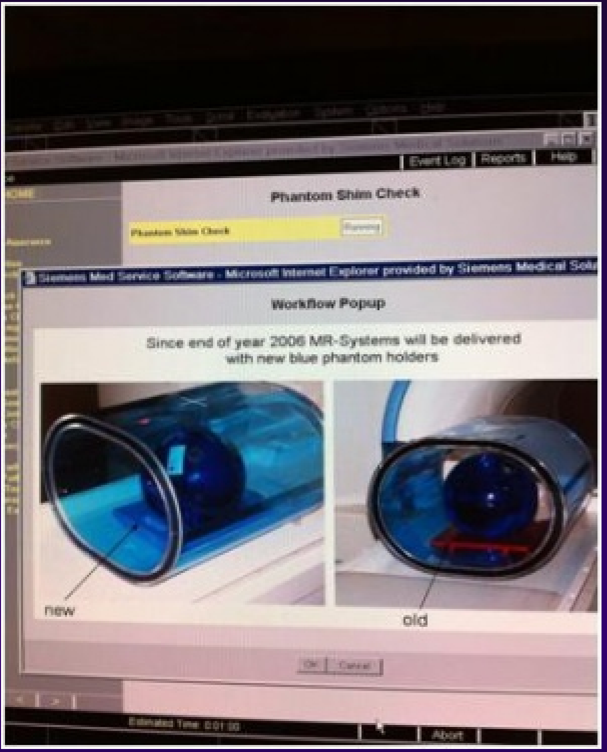
Siemens: Phantom shim check procedure

- Accessible field map function: Phantom shim check
  - Requires a service password which is typically easily obtained
- Phantom: 24 cm homogenous sphere
- Coil: Body



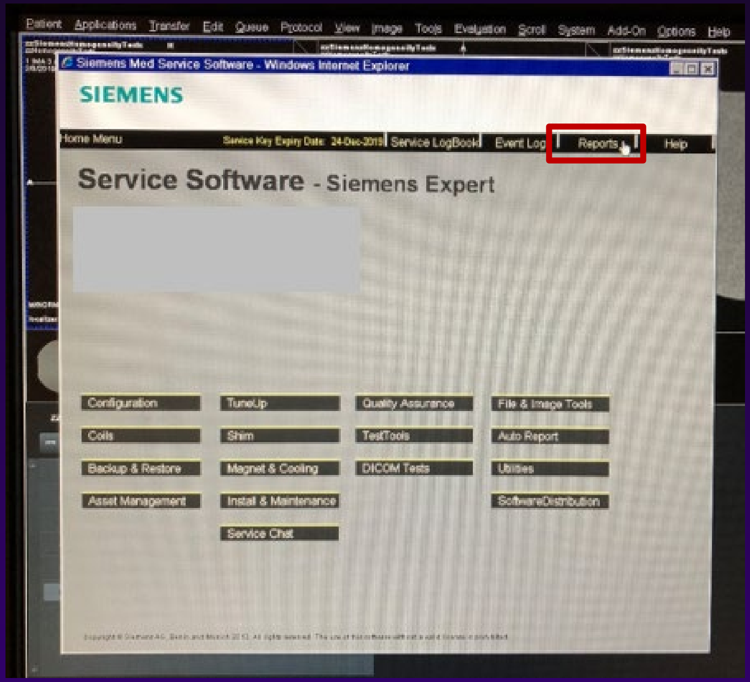


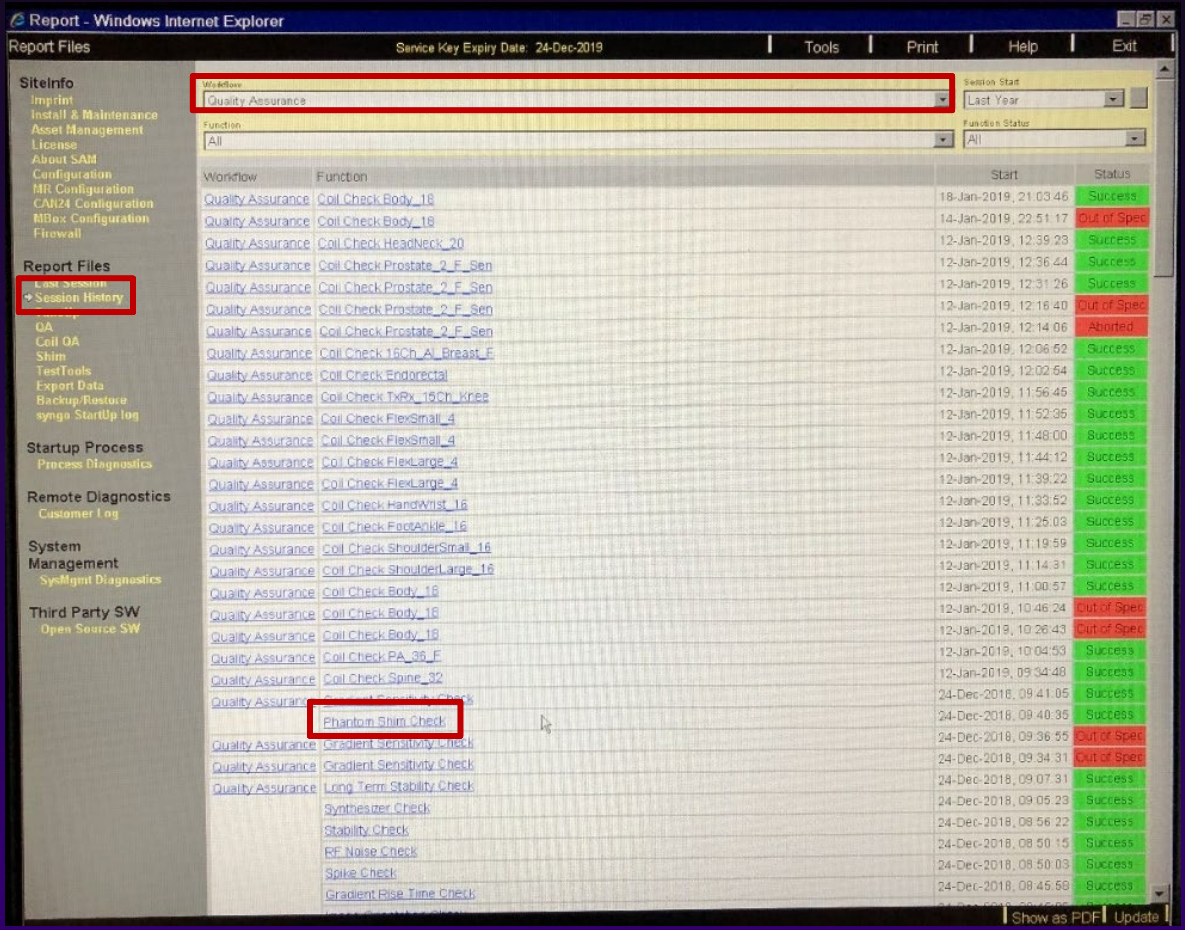
Quality Assurance→Phantom Shim Check

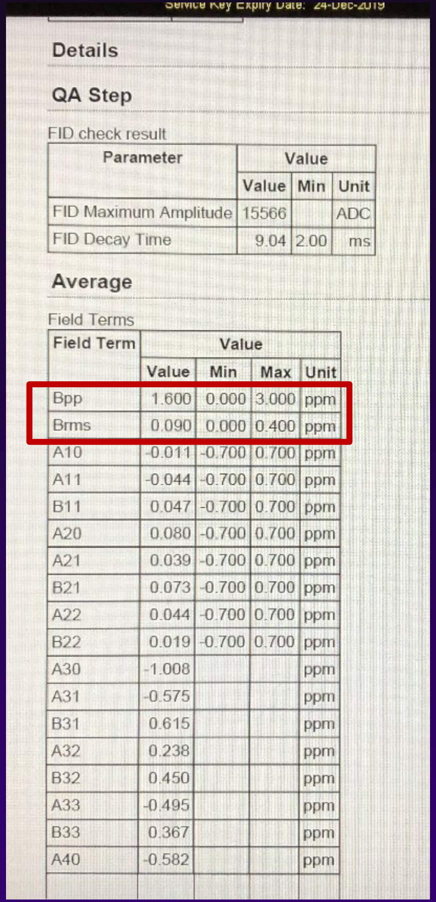


→Hit "Go"

Siemens: Phantom shim check results







Details

QA Step

FID check result

Parameter	Value	Min	Unit
FID Maximum Amplitude	15566		ADC
FID Decay Time	9.04	2.00	ms

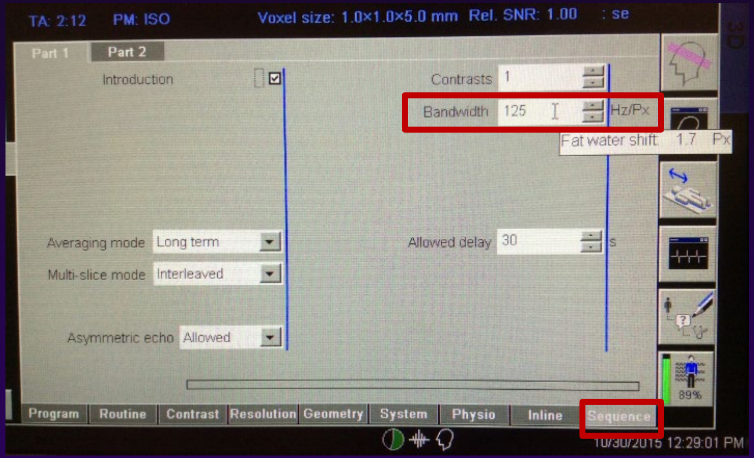
Average

Field Terms

Field Term	Value	Min	Max	Unit
Bpp	1.600	0.000	3.000	ppm
Brms	0.090	0.000	0.400	ppm
A10	-0.011	-0.700	0.700	ppm
A11	-0.044	-0.700	0.700	ppm
B11	0.047	-0.700	0.700	ppm
A20	0.080	-0.700	0.700	ppm
A21	0.039	-0.700	0.700	ppm
B21	0.073	-0.700	0.700	ppm
A22	0.044	-0.700	0.700	ppm
B22	0.019	-0.700	0.700	ppm
A30	-1.008			ppm
A31	-0.575			ppm
B31	0.615			ppm
A32	0.238			ppm
B32	0.450			ppm
A33	-0.495			ppm
B33	0.367			ppm
A40	-0.582			ppm

Siemens: Other options

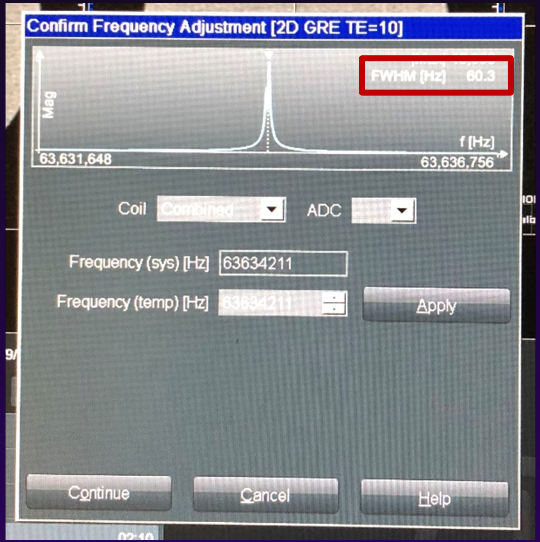
BW difference is generally accessible



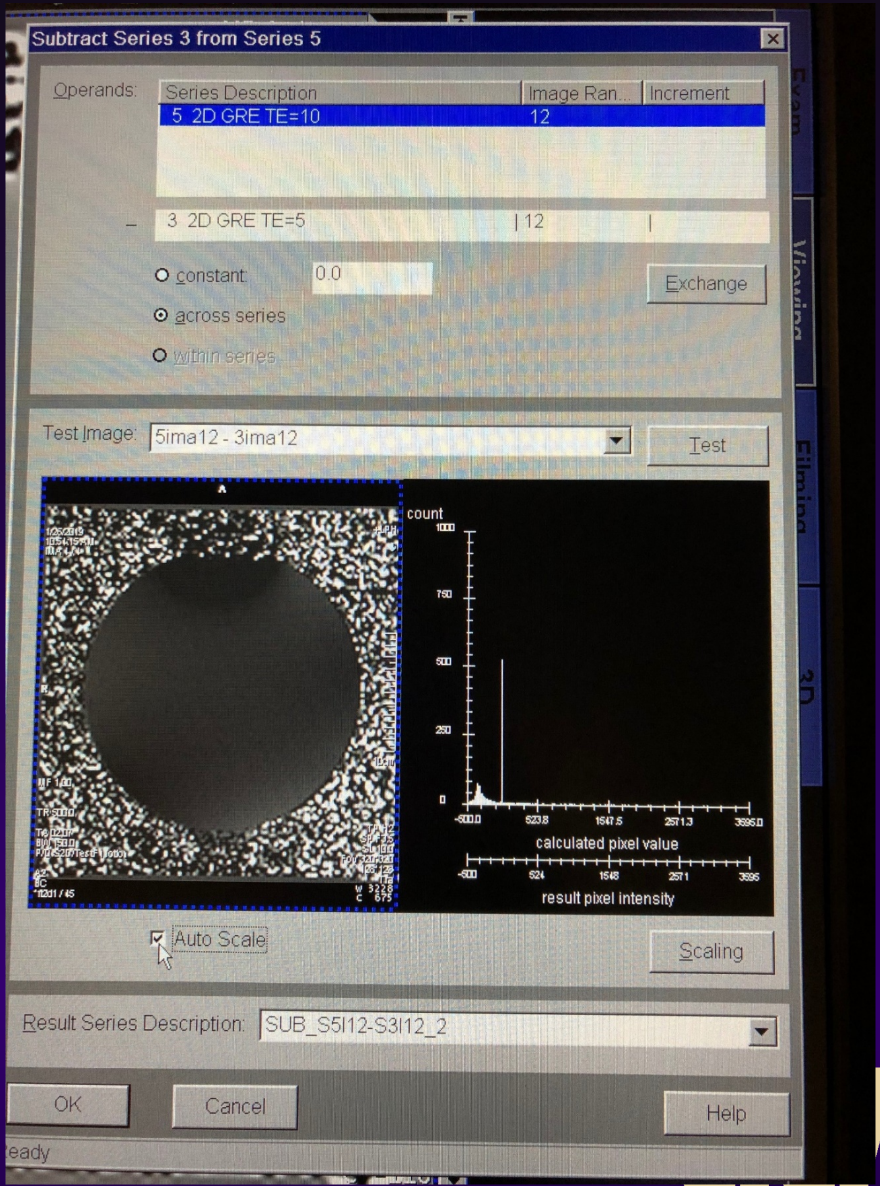
$$\Delta B_o\ (ppm) = \frac{BW_1 \times BW_2 \times (x_1 - x_2)}{\gamma \times B_0 \times FOV \times (BW_2 - BW_2)}$$

BW in Hz – multiply Hz/pixel by number of pixels in FE direction

Spectral peak (newer systems)



- After localizer, while setting up another protocol, System→Adjustments→Confirm frequency adjustment
- After pre-scan begins, spectrum displayed
- FWHM displayed or estimate by moving vertical line



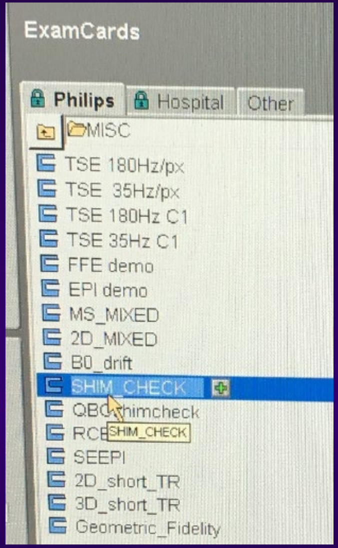
Siemens: Comparing methods

Siemens	**Availability and accessibility**	**Immediately actionable by vendor**	**Provides spatial information**	**Quick results at workstation**
Spectral peak	+	-	-	+
Phase difference	+	-	+	+
Phantom shim check	+	+	-	+
Bandwidth difference	+	-	-	+

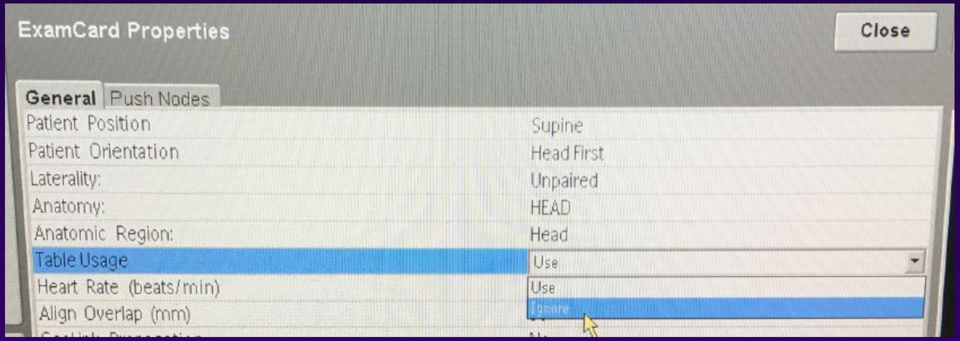
Philips: Shim check procedure

- Accessible field map function: Shim check
- Phantom: 40 cm disk
- Coil: Body

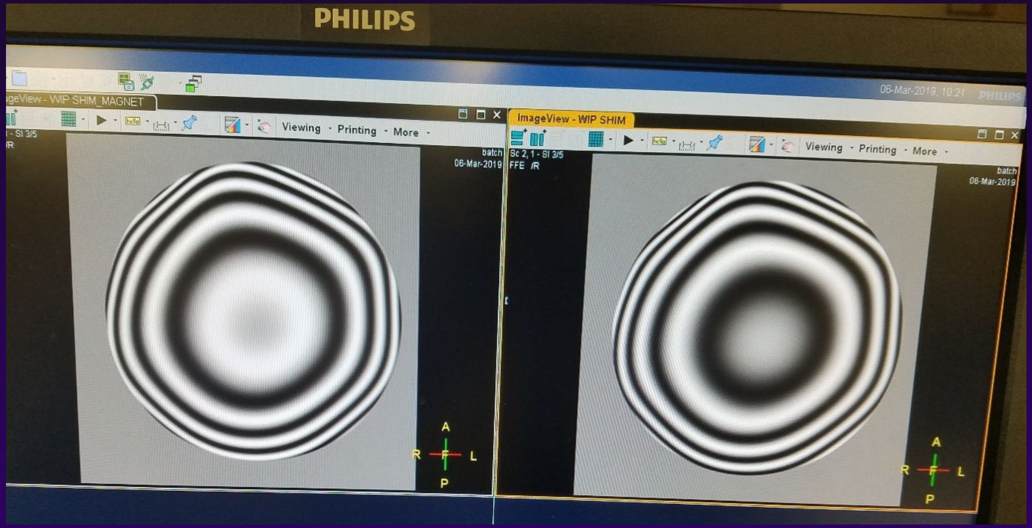
Phantom studies → MISC



Run as is. Example 1.5T parameters below	
Sequence	FFE
TR	400 ms
TE	16 ms
FA	30°
FOV	45 cm



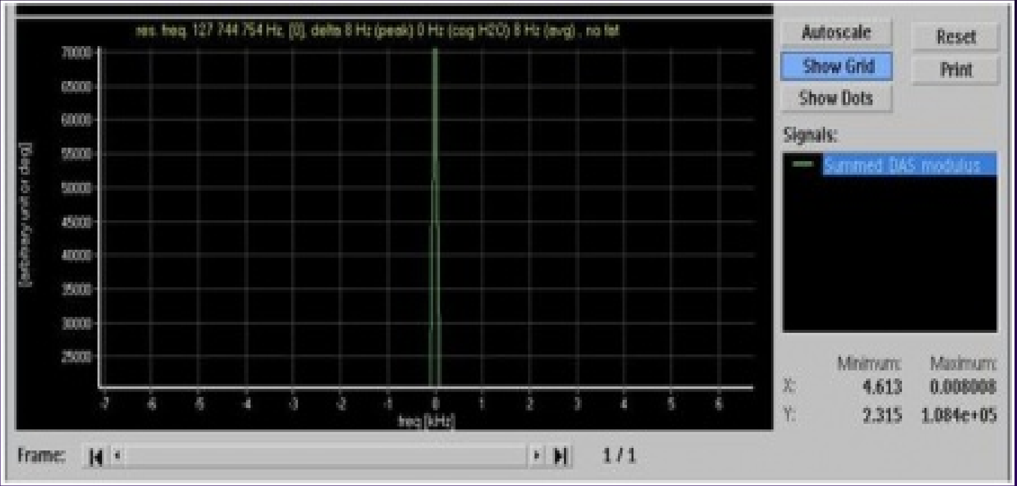
Philips: Shim check results



- Each B→W transition is 1.0ppm. (1 full cycle is 1.0 ppm)
- Count number N of B→W transitions, $\Delta B_{0,pp} = N \times 1.0ppm$
- Re-position phantom and run in 3 planes

Philips: Other options

Spectral peak



After running non-survey scan
Examination→Data Monitoring→
F0→Show Latest
Zoom in on half of Y Maximum to estimate FWHM

BW difference

- Older systems display fat-water shift in pixels instead of bandwidth/pixel
- Calculate Hz/pixel:

$$\frac{Hz}{pixel} = \frac{3.5ppm \times \gamma(\frac{MHz}{T}) \times B_0(T)}{fat - water\ shift\ (pix)}$$

Phase difference map

- Phase images can be reconstructed also by selecting M (magnitude) and P (phase) on Postproc→Images on the exam card.
- Use image algebra in viewing environment to subtract
- If necessary, reduce TE difference to reduce phase wraps

Field mapping

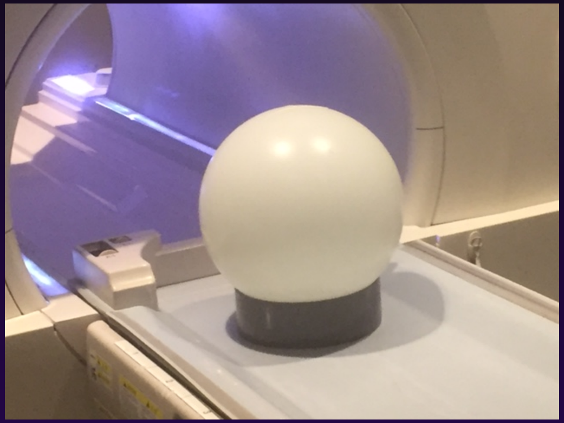
- SPT tools can be used with a service dongle

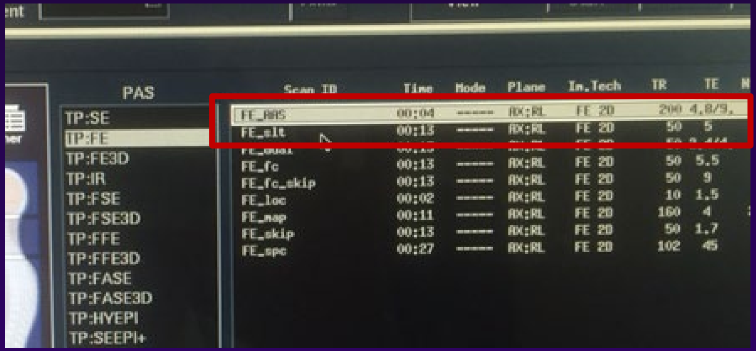
Philips: Comparing methods

Siemens	**Availability and accessibility**	**Immediately actionable by vendor**	**Provides spatial information**	**Quick results at workstation**
Spectral peak	+	-	-	+
Phase difference	+	-	+	+
Shim check	+	+	-	+
Field mapping	-	+	+	+
Bandwidth difference	+	-	-	+

Toshiba/Canon: Phase difference procedure

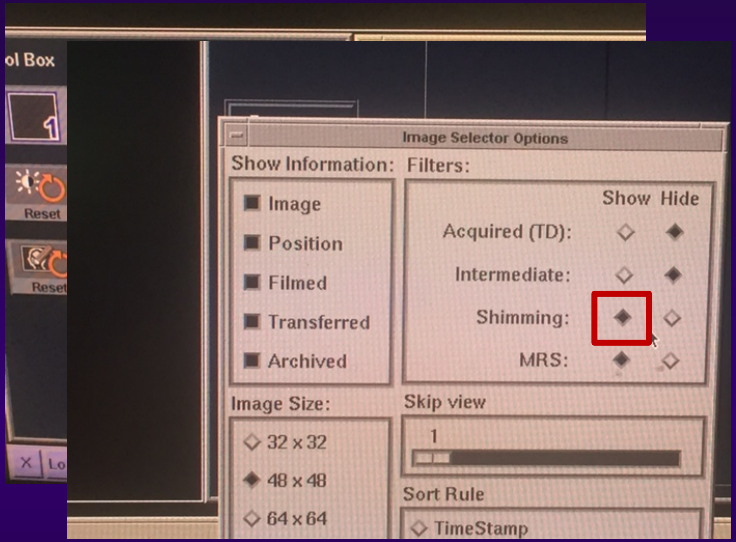
- Phantom: 30 cm spherical
- Coil: Body
- Protocol: FE_AAS



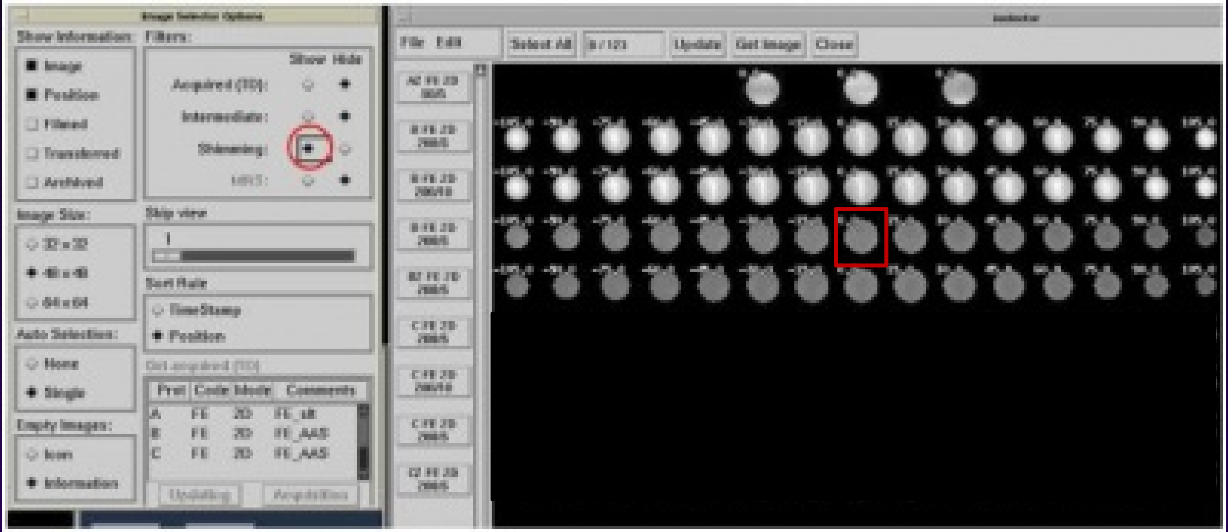


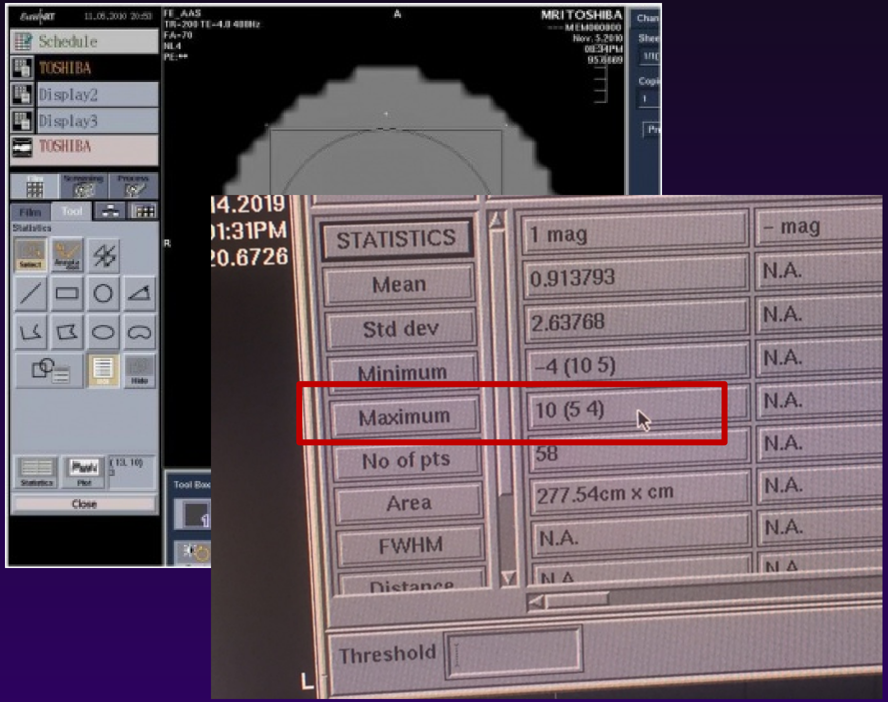
Run in axial plane

Image selector window



Toshiba/Canon: Phase difference results





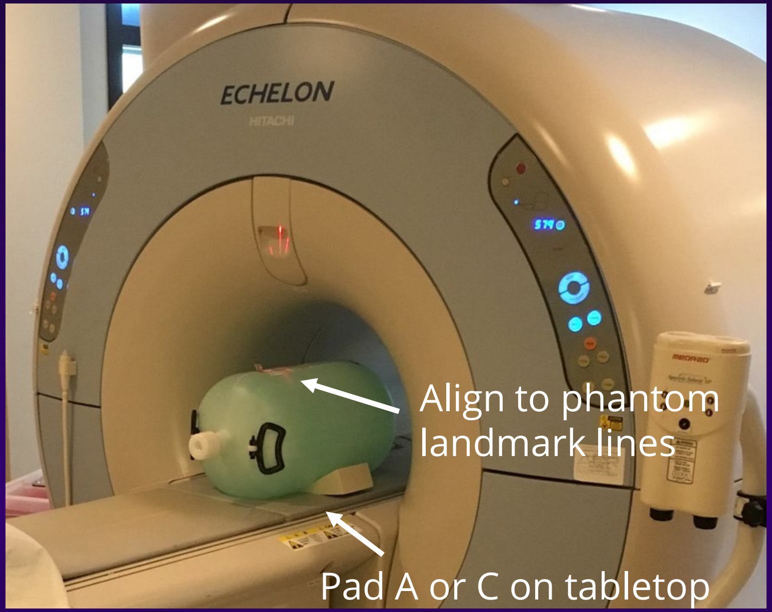
- Repeat in sagittal and coronal planes
- Field homogeneity (within DSV = ROI diameter) is the absolute max pixel value found in the ROI in any plane
- Absolute pixel value of 100 corresponds to 1 ppm

Hitachi: Fine magnetic field analysis set-up

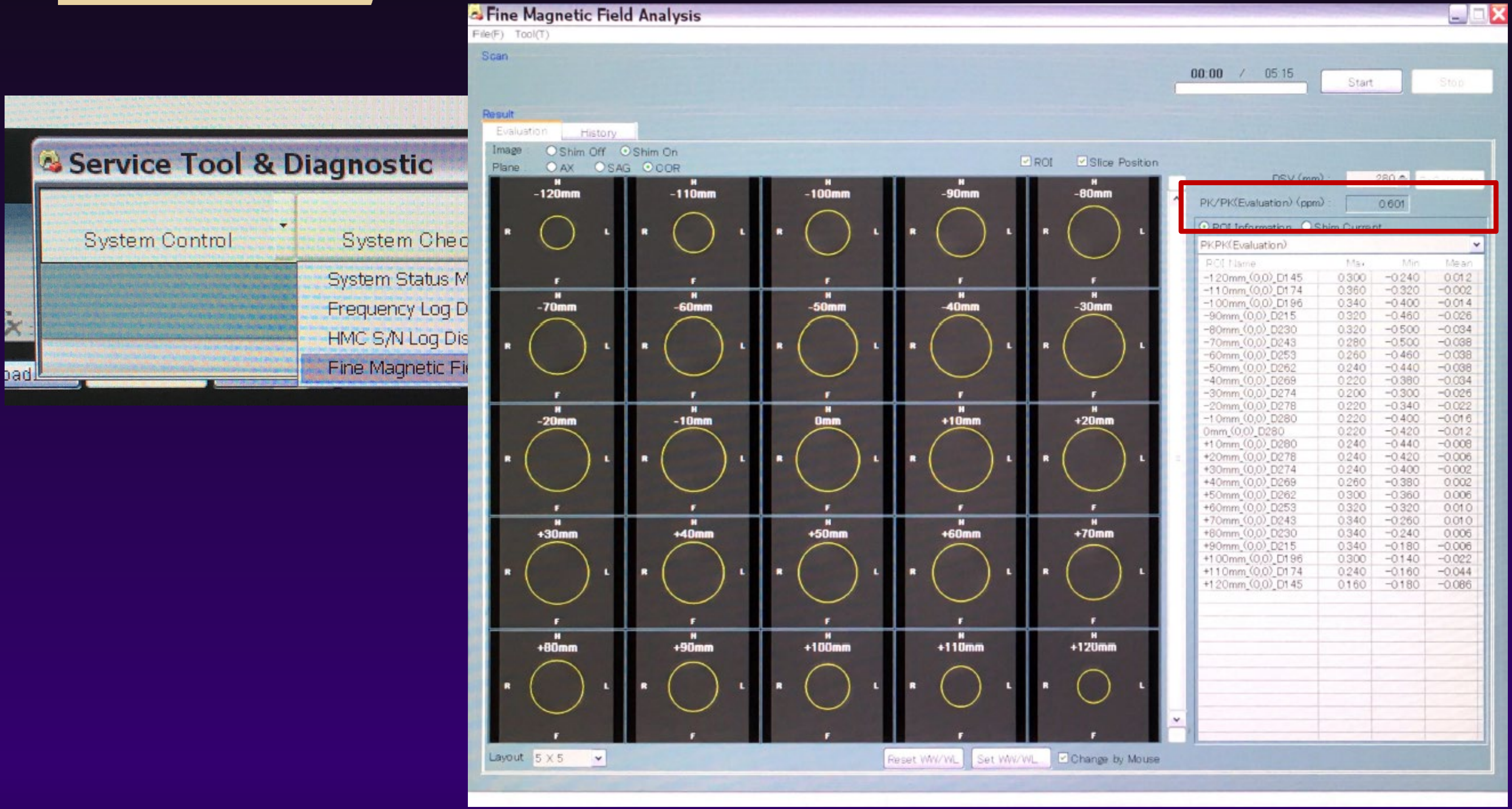
- Oasis & Echelon
- Phantom: Bottle 11
- Coil: RAPID body (Oasis) or T/R Body (Echelon)
- Protocol: Fine magnetic field analysis tool

RAPID body coil, laterally centered, no pads (required for valid results)

Align laser with phantom landmarks, not coil



Hitachi: Fine magnetic field analysis results



- Hitachi recommends service call if >1.0ppm for Shim On and >5.0 ppm for Shim Off
- ROI placement is automatic – very sensitive to lateral positioning!

Hitachi: SHIM procedure

- AIRIS, Altaire
- Phantom: #4 bottle (AIRIS) or D bottle (Altaire)
- Coil: Head

Axial:	TR= 1850, Multi Slice=15, Presat=0, W=11, L=500, Prescan=ON
Sagittal:	TR= 2430, Multi Slice=15, Presat=4, W=11, L=500, Prescan=ON
Coronal:	TR= 2430, Multi Slice=15, Presat=4, W=11, L=500, Prescan=ON

SNR analysis card – place measurement ROIs and record Max and Min for each slice

Slice Number	Slice position (mm)	ROI diameter (mm)
1	-70	110
2	-60	134
3	-50	150
4	-40	160
5	-30	170
6	-20	175
7	-10	178
8	0	180
9	10	178
10	20	175
11	30	170
12	40	160
13	50	150
14	60	134
15	70	110

Calculate $\Delta B_{0,pp}$ for each slice:

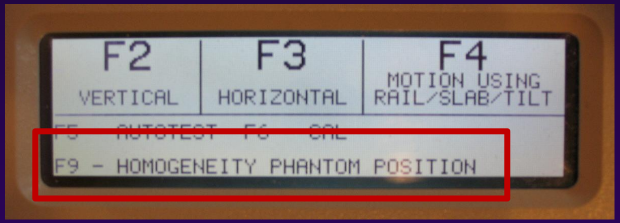
Airis 2:	$\Delta B_0 = 0.114$ ppm * Max(Rel.) – Min(Rel.)
Airis Elite:	$\Delta B_0 = 0.104$ ppm * Max(Rel.) – Min(Rel.)
Altaire:	$\Delta B_0 = 0.068$ ppm * Max(Rel.) – Min(Rel.)

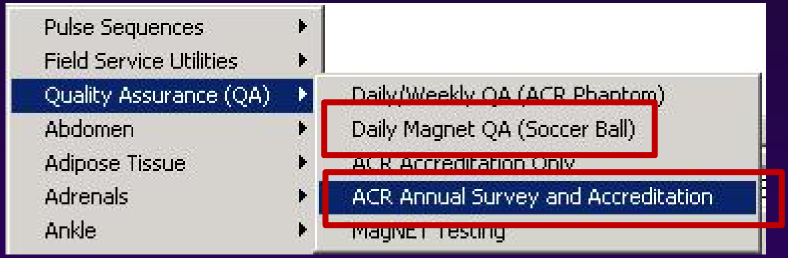
Determine largest $\Delta B_{0,pp}$ value among all slices from each of three planes and compare to specifications:

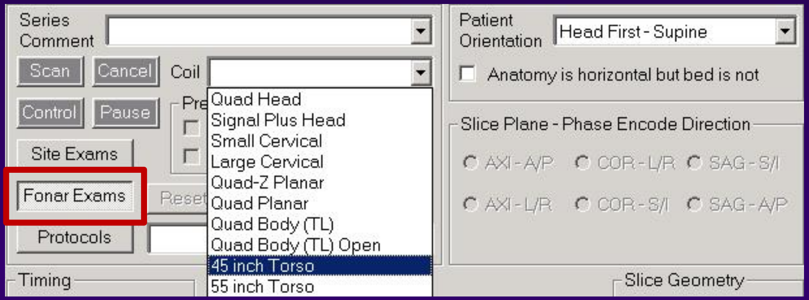
Airis 2:	$\Delta B_0 \leq 1.5$ ppm
Airis Elite:	$\Delta B_0 \leq 1.5$ ppm
Altaire:	$\Delta B_0 \leq 1.75$ ppm

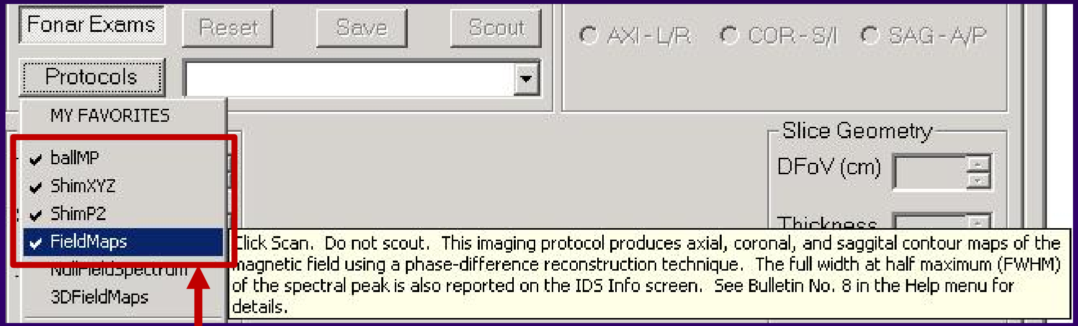
Fonar: Field map procedure

- Accessible field map function
- Phantom: 19 cm soccer ball!
- Coil: 45 inch torso belt coil



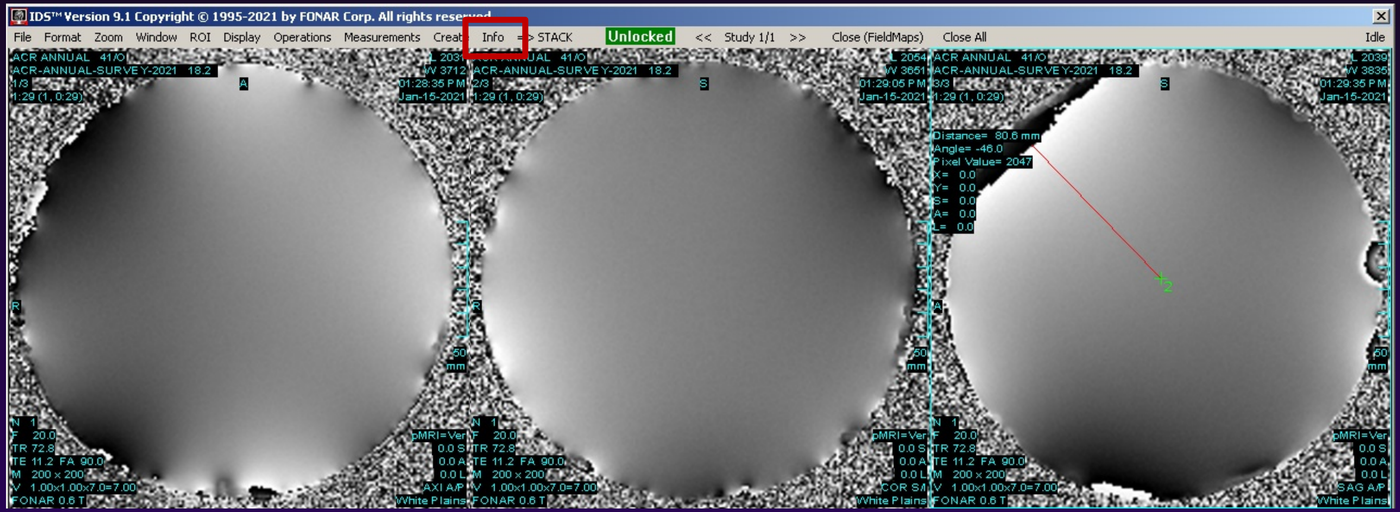






Run these in order

Fonar: Field map results



- Echo spacing such that phase wraps are 1.0ppm apart
- Center of volume always scaled to middle of greyscale range

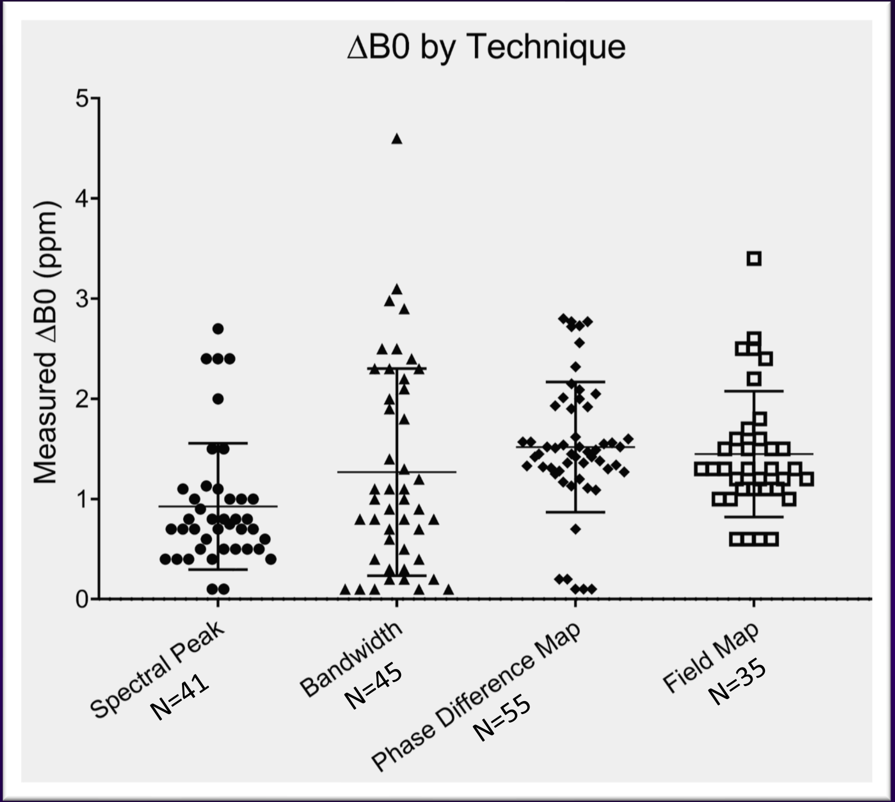
SEQUENCE; PROTOCOL	....	ge5.0RF3.7PE; Fonar\FieldMaps
DESCRIPTOR	....	SSFP-FID GRE: Hz/pix=50.03, B0 Sensitivity 1.0 ppm, EF=67%; FWHM=14 Hz
OPERATING MODE	....	Normal
RECEIVER COIL	....	45 inch Torso
PRE-SCAN CALIBRATIONS	....	C--G
TUNING VARACTORS (V)	....	1.05
TRANSMITTER GAIN	....	Power Amp=30 (default=30)
RECEIVER GAIN	....	Coarse=(-, -) Fine=(575, -)
CENTER FREQUENCY (Hz)	....	25474000
PHASE OVERSAMPLING RATIO (RFoV)	....	1.000
ACQUISITION MATRIX (f x ø)	....	1024 x 200 (For ACR: Nf = 200, Np = 200)
RECONSTRUCTION MATRIX (f x ø)	....	1024 x 200
DISPLAY & STORAGE MATRIX (f x ø)	....	200 x 200

Toshiba, Hitachi, Fonar

Vendor	Method	Availability and accessibility	Immediately actionable by vendor	Provides spatial information	Quick results at workstation
Toshiba	*Phase difference*	+	+	~	+
Hitachi (Oasis, Echelon)	*Fine magnetic field analysis*	+	+	~	+
Hitachi (AIRIS, Altaire)	*SHIM*	+	+	-	+
Fonar	*Field map*	+	+	+	+

Typical values

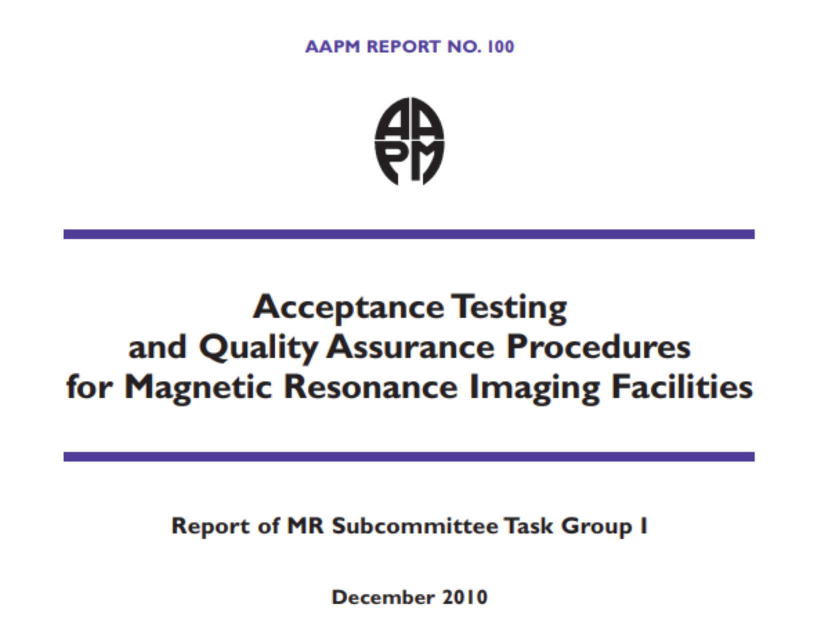
- Gathered from past annual & acceptance tests from TG325 members



Test method and phantom size	Mean of archived data (ppm)	SD of archived data (ppm)
Spectral peak (<30cm)	0.62 (RMS)	0.36
Spectral peak (≥30cm)	1.07 (RMS)	0.69
Phase difference	1.53 (PP)	0.65
Field map	1.45 (PP)	0.63
Bandwidth difference	1.26 (PP)	1.01

More Resources: AAPM Report 100

- Details sources and impacts of poor homogeneity
- Overview of 3 measurement methods
- Advantages and disadvantages of each
- Suggested acceptance criteria for routine and ultrafast imaging



AAPM REPORT NO. 100

Acceptance Testing
and Quality Assurance Procedures
for Magnetic Resonance Imaging Facilities

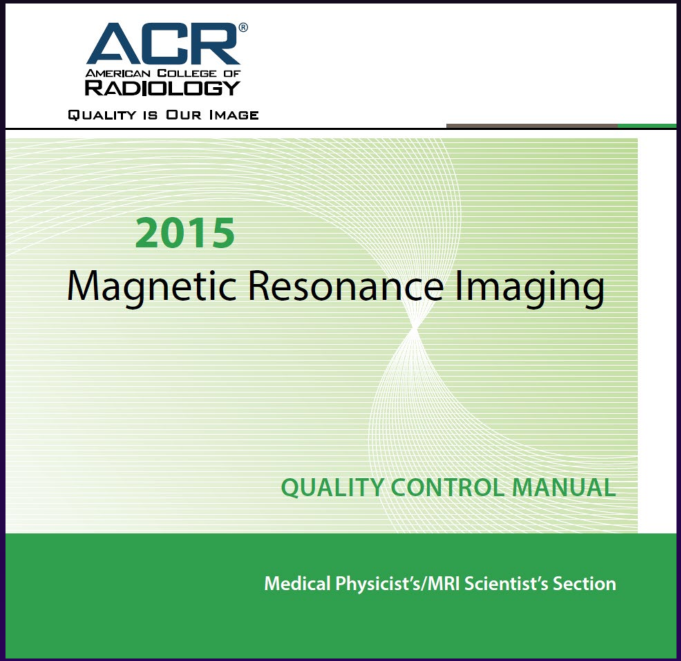
Report of MR Subcommittee Task Group I

December 2010

https://www.aapm.org/pubs/reports/RPT_100.pdf

More Resources: ACR MRI QC Manual

- ACR-specific requirements for B_0 testing
- General theory behind homogeneity testing
- Detailed vendor agnostic descriptions of 4 measurement methods
- Suggested corrective action



https://www.acr.org/-/media/ACR/NOINDEX/QC-Manuals/MR_QCManual.pdf

More Resources

- **Bandwidth difference method:** Chen HH, Boykin RD, Clarke GD, Gao JHT, Roby JW. Routine testing of magnetic field homogeneity on clinical MRI systems. *Med Phys* 2006 33(11)

Routine testing of magnetic field homogeneity on clinical MRI systems

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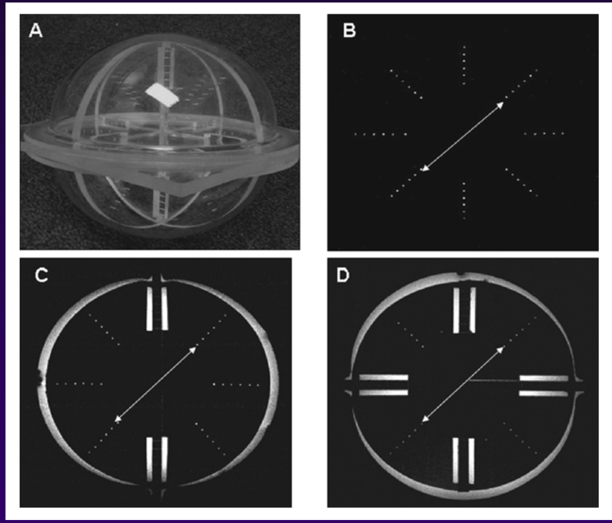

More Resources

MRI Resources website accessible to AAPM members: https://w3.aapm.org/pubs/MRIResources/

Part 1: Motivation & introduction to B0 homogeneity measurement methods

Part 2: Step-by-step homogeneity measurement methods – multiple methods on multiple vendors

Part 3: Typical homogeneity values based on historical results from TG325 members (community contribution encouraged)