NatMEG

the Swedish National Facility for Magnetoencephalography

Data preprocessing using MaxFilter™

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In collaboration with





Learning goals

- 1. To explain what types of artefacts and interference exist in MEG data
- 2. To describe the basics of **signal space separation (SSS)** –based methods for
 - a. Artefact and interference suppression
 - b. Head position tasks: transformation and movement correction
- 3. To **apply these methods** by running MaxFilter[™] software
 - a. Which method(s) to select for what kind of a data set



Outline of the presentation

- Artifact and interference in MEG data
- Introduction to MaxFilter[™] software
- Artefact and interference suppression
 - Internal Active Shielding (IAS)
 - Signal Space Separation (SSS)
 - Temporal extension of Signal Space Separation (tSSS)
- Head position tasks
 - Head position tracking
 - Head position transformation
 - Head movement correction
- Guidelines for method selection in MaxFilter[™] processing



Structure of the presentation

- Theory lecture
- Practice using MaxFilter[™] demo
- Example using MEG data demo

Disclaimer

- The section "Head movement tasks" in this module includes information about methods for
 - head position transformation and
 - head movement correction
 - that are not available for clinical use in US (MaxFilter-US version)



Artifact and interference in MEG data

Learnign goal 1



Artifacts and interference in the MEG

- External magnetic interference
 - traffic, elevators, ...
- Physiological artifacts
 - blinks, saccades
 - cardiac activity
 - muscular activity
- Non-physiological close-by artifacts
 - movement (typically with breathing, ballistocardiogram) of metallic objects in the body, e.g., dental work, surgical residuals, jewellery
 - stimulators
- Sensor-specific artifacts
 - signal "jumps" (e.g. due to flux traps)
 - excess sensor noise





Introduction to MaxFilter™ software

Learning goal 3 begins



Introduction to MaxFilter[™] software

- MaxFilter[™] software (Elekta Oy, Finland) is MEG data preprocessing tool for suppression of external and close-by artifacts, and for head movement compensation
- Current software version MaxFilter[™]-2.2 (2012)
- GUI & command line tool (for scripting the analysis) available
- As an input, requires continuous FIFF-format MEG data
- Outputs data file in FIFF-format, original file remains untouched
- Head movement compensation not available in MaxFilter[™]-2.2 US-version
- Note; only parameters and selections relevant for the routine work and that might require change from the default settings are introduced here



Interference suppression

Learning goal 2 a



Basics of interference suppression (1/2)

- Hardware shielding
 - Passive shielding; Magnetically shielded room (MSR)
 - Active shielding; External (EAS) and Internal active shielding (IAS)
- Software shielding
 - Signal space projection (SSP)
 - Signal space separation (SSS)
 - Independent component analysis (ICA)

• ...

Basics of interference suppression (2/2)

- Careful, artefact-free measurement setup recommended
- However, MEG signals are distorted even in ideal environment due to, e.g., hardware inaccuracies
- The signal quality can be enhanced by appropriate signal processing
- The MEG signal is a combination of the pure brain signal and interference => the task is to suppress the interference as much as possible, which requires its accurate measurement
- The signal model should contain the smallest number of parameters that are capable of explaining the data at a given signal-to-noise ratio



Introduction to Signal Space Separation (SSS) –based methods



- SSS separates the magnetic field originating from the external sources (i.e. outside of the sensor helmet) from fields originating from inside the sensor helmet
- Suppresses the external magnetic field (Taulu et al. 2004, 2005, 2006)
- In case of patient/subject related (close-by) artifacts, temporal extension of SSS, tSSS, is used to suppress the close-by artifact in addition to external magnetic fields (Taulu and Simola 2006)
- Head position with respect to sensors can be changed, for whole data file (head position transformation) or for each time point separately (movement correction)
- All these SSS- based processing steps require sufficient number of channels measuring magnetic field (i.e., no saturation has happened)

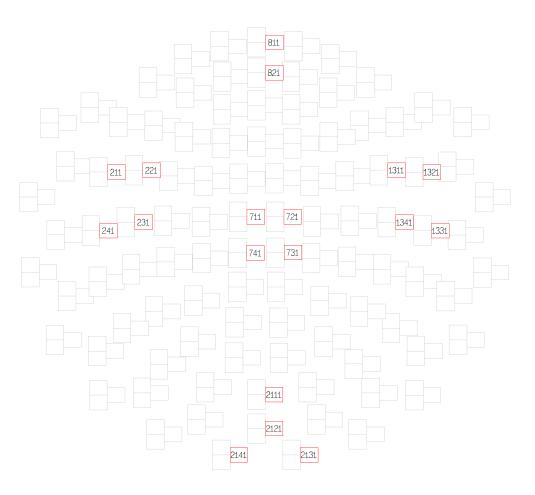


Internal Active Shielding (1/5)

- Internal active shielding can be used to compensate external magnetic fields, especially when single-layer MSR is used
- Aim is to ensure that the channels, especially magnetometers, stay in their dynamic range and measure magnetic fields, i.e, they do not saturate due to the external interference
- Magnetic fields are measured with set of magnetometers



Internal Active Shielding (2/5)





Internal Active Shielding (3/5)

- Feedback coils located at the walls of the MSR are used to produce the compensating magnetic field
- Also some brain-originated might be accidentally suppressed by this procedure
- Thus, the compensating fields need to be cancelled before the data analysis
- SSS suppresses all external magnetic field, also the ones created by the compensation coils, resulting signal where external and compensation fields are suppressed
- It is obligatory to always utilize SSS or tSSS when data have been measured with IAS on



Internal Active Shielding (4/5)

• IAS is turned ON/OFF from the DACQ channel selection window

Acquisition: control	_ 🗆 🗙												
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Stopwatch EEG calibration													
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No responses averaged.													
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EEG013	EEG014	EEG015	EEG016	EEG017	EEG018	EEG019	EEG020	EEG021	EEG022	EEG023	EEG024	EEG025	EEG026	EEG027	EEG028	EEG029	EEG030	EEG031	EEG032	EEG033	EEG034	EEG035	EEG036
EEG037	EEG038	EEG039	EEG040	EEG041	EEG042	EEG043	EEG044	EEG045	EEG046	EEG047	EEG048	EEG049	EEG050	EEG051	EEG052	EEG053	EEG054	EEG055	EEG056	EEG057	EEG058	EEG059	EEG060
EEG061	EEG062	EEG063	EEG064	EEG065	EEG066	EEG067	EEG068	EEG069	EEG070	EEG071	EEG072	EEG073	EEG074	EEG075	EEG076	EEG077	EEG078	EEG079	EEG080	EEG081	EEG082	EEG083	EEG084
EEG085	EEG086	EEG087	EEG088	EEG089	EEG090	EEG091	EEG092	EEG093	EEG094	EEG095	EEG096	EEG097	EEG098	EEG099	EEG100	EEG101	EEG102	EEG103	EEG104	EEG105	EEG106	EEG107	EEG108
EEG109	EEG110	EEG111	EEG112	EEG113	EEG114	EEG115	EEG116	EEG117	EEG118	EEG119	EEG120	EEG121	EEG122	EEG123	EEG124	EEG125	EEG126	EEG127	EEG128	EXCI	IASX+	IASX-	IASY+
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MEG0622	MEG0623	MEG0631	MEG0632	MEG0633	MEG0641	MEG0642	MEG0643	MEG0711	MEG0712	MEG0713	MEG0721	MEG0722	MEG0723	MEG0731	MEG0732	MEG0733	MEG0741	MEG0742	MEG0743	MEG0811	MEG0812	MEG0813	MEG0821
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	MEG1443			MEG1513			MEG1523	MEG1531		MEG1533	MEG1541	MEG1542		MEG1611	MEG1612			MEG1622		MEG1631	MEG1632		MEG1641
MEG1642		MEG1711		MEG1713 MEG1913		MEG1722 MEG1922		MEG1731 MEG1931	MEG1732 MEG1932		MEG1741 MEG1941	MEG1742 MEG1942	MEG1743	MEG1811 MEG2011	MEG1812	MEG1813 MEG2013	MEG1821 MEG2021	MEG1822		MEG1831 MEG2031	MEG1832	MEG1833	MEG1841 MEG2041
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MEG2242				MEG2313		MEG2322		MEG2331	MEG2332		MEG2341	MEG2342		MEG2211	MEG2412		MEG2421	MEG2422		MEG2431	MEG2432	MEG2433	MEG2241
MEG2442		MEG2511		MEG2513	MEG2521	MEG2522	MEG2523	MEG2531	MEG2532	MEG2533	MEG2541	MEG2542	MEG2543	MEG2611	MEG2612		MEG2621	MEG2622	MEG2623	MEG2631	MEG2632	MEG2633	MEG2641
MEG2642		MISC001	MISC002	MISC003	MISC004	MISC005	MISC006	MISC007	MISC008	MISC009	MISC010	MISC011	MISC012	STI001	ST1002	STI003	STI004	ST1005	ST1006	STI007	ST1008	ST1009	STI010
STI011	STI012	STI013	STI014	STI015	STI016	STI101	STI102	SYS101	SYS201														
Number of	channels =	319																					
Commands	5:																						
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Internal Active Shielding (5/5)

• How to know the IAS has been ON/OFF? Elekta software will warn you if data has been measured with IAS on but not been SSS-processed

Basics of interference suppression

- Hardware shielding
 - Passive shielding; Magnetically shielded room (MSR)
 - Active shielding; External (EAS) and Internal active shielding (IAS)
- Software shielding
 - Signal space projection (SSP)
 - Signal space separation (SSS)
 - Independent component analysis (ICA)

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Signal space separation (1/6)

- SSS method [Taulu et al. 2004, 2005, 2006] is based on
 - the quasistatic approximation of Maxwell's equations [see e.g. Hämäläinen 1993]

$$\nabla \cdot \mathbf{B} = 0,$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J}.$$

and

• the fact that there are no sources in the space where the sensors are located, leading to

$$\nabla \times \mathbf{B} = 0.$$



Signal space separation (2/6)

- Magnetic field can be expressed as a gradient of a harmonic scalar potential V: $\mathbf{B}=-\mu_0\nabla V,$
- V satisfies Laplace's equation $\nabla^2 V = 0$ which has series-form solution

$$V(\mathbf{r}) = \sum_{l=1}^{\infty} \sum_{m=-l}^{l} \alpha_{lm} \frac{Y_{lm}(\theta,\varphi)}{r^{l+1}} + \sum_{l=1}^{\infty} \sum_{m=-l}^{l} \beta_{lm} r^{l} Y_{lm}(\theta,\varphi)$$

l=1 m=-l

• Thus, the measured signal vector also has series-form presentation $\phi = \sum_{l=1}^{L_{in}} \sum_{l=1}^{l} \alpha_{lm} \mathbf{a}_{lm} + \sum_{l=1}^{L_{out}} \sum_{l=1}^{l} \beta_{lm} \mathbf{b}_{lm}$

l=1 m=-l



Signal space separation (3/6)

- The default model orders $L_{in} = 8$ and $L_{out} = 3$, for internal and external expansion, respectively, are known to be sufficient for modeling the spatial frequencies present in the data with currently measured SNR [Ahonen et al. 1993]
- Matrix representation:

$$\begin{split} \boldsymbol{\phi} &= \mathbf{S}\mathbf{x} = [\mathbf{S}_{\text{in}} \ \mathbf{S}_{\text{out}}] \begin{bmatrix} \mathbf{x}_{\text{in}} \\ \mathbf{x}_{\text{out}} \end{bmatrix} = \boldsymbol{\phi}_{\text{in}} + \boldsymbol{\phi}_{\text{ou}} \\ \mathbf{S}_{\text{in}} &= [\mathbf{a}_{1,-1} \dots \mathbf{a}_{L_{\text{in}}L_{\text{in}}}] \\ \mathbf{S}_{\text{out}} &= [\mathbf{b}_{1,-1} \dots \mathbf{b}_{L_{\text{out}}L_{\text{out}}}] \\ \mathbf{x}_{\text{in}} &= [\alpha_{1,-1} \dots \alpha_{L_{\text{in}}L_{\text{in}}}]^{\text{T}} \\ \mathbf{x}_{\text{out}} &= [\beta_{1,-1} \dots \beta_{L_{\text{out}}L_{\text{out}}}]^{\text{T}}. \end{split}$$



Signal space separation (4/6)

• Dimension of the SSS basis $n = (L_{in} + 1)^2 + (L_{out} + 1)^2 - 2$ is smaller than the number of channels in modern multichannel devices -> unique decomposition into internal biomagnetic and external interference components: $\hat{\mathbf{x}} = \begin{bmatrix} \hat{\mathbf{x}}_{in} \end{bmatrix} = \mathbf{S}^{\dagger} \phi$

$$\hat{\mathbf{x}} = egin{bmatrix} \hat{\mathbf{x}}_{ ext{in}} \ \hat{\mathbf{x}}_{ ext{out}} \end{bmatrix} = \mathbf{S}^{\dagger} oldsymbol{\phi}$$

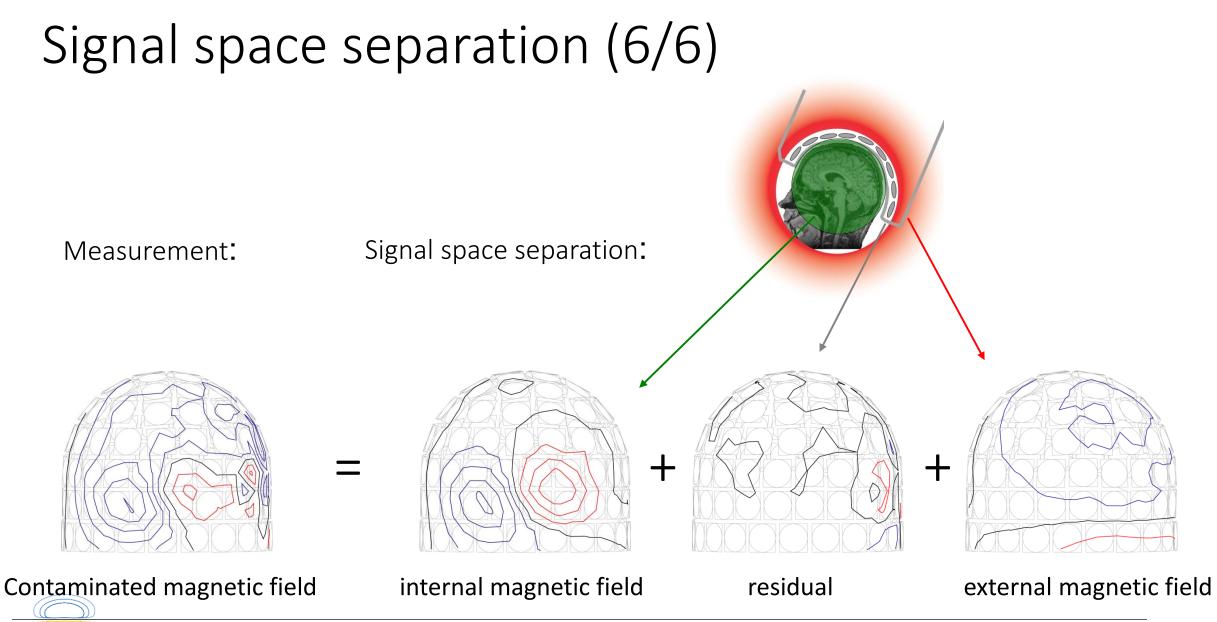
- Number of degrees of freedom using default $L_{\rm in}$ and $L_{\rm out}$ parameters is 95
- SSS is purely spatial operation, no dependence on time



Signal space separation (5/6)

- SSS requires accurate knowledge of the sensor array and its geometry, sensor calibration
- Model is created using all magnetometers and gradiometers, only excluding the channels where the signal does not present magnetic fields, e.g., very noisy or artefact-contaminated channels
- Channels excluded from the model are estimated in the location of original sensors in the processing. Thus, there are always 306 MEG channels in the resulting data





tSSS Basics (1/2)



- In case of close-by artifacts, sources are not purely external and SSS will not suppress them
- Close-by artifacts leak in to both basis, internal and external, and are visible also in signal that is not explained by the model, i.e., residual signal
- Temporal extension of SSS (tSSS):
 - 1. Basic SSS
 - 2. Estimation of the internal, external and residual signals
 - 3. Correlation between internal multiple moments and residual signal
 - 4. If similar temporal waveform found, i.e., correlation stronger than preset threshold, signal is regarded as external origin
 - 5. Correlated temporal waveforms projected out from the SSS-processed data

tSSS Basics (2/2)

- tSSS requires certain time window and cannot be performed for a single time point only
- tSSS works in temporal segments; the number of projected components is data-dependent and can changes over time from window to window
- When no close-by artifacts are present in the data, tSSS reduces to SSS



Head position tasks

Learning goal: 2 b



Head position tracking (1/1)

- The relation between the head and the sensor array is determined with the help of HPI coils
- If continuous HPI (cHPI) is **not** measured, head position is assumed to be stationary
- In cHPI measurement, HPI coils are activated continuously, at coilspecific high-frequency signals (typ. 290–330 Hz)
- Signals reflecting the coil locations, and therefore the head location, are thus embedded in the raw MEG data



Head position transformation (1/1)

- In basic SSS processing, sensor-level signals are presented as multipole moments that are not dependent on the sensor locations.
- The internal part of the magnetic field is transformed back to the sensor level. However, the transformation to the sensor space doesn't need to be the same, but other head position with respect the sensor can be used
- Typically head position transformation is performed to
 - Default (standard) head position (to compare sensor-level data between subjects or patients)
 - Head position of another recording (to compare different measurement sessions of the same subject or patient)
- Reconstruction noise can occur in large head-position transformations. Thus, large transformations are typically not recommended
- If source modelling is performed on individual recordings, there is no need to do head position transformation



Head movement correction (1/2)

- Head movement correction can be used if continuous HPI (cHPI) is **on** during the measurement
- The head movement correction works the same way as the head position transformation; however, the transformation is performed to each data sample separately, taking into account the estimated head position at that time point
- After estimation of the head position, the HPI coil signals are subtracted from the data. If a residual still remains, low-pass filtering can be applied



Head movement correction (2/2)

- The position where the head is transformed in the movement compensation can be selected to be
 - initial head position from the file
 - standard head position
 - head position from a separate fiff-file
 - average head position of a fiff-file (requires 2 steps to produce this)
- As reconstruction noise can be introduced in large transformation, the initial head position or the average head position are typically recommended options



Guidelines for method selection in MaxFilter[™] processing

Learning goal 3 a



Recommendations on how to select parameters for MaxFilter[™] processing (1/2)

- Choosing weather to apply (t)SSS?
 - IAS ON during recording?
 - YES -> SSS or tSSS required
 - NO -> SSS or tSSS not required but recommended
- Choosing between SSS and tSSS?
 - external artifacts only?
 - YES -> use SSS (tSSS also possible)
 - also close-by artifacts or artifacts originating inside the sensor helmet?
 - YES -> use tSSS



Recommendations on how to select parameters for MaxFilter[™] processing (2/2)

- Selecting between head position tasks?
 - cHPI ON during recording?
 - YES -> use head movement compensatation
 - NO -> not possible to use head movement compensation
 - If movement compensation selected, does the initial head position represent well the overall head position in the data file?
 - YES -> head position transformation to the initial head position
 - NO -> head position transformation to the average head position
 - sensor-level comparison of different data sets planned?
 - YES -> use head position transformation to align the data sets
 - NO -> no head position transformation needed



Summary

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- To describe the basics of signal space separation (SSS) –based methods for
 - Artefact and interference suppression
 - Head position tasks: transformation and movement correction
- To **apply these methods** by running MaxFilter[™] software
 - Which method(s) to select for what kind of a data set

