



## King's Research Portal

### *Document Version*

Early version, also known as pre-print

[Link to publication record in King's Research Portal](#)

### *Citation for published version (APA):*

Malik, S. (2015). Optimized Amplitude Modulated Multi-Band RF pulses. In *Proceedings of International Society for Magnetic Resonance in Medicine* (pp. 2398)

### **Citing this paper**

Please note that where the full-text provided on King's Research Portal is the Author Accepted Manuscript or Post-Print version this may differ from the final Published version. If citing, it is advised that you check and use the publisher's definitive version for pagination, volume/issue, and date of publication details. And where the final published version is provided on the Research Portal, if citing you are again advised to check the publisher's website for any subsequent corrections.

### **General rights**

Copyright and moral rights for the publications made accessible in the Research Portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognize and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the Research Portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the Research Portal

### **Take down policy**

If you believe that this document breaches copyright please contact [librarypure@kcl.ac.uk](mailto:librarypure@kcl.ac.uk) providing details, and we will remove access to the work immediately and investigate your claim.

**Optimized Amplitude Modulated Multi-Band RF pulses**

Shaihan J Malik<sup>1,2</sup>, Anthony N Price<sup>2</sup>, and Joseph V Hajnal<sup>1,2</sup>

<sup>1</sup>Division of Imaging Sciences and Biomedical Engineering, Kings College London, London, United Kingdom, <sup>2</sup>Centre for the Developing Brain, Kings College London, London, United Kingdom

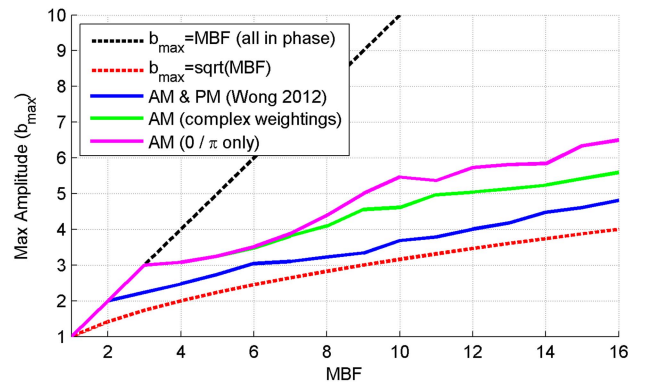
**Target Audience** RF pulse designers and sequence developers working with multi-band RF

**Purpose** Parallel imaging using Multi-band (MB) RF excitation<sup>1</sup> has found much recent interest for accelerated image acquisition. MB RF pulses are generally created by applying a periodic modulation function to pre-existing RF pulse waveforms, resulting in the replication of multiple aliases of the original slice profile to desired locations. A problem is that if implemented in the most straightforward way, the peak amplitude of the modulation function scales with the multi-band factor (MBF; the number of simultaneously excited slices) quickly violating peak RF power constraints of most MR systems. To mitigate this issue Wong<sup>2</sup> showed that the phase of each slice can be optimized independently in order to produce a modulation function whose peak amplitude is much lower than MBF. This approach has been combined with time-shifting to further reduce the peak amplitude<sup>3,4</sup>. An issue is that the resulting MB RF pulses have rapid modulation in both amplitude and phase. Accurate reproduction of this modulation can be problematic. Depending on the hardware, faithful reproduction of rapid phase modulation can be more error prone than amplitude modulation, especially on systems that require frequency rather than phase modulation to be defined by the pulse designer. These issues can be sidestepped if pulses are amplitude modulated (AM) only; in this work we identify optimal phases that lead to strictly AM MB pulses and compare them with the more general solutions requiring amplitude and phase modulation (AM & PM) provided by Wong.

$$b(t) = \sum_j^{MBF} \exp \{i(\gamma G x_j t + \phi_j)\} \quad \text{Eq.1}$$

**Methods** The modulation function  $b(t)$  required to produce slices at locations  $x_j$  with gradient  $G$  is given by Eq.1<sup>2</sup>; phase offsets  $\phi_j$  are to be optimized so as to **minimize** the maximum of the modulation function  $b_{max} = \max\{b(t)\}$ . Given the Fourier relationship between slices and RF waveforms, we can guarantee that  $b(t)$  will be purely real if the phase offsets have conjugate symmetry. Assuming that the slices are distributed symmetrically around a central location  $x=0$  we can form pairs of slices that are equidistant from  $x=0$  (if MBF is odd then the central slice is at location  $x=0$  and is treated independently of the others). Each pair is assigned a phase offset  $\psi$  with one slice taking phase  $+\psi$  and the other  $-\psi$ . A special case is where only real modulations are applied to each slice, in which case each pair of slices is either assigned phase 0 or  $\pi$ . Optimal phase offsets were computed using MATLAB's `fmincon` function with multiple random initializations for MBF 1 to 16.

**Results** The graph plots  $b_{max}$  for each MBF. Reductions in  $b_{max}$  are possible for  $MBF > 3$ ; the optimal phases for  $MBF=4$  to 12 are given in the table.



**Discussion & Conclusions** As might be expected, the AM solutions do not reduce  $b_{max}$  as much as full AM&PM. However large reductions are still generally obtained, particularly for higher MBFs. For example for  $MBF=8$ ,  $b_{max}$  can be reduced from 8 to 4.09 by using an optimized AM pulse, then further to 3.23 for optimal AM&PM modulation (49% reduction compared with 60%). For  $MBF > 9$  the reduction in  $b_{max}$  achieved with AM only pulses is greater than 50%. For low MBF (<6) it is sufficient to only offset slices by 0 or  $\pi$  (pink curve), while for higher factors, phase conjugate solutions are beneficial. The identified optimal phases will be useful for situations where phase or frequency modulation is technically difficult or less stable than AM only.

**References** [1] Larkman DJ, et al. JMRI 13:313-317, 2001. [2] Wong E. Proc ISMRM 2012 p2209. [3] Feinberg DA, et al. PLoS one 5(12):e15710, 2010. [4] Auerbach EJ, et al. MRM 69:1261-7, 2013.

MBF	$\phi / \text{rad}$												$b_{max}$	
	0	$\pi$	$\pi$	0										
4	0	$\pi$	$\pi$	0										3.079
5	0	0	$\pi$	0	0									3.250
6	1.691	2.812	1.157	-1.157	-2.812	-1.691								3.477
7	2.582	-0.562	0.102	0	-0.102	0.562	-2.582							3.814
8	2.112	0.220	1.464	1.992	-1.992	-1.464	-0.220	-2.112						4.090
9	0.479	-2.667	-0.646	-0.419	0	0.419	0.646	2.667	-0.479					4.553
10	1.683	-2.395	2.913	0.304	0.737	-0.737	-0.304	-2.913	2.395	-1.683				4.614
11	1.405	0.887	-1.854	0.070	-1.494	0	1.494	-0.070	1.854	-0.887	-1.405			4.974
12	1.729	0.444	0.722	2.190	-2.196	0.984	-0.984	2.196	-2.190	-0.722	-0.444	-1.729		5.045