AUSTRALIAN RESEARCH COUNCIL
Discovery - Projects
Proposal for Funding Commencing in 2015

DP

PROJECT ID: DP150101011

First Investigator: Prof Rodney Kennedy

Admin Org: The Australian National University

Total number of sheets contained in this Proposal: 71

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CERTIFICATION

Certification by the Deputy/Pro Vice-Chancellor (Research) or their delegate or equivalent in the Administering Organisation

I certify that—

- I have read, understood and complied with the ARC*Funding Rules for schemes under the Discovery Program for the years 2014 and 2015*, read in conjunction with *Part C - Scheme-specific rules for Discovery Projects for funding commencing in 2015*, and to the best of my knowledge all details provided in this Proposal form and in any supporting documentation are true and complete in accordance with these Funding Rules.
- Proper enquires have been made and I am satisfied that the Participants and the organisations listed in this Proposal meet the requirements specified in the ARC *Funding Rules for schemes under the Discovery Program for the years 2014 and 2015*, read in conjunction with *Part C - Scheme-specific rules for Discovery Projects for funding commencing in 2015*. I will notify the ARC if there are changes to any named Participant or organisation after the submission of this Proposal.
- To the best of my knowledge, all Conflicts of Interest relating to parties involved in or associated with this Proposal have been disclosed to this Administering Organisation, and, if the Proposal is successful, I agree to manage all Conflicts of Interest relating to this Proposal in accordance with the *Australian Code for the Responsible Conduct of Research* (2007).
- I have obtained the agreement, attested to by written evidence, of all the relevant participants and organisations necessary to allow the Project to proceed. This written evidence has been retained and will be provided to the ARC if requested.
- This Proposal is not substantially aimed at understanding or treating a human disease or health condition (as per the ARC definition of Medical and Dental Research located on the ARC website).
- This Proposal does not duplicate Commonwealth-funded research including that undertaken in a Commonwealth-funded Research Centre.
- If this Proposal is successful, I am prepared to have the Project carried out as set out in this Proposal and agree to abide by the terms and conditions of the ARC *Funding Rules for schemes under the Discovery Program for the years 2014 and 2015*, read in conjunction with *Part C - Scheme-specific rules for Discovery Projects for funding commencing in 2015* and the ARC *Discovery Projects Funding Agreement for funding commencing in 2015*.
- The Project can be accommodated within the general facilities in this organisation and, if applicable, within the facilities of other relevant organisations specified in this Proposal, and sufficient working and office space is available for any proposed additional staff.
- All funds for this Project will only be spent for the purpose for which they are provided.
- The Project will not be permitted to commence until appropriate ethical clearance(s) has/have been obtained and all statutory requirements have been met.
- I consent, on behalf of all the parties, to this Proposal being referred to third parties, who will remain anonymous, for assessment purposes.
- I consent, on behalf of all the parties, to the ARC copying, modifying and otherwise dealing with information contained in this Proposal.
- To the best of my knowledge, the Privacy Notice appearing at the top of this form has been drawn to the attention of all the Participants whose personal details have been provided at the Personnel section.

PART A - Administrative Summary (DP150101011)

A1. If this proposal is successful, which organisation will it be administered by?

Administering Organisation Name

The Australian National University

A2. Proposal Working Title

(Provide a short descriptive title of no more than 75 characters (approximately 10 words). Please refer to the Instructions to Applicants for further information.)

Harnessing Spherical Geometry in Scientific and Engineering Data Processing

A3. Person Participant Summary

	Person number	Family name	First name	Current organisation
1	1	Kennedy	Rodney	The Australian National University
2	2	Durrani	Salman	The Australian National University
3	3	McEwen	Jason	University College London

	Relevant organisation for this proposal	Role
1	The Australian National University	Chief Investigator
2	The Australian National University	Chief Investigator
3	University College London	Partner Investigator

A4. Organisation Participant Summary

	Organisation number	Short name	Name	Role
1	1	ANU	The Australian National University	Administering Organisation
2	2	UCL	University College London	Other Organisation

A5. Proposal Summary

(Provide a written Proposal summary of no more than 750 characters (approximately 100 words) focussing on the aims, significance and expected outcomes and benefits of the project. Refer to Instructions to Applicants for further information.)

Spherical information underpins many natural phenomena, ranging from the distribution of galaxies in the Universe to the connectivity and neuronal activation in the human brain. Current major investments in scientific and medical instrumentation do not efficiently collect and process the massive amounts of data because they do not properly utilize its inherent spherical geometry.

Through harnessing spherical geometry, this project will address the above shortcomings and will provide advances across all these application domains. By collecting and processing data more efficiently, with greater fidelity, and by revealing features currently hidden, the methods developed will see the full benefit from the instrumentation capturing this data.

A6. Impact Statement

(In no more than 500 characters (approx 75 words), please outline the intended impact of the project. Refer to the Instructions to Applicants for further information.)

Through proper collection and processing of data with spherical geometry, we can reliably learn: how the Universe is evolving; or gauge the impact of melting polar ice sheets on sea-level rise; or assess whether a person is susceptible to Alzheimer's disease. These pressing problems link with our needs to understand where we come from; or how we can protect the environment; or how to improve the quality of life.

PART B - Classification and other statistical information (DP150101011)

B1. Strategic Research Priorities

Does this proposal fall within one of the Strategic Research Priorities?

(Refer to the Instructions to Applicants for further information.)

Strategic Research Priority Selected

No

Select which of the Strategic Research Priorities the proposal falls within, and one or more of the relevant Priority Goals for the designated Strategic Research Priority.

Not applicable for this candidate

B2. Field of Research (FOR)

	Field of Research (FOR)	Field of Research (FOR) Percent
1	090609 - Signal Processing	80
2	010399 - Numerical and Computational Mathematics not elsewhere classified	20

B3. Socio-Economic Objective (SEO-08)

	Socio Economic Objective (SEO)	Socio Economic Objective (SEO) Percent
1	970109 - Expanding Knowledge in Engineering	90
2	970102 - Expanding Knowledge in the Physical Sciences	10

B4. Keywords

	Keywords
1	Fast Algorithms
2	Transform Methods
3	Signal Processing

B5. If the proposed research involves international collaboration, please specify the country/ies involved.

	International Collaboration Country Name
1	United Kingdom
2	United States of America

C1. Please upload a Project Description as detailed in the Instructions to Applicants in no more than 10 A4 pages and in the required format.

Attached PDF

1. PROJECT TITLE

Harnessing Spherical Geometry in Data Collection and Processing: Foundational Methods for Diverse Scientific and Engineering Applications

2. AIMS AND BACKGROUND

2.1. Aims

Scientific analysis that takes into account the spherical geometry of the phenomenon in question is becoming increasingly important in many application domains, for example:

- The melting of polar ice sheets is a major contributor to global sea-level rise. Estimating the trends of the spatial distribution of (for example) Antarctica's ice mass loss can be recovered from processing satellite gravity data.
- The distribution of galaxies in the Universe is being provided by new generation of satellite surveys that will map large areas of the sky with unprecedented detail in many wavelengths. The revealed large scale structure informs our understanding of the Universe and how it is evolving.
- The neuronal pathways in the brain reveal the data highways and our thoughts in action with time. They are being mapped with increasing resolution as we refine our imaging technologies based on magnetic resonance imaging (MRI) and diffusion tensor imaging (DTI).
- The variation in the shape of hippocampus can indicate the likelihood of the presence Alzheimer's disease. Early diagnosis can have a significant impact on the quality of life of many afflicted aging Australians.

Each of these activities is important and merit priority research funding. But any fundamental advance to how we process and collects, through sampling, data captured with spherical geometry, has the potential for significant impact across all these application domains—we can process the data more quickly, cheaply, and accurately, we can ensure fidelity and reveal features hidden with the use of sub-optimal methods, and fully benefit from the expensive scientific instrumentation capturing this data. These advances are the province of Signal Processing.

In research into Signal Processing aspects this Proposal seeks to:

- develop *advanced, fast and robust* signal processing methods for data collected with spherical geometry (spherical signals) building on our recent published work organized as follows:
  - ▷ framework for the spatio-spectral analysis and development of *computationally efficient algorithms* for signal processing in the spherical harmonic and joint spatio-spectral domains;
  - ▷ *optimal* and *efficient* sampling schemes on the sphere and the rotation group with associated *fast* spherical harmonic transforms;
  - ▷ *efficient* signal representations and *robust* processing methods that respect signal *spatial anisotropy*, exploit *signal sparsity* and take into account *spin-valued* and *tensor-valued* signals; and
  - ▷ *low complexity* and *computationally efficient* kernel-based representations of spherical signals as an alternative to the higher dimensionality of spherical harmonic based methods.
- apply the developed tools in real world applications, especially to the processing of:
  - ▷ diffusion tensor imaging (DTI) and magnetic resonance imaging (MRI) data in neuorimaging,
  - ▷ head related transfer function (HRTF) measurements in acoustics, and
  - ▷ cosmic microwave background (CMB) data in cosmology.
- contribute to the development of the research area through building a *long term research capability within Australia* that connects to key European research centres, the research training of PhD students and postdoctoral/early career researchers.

2.2. Background

▷ **Why are spherical signals important?** Spherical signals permit the encoding of three dimensional directional information but represent a non-trivial departure from standard multi-dimensional euclidean-domain signals [1, pp.173–361]. They appear in many diverse, active and emerging applications, which require computationally efficient signal processing techniques for data analysis, such as:

- **Neuroimaging Data in Computational Neuroanatomy —** spherical directional data arises from magnetic resonance imaging (MRI) and diffusion tensor imaging (DTI) of the human brain. Such data enables the analysis of genetic variations in disordered brain function with an ultimate goal to improve early diagnosis. For example, the variation in the shape of hippocampus can indicate the presence Alzheimer's disease, see [2]. In another

example, the DTI measurements of the anisotropic water diffusion in white matter gives directional information of the neuronal pathways in the brain [3]. Our prior work that is relevant to this application can be found in [4,5].

- **CMB Observations in Cosmology —** the imprint of the early Universe in the form of CMB radiation as analysed in cosmology is a spherical signal [6]. The latest public release of CMB data is through the Planck satellite mission. Other projects driven by powerful new instruments under construction, such as the LSST (Large Synoptic Survey Telescope), MWA (Murchison Widefield Array), and SKA (Square Kilometer Array) will produce very large, high resolution data-sets on the celestial sphere. Our prior work that is relevant to this application can be found in [4–7].
- **Head Related Transfer Function in Acoustics —** the directional or angular portion of head related transfer functions (HRTF) in binaural sound representation is a spherical signal [8, 9]. Our prior work that is relevant to this application can be found in [8–10].
- **Gravitational Fields and Topography Data in Geophysics and Planetary Science —** Data representing the gravity models of Earth and topography on Earth or other rocky planet, moon, asteroid, etc., are spherical signals. Our prior work that is relevant to this application can be found in [11].

2.3. Research Challenges

It has been well-established that the Euclidean domain signal processing techniques are required to be reformulated for the analysis of spherical signals, [1, 4, 5, 7, 11–18].

We provide a short account of how one normally defines spherical signals and represents them in spherical harmonic basis as this will enable us to pose the key "Research Challenges" to be addressed in this project.

▷ **What are spherical signals and how are they represented using spherical harmonics?** "Spherical signals" is the shorthand terminology for signals whose domain is the 2-sphere or $\mathbb{S}^2$. Such spherical signals look like

$$f(\theta,\phi), \quad \text{such that} \quad \theta\in[0,\pi],\ \phi\in[0,2\pi),$$

where θ is the co-latitude (or elevation angle or declination but with zero at the north pole) and ϕ is the longitude (or azimuth or right ascension). This domain is shown in Figure 1. Generally we take the signal to be complex-valued but it can be spin- or tensor-valued depending on the application. We also use the shorthand $\widehat{\boldsymbol{x}}\equiv\widehat{\boldsymbol{x}}(\theta,\phi)$ so that a signal can be written $f(\widehat{\boldsymbol{x}})$, and the north pole $\widehat{\boldsymbol{\eta}}$ plays the role of the origin.

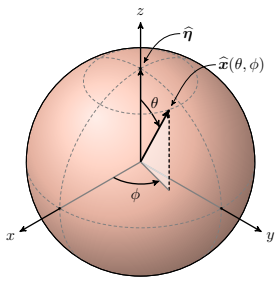

Figure 1: Spherical signal domain

The spherical harmonic representation of a finite energy signal (with natural inner product $\langle\cdot,\cdot\rangle$ on $\mathbb{S}^2$) is

$$\Big\{f(\widehat{\boldsymbol{x}})=\sum_{\ell,m}\langle f,Y_\ell^m\rangle Y_\ell^m(\widehat{\boldsymbol{x}})\colon \text{such that}\ \sum_{\ell,m}\big|\langle f,Y_\ell^m\rangle\big|^2<\infty\Big\}\iff f\in L^2(\mathbb{S}^2)\quad\begin{matrix}\text{(the space of finite}\\ \text{energy spherical signals)}\end{matrix}\qquad(1)$$

where $\langle f,Y_\ell^m\rangle$ is the complex-valued spherical harmonic (Fourier) coefficient of degree ℓ and order m, and constitutes the spectral domain representation (or spectrum) of a spherical signal.

▷ **Limitations with Current Spherical Signal Representations using Spherical Harmonics:** The limitation in the representation of spherical signal given in (1) is not from the use of spherical harmonics, $Y_\ell^m(\widehat{\boldsymbol{x}})$, but with the associated Hilbert space $L^2(\mathbb{S}^2)$ which can be described as the space of finite energy signals. As a space $L^2(\mathbb{S}^2)$ is *too big* — there are many functions in the space that as signals are never going to arise in practice. This constrains the performance of algorithms needed to compute the spherical harmonic coefficients because they need to handle all signal cases. This superfluous capability is a source of inefficiency when computing spectral representations:

> **Research Challenge 1:** *Find a spherical signal space, as an alternative to $L^2(\mathbb{S}^2)$, which is amenable to computationally efficient spectral representations and is well-matched to applications.*

▷ **Spatio-spectral Domain Signal Processing:** The joint spatio-spectral representation of spherical signals reveal information about the localized contribution of spectral components, which is not fully conveyed by either spatial or spectral domain representation of the signal [4,7]. In our earlier work, we have developed windowed spherical harmonic transform [7] in order to obtain the spatio-spectral representation of the signal, with added capability to differentiate localized directional features [4]. Such spatio-spectral representation enables the spatially varying spectral filtering [5] and is capable to deal with anisotropic processes on the sphere. The windowed spherical transform has been formulated in analogy with the STFT in time-frequency analysis. However, there is an important alternative that is captured by the following challenge:

Research Challenge 2: *Develop a general framework that is the analog of the well-known Cohen class of time-frequency distributions [19], which generalizes the famous Wigner-Ville distribution, for spatio-spectral representations of spherical signals to enable robust spatially varying filtering of anisotropic signals.*

▷ **Optimal Sampling Scheme:** The development of sampling schemes on the sphere and computationally efficient spherical harmonic transforms associated with the sampling schemes have have been a major theme of investigation for near two decades in the literature [14, 20]. However the existing schemes, which enable exact computation of the spherical harmonic transform, do not attain the minimal spatial dimensionality determined by the degrees of freedom in harmonic space. We summarize the research challenge as:

Research Challenge 3: *Develop a sampling scheme on the sphere that achieves the* minimal *spatial dimensionality and also supports an accurate and efficient computation of the spherical harmonic transform. Furthermore, refine the sampling scheme to where samples need to be taken in a spatially limited region only, to target applications in acoustics (HRTF) and cosmology (CMB), and extend the transforms to handle spin-valued or tensor-valued signals.*

▷ **Anisotropy, Sparsity and Compressed Sensing:** Anisotropy is a signal attribute which by and large does not exist in temporal signals. One can approach a point on the sphere from any direction and correspondingly a spherical signal may exhibit distinct directional features. The importance of such anisotropy can, for example, be gleaned in the naming of the famous Wilkinson Microwave Anisotropy Probe (WMAP). Although they are complete, spherical harmonics treat directional features impartially and therefore are a less effective representation for spherical signals exhibiting anisotropy. In a similar spirit the tools we need to develop should have a directional character [4, 11–13]. We summarize this as:

Research Challenge 4: *Find alternative spherical signal representations (to spherical harmonics) and associated directional signal processing techniques that enable superior and more efficient processing of anisotropic signals.*

Next, sparsity as a signal attribute opens the door for very significant reduction in complexity by employing methods from *Compressed Sensing* [21]. However, sparsity may not appear in a single orthonormal basis and best expressed with the tools of *over-complete bases or frames* [22, 23]. We summarize this as:

Research Challenge 5: *For spherical signals, what form sparsity should take, in which basis or sets of bases, what processing techniques one should use, and how does this vary across the target application? How does one treat simultaneously the issues of sparsity and anisotropy?*

The techniques in this Proposal relate directly to the applications, indeed many of the cited works above involve the joint work of the three investigators of this Proposal. The final research challenge draws on addressing the applications:

Research Challenge 6: *In order to better inform the further development of theory and design of algorithms, we aim to apply our methods to applications: analysis and acquisition of MRI/DTI in neuroimaging, anisotropic processing of CMB observations in cosmology and HRTF representation in acoustics.*

3. RESEARCH PROJECT

3.1. Significance

▷ **Addressing an important problem:** Based on the research challenges and background presented earlier, the central technical significance of the project is the development of fast and robust spherical signal processing techniques by taking into account:

- the *absence of simple analogy* from 1D and Euclidean Fourier techniques
- the difficulty to efficiently and *regularly sample* on the sphere [14]
- the sampling over spatially limited regions to meet the needs of cosmology and acoustics
- the *high dimensionality* of the conventional spherical harmonic representation of data
- the *high complexity joint spatio-spectral representations* [4, 5, 7]
- the importance of *anisotropy* as a spherical signal attribute
- the implications of the *tensor-valued* spherical signal attribute needed in applications
- the exploration of *spherical signal sparsity* and its exploitation

The consequence of a failure to properly account for these issues may result in false diagnosis of medical imaging data, flawed inference of cosmological data, etc., or certain studies may simply be computationally infeasible and well beyond the realm of real-time processing without fast and efficient algorithms.

▷ **Significance in advancing knowledge:** The research in the area of spherical signal processing has advanced in the engineering literature with the recent developments (e.g., [1, 4, 5, 7, 11–18]). However, it is still underdeveloped, compared to the maturity of research work in Euclidean domain signal processing. This project is significant because it targets this dearth in a realistically scoped suite of research investigations. By taking into account the requirements of applications in the development of computationally efficient and robust spherical signal processing techniques, the proposed project will (i) advance the knowledge in spherical signal processing, (ii) enable the analysis of anisotropic and tensor-valued forthcoming large data-sets, and (iii) promote the cross-disciplinary research.

3.2. Conceptual Framework of our Proposal

In broad brush terms our conceptual framework is as follows:

- to develop further sets of tools of a classical nature, that is, using the spherical harmonic transform and its derivatives, such as the spatio-spectral representations, and (directional) spherical wavelets, building on the recent results of the investigators;
- to design optimal sampling scheme, for spherical band-limited signals, which attains the limit on the spatial dimensionality given by the degrees of freedom in harmonic space and supports the efficient and accurate computation of spherical harmonic transform;
- to highlight a conceptual and practical weakness of the classical methods and develop alternative classes of representations such as based on kernels which should open up new efficient representations of spherical signals and processing algorithms; and
- to apply our methods to applications in neuroimaging, cosmology and acoustics, and close-the-loop to have the needs of the application drive the development of further theory, transforms and algorithms.

3.3. Novelty and Innovation

This project will advance the research in the area of spherical signal processing and serve the needs of computationally efficient and robust algorithms in the application areas. The outcomes of the project are expected to have a significant impact on the developments in the application area. For example, the development of new optimal sampling scheme, supported by computationally efficient, will lead the design of new data acquisition strategies in MRI and DTI. Another specific instance of innovation is the consideration of spin-valued or tensor-valued signals and anisotropy in the development of signal processing techniques, which will enable the analysis of current and forthcoming data-sets defined on the sphere. Further, the outcomes of the project will also promote the interaction between different disciplines, around common signal processing problems.

3.4. Approach and Methodology

▷ **Task/Effort Overview:** We break our work into three broad tasks, reflected in Table 1. The researcher team excluding the PhD students direct effort according to the portions in the table. The effort for each task is mentioned in Table 1.

Table 1: Time/Effort of CI-1, CI-2, RA and PI against Research Tasks.

Research Task	**2014**	**2015**	**2016**	**Total**
Task T1: Analysis in Spatio-Spectral domain and Optimal Sampling	0.4	0.4	0.2	1.0
Task T2: Spherical Signal Processing for Anisotropy and Sparsity	0.4	0.3	0.3	1.0
Task T3: Applications and Advanced Methods	0.2	0.3	0.5	1.0
Total:	1.0	1.0	1.0	3.0

Task T1: Analysis in Spatio-Spectral domain and Optimal Sampling

In broad terms this research task addresses *Key Research Challenges 2, 3, 4 and 6*:

- explore extensions of the new *spatio-spectral transform*, called the spatially localized spherical harmonic transform [5, 7], with respect to optimal and adaptive window design, and apply such advances to the application domains identified in this Proposal;
- develop more sophisticated spatio-spectral distributions, supported by computationally efficient algorithms, analogous to Cohen's class time-frequency distributions [19] with desirable properties and variety of applications;
- develop novel methods for both linear and non-linear filtering or estimation of the anisotropic signals and/or processes in the spatio-spectral domain;
- consider the design of optimal sampling scheme on the sphere and extension of optimal sampling scheme to the rotation group and higher dimensional spheres;
- development of computationally efficient algorithms to carry out the spherical harmonic transform [1], spatio-spectral transform [5, 7], and (directional) spherical wavelets [6, 12, 13, 24, 25];
- consider the extension of the conventional complex-valued transforms to the cases where the signal is *spin-valued* or is *tensor-valued*, as demanded in certain applications.

In the limited space here we will elaborate on just two of the investigations that we propose to study:

▷ **Optimal anisotropic filtering:** The optimal filters have been designed in either spatial or spectral domain [26], which takes into account the knowledge of the energy distribution (isotropic information) of the stochastic process on the sphere and is, therefore, not suitable for the filtering or estimation of anisotropic signal [27]. This motivated us to design optimal filter [28] in the spatio-spectral domain using the filtering framework [5], which enables the spatially varying spectral filtering of signals defined on the 2-sphere. We propose to apply the multiple window method used in time frequency analysis [29] for the improvement of performance of the optimal filter in the spatio-spectral domain. Furthermore, more generalized linear and non-linear filtering, taking into account the anisotropic properties of the signal, in spatio-spectral domain will also be investigated.

▷ **Optimal sampling:** Recently, in 2011, PI McEwen and Wiaux have proposed the most efficient sampling scheme on the 2-sphere using a regular equiangular grid of samples amenable to fast algorithms [14] beating the previous state of the art from 1994 [20]. They have also highlighted the advantages of the sampling theorem in the context of potential applications, notably in the field of compressive sampling [30]. However, there is a discrepancy between the dimensionality of the space of bandlimited spherical signals and the number of sampling points, and this leads to a research question proposed in this project. As a first step towards the design of of optimal sampling scheme on the 2-sphere which meets the dimensionality requirement, we will explore the reduction in the number of samples in the equiangular scheme while taking the accuracy, stability and efficient implementation of the associated spherical harmonic transform into account. Furthermore, the measurement of data is only feasible or reliable in spatially limited region in acoustics (where measurements are not reliable near south pole [9]) and cosmology (where observations are not available around the Galactic equator due to being blocked by the local Milky Way). With the consideration of this requirement, we will keep the provision in the design of the sampling schemes to support *sufficiently accurate* and *efficient* computation of spectral transforms using the measurements made over spatially limited region only.

▷ **Research questions for Task T1:**

- How can we formulate the **kernel based spatio-spectral representations** analogous to Cohen's class of time-frequency distributions, where the different choice of kernel gives rise to different representations?
- What are the the best methods, wavelet [11] or spatio-spectral [4, 5, 7], for **directional processing of anisotropic spherical signals** and how does one properly design and tune these analysis tools?
- How can one formulate the **spatially varying filtering** using different spatio-spectral representations of a signal for the filtering and estimation of **anisotropic** signal?
- Does there exist a set of **sampling points** on $\mathbb{S}^2$ at the dimensionality of the space of bandlimited spherical signals amenable to a **fast algorithm** to compute the spherical harmonic coefficients exactly?
- Is it possible to design **sampling schemes** for **sampling over the spatially limited regions** such that the transforms can be computed accurately or exactly?
- How the above explorations can be modified to incorporate **spin-valued** or **tensor-valued** signals, or to employ compressed sensing techniques when there is signal sparsity, to address problems including more efficient acquisition, denoising, extrapolation [31], inpainting [30] and deconvolution?

Task T2: Spherical Signal Processing for Anisotropy and Sparsity

This research task broadly addresses *Key Research Challenges 1, 4 and 5*:

- expose *limitations* of using spherical harmonics as the preferred basis for spherical signals,
- explore the use of *alternative spherical signal representations* to overcome such limitations,
- consider the systematic incorporation of *anisotropy* (lack of isotropy) into signal and filter design to better resolve anisotropic features
- consider the development of *sparse spherical signal representations* (in noise) and their recovery using the *Compressed Sensing* (CS) methodology, including the use of *frames* [22, 23].

In the limited space here we show some of our ideas are more advanced in their formulation.

▷ **Alternative spherical signal representations:** There are many new research avenues to explore to overcome the limitations of $L^2(\mathbb{S}^2)$. We briefly describe two that we plan to pursue:

- work in a "smaller" Hilbert space called a *reproducing kernel Hilbert space* (RKHS) and written $\mathcal{H}_K(\mathbb{S}^2)$ (of course the RKHS has the same Hilbert dimension as $L^2(\mathbb{S}^2)$ and is not actually smaller; but it excludes non-smooth signals) [1, Chapter 10], and
- exploit *sparsity* and *anisotropy* when they arise using the Compressed Sensing (CS) methodology.

We have the capability to address these ideas with foundational 2-sphere RKHS material in our book [1, Chapter 10], and our preliminary published results on using CS for spherical signals [30, 32, 33]. To convey some of the ideas we are formulating in the development of spherical signal representations we direct the reader's attention to Figure 2.

The nodes labeled #1 and #2 are conventional Hilbert spaces such as treated in [14]. The nodes labeled #3, #4 and #5 are largely novel in the Proposal and involve smoother Hilbert spaces based on the RKHS concept with kernel $K(\widehat{\boldsymbol{x}}, \widehat{\boldsymbol{y}})$. The spin variant is needed for example when modelling polarization information in CMB measurements.

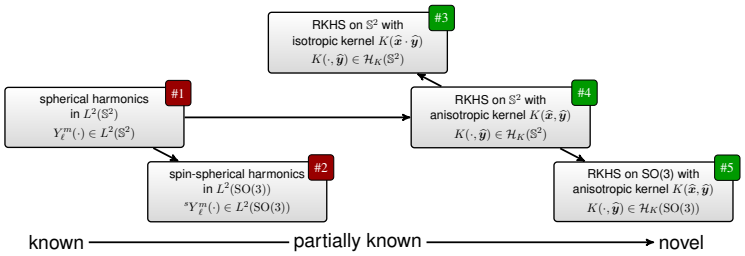

Figure 2: Alternative spherical signal representations: #1 and #2 are standard but #3, #4 and #5 are proposed.

Whatever the RKHS kernel, a subclass of signals on the 2-sphere can be written

$$f(\widehat{\boldsymbol{x}}) = \sum\nolimits_p \alpha_p \, K(\widehat{\boldsymbol{x}}, \widehat{\boldsymbol{y}}_p) \in \mathcal{H}_K$$

where the $\{K(\cdot, \widehat{\boldsymbol{y}}_p)\}_p$ are dense in $\mathcal{H}_K$ but not orthogonal. The lack of orthogonality is not a problem because quantities such as the inner-product can be determined through evaluations of the kernel when it is available in closed-form [34, 35]. In any case this is a viable alternative to expansions in terms of spherical harmonics by restraining the p index to a finite number (making it sparse) and directly modelling the spherical signal variations with smooth kernel "bumps."

▷ **Research questions for Task T2:**

- What is the complete characterization of all RKHS on $\mathbb{S}^2$ with **isotropic kernels** and which of these are the most useful to be used as sparse spherical signal representations?
- Is a more general characterization possible for **anisotropic kernels**? If yes, how does one use a generalization of the von Mises-Fisher distribution called the Kent distribution [36] in the anisotropic case?
- How does one characterize a spherical signal's (true) **sparsity** and which **Compressed Sensing** [21] techniques prove most effective?
- How does one incorporate the constraints and data sets of **specific applications** in the modeling above? For example, can the kernel expansions be made consistent with HEALPix [13, 37] sampling?

Task T3: Applications and Advanced Methods

In broad terms this research task addresses *Key Research Challenge 6*:

- with an aim to close-the-loop to have the needs of the application drive the development of further theory, transforms and algorithms, enable application of our methods, especially to processing of:
  - DTI and MRI data in neuorimaging,
  - CMB data in cosmology, and

  - HRTF observations in acoustics,
- the *feedback* of new practical insights from Task T3 to inform refinements in Tasks T1 and T2.

We show that the research directions proposed in the earlier tasks are aligned with the needs of applications.

▷ **Neuroimaging — Magnetic Resonance Imaging (MRI) and Diffusion Tensor Imaging (DTI):** By measuring the anisotropic motion of water molecules, DTI (a refinement of diffusion MRI) reveal the orientations of fibres in the white matter of the brain corresponding to the major neural highways and thus helps in the characterization of tissue microstructure. For example, to each point in the brain we can associate a voxel and within this voxel the neuronal pathways (clusters of fibres) can be encoded as spherical signals. The totality of such information as we move from voxel to voxel enables us to infer the macroscopic features of the neural pathways and this study is known as *tractography*. Our interest is not in neuroscience, nor the hardware technology but contributing to the modelling with an engineer's eye on implementation, practicality and applying our tools. The particular dimension that enriches or research is the requirement to employ tensor-valued signals, for example, the tensor can characterize a Riemann or Finsler-Riemann [38] surface metric and the fibres correspond to geodesics. This is clearly a non-trivial research application to explore but we have some capability to contribute to international efforts and to extend our methods [3] to the tensor-valued case.

We briefly present the application of research developments proposed in earlier tasks in DTI or MRI.

- The acquisition strategies consider sampling on multiple spherical shells for each voxel of the brain and are too time-consuming since the millions of voxels are generally considered. The total number of samples, and thus total acquisition time, can be reduced with the design of an optimal sampling scheme. Such enhancement in acquisition time is of considerable importance in order to make diffusion MRI or DTI accessible for clinical use by significantly reducing the computational complexity.
- The analysis of the DTI data is sensitive to the presence of noise. The use of isotropic kernels for data smoothing and removal of noise does not preserve diffusion tensor structural features [39]. The development of closed form anisotropic kernels and associated efficient algorithms will help in carrying out the anisotropic smoothing of DTI data along the direction of white matter structures.

▷ **Cosmology — CMB Surveys:** The CMB as a signal is often presented as the prototypical example of a spherical signal. WMAP proved a great boon to cosmology and now the new surveys are delivering the next generation of higher resolution data. This project is poised to couple into the European scientific effort through the participation of the PI McEwen who, since 2003, is an expert in the theory and processing of such data [12, 24, 25]. As remarked before, the PI is a Core Team member of the ESA Planck satellite mission, an expert with the HEALPix and FITS data formats [9, 13, 37], knows its limitations and has other crucial insights. There are many features of interest in the CMB data: measures of anisotropy, presence of cosmic strings, structural elements that imply the presence and distribution of dark energy, foreground (interfering sources) sources and emissions such as from our galaxy.

3.5. Feasibility

We have indicated the timeline for the completion of the research tasks in Table 1. While the Proposal is ambitious, we argue that the proposed investigations are feasible, since the quality and quantity of work is consistent with the recent track record in the field (detailed below and in Section 4) of CI's and PI places them at the "cutting-edge" in development of robust and fast spherical signal processing techniques. Further, the project budget (see Part D and E) is carefully prepared and is aligned with the proposed timeline of the project.

▷ **Relevant and recent publication track record:** In the broad area of 2-sphere signal processing — mostly through support provided in a previous Discovery Grant DP1094350 — we have published (excluding works under review):

- one book (containing 168 pages on 2-sphere research material) [1],
- seven journal papers [4, 5, 7, 15–18] (six in *IEEE Transactions on Signal Processing*), and
- 18 refereed conference papers (including 10 *ICASSP* papers, see Part F).

3.6. National Benefit, Impact and Timeliness

▷ **Strategic and Economic Benefits:** Since we are proposing novel techniques and algorithms that met the needs the arise in our target applications, there is a patent potential in the project. CI-1 Kennedy has experience as inventor with generation of patents and the licensing or assignment of IP. This project would target the generation of intellectual property (IP) with the intent of exploitation by Australian industrial partners with the greatest opportunity being in the area of neuroimaging.

▷ **Research Training:** The project provides research training opportunities for one Research Associate and two PhD students to carry out high-impact and application driven research. A predecessor project (DP1094350) led to the research training of 4 PhD students (3 graduated and 1 in progress) which excellent outcomes including the research generated and international linkages formed through multi-month researcher visits to European researchers (such as with PI-McEwen at UCL) and to Princeton (Assoc Professor Frederik Simons).

▷ **Cost Effective and Value for Money:** The project budget is modest but appropriate for the scope of the project. It is seeking a high profile RA for the duration of the project, and the partial support for PhD students to provide the engine to compete with international efforts. Similarly the travel funding is modest to ensure strong engagement with the international community and the timely delivery of our research findings. There is naturally risk associated with any significant research endeavor but this risk is mitigated because we expect to be able to maintain momentum from our contributions in fundamental aspects (prior work, such as delivered in DP1094350) and carry them into applications, as well as explore deeper fundamental investigations. PI-McEwen can gain early access to space mission data, which by its nature is very expensive to acquire.

▷ **Timeliness and Engagement with International Community:** Earlier in 2013, the International Biomedical and Astronomical Signal Processing (BASP) Frontiers Workshop convened in Switzerland with a number of world-renown and emerging star researchers from diverse fields attending (including CI-1 Kennedy and PI McEwen) with the objective: "to promote synergies between selected topics in astronomy and biomedical sciences, around common challenges for signal processing." Attendance at such single session meetings is primarily by invitation (http://baspfrontiers.epfl.ch). The similar type of activity to promote cross-disciplinary research took place in a conference: Wavelets and Sparsity XV (San Diego, 25–29 August 2013, http://spie.org/OP323), with a special session focussed on signal processing on the sphere where the investigators presented 3 invited papers. CI Kennedy has been also invited and sponsored speaker (as one of 20 only) to present his research in "Science on the Sphere: Royal Society International Scientific Seminar", taking place in London on 14–15 July 2014.

4. ROLE OF PERSONNEL

▷ **CI-1 Kennedy:** Kennedy has a high total commitment to the project (25%) and holds overall responsibility for the research. He has strong participation in all three tasks and is the primary intellectual lead on Task T2 where the most theoretical innovation lies. He will be responsible for the methodology used in the project and for ensuring that the research follows the plan. He would Chair the supervisory panel for the two PhDs in the project. He has an appointment that permits 50% of time on research and this Proposal fits within that limit. He has capacity for two grants (including this Proposal) and currently holds no other grant.

▷ **CI-2 Durrani:** Durrani is 20% committed to the project and is an expert in algorithm development, analysis and computational aspects. He is expected to coordinate Task T1, extending his earlier results in the Proposal area (e.g., [4, 5, 7], and participate strongly in Task T3. He would co-supervise the two PhDs in the project. He current holds one grant and has the time and capacity to participate in this Proposal.

▷ **PI McEwen:** McEwen is 10% committed to the project. He has demonstrated experience in the development and application of spherical signal processing techniques. McEwen as well as being a scientific collaborator in the research, plays a critical role as the interface to application areas: in Cosmology evidence by his affiliations, research record in cosmological observation analysis [6] since 2003, and in *diffusion MRI* [3]. He has collaborated with the CIs in the recent published work [4, 40] and is collaborating on further work in the broad area of the current Proposal.

▷ **RA Research Associate:** The RA will participate in all aspects of the project, that is Tasks T1, T2 and T3. As an early career researcher, the RA can participate in the supervision effort (as a co-supervisor) of the two PhD students. In addition the RA is expected to significantly contribute to the conceptual development of the project. The academic and research training career of the RA is paramount, as it is one important outcome of the project, and will be provided by the three senior investigators, CI-1, CI-2 and PI. Dr Zubair Khalid, who features very strongly in the publications and track record of the team, is an exemplar for the calibre sought for the RA position.

▷ **Two PhD Students:** The PhD students will participate in 3 project tasks under the guidance of the three senior investigators, CI-1, CI-2 and PI, and the RA. PhD-1 is aligned primarily with Task 1 and is expected to have theoretical strengths, and PhD-2 is aligned primarily with Task 3 and should have outstanding application skills.

5. RESEARCH ENVIRONMENT

▷ **Existing local team research environment:** The team research environment within the *Applied Signal Processing Group* (ASP) in the ANU College of Engineering and Computer Science (CECS) is well-established and supportive with

the number of PhD/MPhil students supervised and mentored sustained at around 20 over a number of years. The group comprises 6.5 recurrently funded academics, 5 postdoctoral research fellows and a small number of adjuncts.

▷ **College research environment and strategic plan compatibility:** The proposed research is consistent with the CECS strategic plan for 2010–2015 and beyond, which describes ICT as "a central research activity" within the College which will continue to be "vibrant and fertile for the long term future." This research environment secured a rating of 5 in this Proposal's primary FoR 0906 in both ERA 2010 and ERA 2012. The *Applied Signal Processing Group* (ASP) is one of 14 across the ANU College of Engineering and Computer Science.

▷ **Institutional research environment and strategic plan compatibility:** ANU is described as a "research-intensive, research-led university" and one which "ANU will build research groupings which undertake research of distinction and international impact" in "ANU by 2020" — the strategic plan for the ANU. Across ANU it is expected all areas meet ANU's high standards rather than being a university with pockets of excellence.

6. COMMUNICATION OF RESULTS

The signal processing community is interested in theory, algorithms and deployment in applications. This proposed research will deliver all three and our primary scholarly outlets are the leading IEEE Journals and conferences, such as the *IEEE Transactions on Signal Processing* and *ICASSP*, the world's premier technical conference focused on signal processing and its applications. Quick dissemination will also be facilitated by preprints of the main research articles being made available on the arXiv open access e-print server.

The application community is interested in how the new results from signal processing would advance their field or make better use of their data or improve the design of the experimental practices. With an engagement of collaborators with expertise in different areas, we would seek to have our work applied in those disciplines in their outlets, such as the Journal *Astronomy & Astrophysics* (A&A), and *Monthly Notices of the Royal Astronomical Society*.

The broader community will be informed of our work through public lectures at our host institutions and public venues. Radio programs provide another outlet for communicating our findings as does written material for newspapers and magazines. We believe the general public should be very interested in topics such as modeling the early universe or modeling the functioning of the brain, which is at the heart of this Proposal.

7. MANAGEMENT OF DATA

This project will maintain research data in accordance with the Australian Code for the Responsible Conduct of Research (2007) and ANU's Policy on Responsible Practice of Research (in particular Part A-2: Management of Research Data and Primary Materials). The digital data generated in the project are: 1) the MATLAB source code for mathematical models developed in the project, 2) synthetic data, formatted as MATLAB mat-files, of input and output from the models, and 3) instructions for re-use, all sufficient to reproduce figures and results of published research. This data will be made available to other researchers upon request for discussion, reproduction of the results and re-use. This data will be held on secure networked servers based within the ANU College of Engineering and Computer Science, which are backed-up on a daily basis. This data will be maintained on ANU servers for a minimum of five years from the date on which the corresponding research article are published. The only experimental data required for the project is sourced from currently available open access data-sets and are not "a result of the proposed research", for example, MRI and DTI data-sets and ESA Planck satellite mission data, for applications in neuroimaging and cosmology, respectively.

Finally, accessibility of the research will also be enhanced through preprints of the main research articles being made available on the arXiv open access e-print archive and distribution server.

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C2. Medical and Dental Research Statement

(If applicable, in no more than 750 characters (approx. 100 words), please justify why this Project does not constitute Medical and Dental Research as defined on the ARC website. Refer to the Instructions to Applicants for further information.)

Not applicable

PART D - Project Cost (DP150101011)

D1. What is the proposed budget for your project?

(Please provide details of the budget proposed for your project.)

Proposal Funding Summary

Total requested budget: $625478

Year 1

Description	ARC	AdminOrg		Other Organisation	
	Cash	Cash	In-kind	Cash	In-kind
Direct Cost	202158	16252	84010	0	15000
Personnel	166278	3662	84010	0	15000
CI-1 Kennedy @25%	0	0	53566	0	0
CI-2 Durrani @20%	0	0	30444	0	0
PI McEwen @10%	0	0	0	0	15000
RA @B2, B2, B4	115466	3662	0	0	0
PhD-1 Stipend	25406	0	0	0	0
PhD-2 Stipend	25406	0	0	0	0
Travel	16600	12590	0	0	0
Int Conf - Kennedy	2200	2995	0	0	0
Domestic Conf - Kennedy	700	600	0	0	0
Int Conf - Durrani	2200	2995	0	0	0
Domestic Conf - Durrani	700	600	0	0	0
Int Conf - RA	4100	0	0	0	0
Domestic Conf - RA	1300	0	0	0	0
Int Conf or Visit- PhD-1	2000	2100	0	0	0
Int Conf or Visit PhD-2	2000	2100	0	0	0
Domestic Conf - PhD-1	700	600	0	0	0
Domestic Conf - PhD-2	700	600	0	0	0
International Collaboration Award	19280	0	0	0	0
Jason McEwen	9640	0	0	0	0
Rodney Kennedy	9640	0	0	0	0

Year 2

Description	ARC	AdminOrg		Other Organisation	
	Cash	Cash	In-kind	Cash	In-kind
Direct Cost	205622	16362	86530	0	15000
Personnel	169742	3772	86530	0	15000
CI-1 Kennedy @25%	0	0	55173	0	0
CI-2 Durrani @20%	0	0	31357	0	0
PI McEwen @10%	0	0	0	0	15000
RA @B2, B2, B4	118930	3772	0	0	0
PhD-1 Stipend	25406	0	0	0	0
PhD-2 Stipend	25406	0	0	0	0
Travel	16600	12590	0	0	0
Int Conf - Kennedy	2200	2995	0	0	0

Description	ARC	AdminOrg		Other Organisation	
	Cash	Cash	In-kind	Cash	In-kind
Domestic Conf - Kennedy	700	600	0	0	0
Int Conf - Durrani	2200	2995	0	0	0
Domestic Conf - Durrani	700	600	0	0	0
Int Conf - RA	4100	0	0	0	0
Domestic Conf - RA	1300	0	0	0	0
Int Conf or Visit- PhD-1	2000	2100	0	0	0
Int Conf or Visit PhD-2	2000	2100	0	0	0
Domestic Conf - PhD-1	700	600	0	0	0
Domestic Conf - PhD-2	700	600	0	0	0
International Collaboration Award	19280	0	0	0	0
Jason McEwen	12020	0	0	0	0
Rodney Kennedy	7260	0	0	0	0

Year 3

Description	ARC	AdminOrg		Other Organisation	
	Cash	Cash	In-kind	Cash	In-kind
Direct Cost	217698	16745	89127	0	15000
Personnel	181818	4155	89127	0	15000
CI-1 Kennedy @25%	0	0	56829	0	0
CI-2 Durrani @20%	0	0	32298	0	0
PI McEwen @10%	0	0	0	0	15000
RA @B2, B2, B4	131006	4155	0	0	0
PhD-1 Stipend	25406	0	0	0	0
PhD-2 Stipend	25406	0	0	0	0
Travel	16600	12590	0	0	0
Int Conf - Kennedy	2200	2995	0	0	0
Domestic Conf - Kennedy	700	600	0	0	0
Int Conf - Durrani	2200	2995	0	0	0
Domestic Conf - Durrani	700	600	0	0	0
Int Conf - RA	4100	0	0	0	0
Domestic Conf - RA	1300	0	0	0	0
Int Conf or Visit- PhD-1	2000	2100	0	0	0
Int Conf or Visit PhD-2	2000	2100	0	0	0
Domestic Conf - PhD-1	700	600	0	0	0
Domestic Conf - PhD-2	700	600	0	0	0
International Collaboration Award	19280	0	0	0	0
Jason McEwen	12020	0	0	0	0
Rodney Kennedy	7260	0	0	0	0

Other Organisation Summary

	Year 1		Year 2		Year 3		Year 4		Year 5	
	Cash	In-kind	Cash	In-kind	Cash	In-kind	Cash	In-kind	Cash	In-kind
University College London	0	15000	0	15000	0	15000	0	0	0	0
Total	**0**	**15000**	**0**	**15000**	**0**	**15000**	**0**	**0**	**0**	**0**

E1. Justification of funding requested from the ARC

(In no more than five A4 pages fully justify in terms of need and cost, each budget item requested from the ARC (use the same headings as in the ARC Request Budget Column).)

Attached PDF

E1 – Justification of Funding Requested from the ARC

Personnel

- **Research Associate RA @B2, B2, B4:**

  ▷ **Context:** This item is for a Research Associate (RA) for 3 years at ANU level B2 (years 1 and 2) and ANU level B4 (year 3).

  There is a major opportunity to engage an outstanding RA dedicated to work on the three research tasks in the proposal. This is essential to provide the manpower to deliver on the research. For the RA we identify the following activities:

  - developing substantive research ideas,
  - conducting the research and developing theory,
  - developing and testing algorithms on synthetic (test) data,
  - accessing and converting real data,
  - applying the real-data to the algorithms on the real data,
  - performing analysis on the performance and re-tuning the methods based on their performance,
  - comparison with state of art algorithms from the literature,
  - collaboration with the remaining team members and in particular with the UK based PI
  - guiding and co-supervising PhD students,
  - paper preparation, submission and review processing.

  Each of these sub-tasks are substantial and may take several months each and are repeated throughout the project. This is substantial amount of work requiring high skill levels and through this resourcing the project will achieve its maximum impact.

  ▷ **Salary Levels:** Salary is requested from the ARC at level B2 which is the minimum level that we appoint PhD qualified internationally competitive early career researchers in information sciences-type engineering (telecommunications, signal processing, control) at ANU. Under the ANU EB rules an increment to level B4 after 2 years is possible and expected with the high calibre appointments we make at ANU.

  ▷ **Targeted Quality:** The RA will be hired based on highly-competitive selection criteria according to the project description and also according to ERA rating 5 standards. It is expected for the RA to have recently obtained a PhD degree in areas of signal processing (or cognate area) with specialization in spherical or related signal processing from a reputable national or international university, comparable to the leading Go8 Universities or areas of research excellence in the Australian university sector.

  ▷ **Complementary Strengths:** A candidate with well-developed research skills and demonstrated research achievements will be carefully selected such that he/she *adds to the existing capabilities of the team*. The RA must have published peer-reviewed papers, as the first author, in an area or areas related to the project at the IEEE Transaction level and major IEEE conferences and must have excellent oral and written communication skills.

  ▷ **Capability to Support and Mentor RA:** Both CI's have extensive experience in supervising Postdoctoral Research Fellows funded through the ARC or ANU. For example, CI-1 Kennedy has been, or currently is, the primary supervisor of three Postdoctoral Research Fellows in three ARC-funded projects (DP07, DP10 and DP11). CI-2 Durrani have also co-supervised two Postdoctoral Research Fellows in two other ARC funded projects (DP10 and LP10).

- **PhD-1 Stipend**, and **PhD-2 Stipend:**

  Research training is an extremely important component of any supported research. The passing on of knowledge and training the next generation of researchers is a strong motivation for any research. As given in the main proposal PhD-1 is most strongly associated with Task T1, Analysis in Spatio-Spectral domain and Optimal Sampling, and also part of Task T2, Spherical Signal Processing for Anisotropy and Sparsity. PhD-2 is most strongly associated with Task T3, Applications and Advanced Methods, and also part of Task T2, Spherical Signal Processing for Anisotropy and Sparsity.

The scholarships are set at the necessary rate close to the APA(I) level to attract the best candidates and funding is sought for 3 years for both PhD-1 and PhD-2.

Travel

"Domestic Travel or Visit Justification" means support to attend an Australian sited (international calibre) conference or visit to other research institutions within Australia to conduct joint research relevant to the project or give technical seminars on research coming from the project (usually but not exclusively travel associated with a conference).

This is a domestic component of travel which captures the reality that IEEE conferences in this field are a regular occurrence within Australia. Some examples (but not exhaustively so) are the IEEE sponsored International Conference on Signal Processing and Communication Systems (ICSPCS) which regularly is held in Australia, and the Australian Communication Theory Workshop. Major conferences also come to Australia every 5 years or so and we have the 2015 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP) coming to Brisbane, but there are other cognate conferences.

- **Domestic Travel or Visit - CI-1 Kennedy** $700 per year is requested from the ARC to enable such domestic trips, which is matched by the contribution from the ANU through CIs' Professional Development accounts. Of this total cost of $1,300, it is estimated that $500 will be used for accommodation and meals, $500 for airfares, and $300 for conference registration. This level of funding applies in each of the 3 years of the grant.
- **Domestic Travel or Visit - CI-2 Durrani:** $700 per year is requested from the ARC to enable such domestic trips, which is matched by the contribution from the ANU through CIs' Professional Development accounts. Of this total cost of $1,300, it is estimated that $500 will be used for accommodation and meals, $500 for airfares, and $300 for conference registration. This level of funding applies in each of the 3 years of the grant.
- **Domestic Travel or Visit - RA:** $1,300 per year is requested from the ARC to enable such domestic trips. It is estimated that $500 will be used towards accommodation and meals, $500 for airfares, and $300 for conference registration. This level of funding applies in each of the 3 years of the grant.
- **Domestic Travel or Visit - PhD-1** $700 per year is requested from the ARC to enable such domestic trips, which is matched by the contribution from the ANU. Of this total cost of $1,300, it is estimated that $500 will be used for accommodation and meals, $500 for airfares, and $300 for conference registration. This level of funding applies in each of the 3 years of the grant.

  Domestic Travel or Visit - PhD-2: $700 per year is requested from the ARC to enable such domestic trips, which is matched by the contribution from the ANU. Of this total cost of $1,300, it is estimated that $500 will be used for accommodation and meals, $500 for airfares, and $300 for conference registration. This level of funding applies in each of the 3 years of the grant.
- **International Travel or Visit - CI-1 Kennedy** The cost of attending an international conference for 5 days is estimated as follows: registration = $900 (estimate from previous years), economy airfare to US or Europe = $2,500, accommodation = $200/day (estimate), meals and incidentals = $\$265 \times 0.6 = \$159$/day (using 60% of the minimum ATO rate for level 5 countries), giving a total of $900 + $2,500 + $\$200 \times 5$ + $\$159 \times 5$ = $5,195. $2,200 contribution is requested from the ARC to enable such international trips in each of the 3 years of the project.
- **International Travel or Visit - CI-2 Durrani** The cost of attending an international conference for 5 days is estimated as follows: registration = $900 (estimate from previous years), economy airfare to US or Europe = $2,500, accommodation = $200/day (estimate), meals and incidentals = $\$265 \times 0.6 = \$159$/day (using 60% of the minimum ATO rate for level 5 countries), giving a total of $900 + $2,500 + $\$200 \times 5$ + $\$159 \times 5$ = $5,195. $2,200 contribution is requested from the ARC to enable such international trips in each of the 3 years of the project.
- **International Travel or Visit - RA** The cost of attending an international conference for 5 days is estimated as above but capped to $4,100 in each of the 3 years.
- **International Travel or Visit - PhD-1** The cost of attending an international conference for 5 days is estimated as above but is capped to a total of $4,100 (ARC+ANU) in each of the 3 years. $2,000 is requested from the ARC to enable such international trips in each of the 3 years of the project.

- **International Travel or Visit - PhD-2** The cost of attending an international conference for 5 days is estimated as above but is capped to a total of $4,100 (ARC+ANU) in each of the 3 years. $2,000 is requested from the ARC to enable such international trips in each of the 3 years of the project.

International Collaboration Award

Jason McEwen

Our PI, McEwen, is front stage with access to major European programs and activities reflected in his:

- collaborations with researchers in a number of top European institutions such as Cambridge and EPFL
- expertise in developing mathematical models and algorithms for modeling gravitational fields and topography in Planetary Science
- work on diffusion MRI — one application foci of this project
- analysis of cosmic microwave background (CMB) radiation as a core team member of the ESA Planck satellite mission — also one application focus of this project

We expand on the importance of this latter connection because it cements the case for an *International Collaboration Award* to fully engage and benefit the research in this project and the impact for ARC funded research. The ICA is a portal for the PI and the Australian-based team to participate in the European activities. This has timeless value but the imminent release of Planck data (such as polarized CMB observations of unprecedented sensitivity anticipated in 2014) does make the ICA is particularly timely.

▷ **ICA McEwen Costing Justification:** The costings is based on three trips in the three years:

- 6 weeks visit in 2015: economy airfare from Europe to Australia = $2,500, long term accommodation = $120/day (estimate), meals and incidentals = $50/day bringing the amount to $42 \times \$170 = \$9,640$.
- 8 weeks visit in 2016: economy airfare from Europe to Australia = $2,500, long term accommodation = $120/day (estimate), meals and incidentals = $50/day bringing the amount to $56 \times \$170 = \$12,020$.
- 8 weeks visit in 2017: economy airfare from Europe to Australia = $2,500, long term accommodation = $120/day (estimate), meals and incidentals = $50/day bringing the amount to $56 \times \$170 = \$12,020$.

Rodney Kennedy

As the case for ICA McEwen indicated there is an important Planck data release anticipated in 2014 and it is more important to be in Europe in the early stages of the grant and so the planned duration is 2 months. For the other years direct collaboration can be facilitated with 1 month visits.

▷ **ICA Kennedy Costing Justification:** The costings is based on three trips in the three years:

- 6 weeks visit in 2015: economy airfare from Europe to Australia = $2,500, long term accommodation = $120/day (estimate), meals and incidentals = $50/day bringing the amount to $30 \times \$170 = \$9,640$.
- 4 weeks visit in 2016: economy airfare from Europe to Australia = $2,500, long term accommodation = $120/day (estimate), meals and incidentals = $50/day bringing the amount to $28 \times \$170 = \$7,260$.
- 4 weeks visit in 2017: economy airfare from Europe to Australia = $2,500, long term accommodation = $120/day (estimate), meals and incidentals = $50/day bringing the amount to $28 \times \$170 = \$7,260$.

E2. Details of non-ARC contributions

(In no more than two A4 pages provide an explanation of how non-ARC contributions will support the proposed project (use the same headings as in the non-ARC contributions Budget Column).)

Attached PDF

E2 – Details of non-ARC Contributions

Personnel

- **CI-1 Kennedy @25%:** The ANU will contribute 25% of CI-1's time (0.40 full time equivalent (FTE) + 32.06% on-costs) in each of the 3 years of the grant, which will be spent directly working on this project.
- **CI-2 Durrani @20%:** The ANU will contribute 20% of CI-2's time (0.20 full time equivalent (FTE) + 32.06% on-costs) in each of the 3 years of the grant, which will be spent directly working on this project.
- **PI McEwen @10%:** The PI's institution, UCL, will contribute 10% of PI's time (0.10 full time equivalent (FTE) + 32.06% on-costs) in each of the 3 years of the grant, which will be spent directly working on this project.
- **RA @B2, B2, B4:** The ANU pays the difference between its salary on-costs of 32.06% and the ARC salary on-costs of 28% for the RA, in each of the 3 years of the grant.

Travel

- **Domestic Travel or Visit – CI-1 Kennedy:** The ANU will contribute $600 from the CI-1 ANU-PD account. This level of funding applies in each of the 3 years of the grant.
- **Domestic Travel or Visit – CI-2 Durrani:** The ANU will contribute $600 from the CI-2 ANU-PD account. This level of funding applies in each of the 3 years of the grant.
- **Domestic Travel or Visit – PhD-1:** The ANU will contribute $600 from the travel funding available to PhD-1 as a portion of his/her 3 year total ($6,000). This level of funding applies in each of the 3 years of the grant.
- **Domestic Travel or Visit – PhD-2:** The ANU will contribute $600 from the travel funding available to PhD-2 as a portion of his/her 3 year total ($6,000). This level of funding applies in each of the 3 years of the grant.
- **International Travel or Visit – CI-1 Kennedy:** The ANU will contribute $2,995 from the CI-1 ANU-PD account for international conference attendance. This level of funding applies in each of the 3 years of the grant.
- **International Travel or Visit – CI-2 Durrani:** The ANU will contribute $2,995 from the CI-2 ANU-PD account for international conference attendance. This level of funding applies in each of the 3 years of the grant.
- **International Travel or Visit – PhD-1:** The ANU will contribute $2,100 which is composed of $1,400 from the travel funding available to PhD-1 as a portion of his/her 3 year total ($6,000) and $700 from CI-1 ANU-PD account. This level of funding applies in each of the 3 years of the grant.
- **International Travel or Visit – PhD-2:** The ANU will contribute $2,100 which is composed of $1,400 from the travel funding available to PhD-2 as a portion of his/her 3 year total ($6,000) and $700 from CI-1 ANU-PD account. This level of funding applies in each of the 3 years of the grant.

Travel Costing Justification

- **Domestic Conference Costing:** The cost of attending a domestic conference or workshop for 3 days is estimated as follows: $500 will be used for accommodation and meals, $500 for airfares, and $300 for conference registration for a total of $1,300.
- **International Conference Costing:** The cost of attending an international conference for 5 days is estimated as follows: registration = $900 (estimate from previous years), economy airfare to US or Europe = $2,500 (an estimate which varies depending on the season), accommodation = $200/day (estimate), meals and incidentals = $\$265 \times 0.6 = \$159$/day (using 60% of the minimum ATO rate for level 5 countries), giving a total of $900 + $2,500 + $\$200 \times 5$ + $\$159 \times 5$ = $5,195.

PART F - Personnel (Prof Rodney Kennedy)

F1. Personal details

(The personal details will be filled out for you automatically. To update any of your personal details in this form, please update your profile accordingly and your details will update automatically in this form.)

Title

Professor

Family Name

Kennedy

First Name

Rodney

Second Name

Andrew

Person identifier

E1282781

Role

Chief Investigator

F2. Postal address

(The postal address will be filled out for you automatically. To update your postal address, please update your profile accordingly and your postal address will update automatically in this form.)

Postal Address Line 1

RSISE Building 115

Postal Address Line 2

Cnr North and Daley Rds

Locality

Canberra

State

ACT

Postcode

0200

Country

Australia

F3. Are you a current member of the ARC or its selection or other advisory committees?

(This relates only to College of Experts or Selection Advisory Committee members for National Competitive Grants Program funding schemes.)

Current Member of Advisory Committee

No

F4. Please name any Commonwealth-funded Research Centres that you will be associated with as at 1 January 2015.

	Full Legal Name of Centre	Start Date	Cessation Date	Centre Role
1				
2				

	Centre Role if Other
1	
2	

F5. Are you an Indigenous Participant?

Indigenous Participant

No

F6. PhD Qualification

F6.1. Do you hold a PhD or expect to be awarded a PhD qualification in the near future?

PhD Yes/No

Yes

F6.2. If you hold a PhD or expect to be awarded a PhD qualification in the near future, please enter the date your PhD has been awarded or the date your thesis will be submitted, respectively.

Date of Award

20/12/1988

F7. Qualifications

	Degree/Award	Year	Discipline/Field	Organisation Name
1	PhD	1988	Systems Engineering	The Australian National University

	Degree/Award	Year	Discipline/Field	Organisation Name
2	ME	1985	Engineering	The University of Newcastle
3	BE (Hons 1 Medal)	1982	Electrical Engineering	The University of New South Wales

	Country
1	Australia
2	Australia
3	Australia

F8. Current and previous appointment(s)/position(s) – during the past 10 years

	Position	Organisation Name	Department	Year Appointed
1	Professor and Associate Director (Education)	The Australian National University	Research School of Engineering	2014
2	Professor	The Australian National University	Research School of Engineering	2008
3	Professor and Head of Department	The Australian National University	Information Engineering	2006
4	Professor and Head of Department	The Australian National University	Telecommunications Engineering	2003

	Continuity	Employment Kind	Current
1	Permanent	Full Time	Yes
2	Permanent	Full Time	No
3	Permanent	Full Time	No
4	Permanent	Full Time	No

F9. Organisational affiliations for eligibility purposes for this Proposal

(Name of the organisation you will be associated with for the purposes of satisfying the eligibility requirements for your nominated role in undertaking the proposed research (i.e. for a CI this will usually be the Eligible Organisation at which they will employed or hold an adjunct appointment as at 1 January 2015 and beyond; for PIs it will generally be their main employer as at 1 January 2015).)

Organisation Name

The Australian National University

Type of Affiliation

Employee

F10. What is your time commitment (%FTE) to this Project?

25

F11. Are you requesting an International Collaboration Award?

(Note: If you are an Australian-based PI, you must choose 'No'. Also, if you are a PI working in an Australian Eligible Organisation overseas campus you must choose 'No'.)

International Collaboration Award

Yes

F12. Research Opportunity and Performance Evidence (ROPE)

F12.1. Details on your career and opportunities for research over the last 10 years

(Write a maximum of 5250 characters (approx. 750 words). Please detail your career and opportunities over the last 10 years. Please refer to the Instructions to Applicants for the required content and formatting.)

(i) It is 25 years since I received my PhD degree from the Australian National University

(ii) The research component of my employment since 1994 has generally been at 50 percent primarily because of a sequence of higher management responsibility roles ranging from Head of Department, College level Director of Research, and now Associate Director (Education) within Engineering. In addition I have taught at the undergraduate level for the last 5 years which has reduced my research opportunities. I have had no unemployment since taking up academic positions.

(iii) In my current role has two components:
a) 50 percent as "administration-only academic" because of my role as Associate Director (Education) where I am responsible for all undergraduate and Masters level engineering courses. This is primarily a service role and it gives teaching relief for the two undergraduate and Masters courses I normally run, and b) 50 percent "research".
Over the last ten years:
- 2004-2008 [management+research]: I held a higher level management responsibility position at 50 percent of my time (either Head of Department or Director of Research level); the remaining 50 percent was for research and service (including outside service)
- 2009-2012 [undergraduate teaching + research]: my current teaching load is two courses with the balance of time being research, service and heading one of 7 research groups in Engineering (below department level)
- 2013 [undergraduate + postgraduate teaching + research]
- 2014 [Associate Director (Education) + research]
Overall these appointments my research time has been at 50 percent.

(iv) no career interruptions

(v) • research mentoring to me is extensive at ANU, there are research meetings and advice/monitoring is given by very senior staff, there are supervision workshops through central ANU facilities, there is an active seminar program where research is scrutinized and feedback is provided;
• research facilities cover the essentials such as computer, access to supercomputer facilities, all relevant software including Matlab, software to prepare papers and books, library facilities, a laboratory for project development within 10 metres of my office, all PhD students and research colleagues occupy a shared area corresponding to half of one floor within the building to ensure close collaboration.

(vi) none

F12.2. Recent significant research outputs and ARC grants (since 2004)

(Please attach a PDF with a list of your recent significant research outputs and ARC grants most relevant to the Proposal (20 pages maximum). Please refer to the Instructions to Applicants for the required content and formatting.)

F12.2. Recent significant research outputs and ARC grants (since 2004)

(1) Research significant research outputs

(i) Scholarly Books

1.⋆ **R. A. Kennedy** and P. Sadeghi, *Hilbert Space Methods in Signal Processing*. Cambridge, UK: Cambridge University Press, Mar. 2013.

(ii) Scholarly Book Chapters

2. P. D. Samarasinghe and **R. A. Kennedy**, "Regularized image restoration," in *Image Restoration - Recent Advances and Applications*. InTech - Open Access Publisher, April 2012, ch. 6, pp. 119–144.

3.⋆ T. S. Pollock, T. D. Abhayapala, and **R. A. Kennedy**, "Spatial characterization of multiple antenna channels," in *Signal Processing for Telecommunications and Multimedia*, T. A. Wysocki, B. Honary, and B. J. Wysocki, Eds. Springer, 2005, vol. 27, ch. 12, pp. 145–158.

(iii) Refereed Journal Articles

4. A. A. Nasir, X. Zhou, S. Durrani, and **R. A. Kennedy**, "Relaying protocols for wireless energy harvesting and information processing," *IEEE Trans. Wireless Commun.*, vol. 12, pp. 3622–3636, July 2013.

5. A. A. Nasir, H. Mehrpouyan, S. Durrani, S. D. Blostein, **R. A. Kennedy**, and B. Ottersten, "Optimal training sequences for joint timing synchronization and channel estimation in distributed communication networks," *IEEE Trans. Commun.*, vol. 61, pp. 3002–3015, July 2013.

6. A. A. Nasir, H. Mehrpouyan, S. Durrani, S. D. Blostein, **R. A. Kennedy**, and B. Ottersten, "Transceiver design for distributed STBC based AF cooperative networks in the presence of timing and frequency offsets," *IEEE Trans. Signal Process.*, vol. 61, pp. 3143–3158, June 2013.

7.⋆ Z. Khalid, **R. A. Kennedy**, S. Durrani, P. Sadeghi, Y. Wiaux, and J. D. McEwen, "Fast directional spatially localized spherical harmonic transform," *IEEE Trans. Signal Process.*, vol. 61, pp. 2192–2203, May 2013.

8. N. Malagutti, A. Dehghani, and **R. A. Kennedy**, "Robust control design for automatic regulation of blood pressure," *IET Control Theory Appl.*, vol. 7, pp. 387–396, Feb. 2013.

9.⋆ Z. Khalid, P. Sadeghi, **R. A. Kennedy**, and S. Durrani, "Spatially varying spectral filtering of signals on the unit sphere," *IEEE Trans. Signal Process.*, vol. 61, pp. 530–544, Feb. 2013.

10.⋆ P. Sadeghi, **R. A. Kennedy**, and Z. Khalid, "Commutative anisotropic convolution on the 2-sphere," *IEEE Trans. Signal Process.*, vol. 60, no. 12, pp. 6697–6703, Dec. 2012.

11. A. A. Nasir, S. Durrani, and **R. A. Kennedy**, "Particle filters for joint timing and carrier estimation: Improved resampling guidelines and weighted Bayesian Cramér-Rao bounds," *IEEE Trans. Commun.*, vol. 60, no. 5, pp. 1407–1419, May 2012.

12.⋆ Z. Khalid, S. Durrani, P. Sadeghi, and **R. A. Kennedy**, "Spatio-spectral analysis on the sphere using spatially localized spherical harmonics transform," *IEEE Trans. Signal Process.*, vol. 60, no. 3, pp. 1487–1492, Mar. 2012.

13. A. A. Nasir, H. Mehrpouyan, S. Durrani, **R. A. Kennedy**, and S. D. Blostein, "Timing and carrier synchronization with channel estimation in multi-relay cooperative networks," *IEEE Trans. Signal Process.*, vol. 60, no. 2, pp. 793–811, Feb. 2012.

14.⋆ W. Zhang, M. Zhang, **R. A. Kennedy**, and T. D. Abhayapala, "On high resolution head-related transfer function measurements: An efficient sampling scheme," *IEEE Trans. Audio Speech Language Process.*, vol. 20, no. 3, pp. 575–584, Feb. 2012.

15.⋆ L. Wei, **R. A. Kennedy**, and T. A. Lamahewa, "Quadratic variational framework for signal design on the 2-sphere," *IEEE Trans. Signal Process.*, vol. 59, no. 11, pp. 5243–5252, Nov. 2011.

16.⋆ **R. A. Kennedy**, T. A. Lamahewa, and L. Wei, "On azimuthally symmetric 2-sphere convolution," *Digital Signal Process.*, vol. 5, no. 11, pp. 660–666, Sep. 2011.

17. A. A. Nasir, S. Durrani, and **R. A. Kennedy**, "Blind timing and carrier synchronisation in distributed multiple input multiple output communication systems," *IET Commun.*, vol. 5, no. 7, pp. 1028–1037, May 2011.

18.⋆ L. Wei, **R. A. Kennedy**, and T. A. Lamahewa, "An optimal basis of band-limited functions for signal analysis and design," *IEEE Trans. Signal Process.*, vol. 58, no. 11, pp. 5744–5755, Nov. 2010.

19. M. Hossain, D. B. Smith, **R. A. Kennedy**, and K. Sithamparanathan, "Effect of timing error on the performance of BPSK modulation over a fading channel," *IEEE Commun. Lett.*, vol. 14, no. 10, pp. 894–896, Oct. 2010.

20. R. Shams, P. Sadeghi, **R. A. Kennedy**, and R. I. Hartley, "Parallel computation of mutual information on the GPU with application to real-time registration of 3D medical images," *Comput. Meth. Programs Biomed.*, vol. 99, no. 2, pp. 133–146, Aug. 2010.

21. S. Kodituwakku, **R. A. Kennedy**, and T. D. Abhayapala, "Radial function based kernel design for time-frequency distributions," *IEEE Trans. Signal Process.*, vol. 58, no. 6, pp. 3395–3400, Jun. 2010.

22. F. Ge, L. Tan, and **R. A. Kennedy**, "Stability and throughput of FAST transfer control protocol traffic in bi-directional connections," *IET Commun.*, vol. 4, no. 6, pp. 639–644, Apr. 2010.

23.⋆ W. Zhang, T. D. Abhayapala, **R. A. Kennedy**, and R. Duraiswami, "Insights into head related transfer function: Spatial dimensionality and continuous representation," *J. Acoust. Soc. Am.*, vol. 127, no. 4, pp. 2347–2357, Apr. 2010.

24. R. Shams, P. Sadeghi, **R. A. Kennedy**, and R. I. Hartley, "A survey of high performance medical image registration on multi-core, GPU and distributed architectures," *IEEE Signal Process. Mag.*, pp. 50–60, Mar. 2010.

25. T. A. Lamahewa, P. Sadeghi, **R. A. Kennedy**, and P. B. Rapajic, "Model-based pilot and data power adaptation in PSAM with periodic delayed feedback," *IEEE Trans. Wireless Commun.*, vol. 8, no. 5, pp. 2247–2252, May 2009.

26. G. Al-Suhail, L. Tan, and **R. A. Kennedy**, "A cross-layer model for video multicast based TCP-adaptive FEC over heterogeneous networks," *Int. J. Mobile Comput. Multimedia Commun. (IJMCMC)*, vol. 1, no. 1 (Article No. ITJ4898), pp. 53–69, Jan. 2009.

27.⋆ W. Zhang, **R. A. Kennedy**, and T. D. Abhayapala, "Efficient continuous HRTF model using data independent basis functions: Experimentally guided approach," *IEEE Trans. Audio Speech Language Process.*, vol. 17, no. 4, pp. 819–829, May 2009.

28. S. Kodituwakku, **R. A. Kennedy**, and T. D. Abhayapala, "Kaiser window based kernel for time-frequency distributions," *Electron. Lett.*, vol. 45, no. 4, pp. 235–236, Feb. 2009.

29. J. Zhang, **R. A. Kennedy**, and T. D. Abhayapala, "Reduced rank shift invariant technique and its application for synchronization and channel identification in UWB systems," *EURASIP J. Wireless Commun. Networking*, vol. 2008, no. Article ID 892193, p. 13, 2008.

30. Z. B. Krusevac, P. B. Rapajic, and **R. A. Kennedy**, "Communication system model for information rate evaluation of differential detection over time-varying channels," *IET Commun.*, vol. 2, no. 10, pp. 1301–1310, Nov. 2008.

31. P. Sadeghi, **R. A. Kennedy**, P. B. Rapajic, and R. Shams, "Finite-state Markov modeling of fading channels: A survey of principles and applications," *IEEE Signal Process. Mag.*, vol. 25, no. 5, pp. 57–80, Sep. 2008.

32. V. D. Trajkovic, P. B. Rapajic, and **R. A. Kennedy**, "Adaptive ordering for imperfect successive decision feedback multiuser detection," *IEEE Trans. Commun.*, vol. 56, no. 2, pp. 173–176, Feb. 2008.

33. Z. B. Krusevac, P. B. Rapajic, and **R. A. Kennedy**, "Basic binary state-space model for time-varying communication channels: uncertainty and information capacity," *IET Commun.*, no. 5, pp. 990–998, Oct. 2007.

34. T. A. Lamahewa, **R. A. Kennedy**, T. D. Abhayapala, and V. K. Nguyen, "Spatial precoder design for space-time coded MIMO systems: Based on fixed parameters of MIMO channels," *Wireless Personal Commun.*, vol. 43, no. 2, pp. 777–799, Oct. 2007.

35.⋆ **R. A. Kennedy**, P. Sadeghi, T. D. Abhayapala, and H. M. Jones, "Intrinsic limits of dimensionality and richness in random multipath fields," *IEEE Trans. Signal Process.*, vol. 55, no. 6, pp. 2542–2556, Jun. 2007.

36. S. Krusevac, P. B. Rapajic, and **R. A. Kennedy**, "Effect of signal and noise mutual coupling on MIMO channel capacity," *Wireless Personal Commun.*, vol. 40, no. 3, pp. 317–328, Feb. 2007.

37. M. I. Y. Williams, T. D. Abhayapala, and **R. A. Kennedy**, "Generalized broadband beamforming using a modal subspace decomposition," *EURASIP Journal on Advances in Signal Processing*, no. Article ID 68291, p. 9 pages, 2007.

38. S. Krusevac, P. B. Rapajic, and **R. A. Kennedy**, "Mutual coupling effect on thermal noise in multi-element antenna systems," *Progress in Electromagnetics Research, PIERS 59*, pp. 325–333, Aug. 2006.

39. T. A. Lamahewa, M. L. Simon, T. D. Abhayapala, and **R. A. Kennedy**, "Exact pairwise error probability analysis of space-time codes in spatially correlated fading channels," *J. Telecomm. Inf. Tech., JTIT*, no. 1, pp. 60–68, Jan. 2006.

40. T. A. Lamahewa, M. K. Simon, **R. A. Kennedy**, and T. D. Abhayapala, "Performance analysis of space-time codes in realistic propagation environments: A moment generating function-based approach," *J. Commun. Networks (JCN)*, vol. 7, no. 4, pp. 450–461, Dec. 2005.

41. V. D. Trajkovic, P. B. Rapajic, and **R. A. Kennedy**, "Turbo DFE algorithm with imperfect decision feedback," *IEEE Signal Process. Lett.*, vol. 12, no. 12, pp. 820–823, Dec. 2005.

42. J. Zhang, **R. A. Kennedy**, and T. D. Abhayapala, "Cramér-Rao lower bounds for the synchronization of UWB signals," *EURASIP J. Appl. Signal Process.*, vol. 2005, no. 3, pp. 426–438, 2005.

43. P. D. Teal and **R. A. Kennedy**, "Bounds on extrapolation of field knowledge for long-range prediction of mobile signals," *IEEE Trans. Wireless Commun.*, vol. 3, no. 2, pp. 672–676, Mar. 2004.

(iv) Refereed Conference Papers

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150. T. A. Lamahewa, M. Simon, T. D. Abhayapala, and **R. A. Kennedy**, "Exact pairwise error probability analysis of space-time codes in realistic propagation environments," in *Proc. 3rd Workshop on the Internet, Telecommunications and Signal Process., WITSP'2004*, Adelaide, Australia, Dec. 2004, pp. 170–175.

151. Z. B. Krusevac, P. B. Rapajic, and **R. A. Kennedy**, "On channel uncertainty modeling - an information theoretic approach," in *Proc. IEEE Global Telecommunications Conference, 2004. GLOBECOM'2004*, vol. 1, Dallas, Texas, Nov. 2004, pp. 410–414.

152. Z. B. Krusevac, P. B. Rapajic, and **R. A. Kennedy**, "Concept of time varying binary symmetric model-channel uncertainty modeling," in *Proc. 9th International Conference on Communications Systems, ICCS'2004*, Singapore, Sep. 2004, pp. 598–602.

153. L. Hanlen, A. J. Grant, and **R. A. Kennedy**, "On capacity for single-frequency spatial channels," in *IEEE Information Theory Workshop, ITW'2004*, San Antonio, Texas, Oct. 2004, pp. 446–451.

154. Z. B. Krusevac, P. B. Rapajic, and **R. A. Kennedy**, "Channel uncertainty effect upon the information capacity of mobile communications channels," in *Proc. IEEE Vehicular Technology Conference (Fall), VTC'2004-Fall*, vol. 6, Los Angeles, California, Sep. 2004, pp. 4207–4211.

155. V. D. Trajkovic, P. B. Rapajic, and **R. A. Kennedy**, "A new adaptive ordering method for successive decision feedback multiuser detection," in *Proc. IEEE Vehicular Technology Conference (Fall), VTC'2004-Fall*, vol. 3, Los Angeles, California, Sep. 2004, pp. 1944–1948.

156. T. A. Lamahewa, T. D. Abhayapala, and **R. A. Kennedy**, "Effect of transmit antenna configuration on rank-determinant criteria of space-time trellis codes," in *Proc. IEEE Eighth International Symposium on Spread Spectrum Techniques and Applications, ISSSTA'2004*, Sydney, Australia, Aug. 2004, pp. 750–754.

157. S. Krusevac, P. B. Rapajic, and **R. A. Kennedy**, "The method for MIMO channel capacity estimation in the presence of spatially correlated noise," in *IEEE Eighth International Symposium on Spread Spectrum Techniques and Applications, ISSSTA'2004*, Sydney, Australia, Aug. 2004, pp. 511–514.

158. J. Zhang, T. D. Abhayapala, and **R. A. Kennedy**, "Principal components tracking algorithms for synchronization and channel identification in UWB systems," in *IEEE Eighth International Symposium on Spread Spectrum Techniques and Applications, ISSSTA'2004*, Sydney, Australia, Aug. 2004, pp. 369–373.

159. Z. B. Krusevac, P. B. Rapajic, and **R. A. Kennedy**, "Information theoretic approach to finite state Markov modelling of time varying channels," in *Proc. IEEE Eighth International Symposium on Spread Spectrum Techniques and Applications, ISSSTA'2004*, Sydney, Australia, Aug. 2004, pp. 97–101.

160. T. A. Lamahewa, T. D. Abhayapala, and **R. A. Kennedy**, "Fading resistance of orthogonal space-time block codes under spatial correlation," in *Proc. 5th IEEE Workshop on Signal Processing Advances in Wireless Communications, SPAWC'2004*, Lisbon, Portugal, Jul. 2004, pp. 278–282.

161. T. S. Pollock, T. D. Abhayapala, and **R. A. Kennedy**, "Limits to multi-antenna capacity of spatially selective channels," in *International Symposium on Information Theory, 2004. ISIT'2004*, Chicago, IL USA, Jun. 2004, p. 244.

162. **R. A. Kennedy** and T. D. Abhayapala, "Source-field wave-field concentration and dimension: Towards spatial information content," in *International Symposium on Information Theory, ISIT'2004*, Chicago, IL USA, Jun. 2004, p. 243.

163. J. Zhang, **R. A. Kennedy**, and T. D. Abhayapala, "Cramér-Rao lower bounds for the time delay estimation of UWB signals," in *2004 IEEE International Conference on Communications, ICC'2004*, vol. 6, Paris, France, Jun. 2004, pp. 3424–3428.

164. W. G. Lim, T. D. Abhayapala, and **R. A. Kennedy**, "Reliability based soft transition technique for dual-mode blind equalizers," in *Proc. 2004 IEEE International Conference on Communications, ICC'2004*, vol. 5, Paris, France, Jun. 2004, pp. 2631–2635.

165. S. Krusevac, P. B. Rapajic, and **R. A. Kennedy**, "Channel information capacity estimation for mutually coupled transmitted antenna," in *Proc. Progress in Electromagnetics Research Symposium 2004*, Pisa, Italy, Mar. 2004.

166. S. Krusevac, P. B. Rapajic, and **R. A. Kennedy**, "Method for MIMO channel capacity estimation for electromagnetically coupled transmit antenna elements," in *Proc. 5th Australian Communications Theory Workshop, AusCTW'2004*, Newcastle, Australia, Feb. 2004, pp. 122–126.

167. Z. B. Krusevac, P. B. Rapajic, and **R. A. Kennedy**, "Information capacity analysis of the time varying binary symmetric channel," in *Proc. 5th Australian Communications Theory Workshop, AusCTW'2004*, Newcastle, Australia, Feb. 2004, pp. 86–90.

168. L. Hanlen, A. J. Grant, and **R. A. Kennedy**, "On the capacity of operator channels," in *Proc. 5th Australian Communications Theory Workshop, AusCTW'2004*, Newcastle, Australia, Feb. 2004, pp. 23–27.

169. J. Zhang, **R. A. Kennedy**, and T. D. Abhayapala, "Rank reduced ESPRIT techniques in the estimation of principal signal components," in *Proc. 5th Australian Communications Theory Workshop, AusCTW'2004*, Newcastle, Australia, Feb. 2004, pp. 13–17.

(v) Other

170. **R. A. Kennedy**, D. Miniutti, X. Ouyang, and M. Ghosh, *United States Patent: US 7,269,216 — Blind Magnitude Equalizer for Segment Sync-Based Timing Recovery of Receivers*. US Patent Office, Sep. 2007, US 7,269,216, Publication Date: September 11 2007 (Filing Date: 6 May 2002) Docket No. 702289 (PHIL06-02289).

171. **R. A. Kennedy** and T. D. Abhayapala, *United States Patent: US 7,054,359 — VSV-MOE Pre-Equalizer for 8-VSB DTV*. US Patent Office, May 2006, US 7,054,359, Publication Date: May 30 2006 (Filing Date: 6 May 2002).

(2) List of ARC Grants Awarded in the Last Ten Years

Project Id	CI/PI/Fellow Name/s	Amount	Years	Project Title	Outputs
DP110102548	R. A. Kennedy, T. A. Lamahewa, X. Zhou, G. Giannakis	$255,000	2011-2013	Optimum Cross-Layer Design in Wireless Communication Systems with Channel Uncertainty	4, 44, 45, 54, 61
LP100100588	R. A. Kennedy, R. Shams, A. P. Rendell, P. Sadeghi, H. J. Gardner, N. Govindaraju, P. England, L. Zhou, E. Chang, S. Li, F. Hsu	$805,000	2010-2012	Advancing Medical Image Analysis through High Performance Heterogeneous Computing, Numerical Simulation, and Novel Human Computer Interfaces	47, 48, 49
DP1094350	R. A. Kennedy, P. Sadeghi	$240,000	2010-2012	Signal Concentration, Robust Signal Processing and Information Theory on the Unit Sphere	1, 7, 9, 10, 12, 15, 16, 18, 49, 52, 53, 57–59, 64–66, 69, 71, 76, 77, 87, 88, 92
DP0773898	R. A. Kennedy, P. Sadeghi, P. Rapajic	$315,000	2007-2009	Model-Based Approach to Adaptive Channel Coding and Estimation for Future Wireless Communication Systems	25, 20, 31, 112

The publications exclude papers by other investigators on the grant, papers under review and papers in preparation; see progress reports.

F12.3. Ten career-best research outputs

(Please attach a PDF with a list of your ten career-best research outputs (five pages maximum). Please refer to the Instructions to Applicants for the required content and formatting.)

Attached PDF

F12.3. Ten career-best publications

1. Z. Ding, **R. A. Kennedy**, B. D. O. Anderson, and C. R. Johnson Jr, "Ill-convergence of Godard blind equalizers in data communication systems," *IEEE Trans. Commun.*, vol. 39, no. 9, pp. 1313–1327, Sep. 1991, (Cited by 216).

   Significance and Impact: *This well-cited paper was the first to rigorously expose the possible failure of the most commonly used blind algorithm which is widely used in communication and surveillance systems.*

2. D. B. Ward, **R. A. Kennedy**, and R. C. Williamson, "Theory and design of broadband sensor arrays with frequency invariant far-field beam patterns," *J. Acoust. Soc. Am.*, vol. 97, no. 2, pp. 1023–1034, Feb. 1995, (Cited by 234).

   Significance and Impact: *The paper provides the first and major benchmark technique for the design of (high fractional) broadband arrays with arbitrary beam-pattern shape and frequency invariance property.*

3.⋆ P. D. Teal, T. D. Abhayapala, and **R. A. Kennedy**, "Spatial correlation for general distributions of scatterers," *IEEE Signal Process. Lett.*, vol. 9, no. 10, pp. 305–308, Oct. 2002, (Cited by 106).

   Significance and Impact: *This seminal paper reveals a deep relationship between spatial correlation and angular distributions making superfluous the bulk of papers dealing with analysis using any specific angular power distribution.*

4.⋆ **R. A. Kennedy**, T. A. Lamahewa, and L. Wei, "On azimuthally symmetric 2-sphere convolution," *Digital Signal Process.*, vol. 5, no. 11, pp. 660–666, Sep. 2011, (Cited by 13, outcome from **DP1094350**).

   Significance and Impact: *This paper fully characterizes convolution with an isotropic or symmetric kernel on the 2-sphere and shows difference formulations in the literature are fundamentally equivalent.*

5.⋆ **R. A. Kennedy**, T. D. Abhayapala, and D. B. Ward, "Broadband nearfield beamforming using a radial beampattern transformation," *IEEE Trans. Signal Process.*, vol. 46, no. 8, pp. 2147–2156, Aug. 1998, (Cited by 102).

   Significance and Impact: *This seminal paper solves in full generality a design problem regarded as very difficult: joint broadband (high fractional bandwidth) and nearfield beamforming by introducing new design methods.*

6.⋆ **R. A. Kennedy**, P. Sadeghi, T. D. Abhayapala, and H. M. Jones, "Intrinsic limits of dimensionality and richness in random multipath fields," *IEEE Trans. Signal Process.*, vol. 55, no. 6, pp. 2542–2556, Jun. 2007, (Cited by 71, outcome from **DP0343804**).

   Significance and Impact: *Reveals the implementation independent limits to multipath richness. It can be used to determine the number of MIMO antennas usable in a region, identify capacity thresholds, etc.*

7.⋆ **R. A. Kennedy** and P. Sadeghi, *Hilbert Space Methods in Signal Processing*. Cambridge, UK: Cambridge University Press, Mar. 2012, (Cited by 12, outcome from **DP1094350**).

   Significance and Impact: *Graduate text of 420 pages with research monograph material on spherical signal signal processing.*

8. P. Sadeghi, **R. A. Kennedy**, P. B. Rapajic, and R. Shams, "Finite-state Markov modeling of fading channels: A survey of principles and applications," *IEEE Signal Process. Mag.*, vol. 25, no. 5, pp. 57–80, Sep. 2008, (Cited by 120, outcome from **DP0773898**).

   Significance and Impact: *Major highly cited survey paper containing original material. In the list of the most highly cited papers for IEEE Signal Processing Magazine (called h-core) under Google Scholar Metrics.*

9. B. D. Radlović, R. C. Williamson, and **R. A. Kennedy**, "Equalization in an acoustic reverberant environment: Robustness results," *IEEE Trans. Speech Audio Process.*, vol. 8, no. 3, pp. 311–319, May 2000, (Cited by 94).

   Significance and Impact: *Fundamental paper which shows that acoustic equalization is ill-posed and practically impractical. Using theory counters a number of techniques that appear in the literature which do not use real data.*

10. R. Shams, P. Sadeghi, **R. A. Kennedy**, and R. I. Hartley, "A survey of high performance medical image registration on multi-core, GPU and distributed architectures," *IEEE Signal Process. Mag.*, pp. 50–60, Mar. 2010, (Cited by 82).

    Significance and Impact: *Rapidly cited paper which has impact in exposing the signal processing community to modern, cheap massively parallel architectures based on the GPU and applied to medical imaging.*

F12.4. Further evidence in relation to research impact and contributions to the field over the last 10 years most relevant to this Proposal

(Write a maximum of 7500 characters (approx. 1000 words). Please detail further evidence in relation to research impact and contributions to the field over the last 10 years. Please refer to the Instructions to Applicants for the required content and formatting.)

Broadly all the following in the signal processing field:

• Two US Patents, listed in Other publications, related to research contracts with Fox Digital Los Angeles CA and Philips Briarcliff Manor NY (listed under Other in F12.2).

Demonstration of Tangible Impact for End-users: The work under undertaken was part of a collaborative research activity involving US industry partners and Cornell University in characterizing the deficiencies of the first digital TV standard that was deployed in the US. Millions of end-users had serious reception problems, which we characterized through an extensive measurement campaign primarily in homes in the Los Angeles region and ultimately led to a new digital TV standard being shown necessary. The tangible impact is now successful broadcast HD TV enjoyed in the US and other countries that adopted the same updated standard.

• Advisor or on Evaluation Panels to foreign grant awarding bodies in New Zealand (FRST), Swedish Research Council, Denmark, Qatar, and Hong Kong

• Awarded Fellow IEEE in 2005 (approximately 40 in Australia)
• 2004-2005 Program Leader Wireless Signal Processing Program NICTA
• 2006-2008 Head of Department of Information Engineering RSISE
• 2008-2009 Director of Research, College of Engineering and Computer Science at ANU
• 2014 Associate Director (Education) for Engineering, oversight and management of undergraduate and postgraduate masters education programs, curriculum development and Engineering accreditation
• 38 completed PhD Students (+ 7 current or completing PhDs), 4 Research Masters Students
• 21 External Grants/Contracts exceeding $3M (majority sourced from industry)
• Member of the Editorial Board of International Journal of Adaptive Control and Signal Processing, 1991 to present.
• Associate Editor of IEEE Transactions on Communications: Editor for Data Communications, 1995 to 2005.
• Member of the Editorial Board of Foundations and Trends in Communications and Information Theory, 2004 to present.
• General Co-chair with Prof Alex Grant of 2005 IEEE ISIT, Adelaide.
• Paper reviewer for 15 journals including the Transactions for IEEE Communications, Information Theory and Signal Processing
• Member of the ARC Research Evaluation Committee (REC) for the 2010 ERA process
• Paper among the most highly cited papers for IEEE Signal Processing Magazine (h-core) under Google Scholar Metrics
• On discipline expectations, signal processing does not generally cite highly like Computer Vision or Machine Learning due to the restrictions on the number of references that a paper can cite (for example IEEE Transactions on Signal Processing has an average of 17 references per paper and ICASSP has an average of 7 papers, both are relatively low).
• My overall h-index above 30 and total citations around 4000.

F12.5. A statement on your most significant contributions to the research field of this Proposal

(Write a maximum of 3750 characters (approx. 500 words). Please refer to the Instructions to Applicants for the required content and formatting.)

In the research field relevant to this Proposal:

• I have a large number of contributions in the cognate areas of mobile communication systems, signal processing and related areas (over 300 refereed and published or accepted works) which are the result of collaborations with many PhD students, colleagues, industry partners and international researchers. All contributions such as refereed works require an advancement to knowledge.

• For some of this work I was awarded an IEEE Fellow of which there are only 40 or so in Australia and only a limited number in the Signal Processing/Communications area. My experience, evidenced through such awards, contributes to leading this Proposal.

• The earlier results relevant to this Proposal date back to 2002 and are in developing notions of dimensionality for spherical domains but including wave equation constraints, abstract MIMO channel models relying on spherical domains around the transmitter and receiver, spatial correlation models for spherical regions and entropy notions for spherical regions.

• The more recent results have been related to ARC Discovery grant DP1094350 "Signal Concentration, Robust Signal Processing and Information Theory on the Unit Sphere" where there have been 28 publications to date in the leading IEEE Journals and conferences such as six journal papers primarily in IEEE Transactions on Signal Processing and 21 conference papers many in ICASSP, the world's largest and most comprehensive technical conference focused on signal processing and its applications, and 1 published book (see below). Some of the deep contributions are: (i) the construction of the first commutative convolution notion on the sphere and (ii) a fully anisotropic spatio-spectral notion which is broadly analogy to the short-time Fourier transform in conventional signal processing. These are deep results that have advanced the field and are fundamental contributions that contribute to the technical aspects of the current Proposal.

• There is a 433 page (including front matter) research monograph called "Hilbert Space Methods in Signal Processing" published by Cambridge University in March 2013. It contains a treatment of Reproducing Kernel Hilbert Spaces and a complete classification of isometric kernels and the contraction of 4 closed form kernels that can be used for kernel evaluations of the inner product. Again these results are part of the basis for the investigations in this grant Proposal.

PART F - Personnel (Dr Salman Durrani)

F1. Personal details

(The personal details will be filled out for you automatically. To update any of your personal details in this form, please update your profile accordingly and your details will update automatically in this form.)

Title

Doctor

Family Name

Durrani

First Name

Salman

Person identifier

M1243098

Role

Chief Investigator

F2. Postal address

(The postal address will be filled out for you automatically. To update your postal address, please update your profile accordingly and your postal address will update automatically in this form.)

Postal Address Line 1

Research School of Engineering (Building 115)

Postal Address Line 2

ANU College of Engineering and Computer Science

Locality

Canberra

State

ACT

Postcode

0200

Country

Australia

F3. Are you a current member of the ARC or its selection or other advisory committees?

(This relates only to College of Experts or Selection Advisory Committee members for National Competitive Grants Program funding schemes.)

Current Member of Advisory Committee

No

F4. Please name any Commonwealth-funded Research Centres that you will be associated with as at 1 January 2015.

	Full Legal Name of Centre	Start Date	Cessation Date	Centre Role
1				
2				

	Centre Role if Other
1	
2	

F5. Are you an Indigenous Participant?

Indigenous Participant

No

F6. PhD Qualification

F6.1. Do you hold a PhD or expect to be awarded a PhD qualification in the near future?

PhD Yes/No

Yes

F6.2. If you hold a PhD or expect to be awarded a PhD qualification in the near future, please enter the date your PhD has been awarded or the date your thesis will be submitted, respectively.

Date of Award

26/11/2004

F7. Qualifications

	Degree/Award	Year	Discipline/Field	Organisation Name
1	PhD in Electrical Engineering	2004	Telecommunications	The University of Queensland
2	BSc (Hons)	2000	Electronics and Telecommunications	The University of Engineering & Technology, Lahore

	Country
1	Australia
2	Pakistan

F8. Current and previous appointment(s)/position(s) – during the past 10 years

	Position	Organisation Name	Department	Year Appointed
1	Senior Lecturer	The Australian National University	Research School of Engineering, College of Engineering & Computer Science	2012
2	Lecturer	The Australian National University	Research School of Engineering, College of Engineering & Computer Science	2005
3	Research Assistant	The University of Queensland	School of ITEE	2004

	Continuity	Employment Kind	Current
1	Permanent	Full Time	Yes
2	Permanent	Full Time	No
3	Contract	Part Time	No

F9. Organisational affiliations for eligibility purposes for this Proposal

(Name of the organisation you will be associated with for the purposes of satisfying the eligibility requirements for your nominated role in undertaking the proposed research (i.e. for a CI this will usually be the Eligible Organisation at which they will employed or hold an adjunct appointment as at 1 January 2015 and beyond; for PIs it will generally be their main employer as at 1 January 2015).)

Organisation Name

The Australian National University

Type of Affiliation

Employee

F10. What is your time commitment (%FTE) to this Project?

20

F11. Are you requesting an International Collaboration Award?

(Note: If you are an Australian-based PI, you must choose 'No'. Also, if you are a PI working in an Australian Eligible Organisation overseas campus you must choose 'No'.)

International Collaboration Award

No

F12. Research Opportunity and Performance Evidence (ROPE)

F12.1. Details on your career and opportunities for research over the last 10 years

(Write a maximum of 5250 characters (approx. 750 words). Please detail your career and opportunities over the last 10 years. Please refer to the Instructions to Applicants for the required content and formatting.)

(i)
It is 9 years and 3 months since I received my PhD degree from the University of Queensland, Brisbane in Nov. 2004.

(ii and iii)
In March 2005, I joined the faculty at the Research School of Engineering, Australian National University, Canberra as a full-time, continuing Lecturer. I was promoted to Senior Lecturer (current position) from January 2012.

Both of my ANU appointments have been standard faculty positions with a nominal 50% research and 50% teaching and admin load (teaching load of two courses/year). Since the last five years, I have consolidated all my teaching into Semester 1 (comprising 13 weeks in the year). This allows me to work full-time on research for the rest of the year.

I have 69 peer-reviewed publications to date, comprising 1 book chapter, 23 journal papers (including 17 papers in six different top ranked IEEE journals in my research field) and 45 conference papers (including papers in top conferences such as ICC, GLOBECOM, ICASSP, SPAWC, PIMRC, VTC).

According to Google Scholar, my papers have 409 citations at a citation h-index of 11 and citation g-index of 17.

(iv)
I have had no significant interruption to my career.

(v)
I am a member of the Applied Signal Processing (ASP) group at the College of Engineering and Computer Science, ANU. The groups' main research activities are aligned with the 0906 Field Of Research (FOR) Code, which was rated at 5 ("well above world standard") by the 2012 and 2010 ERA initiatives.

While I was an ECR, I received consistent and excellent research mentoring within the ASP group. This included participation in two completed ARC projects as a researcher:
(i) DP0773898 "Model-based Approach to Adaptive Channel Coding and Estimation" from 2009-2010 which resulted in 3 IEEE journal papers and 1 conference paper and
(ii) DP1094350 "Signal Concentration, Robust Signal processing and Information Theory on the Unit Sphere" from 2010-2012 which resulted in 3 IEEE journal paper and 5 conference papers.

(vi)
No other aspects to report.

F12.2. Recent significant research outputs and ARC grants (since 2004)

(Please attach a PDF with a list of your recent significant research outputs and ARC grants most relevant to the Proposal (20 pages maximum). Please refer to the Instructions to Applicants for the required content and formatting.)

F12.2. Recent Significant Publications (since 2004)

1. Research Publications Published in the Last Ten Years

1(b) Scholarly Book Chapters

1. **S. Durrani** and M. E. Bialkowski, "Smart Antennas for Code Division Multiple Access Systems," In C. Sun, J. Cheng and T. Ohira, editors, *Handbook on Advancements in Smart Antenna Technologies for Wireless Networks*, Information Science Reference, pp. 352-370, July 2009.

1(c) Refereed Journal Articles

2. Z. Khalid, **S. Durrani** and J. Guo, "A Tractable Framework for Exact Probability of Node Isolation and Minimum Node Degree Distribution in Finite Multi-hop Networks," *IEEE Transactions on Vehicular Technology*, 2014 (accepted: 24-11-2013).

3. J. Guo, **S. Durrani** and X. Zhou, "Outage Probability in Arbitrarily-Shaped Finite Wireless Networks," *IEEE Transactions on Communications*, vol. 62, no. 2, pp. 699–712, Feb. 2014.

4. S. N. Islam, P. Sadeghi and **S. Durrani**, "Error Performance Analysis of AF and DF Multi-way Relay Networks with BPSK Modulation," *IET Communications*, vol. 15, no. 7, pp. 1605–1616, Oct. 2013.

5. A. A. Nasir, H. Mehrpouyan, **S. Durrani**, S. Blostein, R. A. Kennedy and B. Ottersten, "Optimal Training Sequences for Joint Timing Synchronization and Channel Estimation in Distributed Communication Networks," *IEEE Transactions on Communications*, vol. 61, no. 7, pp. 3002–3015, July 2013.

6. A. A. Nasir, X. Zhou, **S. Durrani** and R. A. Kennedy, "Relaying Protocols for Wireless Energy Harvesting and Information Processing," *IEEE Transactions on Wireless Communications*, vol. 12, no. 7, pp. 3622–3636, July 2013.

7. A. A. Nasir, H. Mehrpouyan, **S. Durrani**, S. D. Blostein, R. A. Kennedy and B. Ottersten, "Transceiver Design for Distributed STBC Based AF Cooperative Networks in the Presence of Timing and Frequency Offsets," *IEEE Transactions on Signal Processing*, vol. 61, no. 12, pp. 3143–3158, June 2013.

8. Z. Khalid and **S. Durrani**, "Distance Distributions in Regular Polygons," *IEEE Transactions on Vehicular Technology*, vol. 62, no. 5, pp. 2363–2368, June 2013.

9.⋆ Z. Khalid, R. A. Kennedy, **S. Durrani**, P. Sadeghi, Y. Wiaux, and J. D. McEwan, "Fast Directional Spatially Localized Spherical Harmonic Transform," *IEEE Transactions on Signal Processing*, vol. 61, no. 9, pp. 2192–2203, May 2013.

10.⋆ Z. Khalid, P. Sadeghi, R. A. Kennedy and **S. Durrani**, "Spatially Varying Spectral Filtering of Signals on the Unit Sphere," *IEEE Transactions on Signal Processing*, vol. 61, no. 3, pp. 530–544, Feb. 2013.

11. A. A. Nasir, **S. Durrani** and R. A. Kennedy, "Particle Filters for Joint Timing and Carrier Estimation: Improved Resampling Guidelines and Weighted Bayesian Cramer-Rao Bounds," *IEEE Transactions on Communications*, vol. 60, no. 5, pp. 1407–1419, May 2012.

12.⋆ Z. Khalid, **S. Durrani**, P. Sadeghi and R. A. Kennedy, "Spatio-spectral Analysis of Signals on the Sphere Using Spatially Localized Spherical Harmonics Transform," *IEEE Transactions on Signal Processing*, vol. 60, no. 3, pp. 1487–1492, March 2012.

13. A. Nasir, H. Mehrpouyan, S. Blostein, **S. Durrani** and R. A. Kennedy, "Timing and Carrier Synchronization with Channel Estimation in Multi-Relay Cooperative Networks," *IEEE Transactions on Signal Processing*, vol. 60, no. 2, pp. 793–811, Feb. 2012.

14. A. A. Nasir, **S. Durrani** and R. A. Kennedy, "Blind Timing and Carrier Synchronization in Distributed MIMO Communication Systems," *IET Communications*, vol. 5, no. 7, pp. 1028–1037, May 2011.

15. X. Zhou, T. Lamahewa, P. Sadeghi and **S. Durrani**, "Two-way Training: Optimal Power Allocation for Pilot and Data Transmission," *IEEE Transactions on Wireless Communications*, vol. 9, no. 2, pp. 564–569, Feb. 2010.

16. X. Zhou, **S. Durrani** and H. Jones, "Connectivity Analysis of Wireless Ad hoc Networks with Beamforming," *IEEE Transactions on Vehicular Technology*, vol. 58, no. 9, pp. 5247–5257, Nov. 2009.

17. X. Zhou, P. Sadeghi, T. Lamahewa and **S. Durrani**, "Design Guidelines for Pilot Transmission in MIMO Systems with Feedback," *IEEE Transactions on Signal Processing*, vol. 57, no. 10, pp. 4014–4026, Oct. 2009.

18. X. Zhou, P. Sadeghi, T. Lamahewa and **S. Durrani**, "Optimizing Antenna Configuration for MIMO Systems with Imperfect Channel Estimation," *IEEE Transactions on Wireless Communications*, vol. 8, no. 3, pp. 1177–1181, Mar. 2009.

19. M. E. Bialkowski, P. Uthansakul, K. Bialkowski and **S. Durrani**, "Investigating the Performance of MIMO Systems from an Electromagnetic Perspective," *Microwave and Optical Technology Letters*, vol. 48, no. 7, pp. 1233–1238, July 2006.

20. **S. Durrani** and M. E. Bialkowski, "Analysis of the error performance of adaptive array antennas for CDMA with noncoherent *M*-ary orthogonal modulation in Nakagami fading," *IEEE Communications Letters*, vol. 9, no. 2, pp. 148–150, Feb. 2005.

21. **S. Durrani** and M. E. Bialkowski, "Effect of mutual coupling on the interference rejection capabilities of linear and circular arrays in CDMA systems," *IEEE Transaction on Antennas and Propagation*, vol. 52, no. 4, pp. 1130–1134, Apr. 2004.

1(d) Refereed Conference Papers

22.⋆ Z. Khalid, R. A. Kennedy and **S. Durrani**, "On the Choice of the Window for Spatial Smoothing of Spherical Data," in *Proc. IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, Florence, Italy, May 2014 (accepted: 03-02-2014).

23. A. A. Nasir, X. Zhou, **S. Durrani** and R. A. Kennedy, "Throughput and Ergodic capacity of Wireless Energy Harvesting Based DF Relaying Network," *Proc. IEEE International Conference on Communications (ICC)*, Sydney, Australia, June 2014 (accepted: 13-01-2014).

24.⋆ Z. Khalid, R. A. Kennedy, P. Sadeghi and **S. Durrani**, "Spatio-spectral Formulation and Design of Spatially-Varying Filters for Signal Estimation on the 2-Sphere," in *Proc. SPIE Wavelets and Sparsity XV*, San Diego, USA, Sep. 2013, vol. 8858, pp. 88580L-1-88580L-13 (**invited paper**).

25. A. A. Nasir, H. Mehrpouyan, **S. Durrani**, S. D. Blostein and R. A. Kennedy "DSTBC based DF Cooperative Networks in the Presence of Timing and Frequency Offsets," in *Proc. IEEE Signal Processing Advances in Wireless Communications (SPAWC)*, Darmstadt, Germany, June 2013.

26.⋆ D. H. Chae, Y. Alem, **S. Durrani** and R. A. Kennedy, "Performance study of compressive sampling for ECG signal compression in noisy and varying sparsity acquisition," in *Proc. IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, Vancouver, Canada, May 2013.

27. Z. Khalid and **S. Durrani**, "Connectivity of Three Dimensional Wireless Sensor Networks Using Geometrical Probability," in *Proc. Australian Communications Theory Workshop (AusCTW)*, Adelaide, Jan., 2013.

28. W. Tushar, J. Zhang, D. B. Smith, H. V. Poor, G. Platt and **S. Durrani**, "An Efficient Energy Curtailment Scheme For Outage Management in Smart Grid," in *Proc. IEEE Global Communications Conference (Globecom)*, California, USA, Dec. 3-7, 2012.

29. A. A. Nasir, H. Mehrpouyan, Steven D. Blostein, **S. Durrani**, R. A. Kennedy, "Estimation of Synchronization Parameters in AF Cooperative Networks," in *Proc. IEEE International Conference on Communications (ICC)*, Ottawa, Canada, June 10-15, 2012.

30.⋆ Z. Khalid, **S. Durrani**, R. A. Kennedy and P. Sadeghi, "Concentration uncertainty principles for signals on the unit sphere," in *Proc. IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, Kyoto, Japan, Mar. 25-30, 2012.

31.⋆ Z. Khalid, **S. Durrani**, R. A. Kennedy and P. Sadeghi, "Ambiguity function and Wigner distribution on the sphere," in *Proc. IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, Kyoto, Japan, Mar. 25-30, 2012.

32.⋆ Z. Khalid, R. A. Kennedy, **S. Durrani** and P. Sadeghi, "Conjugate gradient algorithm for extrapolation of sampled bandlimited signals on the 2-sphere," in *Proc. IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, Kyoto, Japan, Mar. 25-30, 2012.

33.⋆ Z. Khalid, **S. Durrani**, R. A. Kennedy and P. Sadeghi, "Revisiting Slepian Concentration Problem on the Sphere for Azimuthally Non-Symmetric Regions," in *Proc. International Conference on Signal Processing and Communication Systems (ICSPCS)*, Hawaii, USA, Dec. 12-14, 2011.

34. A. A. Nasir, **S. Durrani** and R. A. Kennedy , "Achieving Cooperative Diversity with Multiple Frequency Offset Estimation," in *Proc. International Conference on Signal Processing and Communication Systems (ICSPCS)*, Hawaii, USA, Dec. 12-14, 2011.

35. A. A. Nasir, **S. Durrani** and R. A. Kennedy, "Blind Timing and Carrier Synchronization in Decode and Forward Cooperative Systems," in *Proc. IEEE International Conference on Communications (ICC)*, Kyoto, Japan, June 5-9, 2011.

36.⋆ Z. Khalid, **S. Durrani**, P. Sadeghi and R. A. Kennedy, "On the construction of low-pass filters on the unit sphere," in *Proc. IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, Prague, Czech Republic, May 22-27, 2011.

37. A. A. Nasir, **S. Durrani** and R. A. Kennedy, "Mixture Kalman Filtering for joint carrier recovery and channel estimation in time-selective Rayleigh fading channels," in *Proc. IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, Prague, Czech Republic, May 22-27, 2011.

38. A. A. Nasir, **S. Durrani** and R. A. Kennedy, "A Particle Filter for Joint Blind Carrier Frequency Offset Estimation and Data Detection," in *Proc. International Conference on Signal Processing and Communication Systems (ICSPCS)*, Gold Coast, Dec. 13-15, 2010.

39. O. Hashmi, S. Kodituwakku and **S. Durrani**, "Frequency Prioritised Queuing in Real-Time Electrocardiograph Systems," in *Proc. International Conference on Signal Processing and Communication Systems (ICSPCS)*, Gold Coast, Dec. 13-15, 2010.

40. **S. Durrani**, X. Zhou, A. Chandra, "Effect of Mobility on Connectivity of Vehicular Ad Hoc Networks," in *Proc. IEEE Vehicular Technology Conference (VTC)*, Ottawa, Canada, $6-9$ September, 2010.

41. A. A. Nasir, **S. Durrani** and R. A. Kennedy, "Blind Fractionally Spaced Equalization and Timing Synchronization in Wireless Fading Channels," in *Proc. 2nd International Conference on Future Computer and Communication (ICFCC)*, vol. 3, Wuhan, China, 21-24 May, 2010, pp. 15-19.

42. A. A. Nasir, **S. Durrani** and R. A. Kennedy, "Performance of Coarse and Fine Timing Synchronization in OFDM Receivers," in *Proc. 2nd International Conference on Future Computer and Communication (ICFCC)*, vol. 2, Wuhan, China, 21-24 May, 2010. pp. 412-416.

43. A. A. Nasir, **S. Durrani** and R. A. Kennedy, "Modified Constant Modulus Algorithm for joint blind equalization and synchronization," in *Proc. Australian Communications Theory Workshop (AusCTW)*, Canberra, Feb. 2-6, 2010.

44. X. Zhou, T. Lamahewa, P. Sadeghi and **S. Durrani**, "Optimizing Training-based Transmission for Correlated MIMO systems with Hybrid Feedback," in *Proc. IEEE Global Telecommunications Conference (Globecom)*, Hawaii, USA, Nov 30 - Dec. 4, 2009.

45. X. Zhou, **S. Durrani** and H. Jones, "Connectivity of Ad Hoc Networks: Is Fading Good or Bad?," in *Proc. International Conference on Signal Processing and Communication Systems (ICSPCS)*, Gold Coast, Dec. 15-17, 2008.

46. X. Zhou, T. Lamahewa, P. Sadeghi and **S. Durrani**, "Capacity of MIMO Systems: Impact of Spatial Correlation with Channel Estimation Errors," in *Proc. IEEE International Conference on Communication Systems (ICCS)*, Guangzhou, China, Nov. 19-21, 2008, pp. 817-822.

47. **S. Durrani**, X. Zhou and H. Jones, "Connectivity of Wireless Ad Hoc Networks with Random Beamforming: An Analytical Approach," in *Proc. IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Cannes, France, Sep. 15-18, 2008.

48. X. Zhou, T. Lamahewa, P. Sadeghi and **S. Durrani**, "Designing PSAM Schemes: How Optimal are SISO Pilot Parameters for Spatially Correlated SIMO?," in *Proc. IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Cannes, France, Sep. 15-18, 2008.

49. X. Zhou, T. Lamahewa, P. Sadeghi and **S. Durrani**, "Designing PSAM Schemes: How Optimal are SISO Pilot Parameters for Spatially Correlated SIMO?," in *Proc. IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Cannes, France, Sep. 15-18, 2008.

50. X. Zhou, **S. Durrani** and H. Jones, "Analytical Study of Connectivity in Wireless Ad hoc Networks with Random Beamforming," in *Proc. International Conference on Signal Processing and Communication Systems (ICSPCS)*, Gold Coast, Dec. 17-19, 2007.

51. **S. Durrani**, M. E. Bialkowski and S. Latif, "Statistical properties of a parametric channel model for multiple antenna systems," in *Proc. IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Athens, Greece, Sep. 3-7, 2007.

52. X. Zhou, H. Jones, **S. Durrani** and A. Scott, "Effect Of Beamforming On The Connectivity Of Ad Hoc Networks," in *Proc. Australian Communications Theory Workshop (AusCTW)*, Adelaide, Feb. 5-7, 2007, pp. 13-18.

53. S. Pan, **S. Durrani** and M. E. Bialkowski, "MIMO Capacity for Spatial Channel Model Scenarios," in *Proc. Australian Communications Theory Workshop (AusCTW)*, Adelaide, Feb. 5-7, 2007, pp. 25-29.

54. **S. Durrani** and M. E. Bialkowski, "A Parametric Channel Model for Smart Antennas Incorporating Mobile Station Mobility,"in *Proc. IEEE Vehicular Technology Conference (VTC)*, vol. 6, Melbourne, May 7-10, 2006, pp. 2803 - 2807.

55. M. E. Bialkowski, **S. Durrani**, P. Uthansakul, and K. Bialkowski, "A Simple Electromagnetic Model for Understanding the Operation of a MIMO System," in *Proc. IEEE Symposium on Antennas and Propagation (AP-S)*, vol. 2A, Washington, July 3-8, 2005, pp. 305-308.

56. P. Uthansakul, M. E. Bialkowski, **S. Durrani**, K. Bialkowski and A. Postula, "Effect of Line of Sight Propagation on Capacity of an Indoor MIMO System," in *Proc. IEEE Symposium on Antennas and Propagation (AP-S)*, vol. 2B, Washington, July 3-8, 2005, pp. 707-710.

57. M. E. Bialkowski, **S. Durrani**, K. Bialkowski and P. Uthansakul, "Understanding and analyzing the performance of MIMO systems from the microwave perspective," in *Proc. IEEE International Microwave Symposium (IMS)*, Long Beach, California, June 12-17, 2005, pp. 2251-2254.

58. **S. Durrani** and M. E. Bialkowski, "A simple model for performance evaluation of a smart antenna in a CDMA system," in *Proc. IEEE International Symposium on Spread Spectrum Techniques and Applications (ISSSTA)*, Sydney, Australia, Aug. 30 - Sep. 2, 2004, pp. 379-383.

59. **S. Durrani** and M. E. Bialkowski, "Performance of hierarchical beamforming in a Rayleigh fading environment with angle spread," in *Proc. International Symposium on Antennas (ISAP)*, vol. 2, Sendai, Japan, Aug. 17-21, 2004, pp. 937-940.

60. **S. Durrani** and M. E. Bialkowski, "Effect of angular energy distribution of an incident signal on the spatial fading correlation of a uniform linear array," in *Proc. International Conference on Microwaves, Radar and Wireless Communications (MIKON)*, vol. 2, Warsaw, Poland, May 17-19, 2004, pp. 493-496.

61. **S. Durrani** and M. E. Bialkowski, "Performance analysis of beamforming in Ricean fading channels for CDMA systems," in *Proc. Australian Communications Theory Workshop (AusCTW)*, Newcastle, Australia, Feb. 4-6, 2004, pp. 1-5.

2. List of ARC Grants Awarded in the Last Ten Years

Project Id	CI/PI/Fellow Name/s	Amount	Years	Project Title	Outputs
DP140101133	S. Durrani, X. Zhou, H. Mehrpouyan, S. D. Blostein	$365,000	2014-2016	Realizable Synchronization Techniques: Unlocking the Potential of Future Wireless Networks	None to date.

Note: Grant has just commenced in 2014.

F12.3. Ten career-best research outputs

(Please attach a PDF with a list of your ten career-best research outputs (five pages maximum). Please refer to the Instructions to Applicants for the required content and formatting.)

Attached PDF

F12.3. Ten career-best publications

1. **S. Durrani** and M. E. Bialkowski, "Effect of mutual coupling on the interference rejection capabilities of linear and circular arrays in CDMA systems," *IEEE Transaction on Antennas and Propagation*, vol. 52, no. 4, pp. 1130–1134, Apr. 2004 (Cited by 73).

   Significance and Impact: *This paper proposes a practically elegant method to model mutual coupling, which has been adopted as a benchmark method by Antennas and Propagation community.*

2. A. A. Nasir, H. Mehrpouyan, S. D. Blostein, **S. Durrani** and R. A. Kennedy, "Timing and Carrier Synchronization with Channel Estimation in Multi-Relay Cooperative Networks," *IEEE Transactions on Signal Processing*, vol. 60, no. 2, pp. 793–811, Feb. 2012., (Cited by 23).

   Significance and Impact: *This paper provides a truly complete synchronization solution for cooperative systems with amplify-and-forward and decode-and-forward relaying.*

3. A. A. Nasir, X. Zhou, **S. Durrani** and R. A. Kennedy, "Relaying Protocols for Wireless Energy Harvesting and Information Processing," *IEEE Transactions on Wireless Communications*, vol. 12, no. 7, pp. 3622–3636, July 2013, (Cited by 16).

   Significance and Impact: *The first paper to consider wireless energy harvesting in the context of relay based wireless systems.*

4.⋆ Z. Khalid, **S. Durrani**, P. Sadeghi and R. A. Kennedy, "Spatio-spectral Analysis of Signals on the Sphere Using Spatially Localized Spherical Harmonics Transform," *IEEE Transactions on Signal Processing*, vol. 60, no. 3, pp. 1487–1492, March 2012, (Cited by 9).

   Significance and Impact: *This paper proposes a new spatio-spectral analysis technique, which can reveal spatially-localized spectral contributions not obtainable from traditional spherical harmonics analysis.*

5. X. Zhou, T. Lamahewa, P. Sadeghi and **S. Durrani**, "Two-way Training: Optimal Power Allocation for Pilot and Data Transmission," *IEEE Transactions on Wireless Communications*, vol. 9, no. 2, pp. 564–569, Feb. 2010, (Cited by 16).

   Significance and Impact: *The first paper to tackle the optimal power allocation problem in two-way training systems, providing simple analytical results which give near optimal performance in various practical scenarios.*

6.⋆ Z. Khalid, R. A. Kennedy, **S. Durrani**, P. Sadeghi, Y. Wiaux and J. D. McEwan, "Fast Directional Spatially Localized Spherical Harmonic Transform," *IEEE Transactions on Signal Processing*, vol. 61, no. 9, pp. 2192-2203, May 2013, (Cited by 3).

   Significance and Impact: *This paper proposes a fast algorithm for the efficient computation of a transform which can reveal localized directional content in the spatio-spectral domain, with many practical application.*

7.⋆ Z. Khalid, P. Sadeghi, R. A. Kennedy and **S. Durrani**, "Spatially Varying Spectral Filtering of Signals on the Unit Sphere," *IEEE Transactions on Signal Processing*, vol. 61, no. 3, pp. 530–544, Feb. 2013, (Cited by 4).

   Significance and Impact: *This paper presents a general framework for spatially-varying spectral filtering of signals defined on the unit sphere, as an analogy to joint time-frequency filtering.*

8. X. Zhou, P. Sadeghi, T. Lamahewa and **S. Durrani**, "Design Guidelines for Pilot Transmission in MIMO Systems with Feedback," *IEEE Transactions on Signal Processing*, vol. 57, no. 10, pp. 4014–4026, Oct. 2009, (Cited by 12).

   Significance and Impact: *This paper establishes comprehensive design guidelines for the allocation of pilot and data symbols in MIMO systems taking channel feedback delay into account.*

9. X. Zhou, **S. Durrani** and H. Jones, "Connectivity Analysis of Wireless Ad hoc Networks with Beamforming," *IEEE Transactions on Vehicular Technology*, vol. 58, no. 9, pp. 5247–5257, Nov. 2009, (Cited by 12).

   Significance and Impact: *This paper proposes a general analytical framework for evaluating the impact of beamforming on the connectivity of future wireless ad hoc networks - a problem hitherto unsolved in the literature.*

10. M. E. Bialkowski, P. Uthansakul, K. Bialkowski and **S. Durrani**, "Investigating the Performance of MIMO Systems from an Electromagnetic Perspective," *Microwave and Optical Technology Letters*, vol. 48, no. 7, pp. 1233–1238, July 2006, (Cited by 27).

    Significance and Impact: *This paper provides a method to accurately model MIMO system capacity in the strict electromagnetic sense, when both antennas and scattering objects are formed by wire dipoles.*

F12.4. Further evidence in relation to research impact and contributions to the field over the last 10 years most relevant to this Proposal

(Write a maximum of 7500 characters (approx. 1000 words). Please detail further evidence in relation to research impact and contributions to the field over the last 10 years. Please refer to the Instructions to Applicants for the required content and formatting.)

[1] RESEARCH OUTPUTS OTHER THAN PUBLICATIONS

[1.1] Invited Talks:
(i) Invited talk at 2013 Australian Communications Theory Workshop, Adelaide.
(ii) Invited talk at 2009 Workshop on Wireless Communications, The University of Engineering & Technology, Lahore, Pakistan.
(iii) Invited talk at 2004 Workshop on Sensor Networks, The University of Technology, Sydney, Australia.

[1.2] International Visits and Invited Departmental Seminars
(i) 2012 seminar at Queen's University, Kingston, Canada (hosted by Prof. Steven Blostein)
(ii) 2010 seminar at University of British Columbia, Vancouver (hosted by Prof. Vikram Krishnamurthy, Canada Research Chair in Statistical Signal Processing).
(iii) 2010 seminar at Carleton University, Ottawa (hosted by Prof. David Falconer and Prof. Halim Yanikomeroglu).
(iv) 2005 visiting researcher at Wireless Signal Processing, NICTA, Canberra (hosted by Prof. Thushara Abhayapala)

[1.3] Professional Activities:
I have served as Technical Programme Committee Member for leading international conferences:
(i) 2014 IEEE International Conference on Communications (ICC), Sydney, Australia.
(ii) 2013 IEEE International Conference on Communications (ICC), Budapest, Hungary.
(iii) 2012 IEEE International Conference on Communications (ICC), Ottawa, Canada.
(iv) 2012 IEEE Personal, Indoor, and Mobile Radio Communication Conference (PIMRC), Sydney, Australia.
(v) 2012 Australian Communications Theory Workshop (AusCTW), Wellington, New Zealand.
(vi) 2011 IEEE Personal, Indoor, and Mobile Radio Communication Conference (PIMRC), Toronto, Canada.

I was Session Chair at 2007 IEEE PIMRC conference, Athens, Greece (Session 36: Smart Antennas I and Session 62: Self-organization of wireless networks). I was a Local Organising Committee Member for 2005 AusCTW in Brisbane.

[1.4] Research Funding:
1 ARC DP grant as lead chief investigator ($365,000) and 2 ANU internal grants as sole chief investigator ($5000 each in 2007 and 2006).

[1.5] Review and Service:
I have been a regular reviewer for 12 leading international journals in my research field (IEEE Transactions on Wireless Communications, IEEE Transactions on Communications, IEEE Transactions on Vehicular Technology, IEEE Transactions on Signal Processing, IEEE Transactions on Antennas and Propagation, IEEE Signal Processing Letters, IEEE Communications Letters, IEEE Sensors Journal, IET Communications, EURASIP Journal on Wireless Communications and Networking, Wireless Communications and Mobile Computing (Wiley), International Journal of Antennas and Propagation).

I have been a regular reviewer for leading international conferences (such as IEEE Global Telecommunications Conference (Globecom) and IEEE International Conference on Communications (ICC), IEEE Vehicular Technology Conference (VTC), International Conference on Signal Processing and Communication Systems (ICSPCS) and Australian Communications Theory Workshop (AusCTW)).

[1.6] PhD supervision and Examination:
(i) I have successfully supervised 6 PhD students (graduated: 3, current: 3) and 5 Masters students (graduated: 4, current: 1).
(ii) I have served as examiner for three external PhD thesis (2013: QUT, 2009: QUT, 2008: Monash University) and three external MPhil theses (2011: QUT, 2009: Victoria University, 2008: University of Queensland).

[1.7] Other Professional Activities:

I am a Senior Member of Institute of Electrical and Electronics Engineers (IEEE), USA, a Senior Fellow of Higher Education Academy (HEA), UK and a Member of Engineers Australia.

[2] EVIDENCE FOR THE QUALITY OF RESEARCH OUTPUTS

[2.1] Citation Metrics:
In the last 10 years, I have published 1 book chapter, 21 journal papers (2010 ERA ranking: 19 A/A+, 2B) and 39 conference papers.

According to Google Scholar, my 61 peer-reviewed publications in the last 10 years have 350 citations at a citation h-index of 11. The growing impact of my research is also evidenced by the fact that my work has been cited 122 times in 2013.

Four of my published papers are in the top 10% highly cited papers for the respective journals in their publication years (2013 IEEE Transactions on Wireless Propagation, 2012 IEEE Transactions on Signal Processing, 2006 Microwave and Optical Technology Letter and 2004 IEEE Transaction on Antennas and Propagation, respectively).

[2.2] Quality of Publication Outputs:
In the last 10 years, I have published papers in leading IEEE journals (which have a rigorous review process) in my research field. Below I give the Thompson ISI 2012 five year Impact Factor [IF], 2010 ERA journal ranking [ERA] and number of papers [n] in each outlet:
IEEE Transactions on Signal Processing (IF = 3.068, ERA= A+, n = 6),
IEEE Transactions on Wireless Communications (IF = 2.744, ERA = A, n = 3),
IEEE Transactions on Vehicular Technology (IF =2.019, ERA = A, n = 3),
IEEE Transactions on Communications (IF = 1.743, ERA = A+, n =3),
IEEE Transaction on Antennas and Propagation (IF = 2.648, ERA = A, n = 1),
IEEE Communication Letters (IF = 1.222, ERA = A, n = 1)

Note that IEEE Transactions on Signal Processing and IEEE Transactions on Wireless Communications are No. 1 and No. 2 ranked journals in Electrical and Electronic Engineering (out of 243) according to the 2012 Journal Citation Report (JCR) by Thompson ISI [journal ranking by eigen-factor score, which measures journal influence in the scientific community].

In addition, 54 out of 61 publications in the last ten years are indexed in IEEE Xplore digital library which is the online digital library with the greatest impact and readership in my research field.

[2.3] Awards:
I have received numerous awards and travel grants in my career. In the last 10 years, this includes a 2007 ARC Australian Communications Research Network travel grant ($2000).

[2.4] Esteem Measures:
I was elevated to the grade to Senior Member of IEEE in 2010, only 5 years after my PhD (less than 8% of approximately 388,000 IEEE members world-wide hold this grade which requires demonstration of significant professional and research achievements).

F12.5. A statement on your most significant contributions to the research field of this Proposal

(Write a maximum of 3750 characters (approx. 500 words). Please refer to the Instructions to Applicants for the required content and formatting.)

I have worked in the cognate field of signal processing for wireless communication systems for over a decade. The well cited works include research on (i) mutual coupling effects in smart antenna systems (ii) synchronization and channel estimation algorithms for wireless networks and (ii) signal processing at relays to enable wireless energy harvesting. I also have a background in biomedical signal processing, with a recent paper on compressive sampling for Electrocardiography (ECG) accepted in ICASSP.

I started work on spherical signal processing from 2010 onwards when I was participated as a researcher in an ARC Discovery Project DP1094350 “Signal Concentration, Robust Signal processing and Information Theory on the Unit Sphere”, which resulted in 3 IEEE Transaction on Signal Processing journal papers and 5 conference papers (including 4 ICASSP papers).

My most significant contribution to this research field is the development of a new spatio-spectral analysis technique, which can reveal spatially-localized spectral contributions not obtainable from traditional spherical harmonics analysis. This technique is analogous to the short-time Fourier transform in conventional signal processing.

Other very recent relevant contributions include (i) development of fast implementation algorithms for the new spatio-spectral analysis technique and (ii) development of a general framework for spatially-varying spectral filtering of signals defined on the unit sphere, as an analogy to joint time-frequency filtering.

In summary, the basics of the important issues related to spherical signal processing have been mastered. In the current research proposal, I will apply the above demonstrated expertise to the design of advanced universal methods for processing data collected with spherical geometry.

PART F - Personnel (Dr Jason McEwen)

F1. Personal details

(The personal details will be filled out for you automatically. To update any of your personal details in this form, please update your profile accordingly and your details will update automatically in this form.)

Title

Doctor

Family Name

McEwen

First Name

Jason

Person identifier

27297603

Role

Partner Investigator

F2. Postal address

(The postal address will be filled out for you automatically. To update your postal address, please update your profile accordingly and your postal address will update automatically in this form.)

Postal Address Line 1

Department of Physics and Astronomy

Postal Address Line 2

University College London

Locality

London

Postcode

WC1E 6BT

Country

United Kingdom

F3. Are you a current member of the ARC or its selection or other advisory committees?

(This relates only to College of Experts or Selection Advisory Committee members for National Competitive Grants Program funding schemes.)

Current Member of Advisory Committee

No

F4. Please name any Commonwealth-funded Research Centres that you will be associated with as at 1 January 2015.

	Full Legal Name of Centre	Start Date	Cessation Date	Centre Role
1				
2				

	Centre Role if Other
1	
2	

F5. Are you an Indigenous Participant?

Indigenous Participant

No

F6. PhD Qualification

F6.1. Do you hold a PhD or expect to be awarded a PhD qualification in the near future?

PhD Yes/No

Yes

F6.2. If you hold a PhD or expect to be awarded a PhD qualification in the near future, please enter the date your PhD has been awarded or the date your thesis will be submitted, respectively.

Date of Award

01/05/2007

F7. Qualifications

	Degree/Award	Year	Discipline/Field	Organisation Name
1	PhD	2007	Physics	University of Cambridge
2	BE (Hons I)	2002	Engineering	University of Canterbury, Christchurch

	Country
1	United Kingdom
2	New Zealand

F8. Current and previous appointment(s)/position(s) – during the past 10 years

	Position	Organisation Name	Department	Year Appointed
1	Lecturer in Cosmology and Astrophysics	University College London	Space and Climate Physics	2013
2	Newton International Fellowship (funded by the Royal Society and the British Academy)	University College London	Physics and Astronomy	2012
3	Visiting Researcher (whilst awaiting visa)	Victoria University	Engineering and Computer Science	2011
4	Leverhulme Early Career Fellowship	University College London	Physics and Astronomy	2011
5	Postdoctoral Researcher	Swiss Federal Institute of Technology, Lausanne	Electrical Engineering	2010
6	Quantitative Analyst	Credit Suisse AG	Global Modelling and Analytics Group	2008
7	Junior Research Fellow	University of Cambridge	Clare College	2007
8	Postdoctoral Teaching Associate	University of Cambridge, UK	King's College	2006
9	Research Associate	University of Cambridge, UK	Physics	2006

	Continuity	Employment Kind	Current
1	Contract	Full Time	Yes
2	Contract	Full Time	No
3	Contract	Full Time	No
4	Contract	Full Time	No
5	Contract	Full Time	No
6	Contract	Full Time	No
7	Contract	Full Time	No
8	Contract	Full Time	No
9	Contract	Full Time	No

F9. Organisational affiliations for eligibility purposes for this Proposal

(Name of the organisation you will be associated with for the purposes of satisfying the eligibility requirements for your nominated role in undertaking the proposed research (i.e. for a CI this will usually be the Eligible Organisation at which they will employed or hold an adjunct appointment as at 1 January 2015 and beyond; for PIs it will generally be their main employer as at 1 January 2015).)

Organisation Name

University College London

Type of Affiliation

Employee

F10. What is your time commitment (%FTE) to this Project?

10

F11. Are you requesting an International Collaboration Award?

(Note: If you are an Australian-based PI, you must choose 'No'. Also, if you are a PI working in an Australian Eligible Organisation overseas campus you must choose 'No'.)

International Collaboration Award

Yes

F12. Research Opportunity and Performance Evidence (ROPE)

F12.1. Details on your career and opportunities for research over the last 10 years

(Write a maximum of 5250 characters (approx. 750 words). Please detail your career and opportunities over the last 10 years. Please refer to the Instructions to Applicants for the required content and formatting.)

(i)
I was awarded my PhD, nearly 6 years ago, from the University of Cambridge in May 2007.

(ii)
From Sep 2007 – Sep 2008 I held a Junior Research Fellowship at Clare College, Cambridge. The success rate for this fellowship was 0.4%. This was a 100% research position.

Form Oct 2008 – May 2010, I worked in industry as a Quantitative Analyst.

From Jun 2010 – May 2011, I held a postdoctoral position at Ecole Polytechnique Federale de Lausanne (EPFL). It was a 100% research position.

From Sep 2011 – Jan 2012, I held a Leverhulme Early Career Fellowship, supported by the Leverhulme Trust, at University College London (UCL). It was a 100% research position.

From Jan 2012– Jul 2013, I held a Newton International Fellowship at University College London (UCL). This Fellowship is awarded to only the very best early stage post-doctoral researchers from all over the world. It is supported by The British Academy and the Royal Society. The success rate is generally 7-8%. It was a 100% research position.

During these postdoctoral and fellowship positions, I have supervised ten Masters or PhD students on research projects. These projects led to five journal publications.

Currently, I am a Lecturer in Cosmology at the Mullard Space Science Laboratory (MSSL), University College London (UCL). At present I am 100% research focused without any teaching commitments.

(iii)
All my appointments have been research only.

(iv)
No interruptions. Between fellowship positions, I worked in industry (economics) for a period of two years.

(v)
I am Core Team Member, Plank Satellite Mission, European Space Agency (ESA).

(vi)
No other aspects to report.

F12.2. Recent significant research outputs and ARC grants (since 2004)

(Please attach a PDF with a list of your recent significant research outputs and ARC grants most relevant to the Proposal (20 pages maximum). Please refer to the Instructions to Applicants for the required content and formatting.)

F12.2. Recent Significant Publications (since 2004)

1. Research Publications Published in the Last Ten Years

1(a) Refereed Journal Articles

1.⋆ Planck Collaboration XXVI. "Planck 2013 results: Background geometry and topology of the Universe," *Astron. & Astrophys.*, in press, 2014. (Accepted: 23 Feb. 2014)

2. Planck Collaboration XXV. "Planck 2013 results: Searches for cosmic strings and other topological defects," *Astron. & Astrophys.*, in press, 2014. (Accepted: 23 Jan. 2014)

3.⋆ Planck Collaboration XXVI. "Planck 2013 results: Isotropy and statistics of the CMB," *Astron. & Astrophys.*, in press, 2014. (Accepted: 1 Jan. 2014)

4.⋆ S. M. Feeney, D. Marinucci, **J. D. McEwen**, H. V. Peiris, B. Wandelt, and V. Cammarota, "Sparse inpainting and isotropy," *J. Cosmol. Astropart. P.*, 2014(1):050, 2014.

5. R. E. Carrillo, **J. D. McEwen**, and Y. Wiaux, "PURIFY: a new approach to radio-interferometric imaging," *Mon. Not. Roy. Astron. Soc.*, in press, 2014. (Accepted: 28 Jan. 2014)

6. P. M. Sutter, B. D. Wandelt, **J. D. McEwen**, E. F. Bunn, A. Karakci, A. Korotkov, P. Timbie, G. S. Tucker, and L. Zhang, "Probabilistic image reconstruction for radio interferometers," *Mon. Not. Roy. Astron. Soc.*, 438(1):768-778, 2014

7. L. Wolz, **J. D. McEwen**, F. B. Abdalla, R. E. Carrillo, and Y. Wiaux, "Revisiting the spread spectrum effect in radio interferometric imaging: a sparse variant of the w-projection algorithm," *Mon. Not. Roy. Astron. Soc.*, 436(3):1993-2003, 2013

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9.⋆ B. Leistedt, **J. D. McEwen**, P. Vandergheynst, and Y. Wiaux, "S2LET: A code to perform fast wavelet analysis on the sphere," *Astron. & Astrophys.*, 558(A128):1-9, 2013.

10. S. M. Feeney, M. C. Johnson, **J. D. McEwen**, D. J. Mortlock, and H. V. Peiris, "Hierarchical Bayesian detection algorithm for early-Universe relics in the cosmic microwave background," *Phys. Rev. D.*, 88(4):043012, 2013.

11. R. E. Carrillo, **J. D. McEwen**, D. Van De Ville, J.-Ph. Thiran, and Y. Wiaux, "Sparsity averaging for compressive imaging," *IEEE Sig. Proc. Let.*, 20(6):591-594, 2013.

12.⋆ **J. D. McEwen**, G. Puy, J.-Ph. Thiran, P. Vandergheynst, D. Van De Ville, and Y. Wiaux, "Sparse image reconstruction on the sphere: implications of a new sampling theorem," *IEEE Trans. Image Proc.*, 22(6):2275-2285, 2013.

13.⋆ Z. Khalid, R. A. Kennedy, S. Durrani, P. Sadeghi, Y. Wiaux, and J. D. McEwen, "Fast directional spatially localized spherical harmonic transform," *IEEE Trans. Signal Process.*, vol. 61, no. 9, pp. 2192–2203, 2013.

14. B. Leistedt and **J. D. McEwen**, "Exact wavelets on the ball," *IEEE Trans. Sig. Proc.*, vol. 60, no. 12, pp. 6257-6269, Dec. 2012.

15.⋆ R. E. Carrillo, **J. D. McEwen**, and Y. Wiaux, "Sparsity Averaging Reweighted Analysis (SARA): a novel algorithm for radio interferometric imaging," *Mon. Not. Roy. Astron. Soc.*, vol. 426, no. 2, pp. 1318-1332, Oct. 2012.

16. **J. D. McEwen**, S. M. Feeney, M. C. Johnson, and H. V. Peiris, "Optimal filters for detecting cosmic bubble collisions," *Phys. Rev. D.*, vol. 85, no. 10, pp. 103502 (11 pages), May 2012.

17.⋆ **J. D. McEwen** and Y. Wiaux, "A novel sampling theorem on the sphere," *IEEE Trans. Sig. Proc.*, vol. 59, no. 12, pp. 5876–5887, Dec. 2011.

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19.⋆ **J. D. McEwen**, Y. Wiaux, and D. M. Eyers, "Data compression on the sphere," *Astron. & Astrophys.*, vol. 531, no. A98, pp. 1-13, June 2011.

20.⋆ **J. D. McEwen**, "Fast, exact (but unstable) spin spherical harmonic transforms," *All Res. J. Phys.*, vol. 1, no. 1, pp. 4-18, 2011.

21. M. Bridges, **J. D. McEwen**, M. Cruz, M. P. Hobson, A. N. Lasenby, P. Vielva, and E. Martinez-Gonzalez, "Bianchi VIIh signatures and the cold spot texture," *Mon. Not. Roy. Astron. Soc.*, vol. 390, no. 4, pp. 1372-1376, Sep. 2008.

22. **J. D. McEwen** and A. M. M. Scaife, "Simulating full-sky interferometric observations," *Mon. Not. Roy. Astron. Soc.*, vol. 389, no. 3, pp. 1163-1178, Aug. 2008.

23.⋆ **J. D. McEwen**, M. P. Hobson, A. N. Lasenby, and D. J. Mortlock, "A high-significance detection of non-Gaussianity in the WMAP 5-year data using directional spherical wavelets," *Mon. Not. Roy. Astron. Soc.*, vol. 388, no. 2, pp. 659-662, Aug. 2008.

24.⋆ Y. Wiaux, **J. D. McEwen**, P. Vandergheynst, and O. Blanc, "Exact reconstruction with directional wavelets on the sphere," *Mon. Not. Roy. Astron. Soc.*, vol. 388, no. 2, pp. 770-788, Aug. 2008.

25.⋆ **J. D. McEwen**, M. P. Hobson, and A. N. Lasenby, "Optimal filters on the sphere," *IEEE Trans. Sig. Proc.*, vol. 56, no. 8, pp. 3813-3823, Aug. 2008.

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27.⋆ **J. D. McEwen**, P. Vielva, Y. Wiaux, R. B. Barreiro, L. Cayon, M. P. Hobson, A. N. Lasenby, E. Martinez-Gonzalez, and J. L. Sanz, "Cosmological applications of a wavelet analysis on the sphere," *J. Fourier Anal. and Appl.*, vol. 13, no. 4, pp. 495-510, 2007. (invited paper)

28.⋆ Y. Wiaux, **J. D. McEwen**, and P. Vielva, "Complex data processing: fast wavelet analysis on the sphere," *J. Fourier Anal. and Appl.*, vol. 13, no. 4, pp. 477-493, 2007. (invited paper)

29.⋆ **J. D. McEwen**, P. Vielva, M. P. Hobson, E. Martinez-Gonzalez, and A. N. Lasenby, "Detection of the ISW effect and corresponding dark energy constraints made with directional spherical wavelets," *Mon. Not. Roy. Astron. Soc.*, vol. 376, no. 3, pp. 1211-1226, 2007.

30.⋆ **J. D. McEwen**, M. P. Hobson, D. J. Mortlock, and A. N. Lasenby, "Fast directional continuous spherical wavelet transform algorithms," *IEEE Trans. Sig. Proc.*, vol. 55, no. 2, pp. 520-529, Feb. 2007.

31. M. Bridges, **J. D. McEwen**, A. N. Lasenby, and M. P. Hobson, "Markov chain Monte Carlo analysis of Bianchi VIIh models," *Mon. Not. Roy. Astron. Soc.*, vol. 377, no. 4, pp. 1473-1480, 2007.

32. **J. D. McEwen**, M. P. Hobson, A. N. Lasenby, and D. J. Mortlock, "Non-Gaussianity detections in the Bianchi VIIh corrected WMAP 1-year data made with directional spherical wavelets," *Mon. Not. Roy. Astron. Soc.*, vol. 369, no. 4, pp. 1858-1868, July 2006.

33.⋆ **J. D. McEwen**, M. P. Hobson, A. N. Lasenby, and D. J. Mortlock, "A high-significance detection of non-Gaussianity in the WMAP 3-year data using directional spherical wavelets," *Mon. Not. Roy. Astron. Soc.*, vol. 371, no. 1, pp. L50-L54, May 2006.

34.⋆ **J. D. McEwen**, M. P. Hobson, A. N. Lasenby, and D. J. Mortlock, "A high-significance detection of non-Gaussianity in the WMAP 1-year data using directional spherical wavelets," *Mon. Not. Roy. Astron. Soc.*, vol. 359, no. 4, pp. 1583-1596, 2005.

1(b) Refereed Conference Papers

35. B. Leistedt, H. V. Peiris, and **J. D. McEwen**, "Flaglets for studying the large-scale structure of the Universe," *Proc. Wavelets and Sparsity XIV, SPIE international symposium on optics and photonics*, 2013. (invited paper)

36.⋆ **J. D. McEwen**, P. Vandergheynst, and Y. Wiaux, "On the computation of directional scale-discretized wavelet transforms on the sphere," *Proc. Wavelets and Sparsity XIV, SPIE international symposium on optics and photonics*, 2013. (invited paper)

37.⋆ R. A. Kennedy, P. Sadeghi, Z. Khalid, and **J. D. McEwen**, "Classification and construction of closed-form kernels for signal representation on the 2-sphere," *Proc. Wavelets and Sparsity XIV, SPIE international symposium on optics and photonics*, 2013. (invited paper)

38. **J. D. McEwen** and B. Leistedt, "Fourier-Laguerre transform, convolution and wavelets on the ball," *Proc. 10th International Conference on Sampling Theory and Applications (SampTA)*, pages 329-333, 2013. (invited paper)

39. R. E. Carrillo, **J. D. McEwen**, and Y. Wiaux, "On sparsity averaging," *Proc. 10th International Conference on Sampling Theory and Applications (SampTA)*, pages 329-333, 2013. (invited paper)

40. L. Wolz, F. B. Abdallah, R. E. Carrillo, Y. Wiaux, and **J. D. McEwen**, "The varying-w spread spectrum effect for radio interferometrc imaging," *Proc. Biomedical and Astronomical Signal Processing Frontiers (BASP)*, 2013.

41. B. Leistedt and **J. D. McEwen**, "Flaglets: Exact wavelets on the ball," *Proc. Biomedical and Astronomical Signal Processing Frontiers (BASP)*, 2013.

42. R. E. Carrillo, **J. D. McEwen**, and Y. Wiaux, "Sparsity averaging for radio interferometric imaging," *Proc. Biomedical and Astronomical Signal Processing Frontiers (BASP)*, 2013

43. **J. D. McEwen**, S. M. Feeney, M. C. Johnson, and H. V. Peiris, "Detecting candidate cosmic bubble collisions with optimal filters," *Proc. 47th Rencontres de Moriond*, 2012.

44.⋆ **J. D. McEwen** and Y. Wiaux, "Compressed sensing for radio interferometric imaging: review and future direction," *Proc. 18th IEEE International Conference on Image Processing (ICIP)*, 2011. (invited paper)

45.⋆ **J. D. McEwen**, G. Puy, J.-Ph. Thiran, P. Vandergheynst, D. Van De Ville, and Y. Wiaux, "Sampling theorems and compressive sensing on the sphere," *Proc. Wavelets and Sparsity XIV, SPIE international symposium on optics and photonics*, 2011.

46. **J. D. McEwen** and Y. Wiaux, "Intrinsic advantages of the w component and spherical imaging for wide-field radio interferometry," *Proc. XXXth General Assembly and Scientific Symposium of the International Union of Radio Science*, 2011.

47.⋆ **J. D. McEwen**, G. Puy, J.-Ph. Thiran, P. Vandergheynst, D. Van De Ville, and Y. Wiaux, "Implications for compressed sensing of a new sampling theorem on the sphere," *Proc. Signal Processing with Adaptive Sparse Structured Representations (SPARS)*, 2011.

48.⋆ A. Daducci, **J. D. McEwen**, D. Van De Ville, J.-P. Thiran, and Y. Wiaux, "Harmonic analysis of spherical sampling in diffusion MRI," *Proc. 19th Annual Meeting of the International Society for Magnetic Resonance in Medicine*, 2011.

49.⋆ **J. D. McEwen**, "Detecting dark energy with wavelets on the sphere," *Proc. Wavelets XII, SPIE international symposium on optics and photonics* 2007. (invited paper)

50. **J. D. McEwen**, P. Vielva, M. P. Hobson, E. Martnez-Gonzlez, and A. N. Lasenby, "Detection of the ISW effect and corresponding dark energy constraints," *Proc. XLIst Rencontres de Moriond*, 2006.

51.⋆ **J. D. McEwen**, M. P. Hobson, A. N. Lasenby, and D. J. Mortlock, "A fast directional continuous spherical wavelet transform," *Proc. XXXIXth Rencontres de Moriond*, 2004.

2. List of ARC Grants Awarded in the Last Ten Years

No ARC grants awarded in the last ten years. PI is not Australian and is based in Europe.

F12.3. Ten career-best research outputs

(Please attach a PDF with a list of your ten career-best research outputs (five pages maximum). Please refer to the Instructions to Applicants for the required content and formatting.)

Attached PDF

F12.3 Ten career-best publications

1.⋆ **J. D. McEwen**, P. Vielva, M. P. Hobson, E. Martinez-Gonzalez, and A. N. Lasenby, "Detection of the integrated SachsWolfe effect and corresponding dark energy constraints made with directional spherical wavelets," *Mon. Not. R* vol. 376, no. 3, pp. 1211–1226, 2007, (Cited by 88).

Significance and Impact: *Using sophisticated directional wavelets on the sphere this paper makes one of the most statistically significant detections of the integrated Sachs-Wolfe (ISW) effect, providing independent evidence for dark energy.*

2.⋆ Y. Wiaux, **J. D. McEwen**, P. Vandergheynst, and O. Blanc, "Exact reconstruction with directional wavelets on the sphere," *Mon. Not. Roy. Astron. Soc.*, vol. 388, no. 2, pp. 770–788, Aug. 2008, (Cited by 60).

Significance and Impact: *A new kernel dilation in harmonic space is used to define directional wavelets with exact reconstruction properties for representing band-limited signals on the sphere.*

3.⋆ **J. D. McEwen**, P. Vielva, Y. Wiaux, R. B. Barreiro, L. Cayon, M. P. Hobson, A. N. Lasenby, E. Martinez-Gonzalez, and J. L. Sanz, "Cosmological applications of a wavelet analysis on the sphere," *J. Fourier Anal. and Appl.*, vol. 13, no. 4, pp. 495-510, 2007, (Cited by 47, invited paper).

Significance and Impact: *This paper highlights deviations from both statistical isotropy and Gaussianity in CMB data which suggest more exotic cosmological models may be required to explain our Universe.*

4.⋆ **J. D. McEwen**, M. P. Hobson, D. J. Mortlock, and A. N. Lasenby, "Fast directional continuous spherical wavelet transform algorithms," *IEEE Trans. Sig. Proc.*, vol. 55, no. 2, pp. 520–529, Feb. 2007, (Cited by 42).

Significance and Impact: *This contribution describes the construction of a spherical wavelet analysis through the inverse stereographic projection of the Euclidean planar wavelet framework and corresponding computationally efficient algorithms.*

5.⋆ **J. D. McEwen** and Y. Wiaux, "A novel sampling theorem on the sphere," *IEEE Trans. Sig. Proc.*, vol. 59, no. 12, pp. 5876–5887, Dec. 2011, (Cited by 31).

Significance and Impact: *This is a breakthrough paper which advances the classical results of 1994 Driscoll and Healy by a factor of 2 and extends the analysis to spin-spherical harmonics. 1990s.*

6.⋆ **J. D. McEwen**, M. P. Hobson, and A. N. Lasenby, "Optimal filters on the sphere," *IEEE Trans. Sig. Proc.*, vol. 56, no. 8, pp. 3813–3823, Aug. 2008, (Cited by 17).

Significance and Impact: *This paper is the first to formulate optimal directional and scale adaptive filters on the sphere for detecting compact objects embedded in a stochastic background.*

7.⋆ **J. D. McEwen** and Y. Wiaux, "Compressed sensing techniques for radio interferometric imaging on a wide field-of-view," *Mon. Not. Roy. Astron. Soc.*, vol. 413, no. 2, pp. 1318-1332, May 2011, (Cited by 22).

Significance and Impact: *Compressed sensing techniques for interferometric imaging are extended to a wide field-of-view in a spherical coordinate system eliminating any distorting projection.*

8.⋆ B. Leistedt and **J. D. McEwen**, "Exact wavelets on the ball," *IEEE Trans. Sig. Proc.*, vol. 60, no. 12, pp. 6257–6269, Dec. 2012 (Cited by 9).

Significance and Impact: *The first exact wavelet transform on the three-dimensional ball is developed, with fast algorithms, leading to wavelets defined naturally in spherical coordinates for analysing galaxy surveys and other spherical data-sets.*

9.⋆ **J. D. McEwen**, M. P. Hobson, A. N. Lasenby, and D. J. Mortlock, "A high-significance detection of non-Gaussianity in the WMAP 1-year data using directional spherical wavelets," *Mon. Not. Roy. Astron. Soc.*, vol. 359, no. 4, pp. 1583–1596, Apr. 2005 (Cited by 104).

Significance and Impact: *One of the most statistically significant detections of deviations from Gaussianity is made in WMAP CMB observations due to the effectiveness of directional wavelet analysis on the sphere.*

10. M. Bridges, **J. D. McEwen**, A. N. Lasenby, and M. P. Hobson, "Markov chain Monte Carlo analysis of Bianchi VII_h models," *Mon. Not. Roy. Astron. Soc.*, vol. 377, no. 4, pp. 1473–1480, Mar. 2007 (Cited by 34).

Significance and Impact: *The first full-sky Bayesian analysis to test WMAP data for evidence of models of rotating universes is performed, placing robust constraints on the anisotropy of the Universe.*

F12.4. Further evidence in relation to research impact and contributions to the field over the last 10 years most relevant to this Proposal

(Write a maximum of 7500 characters (approx. 1000 words). Please detail further evidence in relation to research impact and contributions to the field over the last 10 years. Please refer to the Instructions to Applicants for the required content and formatting.)

(1) Research outputs other than publications

(1a) International Conference Organisation:
• Biomedical and Astrophysical Signal Processing (BASP) Fontiers 2013, Co-chair
• Biomedical and Astrophysical Signal Processing (BASP) Fontiers 2011, Scientific Organising Committee

The objective of BASP is "to promote synergies between selected topics in astronomy and biomedical sciences, around common challenges for signal processing."

(1b) International Research Collaborations:
• Core Team Member, Planck Satellite Mission European Space Agency (ESA)
Area of collaboration: ESA satellite mission to measure the temperature and polarisation of the CMB.
• Professor Pierre Vandergheynst, Dr Yves Wiaux & Dr David Shuman Ecole Polytechnique Federale de Lausanne (EPFL), Switzerland
Area of collaboration: spherical signal processing, compressive sensing and wavelets on graphs
• Dr Hiranya Peiris, Stephen Feeney (PhD student) & Boris Leistedt (PhD student) University College London (UCL)
Area of collaboration: new wavelet methodologies and applications in cosmology
• Dr Matthew Johnson
Perimeter Institute for Theoretical Physics, Canada
Area of collaboration: detecting cosmic bubble collisions
• Dr Filipe Abdalla
University College London (UCL)
Area of collaboration: radio interferometry
• Professor Mike Hobson & Dr Farhan Ferroz
University of Cambridge
Area of collaboration: Bayesian inference, machine learning and applications in cosmology

(1c) International Talks (in the last 10 years)
I have given 42 international talk in UK, Italy, Spain, France, Belgium, Netherlands, Germany,Turkey, Switzerland, South Africa, USA, Canada, New Zealand and Australia. Below is a selection of recent talks since 2012:

• Sep 2013: Sparsity, Euclid and the SKA, Synergistic Science with Euclid and the Square Kilometre Array, Oxford, UK
• Aug 2013: Scale-discretised wavelets on the sphere, Wavelets XV, SPIE Optics and Photoics, San Diego, USA
• Jul 2013: Fourier-Laguerre transform, convolution and wavelets on the ball, 10th International Conference on Sampling Theory and Applications (SampTA), Bremen, Germany
• Jun 2013:Signal processing on spherical manifolds, Probabilistic And Statistical techniques for Cosmological AnaLysis (PASCAL) workshop, Rome, Italy
• Apr 2013: Exploiting sparsity for CMB data analysis, London Cosmology Discussion Meeting (LCDM), Royal Astronomical Society, London, UK
• Apr 2013: Background geometry and topology of the Universe: Bianchi VIIh cosmologies and Planck, The Universe as seen by Planck, ESLAB Symposium, ESA/ESTEC, The Netherlands
• Mar 2013: Sparsity: CosmoStats meets Cosmo Informatics, CosmoStats 2013, Banff, Canada
• Mar 2013: Signal processing onspherical manifolds, School of Information Science and Engineering, Australian National University (ANU), Australia
• Mar 2013: Towards realistic radio interferometric imaging with compressive sensing, Astronomy and Astrophysics, Victoria University, NZ
• Jan 2013: Radio interferometric imaging with compressive sensing, London Cosmology Discussion Meeting (LCDM), Royal Astronomical Society, London, UK
• Nov 2012: Towards compressive sensing imaging of real radio interferometric observations, Calibration and Imaging for the Square Kilometre Array (CALIM) 2012, Cape Town,South Africa
• Oct 2012: Cosmological signal processing, Institute of Cosmology and Gravitation, University of

Portsmouth, UK
• Oct 2012: Cosmological signal processing, Department of Physics and Astronomy, University of Southampton, UK
• Sep 2012: Spherical wavelet-Bayesian cosmic string tension estimation, Big 3 (Big Bang, Big Data, Big Computing), Paris, France
• May 2012: Implications of a new sampling theorem for sparse signal reconstruction on the sphere, Astronomical Data Analysis (ADA) 7, Cargese, Corsica
• Mar 2012: Spherical signal processing for cosmology, Signal Processing for the Physical Sciences, The Kavli Royal Society International Centre, Buckinghamshire, UK
• Mar 2012: Detecting cosmic bubble collisions with optimal filters, Recontres de Moriond, La Thuile, Italy
• Jan 2012: Spherical signal processing and the multiverse, IFCA Seminar, University of Cantabria, Santander, Spain
Jan 2012: Sampling theorems and compressed sensing on the sphere, BASP Seminar, Ecole Polytechnique Federale de Lausanne (EPFL), Lausanne, Switzerland

(1d) Referee for Academic Journals
• IEEE Transactions on Signal Processing
• IEEE Signal Processing Letters
• IEEE Journal of Selected Topics in Signal Processing
• Applied and Computational Harmonic Analysis
• Annals of Statistics
• Signal Image and Video Processing
• Measurement Science and Technology
• Monthly Notices of the Royal Astronomical Society
• Proceedings of the Royal Society A
• Publications of the Astronomical Society of Japan
• European Journal of Physics

(1e) Professional Affiliations
• Institute of Electrical and Electronic Engineers (IEEE)
• Royal Astronomical Society (RAS)

(2) Evidence for the quality of your research outputs

(2a)
• 34 Journal papers (all since 2005, including 18 first author journal papers) and 17 conference papers.
• My papers have been heavily cited by astronomy and signal processing communities.
• h index = 16, citations = 825.

(2b) Invited Journal Papers:
• J. D. McEwen, P. Vielva, Y. Wiaux, R. B. Barreiro, L. Cayon, M. P. Hobson, A. N. Lasenby, E. Martinez-Gonzalez, and J. L. Sanz, Cosmological applications of a wavelet analysis on the sphere," J. Fourier Anal. and Appl., vol. 13, no. 4, pp. 495-510, 2007.
• Y. Wiaux, J. D. McEwen, and P. Vielva, Complex data processing: fast wavelet analysis on the sphere," J. Fourier Anal. and Appl., vol. 13, no. 4, pp. 477-493, 2007.

(2c) Invited Conference Papers:
• B. Leistedt, H. V. Peiris, and J. D. McEwen, "Flaglets for studying the large-scale structure of the Universe", Proc. Wavelets and Sparsity XIV, SPIE international symposium on optics and photonics, 2013.
• J. D. McEwen, P. Vandergheynst, and Y. Wiaux, "On the computation of directional scale-discretized wavelet transforms on the sphere," Proc. Wavelets and Sparsity XIV, SPIE international symposium on optics and photonics, 2013.
• R. A. Kennedy, P. Sadeghi, Z. Khalid, and J. D. McEwen, ``Classification and construction of closed-form kernels for signal representation on the 2-sphere.," Proc. Wavelets and Sparsity XIV, SPIE international symposium on optics and photonics, 2013.
• J. D. McEwen and Y. Wiaux, Compressed sensing for radio interferometric imaging: review and future direction," Proc. 18th IEEE International Conference on Image Processing (ICIP), 2011.
• J. D. McEwen, Detecting dark energy with wavelets on the sphere," Proc. Wavelets XII, SPIE international symposium on optics and photonics 2007.

(2d) Awards
• 2013 Royal Astronomical Society Grant for student support
• 2012 Royal Astronomical Society Grant for conference support
• 2011 Royal Astronomical Society Grant for conference support
• 2011 URSI General Assembly and Scientific Symposium Young Researcher Award
• 2006 Lundgren Research Award
• 2005 Cambridge Philosophical Society Research Studentship
• 2005 Cambridge Philosophical Society Travel Award
• 2002 – 2005 Commonwealth Scholarship for study towards a PhD at the University of Cambridge

F12.5. A statement on your most significant contributions to the research field of this Proposal

(Write a maximum of 3750 characters (approx. 500 words). Please refer to the Instructions to Applicants for the required content and formatting.)

This proposal, because it covers modeling functions on the sphere, is highly correlated with my research. An examination of my publications reveals that most deal with spherical modeling in one way or another. My work is most strongly represented by applications in astrophysics and theoretical contributions in signal processing. This reflects my background with my undergraduate work in engineering and PhD in Cambridge in Astrophysics and Cosmology.

Observations in cosmology are made on the celestial sphere, hence data analysis tools for application in cosmology must respect the underlying geometry where the data live. Measurements of the microwave sky make by recent NASA and ESA satellites, such as WMAP and Planck, respectively, are thus naturally defined on the sphere.

I have pioneered the development of wavelet analysis techniques on spherical manifolds and also the application of these techniques to extract cosmological informations from WMAP and Planck. I developed fast algorithms to render continuous wavelet transforms on the sphere feasible for large cosmological data-sets. I used my techniques to constrain the dark energy of the Universe and to probe the physics of the origin of structure in the early Universe. However, the continuous wavelet transform on the sphere cannot be used to reconstruct signals from their wavelet representation. This severely limits the practical application of such an analysis. I resolved this limitation by developing a new scale-discretised wavelet methodology on the sphere that supports exact reconstruction. I also developed fast algorithms for this new methodology to enable its practical application.

In addition to wavelet methods, I have also developed other fundamental signal processing theorems on spherical geometries. I redefined the 1994 sampling theorem on the sphere to reduce the number of samples required by a factor of two -- the most fundamental property of a sampling theorem. I also developed compressive sensing techniques and anisotropic optimal filter theory on the sphere, which, for example I used to restrain the multi-Universe scenario.

My expertise in theoretical signal processing on the sphere and how these fundamental results can be applied to applications, such as cosmology, will contribute directly to all Tasks of this proposal. For Task 1, my expertise in sampling theories, fast algorithms, and optimal filtering will be exploited. For Task 2, my background on compressive sensing on spherical manifolds will be directly relevant. For Task 3, my extensive background and experience in the analysis of cosmological data will be leveraged to close-the-loop between theory and applications, so that important application challenges feed into the development of new theory. In particular, since I am a Core Team member of the ESA Planck satellite mission, I have developed an in-depth understanding of the intricacies of Planck data, that will be invaluable for the proposal. My expertise is all of these areas is demonstrated in my publication record.

PART G - Research Support (DP150101011)

G1. Research support for all participants

(For each participant on this Proposal, provide details of research funding (ARC and other agencies in Australia and overseas) for the years 2013 to 2017 inclusive. That is, list all projects/proposals/awards/ fellowships awarded or requests submitted involving that Participant for funding. Please refer to the Instructions to Applicants for submission requirements.)

Part G1 – Research Support

Description (all named investigators on any proposal or grant/ project/ fellowship in which a Participant is/was involved, project title, source of support, scheme and round)	**Same Research Area** (Yes/No)	**Support Type** (Requested/Current/Past)	**Proposal/ Project ID** (if applicable)	**2013** ($'000)	**2014** ($'000)	**2015** ($'000)	**2016** ($'000)	**2017** ($'000)
R. A. Kennedy, **S. Durrani**, J. D. McEwen: "Harnessing Spherical Geometry in Scientific and Engineering Data Processing," ARC, DP15 round 1.	Yes	R	DP150101011	0	0	202	206	218
R. A. Kennedy, T. A. Wysocki: "Modelling Molecular Communications at the Nano-scale," ARC, DP15 round 1.	No	R	DP150101322	0	0	171	183	195
S. Durrani, X. Zhou, H. Mehrpouyan and S. D. Blostein: "Realizable Synchronization Techniques: Unlocking the Potential of Future Wireless Networks," ARC, DP14 round 1.	No	C	DP140101133	0	120	100	145	0
R. A. Kennedy, T. A. Lamahewa, X. Zhou, G. Giannakis: "Optimum Cross-Layer Design in Wireless Communication Systems with Channel Uncertainty," ARC, DP11 round 1.	No	P	DP110102548	85	0	0	0	0

PART H - Statements on Progress on ARC-funded Projects (DP150101011)

H1. For each participant on this Proposal, please attach a statement detailing progress for each Project/Award/Fellowship involving that participant who has been awarded funding for 2013 under the ARC Discovery Projects, Discovery Indigenous, Discovery Early Career Researcher Award, Linkage Projects schemes or any ARC Fellowship scheme.

	Project ID	First named investigator	Scheme	Statement
1	DP110102548	Prof Rodney Kennedy	Discovery Program	

Part H–Statement on Progress for DP110102548:

Optimum cross-layer design in wireless communication systems with channel uncertainty

The project has proven to be a very successful and fruitful one. So far, it has resulted in the production of 13 journal articles (11 published or accepted) and 15 conference papers. Novel cross-layer design solutions have been proposed to solve a wide range of research problems in wireless networks, including secure communication, energy-constrained communication, synchronization, and small cell deployments. There have been some delays in the early stage of the project since Lamahewa moved from ANU to DSTO which required significant clearance. Further, Lamahewa has ongoing health concerns which meant he was for a time unavailable. Ali Nasir was appointed to a short term Postdoctoral Fellowship (which ends in February 2014).

Journal Articles:

- B. He and **X. Zhou**, "Secure On-Off Transmission Design with Channel Estimation Errors," *IEEE Trans. Inf. Foren. Sec.*, vol. 8, no. 12, pp. 1923-1936, Dec. 2013.
- X. Zhang, **X. Zhou**, and M. R. McKay, "Enhancing Secrecy with Multi-Antenna Transmission in Wireless Ad Hoc Networks," *IEEE Trans. Inf. Foren. Sec.*, vol. 8, no. 11, pp. 1802-1814, Nov. 2013.
- A. A. Nasir, **X. Zhou**, S. Durrani, and **R. A. Kennedy**, "Relaying protocols for wireless energy harvesting and information processing," *IEEE Trans. Wireless Commun.*, vol. 12, pp. 3622–3636, July 2013.
- H. Pezeshki, **X. Zhou**, B. Maham, "Jamming Energy Allocation in Training-Based Multiple Access Systems," *IEEE Commun. Lett.*, vol. 17, no. 6, pp. 1140-1143, Jun. 2013.
- H. Wang, **X. Zhou**, and M. C. Reed, "Physical Layer Security in Cellular Networks: A Stochastic Geometry Approach," *IEEE Trans. Wireless Commun.*, vol. 12, no. 6, pp. 2776-2787, Jun. 2013.
- X. Zhang, **X. Zhou**, and M. R. McKay, "On the Design of Artificial-Noise-Aided Secure Multi-Antenna Transmission in Slow Fading Channels," *IEEE Trans. Veh. Technol.*, vol. 62, no. 5, pp. 2170-2181, Jun. 2013.
- C.-W. Huang, T.-H. Chang, **X. Zhou**, and Y.-W. P. Hong, "Two-Way Training for Discriminatory Channel Estimation in Wireless MIMO Systems," *IEEE Trans. Signal Processing*, vol. 61, no. 10, pp. 2724-2738, May, 2013.
- W. Saad, **X. Zhou**, B. Maham, T. Basar, and H. V. Poor, "Tree Formation with Physical Layer Security Considerations in Wireless Multi-Hop Networks," *IEEE Trans. Wireless Commun.*, vol. 11, no. 11, pp. 3980-3991, Nov. 2012.
- **X. Zhou**, B. Maham, and A. Hjorungnes, "Pilot Contamination for Active Eavesdropping," *IEEE Trans. Wireless Commun.*, vol. 11, no. 3, pp. 903-907, Mar. 2012.
- H. Wang, **X. Zhou**, and M. C. Reed, "Coverage and Throughput Analysis with a Non-Uniform Small Cell Deployment," *IEEE Trans. Wireless Commun.*, 2014 (In press, accepted for publication 21-Dec-2013).
- A. O. Isikman, H. Mehrpouyan, A. A. Nasir, A. G. Amat, and **R. A. Kennedy**, "Joint phase noise estimation and data detection in coded MIMO systems," *IET Commun.*, 2014 (accepted for publication 8 November 2013).
- A. A. Nasir, **X. Zhou**, S. Durrani, and **R. A. Kennedy**, "Wireless energy harvesting and information relaying: Adaptive time-switching protocols and throughput analysis," *IEEE Trans. Wireless Commun.*, 2014 (under review).
- O. H. Salim, A. A. Nasir, H. Mehrpouyan, W. Xiang, S. Durrani, and **R. A. Kennedy**, "Channel, phase noise, and frequency offset in OFDM systems: Joint estimation, data detection, and hybrid Cramer-Rao lower bound," *IEEE Trans. Commun.*, 2014 (under review).

PART I - Additional Details (DP150101011)

I1. Other agencies

Have you submitted or do you intend to submit a similar Proposal to any other agency?

Other Agency Submission

No

If Yes, please select one of the following:

Other Agency Name

Not applicable for this candidate

If Other is selected above, please enter the full name of the agency:

Not applicable for this candidate