SUSTAINABLE DEVELOPMENT
OF
THE SPACE ENVIRONMENT:
A PRAGMATIC APPROACH TO POLICY FORMULATION

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Contents

Acronyms and Abbreviations

AIAA	American Institute of Aeronautics and Astronautics
ASR	Advances in Space Research (journal)
CNES	Centre National d’Etudes Spatiales (French space agency)
COPUOS	Committee on the Peaceful Uses of Outer Space (UN)
COSPAR	Committee on Space Research
ESA	European Space Agency
ESPI	European Space Policy Institute
FAA	Federal Aviation Administration
GEO	geostationary orbit
GPS	Global Positioning System
IAA	International Academy of Astronautics
IAC	International Astronautical Congress
IADC	Inter-Agency Space Debris Coordination Committee
IAF	International Astronautical Federation
IISL	International Institute of Space Law
ITU	International Telecommunication Union
LEO	Low Earth Orbit
NASA	National Aeronautics and Space Administration
OOSA	Office for Outer Space Affairs (UN)
OST	Outer Space Treaty
STFF	Space: The Fragile Frontier (‘Central Work’)
UN	United Nations

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Abstract

The published works described in this thesis commentary form the basis of a submission for a PhD degree in Space Policy. The body of work represents an original and coherent contribution to the space profession in the general subject areas of space policy and environmental sustainability.

At its most fundamental level, the research embodied within the published works is designed to address the question of whether it is possible to establish an optimal balance between expansion of activity in space and protection of the fragile space environment.

The texts submitted in support of this thesis represent a body of peer-reviewed work centred on a monograph entitled “Space: The Fragile Frontier”, which is the first academic text to draw together the recognised issues of Earth orbital debris and planetary protection, set them in the context of space law and ethical policies, and encourage a sustainable and environmentally-friendly approach to space exploration and development.

The published works described here cover a two-decade period of research surrounding this ‘Central Work’ and are based on a systematic acquisition and understanding of a body of knowledge at the forefront of an area of professional practice – specifically at the interface between space technology and space policy. This commentary describes the aims of the research and the central themes that coalesce to form the connective thread that ties the Submitted Works together: a pragmatic approach to developing a policy for sustainable development of the space environment.

An analysis of citations shows that the work has been widely cited within and beyond the space community and has made a significant impact and coherent contribution to the field. The body of work continues to feature in academic publications and, because of the long-term nature of space-related developments, is expected to guide and influence workers in the field for the foreseeable future.

1. Introduction

This thesis - “Sustainable Development of the Space Environment: A Pragmatic Approach to Policy Formulation” - constitutes a commentary to the Existing Published Works that form the basis of a submission for a PhD degree in Space Policy.

The texts submitted in support of this thesis represent a body of peer-reviewed work published during a period of research spanning some two decades. They include an 80,000-word monograph entitled “Space: The Fragile Frontier”, published by the American Institute of Aeronautics and Astronautics (AIAA) in 2006 and considered here as the ‘Central Work’ (Williamson, 2006a), and a number of supporting works published both before and after the Central Work (discussed in detail in section 4).

The body of work was targeted from the outset at the international space community. This commentary will demonstrate that the Submitted Works are based on a systematic acquisition and understanding of a body of knowledge at the forefront of an area of professional practice – specifically at the interface between space technology and space policy. By means of a literature review and analysis of citations, it will also show that the work has made a significant impact and coherent contribution to the field.

1.1 Commentary Structure

This commentary is structured to provide a clear and logical overview of an original and forward-looking research topic - encapsulated in the phrase ‘the sustainable development of outer space’ - which has risen in prominence among the space science and technology community throughout the period of this research. Although the general concepts of sustainability and sustainable development are widely recognised with regard to the Earth’s environment, the application of these concepts to the space environment is, arguably, less well known. The commentary will explain the relevance of the research and set the Published Works in the wider academic context.

This begins (in subsection 1.2) with a definitional note on the space environment and space sustainability and a statement on the relevance and importance of the topic. By way of further explanation, subsection 1.3 discusses the rationale for the study and the scientific context in which the work exists. This is intended to show, in brief, why the Published Works considered here were produced and what their publication was intended to achieve within the relevant academic community and beyond.

Section 2 provides an overview of the Professional Context in which the published works were undertaken, including a brief description of the space community (2.1), biographical information on the author (2.2) and a short exposition of the research journey undertaken in producing the Submitted Works themselves (2.3). In addition to providing a guide to the professional community in which the author operates, it is intended to show how the author's scientific and engineering background informed the methodologies adopted for the long-term study of the topic and resulted in original contributions to the space community.

This is followed by an explanation of the research process and methodologies employed in producing the Submitted Works, a statement of the central hypothesis and a description of general aims and themes of the research (section 3).

Section 4 then details the Submitted Works themselves, beginning with the reasoning behind their selection (4.1). This is intended to show how the research journey embodied by the Submitted Works began with a number of Antecedent Works (4.2) that led to the Central Work (4.3) and how the themes of environmental protection and space sustainability developed throughout this formative period. It also demonstrates the coherence of the body of work in general and, in retrospect, allows the identification of what has been termed a 'golden thread' (Smith, 2015) running through the work (i.e. the theme of sustainable development of the space environment). The section concludes with details of works that were published following the Central Work (in 4.4 Subsequent Works).

There follows, in section 5, an analysis of the Impact of the Submitted Works, including a review of relevant literature (5.1), a citation analysis (5.2) and a critical evaluation of the works in the context of the professional space community (5.3).

This section demonstrates the original contributions to the extended space community made by the body of Submitted Works presented here and some examples of how it has influenced the work of other academics, both within the space field and beyond.

In recognition that the task does not begin and end with the Submitted Works considered here, subsection 6 discusses the evolution and continuation of the research journey. The commentary then presents its Conclusions (7).

References and a bibliography are included at the end of the document, along with appendices that provide (A) a database of citations and (B) a note of other texts included as background but not as a formal part of the Submitted Works. A list of acronyms and abbreviations used in this commentary is included in the preliminary pages.

1.2 Definitions

1.2.1 Space Environment

Although there is still no legally agreed definition of where 'space' begins, it is widely understood for practical purposes to start at an altitude of 100km above the Earth's surface (Benko & Gebhard, 1993)[1]. As such, the region beyond what we would broadly describe as Earth's immediate environment is known as the space environment. Scientifically speaking, it is described by a physical environment in terms of temperature, radiation, microgravity and other factors, and it includes the surfaces of the planetary bodies, the orbits around them and the space in between; more generally, the space environment is defined as a place to live and work, conduct scientific investigations and operate spacecraft and other systems (Williamson, 2001b, p351).

[1] an interesting historical discussion is provided at the NASA Dryden Flight Research Center URL:
http://www.nasa.gov/centers/dryden/news/X-Press/stories/2005/102105_Schneider.html

The first spacecraft, launched in the late 1950s, were dedicated to the characterisation of certain physical elements of the space environment. For example, Sputnik 2 carried a package of solar ultraviolet and X-ray detectors, while Explorer 1 incorporated thermometers, a cosmic ray detector and a Geiger counter, which detected what became known as the Van Allen radiation belts (Williamson 2006a, pp30-31). Since then, a great deal of research has been conducted on conditions in the space environment and much has been written on the subject (e.g. Gombosi, 1998; Kallenrode, 2004; Pisacane, 2008; Prolss, 2004).

Humans have been active in space since the launch of the first Sputnik satellite into orbit around the Earth on 4 October 1957, an event now widely considered to mark the dawn of the Space Age (Williamson 2006d, p1). Although an analysis of the cultural impact of this event is beyond the purview of this commentary, an extensive body of literature is available to place coverage of this topic in the Submitted Works in context. For example, a contemporary discussion such as in Mehrens (1959) may be compared with more recent analyses by authors such as Wang (2009), Andrews & Siddiqi (2011) and Majsova (2015).

Since this historic event, an increasing number of nations have become active in launching spacecraft into Earth orbit and beyond. The total number of spacecraft of all descriptions and sizes launched since 1957 has now exceeded 7000 (UN OOSA, 2016a), and space is a multifaceted, international business. The majority of the spacecraft population has been launched into what is known as low Earth orbit (LEO), which can be defined as “a nominally circular orbit of low altitude (typically less than 1000km)” occupied predominantly by remote sensing, scientific and military satellites along with human-tended spacecraft such as the International Space Station (Williamson, 2001b, p217). Most commercial communications satellites reside in the higher geostationary orbit (GEO) – at a height of about 36,000km – while others, such as navigation satellites, operate from medium altitude orbits between LEO and GEO.

Space is, at the same time, highly specialised and broadly relevant to society. While the design, manufacture and operation of space-based engineering hardware involves a small subset of the population, the applications and implications of their endeavours have a deep but often overlooked or poorly understood impact on the general population or ‘user community’ (White, 1998). Commercial applications range from GPS ‘satnav’ in motor vehicles and precision timing for financial transactions to high-resolution imaging and crop-health surveys. Societal impact includes anything from an appreciation of Hubble Space Telescope images of distant galaxies to the ramifications of the discovery of planets – and potentially life - beyond our solar system (Codignola & Schrogl, 2009).

1.2.2 Space Sustainability & Debris

The issue of sustainability in space is important in the same way as sustainability on Earth, not least because, as explained above in terms of applications, what we can do in and from space is important for people on Earth (Newman, 2015b). Research on the subject of ‘space sustainability’ is worthwhile for this reason alone. Indeed, not to consider the sustainable development of the space environment would be tantamount to relinquishing the benefits we currently receive from space systems (as the Submitted Works are intended to demonstrate).

In a terrestrial context, ‘sustainability’ is broadly understood to mean ‘capable of being maintained without exhausting natural resources or causing severe environmental damage’ (Williamson, 2006b), but the concept and culture of environmental sustainability is directly transferable to the space environment and, in the author’s opinion, should be a prerequisite for future space exploration and development as part of a long term, sustainable strategy. The Bibliography below includes a number of texts related to terrestrial sustainability (Dale & Robinson, 2014; Dovers & Hussey, 2013; Cabezas & Diwekar, 2013).

The well catalogued increase of debris in low Earth orbit (Flury, 1988) provides an example of the space sustainability issue: if we ignore the debris and do nothing to mitigate it, this class of orbit will eventually no longer be able to sustain, *inter alia*, the operation of imaging and remote sensing satellites for synoptic weather forecasting and climate studies (including monitoring global temperatures, ice sheets, the ozone hole and so on). Among other things, this would seriously degrade our ability to forecast devastating weather systems and save lives (Anz-Meader, 2001).

The issue of orbital debris is key to the space sustainability debate and is an important aspect of the Submitted Works; indeed it was the subject of an entire chapter of the Central Work (Williamson, 2006a), which is discussed further in subsection 4.3. Examples of the broad range of literature that has informed the discussion are included in the Bibliography of this commentary. There is, however, much greater depth to space sustainability than the issue of debris in LEO. The following subsection will illustrate the way in which the published works have sought to extend and develop the scope of this field of study.

1.3 Study Rationale and Originality

This subsection explains why this body of research on sustainable development of the space environment was undertaken and provides an overview of the scientific context in which the work exists. It also explains why the work presented here is an original contribution to the interlinked fields of space law, space policy and space sustainability.

The author's contributions to the field have all been made in the context of an international drive - which dates back to the late 1950s - to explore and develop parts of the space environment; unfortunately this drive has not always been undertaken in an environmentally-friendly or sustainable fashion (Kessler, 1986; Eichler & Rex, 1989). It was a realisation of this that led to the author's initial research into the topic of sustainable development and the issues surrounding a putative space environment protection policy.

Some space professionals were already convinced in the 1980s that, because of the increase in orbital debris, low Earth orbit required protective measures to be taken (Flury, 1988), but it has taken a number of collision events in the 21st century for debris mitigation measures in LEO to become recognised policy. This has not, however, been widely extended to the much higher geostationary orbit, despite that being home to most commercial communications satellites (Williamson, 2002b). This observed lack of consideration was a contributory reason for the publication of the body of work submitted here.

Where ‘pure science’ applications of space are concerned, the argument for protection is relatively easy, which is why NASA has had a ‘planetary protection policy’ for many decades (Tennen, 2002). However, the protection it provides is mainly biological in nature, the aim being not to contaminate planetary environments in case they harbour something we might recognise as ‘life’ (Sterns & Tennen, 1980).

A further reason for producing the published works presented here was an identification of the need to extend this protection to unique physical features of planetary landscapes, partly to preserve them for science but also for ethical and cultural reasons (Steiner, 2002). For example, extensive mining operations on the near side of the Moon, which permanently faces Earth, would be visible from Earth (through binoculars or small telescopes) and would have an irreversible cultural impact. This led to consideration of the ethical dimension of space exploration and development, and the issues surrounding the exposition of an ethical code or internationally-agreed policy for space sustainability (see 3.2 Aims and Themes).

The rationale behind the body of published works has both pragmatic and aspirational elements. This area of research is significant and impactful because the sustainability of our orbital assets affects the daily lives and general quality-of-life of a large proportion of the planet’s population. Additionally, the sustainability of scientific observations in space and the protection of the space environment helps preserve an element of our cultural identity and is part of what makes us human according to current cultural norms (Gorman, 2009).

In much of space literature published in the 20th Century, the assertion that there is an insatiable human desire to explore and develop new environments was promoted uncritically. However, debates in contemporary cultural and space archaeological study have questioned this traditional acceptance. Understandably, the Submitted Works have tended to adopt the traditional view, but the space community could benefit from encompassing theories of behavioural modernity. Works such as those by Noble & Davison (1991), Sterelny (2011) and Hopkinson (2013) provide significant discussion of these areas of archaeological and sociological study, with

Roberts (2016) providing an interesting counterpoint to these debates. Such discussions remain outside the remit of the Submitted Works, although writers such as Slobodian (2015) and Roberts (2016) clearly identify that such theoretical underpinning is a necessary component of space studies and will undoubtedly be of significance when discussing underlying behavioural norms in space activity.

Although others had written about protecting the space environment before, it was evident that no-one had undertaken their research from the perspective of a space technologist. Authors had tended to address the subject from ethical or legal perspectives, for example (Uhlir & Bishop, 1986; Rolston, 1986; Lyall, 1999), but had failed to engage to any great extent with the technology that was actually doing the damage.

The one exception was a small group of scientists and engineers within a number of space agencies (most notably NASA and ESA) who were concerned about the increasing amounts of orbital debris produced by bad practices in the space launch industry and satellite industry generally (Flury, 1988). As mentioned previously, much of the research concentrated on the most used part of the space environment known as low Earth orbit (LEO).

In general terms, the intention of the Submitted Works was to bring the various aspects of the subject together, present them in a coherent way and analyse them from a scientific and engineering perspective (which had not been done before). An early example was the author's analysis of the space law treaties in terms of protection of the space environment (Williamson, 1997), which is discussed further in 4.2 Antecedent Works.

The Central Work - "Space: The Fragile Frontier" (Williamson, 2006a) – was the first serious, academic text to draw together the recognised issues of Earth orbital debris and planetary protection, set them in the context of space law and ethical policies, and encourage a sustainable approach to space exploration and development. It was designed, in part, to gather and present data on existing debris in Earth's orbital environment, the potential evolution of that debris population and the mitigation measures that should curb its growth. It then extended this presentation to the planetary bodies, such as the Moon and Mars, and expanded discussion of the existing ‘planetary protection’ regime, which was limited to biological contamination (forward contamination of other celestial bodies and back-contamination of the Earth).

The Central Work itself was original at the time of publication, and is still considered unique, for three main reasons:

- the research was conducted by a space technology practitioner rather than a law, ethics or philosophy professional;
- the research extends the technical issues beyond low Earth orbit to other planetary bodies (both orbits and surfaces) and beyond biological contamination to geomorphological issues and commercial impacts;
- the research presents a multidisciplinary consideration of a putative space sustainability/environment protection policy, *inter alia,* by extending aspects of terrestrial environmentalism to the space environment.

All of the Submitted Works (described in detail in Section 4) are original and have been published in peer-reviewed journals, professional peer-reviewed conference proceedings, or monographs produced by academic publishers.

The target audience is what is generally known as ‘the space community’, a broad-based international community of professionals with interests in space from planetary science and rocket engineering to satellite insurance and artefact preservation (see 2.1). That said, the key stakeholders in the future are the younger demographic, simply because they will have the biggest influence in the future; so, although the first aim of the Submitted Works was to inform, a second aim was to influence.

Space exploration and development is a long-term matter and is already multigenerational. Many of those involved with the early satellites and many of the early astronauts are now long gone. Today’s young satellite engineers have never known a world without satellite television, space-based weather forecasting and satellite navigation. Individuals born after November 2000 have always lived in an era when, at any given time, at least two people were living and working in space (one reason, at least, why the Space Age deserves its initial capitals).

This multigenerational aspect means that current stakeholders and subsequent generations will need to be educated and informed on the subject of space sustainability and environmental protection until it becomes ingrained, much like terrestrial environmentalism is today. In fact, the terrestrial environmental ('green') movement is used throughout the Central Work and other submitted texts as an analogy to indicate mankind's collective resistance to new ideas and to encourage interested participants that persistence pays.

The long-term nature of space sustainability research is reflected in the 20-year span of the Submitted Works presented here, while its continuing relevance is illustrated by the fact that key works (e.g. from 2003 and 2006) are still being cited in 2017 (see 5.2 Citation Analysis and section 5 in general for further consideration of the long-term nature of the research topic).

The potential impact of this body of work – in providing a solid informational background and a carefully argued proposition – is that key stakeholders in the future use of the space environment will be influenced sufficiently to consider their actions, the ramifications of their space mission plans and system designs, and the environmental impacts of their business plans.

In the broadest sense, the intended outcome was to produce a body of work that would influence national, regional and international policy and embed sustainability measures within space activity.

The following section provides an overview of the professional context in which the author operates as a space technology practitioner and, by way of background, summarises the events that led to the body of work under consideration here.

2. Professional Context

2.1 The Space Community

The author of the published works presented here operates in a small segment of society known as the ‘space profession’ or ‘space community’. It comprises a wide variety of professionals which includes, *inter alia*, engineers, scientists, lawyers, insurers, academics and policy makers, who are employed, for example, by industrial contractors, government agencies, other private sector bodies and academic institutions.

The subject of ‘space’, which is also the core subject matter of this study, is what ties these disparate professionals together and effectively acts as a prefix for their specialist subject areas: space science, space law, space policy, etc.

The body of work presented here is therefore targeted initially at a relatively small professional community but, if one includes the public ‘user community’ and those whose work is influenced by space (such as artists), the issues are relevant to a much broader segment of society. For this reason, in parallel with the Submitted Works, the author published a number of non-academic articles and commentaries aimed at a broader audience, a selection of which have been included in Appendix B: Background Texts to illustrate the interplay between the academic works and more general texts.

2.2 The Author

Proper consideration of the technical (scientific and engineering) subject matter of this study in the context of commercial applications and environmental issues requires an unusual skillset. It includes an ability to understand the technical aspects while appreciating the need - and possessing the capability - to explain the issues in an accessible manner.

The author’s background – a BSc in Physics & Astrophysics and industrial experience in microwave engineering, satellite communications and technical management – led to his current role as an independent Space Technology Consultant, technical writer & lecturer. His key, long-term client is one of the world's leading space insurance brokerages, which arranges launch and orbital-lifetime insurance for commercial satellite projects.

As a consultant, the author's role is, at its core, one of an educator tasked with translating engineering and technology into plain English. This same philosophy has also informed his writing career, which has seen the publication of six books as sole author, including *The Cambridge Dictionary of Space Technology* (Williamson, 2001b) and some 500 technical magazine articles (leading to three category awards in the Aerospace Journalist of the Year Awards). He has also made contributions to eight other academic texts covering subject matter from satellite antennas to space policy (see Appendix B). Additionally, he has written some 50 technical & corporate publications and edited three international space publications. In the academic realm, he has published some 50 papers, presented workshops to Lancaster University Physics Dept. and acted as Honorary Visiting Fellow (1999-2005) and External Examiner (2004-2008) for Salford University Physics Dept.

There are two main aspects of the author's overall role that have allowed the current line of research to be pursued. The first is a breadth of interest within the general sphere of 'space' - covering science, technology, law, policy and education - and a related capability to analyse and communicate relevant cross-disciplinary aspects. The second is independence from commercial or institutional employers that might otherwise not sanction the research or appreciate the criticism of certain space actors implied by any in-depth analysis of past and current practices in space.

These two aspects help to explain why the work presented here is original (see 1.3) and why the issues contained within had not previously been addressed by the space community. Moreover, it is important to note the extent to which the author's background in general has informed the overall methodology of the study (see 3.3).

2.3 Research Journey

The author’s interest in protection of the space environment dates back to the 1989 International Astronautical Congress (IAC) in Malaga, Spain; the IAC is a major annual space meeting organised by the International Astronautical Federation (IAF), a professional body representing the space community.

At the 1989 IAC, in a session on space debris, a paper (Eichler & Rex, 1989) was presented on the chain reaction or ‘cascade effect’, a mechanism whereby debris objects impact other objects to produce yet more debris, eventually rendering some of the more useful orbits around the Earth inaccessible and unusable. Meanwhile, at the same conference, the technicalities of debris production and its ramifications for commercial operations were being voiced – somewhat tentatively – to an audience of space lawyers (Perek, 1989). It was clear, however, that there was little, if any, interaction between engineering and law communities.

Outside those sessions, among the mainstream conference topics, there appeared to be little recognition of the existence of a problem, let alone the need for a solution. Despite the fact that damage caused to orbiting spacecraft by debris from other spacecraft had already been recorded and analysed, the space community at large seemed content to ignore it. This observation formed the root of the hypothesis inherent in the Submitted Works: that space activity is potentially damaging to the space environment and that this is not sufficiently recognised (see 3.2).

At the following year’s congress, in Dresden, the author made a first attempt to engage with space lawyers by offering a logical framework for definitions of the most common terms in space technology – a basic structure for a common language (Williamson, 1990a; not part of the Submitted Works). This was partly in response to a call from some lawyers for a greater contribution from the space technology fraternity, but was also intended as a modest attempt to help them place their discussions in the proper technical context. The definitions themselves had been written for the first edition of the author’s *Dictionary of Space Technology* (Williamson, 1990b).

It was evident that parts of existing space law, having been written in the late 1960s, failed to address modern-day – let alone future – requirements, at least in part due to insufficient technical input (Blount, 2012). It was also clear that laws or policies relating to Earth orbital debris were only the beginning of the story, as pollution of the Martian environment was already of concern to some forward-looking thinkers in the science/technology and law communities (Sterns & Tennen, 1980).

However, it was only in 1996, while researching a paper on the history of space science missions (Williamson, 1996; not part of the Submitted Works), that the author realised how much hardware had been crashed onto the Moon in the name of space research. The impression that planetary bodies beyond the Earth were not valued for their inherent 'geomorphological qualities' was augmented by the announcement that Japan's Lunar-A spacecraft would carry surface penetrators, which would add to the catalogue of manmade lunar debris.

The research journey continued with the preparation of a paper for the International Institute of Space Law (IISL) on protection of the space environment – or lack of it – under the Outer Space Treaty. This paper is reviewed under Antecedent Works (Williamson, 1997) in subsection 4.2.

It was accompanied by the publication of a number of magazine editorials and commentaries which strove to publicise the author's concerns to a wider audience of space professionals. Some of this appeared under the intentionally provocative heading 'Are We Trashing the Solar System?', specifically with the intention of provoking discussion among the respective readerships (see Appendix B). The reaction was both interesting and informative and the responses served to convince the author that a programme to increase awareness of the issue was justified and necessary.

Although the author's magazine articles and editorials on space environment protection and his appearance on Dr David Livingstone's web-based radio series 'The Space Show' to discuss the Central Work (Livingstone, 2006) are not part of the Submitted Works, they are considered to be part of the 'educational outreach' that is often a subsidiary goal of academic research and therefore a valid element of the academic environment covered in this commentary.

The 1997 IISL paper led to a proposal, by the author, to the International Academy of Astronautics (IAA) for a symposium on ‘Protection of the Space Environment’, which was held as an IAA/IISL Scientific-Legal Round Table at the 1999 IAF Congress in Amsterdam with the author as coordinator (reviewed under Antecedent Works: Williamson, 1999). The role of coordinator allowed the author to make a direct contribution to the professional community above and beyond the presentation of a paper.

The IAA and IISL, respectively, represent engineers and lawyers with professional interests in space; they are affiliated to the IAF and co-organise the annual congress. The objectives of the Round Table were to present the facts regarding actual and potential degradation of the space environment by human activity, particularly that of the planetary bodies; to allow discussion of the problems; and to consider how awareness of the problems might be enhanced among the space community. It attracted a good audience and the rapporteur optimistically reported that the event could be regarded as “one first step to turn around the apparent lack of interest…displayed by the Member States of the UN”.

Following further discussions with colleagues and the publication of additional papers on the subject (Williamson, 2001, 2002a, 2002b) the author decided in early 2002 to propose a monograph for publication. This led, in 2006, to the publication of “Space: The Fragile Frontier” - the Central Work presented here - by the American Institute of Aeronautics and Astronautics (AIAA), a professional body that represents American aerospace engineers and others, and publishes academic texts and trade magazines.

Published precursors to the Central Work include a number of papers presented at colloquia of the IAA and IISL and published thereafter in scientific journals and IISL proceedings, respectively. These are reviewed under Antecedent Works (4.2).

Following publication of the Central Work, the research journey continued with chapter contributions to a multi-author work on sustainable development (Williamson, 2007) and an IAA 'Cosmic Study' on protection of the space environment (Williamson, 2010a), for which the author was also co-editor. Although the latter two were projects involving a number of professionals from various fields (*inter alia,* science, technology, policy and law), the Submitted Works are original, sole contributions. They are reviewed, with others, under Subsequent Works (4.4).

The following section considers the process by which the Submitted Works were produced by reviewing the aims and intentions of the work, the themes that were developed in undertaking the research and the general methodologies employed.

3. The Process: Research Questions and Methodologies

3.1 Basis

Although it has been suggested that in doctoral research "it is the *quality, not process*, that is important", key differences between the traditional PhD and a PhD by Published Works can be identified (Smith, 2015). The traditional PhD is based on a supervised programme of research and submission of a thesis, whereby an academic supervisor guides a candidate in research methodology and other aspects such as presentation skills and ethical considerations. By contrast, a PhD by Published Works is based on a coherent body of work comprising existing peer-reviewed publications that resulted from a period of largely self-guided research with a methodology informed by professional training and subsequent work within the field.

In essence, the PhD by Published Works is a 'reverse engineered' traditional PhD, in which the research methodologies are implicit, rather than designed, and the research questions may evolve with time.

That said, the research that forms the Submitted Works presented here (see section 4) was, from the outset, intended to meet the highest academic standards in terms of peer-review and publication in academic journals/monographs readily accessible to the academic community.

A further consideration is the question of communication and mutual understanding between the many, often disparate, disciplines involved in space research, exploration and development. As a result, the work presented here is multidisciplinary - requiring consideration of scientific, legal and ethical elements – and represents a research programme that is long-term in nature, spanning approximately two decades.

The following subsections are intended to explain the process by which the Published Works considered here were produced.

3.2 Aims and Themes

Increasing scientific exploration and commercial development of the space environment – in common with the Earth's environment - brings challenges and risks to that environment that must eventually be recognised and addressed. The Submitted Works presented here embody the author's research into the impact of scientific space exploration and commercial space development on the space environment.

The fundamental hypothesis that informs and guides this research is that space activity is potentially damaging to the space environment and that this is not sufficiently recognised by governments or private companies that utilise and benefit from that environment.

It was the intention of this work to identify the key environmental challenges and risks, and to consider environmental protection issues in a legal, ethical and policy context.

Specifically, at its most fundamental level, the aim of the research conducted for all of the submitted texts was to determine whether it is possible to establish an optimal balance between expansion of activity in space and protection of the fragile space environment. This was the key research question from the outset. Indeed, the central theme of a "sustainable balance" was introduced as early as the concluding section of the first work considered here (Williamson, 1997).

In pursuing the fundamental research question of a balance between space activity and protection of the space environment, a number of subsidiary questions were identified for the early works reviewed in subsection 4.2:

1. What are the threats to the space environment and how might they evolve?
2. How are the relevant legal, ethical and policy-related issues addressed by the space community?
3. How can sustainable development of space assets be assured?

Subsequent research sought to provide answers to these questions in terms of guidelines and policy, thus addressing the overall space sustainability theme of the work. Understandably, this led to further questions and more nuanced arguments which were addressed in subsequent works (reviewed in 4.3 and 4.4).

As implied by the final question above, a subsidiary theme of the work is the premise that the space environment both requires, and is worthy of, protection from unregulated developments and/or unplanned consequences of space exploration. A key consideration is the degree to which this protection is already provided by the existing body of space law (Williamson, 1997) or other international agreements, and the extent to which further policy-making is required.

A coherent theme throughout the work has been consideration of the sustainable development of the space environment in terms of its key assets, such as orbital positions in geostationary orbit (from which most communications satellites operate) and the surfaces of planetary bodies (with regard to a balance between pure science research and commercial mining applications, for example; Williamson 2006a, pp244-247).

3.3 Methodologies

Space exploration and development is, by its nature, a multidisciplinary endeavour requiring professionals from many different fields to work together. For example, the technical requirements for a space-based telescope may be identified by astronomers (in terms of optical resolution, wavebands of interest, etc), but the realisation of the design relies on the skills of engineering specialists in structural, thermal, power, communications and other aspects of spacecraft engineering. Then, of course, the spacecraft must be launched, which – apart from the obvious role of rocket engineers – requires practitioners in launch insurance, international liability and other legal considerations.

3.3.1 Disciplinarity

As can be seen from this commentary and the published work, space activity occurs in a ‘multidisciplinary community’. This raises an interesting semantic issue related both to the field of study and to the space community more broadly. The Latin prefix ‘multi’ refers, of course, to the ‘many’ different disciplines involved in space exploration and development. An equally common and arguably more accurate term is ‘interdisciplinary’, which implies (again, from the Latin) an interaction ‘between’ or ‘among’ the various disciplines; indeed, this is why the author used the term in ‘Protection of the Space Environment: the advantage of an interdisciplinary approach’ (Williamson, 2008).

Particularly relevant here, however, is the concept of transdisciplinarity, developed by Swiss philosopher and psychologist Jean Piaget some “seven centuries after disciplinarity had evolved” (Nicolescu, 2010). The key here is the Latin prefix ‘trans’, which means ‘across’ or ‘beyond’ (as in trans-lunar, beyond the Moon). Interestingly, the prefix also suggests movement (as in transatlantic, transaction and transmitter), which is particularly apt for space-related subjects. So while an interdisciplinary approach suggests different disciplines working together and transferring methodologies from one discipline to another, a transdisciplinary approach implies working towards something beyond that which exists; theoretical physicist Basarab Nicolescu (2010) refers to it as “contemplating the possibility of a space of knowledge *beyond* the disciplines”. This is exactly what is required to ensure the sustainability of the space environment.

3.3.2 Philosophical basis

Given the multidisciplinary nature of the subject and the Submitted Works themselves, the identification of a single research methodology is neither practical nor, arguably, desirable. The underlying methodology for the published works was grounded in the scientific and engineering background of the author, but was also informed by his experience as an educator and technical writer. As a result, the research benefitted from several different but complementary approaches. Fundamentally, however, the author’s background provided a solid underpinning for the research and a clear focus for the selection of scientific and engineering material under a 'desk-based' research methodology.

Thus the author used this 'scientific method' as the primary tool by which data collection for the desk-based research was undertaken. Inevitably, this raises questions regarding the philosophy of science and debates over the constitution of 'the scientific method'. Such debates have evolved across the history of philosophical thought, from the writings of Kant in *Critique of Pure Reason* (1781) through to discussions by Koestler (1959) and Kearney (1971). Thomas Kuhn, in *The Structure of Scientific Revolutions (1996)*, identified that there have been numerous 'paradigm shifts' in the study of science - the 'paradigm' being the general conception of the nature of scientific endeavour within which enquiries are undertaken. As such, the paradigm includes the general methods and techniques that members of the scientific community have in common and incorporates explicit rules for the investigation of certain phenomenon. The essence of this 'Kuhnian view' is, therefore, that natural sciences (specifically for this discussion, the study of physics) have a single, dominant scientific method: the requirements for making and recording observations, presenting these observations and drawing conclusions based on those findings. In some cases, this extends to making predictions based on the general acceptance of those conclusions (Weatherall, 1968).

It was the author's familiarity and expertise with these established principles, used throughout the Central Work (see 4.3), that enabled evaluation of the material collected within the 'desk-based' study. This expertise was particularly important in evaluating and critically analysing the writings in respect of the debris situation in Earth orbit (chapter 3), which was the subject of many previous academic works (e.g. Flury, 1988; ESA, 1999; Anz-Meader, 2001). The resulting conclusions were based on these works and predictions were made in relation to potential debris issues in higher, less populated orbits (such as geostationary orbit). The same research methodology was employed for chapter 4, which included - as Table 3 - a 'lunar and planetary impact catalogue' and details of biological 'planetary protection' measures, which had also been the subject of many previous academic works (e.g. Sterns & Tennen, 1989; Bohlmann, 2003).

The application of engineering principles within the published work was possible given the specific practical training and expertise of the author. According to Koen (2003), the engineering method constitutes the use of heuristics (often characterised as an intuitive method, rule-of-thumb or educated guess) to produce the best outcome in a poorly understood situation. Engineering, therefore, seeks to take theoretical technical solutions, identify the most appropriate, balance competing solutions against practicality and cost, and implement the solutions in the real world (Koen, 2003). Within the scope of the Submitted Works, this resulted in the identification of problems regarding the operation of spacecraft systems within the unique environment of space, and the provision of solutions based upon the identification of appropriate systems related to spacecraft design and operations. This was significant for the sections that analysed environmental issues and sought to recommend a course of action to mitigate or avoid those issues.

3.3.3 Data Collection

In colloquial English, the terms ‘data’ and ‘information’ are often considered synonymous; however, in space science applications (such as space astronomy or Earth imaging) data refers to the basic output of sensors and information refers to a derived data-product (such as a star map or an image of the Earth’s surface). Although the Submitted Works do not involve the collection of empirical scientific data through experimentation, observation or other data-collection techniques specifically initiated by the author (a process identified by Gauch (2003) as ‘the scientific method’), they do involve the collection of information derived from the relevant data. As mentioned above, the author’s expertise in science and engineering enabled the identification and analysis of material information from a wide range of sources.

It might be tempting to categorise this methodology as being ‘qualitative’ in nature. Grounded in the social and behavioural sciences, ‘qualitative research’ seeks to identify the opinions and insights of individuals or groups (Denzin & Lincoln, 2011) and involves a range of techniques to generate data, such as questionnaires, interviews and focus groups (for discussion on research design see Creswell, 2017). The Submitted Works do not, however, fall within this definition of qualitative research. They were produced in the realm of the author’s active participation in the professional space community, wherein discourse helped in identifying sources of data and information rather than forming the basis of the data.

For example, with reference to orbital debris data, it was possible to meet and talk directly to some of the key players in the field (from ESA and NASA) to help identify appropriate academic sources. Moreover, when extending the discussion from Earth orbital debris to planetary impacts (Table 3 in Williamson 2006a), it was possible to obtain data from NASA’s leading debris expert and update it, using the aforementioned scientific and engineering training to suit the needs of the text. Personal contacts and working within the space community meant that it was possible, where necessary, to obtain specific permissions at a personal level and, in a few cases, to reference a contribution as a ‘personal communication’. Such engagement with the professional community was an aid to data collection as opposed to a method of collecting substantive data.

3.3.4 Method and Process

As stated earlier, the nature of the PhD by Publication means that much of the methodological underpinning is organic and bespoke to the needs of the individual project. Having discounted data collection through either scientific methods or social science techniques, the dominant methodological approach adopted throughout the published works can be identified as one of secondary or desk-based research. Analogous to an extended literature review (Fink, 2013), the data collection process involved an analytical synthesis of academic literature on specific areas of concern. Taking the Central Work as an example, the desk-based methodology would encompass the following aspects:

a) The formation of a hypothesis regarding the extraterrestrial environment, a process that involved using scientific and engineering knowledge and awareness to identify critical areas of vulnerability that would form discrete chapters of the work.
b) The hypothesis can be retrospectively identified as being informed by the research questions outlined in section 3.2 (above), namely:

1. What are the threats to the space environment and how might they evolve?
2. How are the relevant legal, ethical and policy-related issues addressed by the space community?
3. How can sustainable development of space assets be assured?

c) Collection of materials on the discrete areas identified in each chapter. Materials were subject to practical screening criteria based on quality and relevance. The quality of the material was assessed using the scientific and engineering expertise of the author or, for disciplines outside the author's experience, was based on factors such as peer review, choice of journal/publisher and citations. Occasionally, professional contacts were invaluable in providing scientific and engineering information and when seeking opinions of practitioners in fields such as law and ethics.

d) Within each area of inquiry, the author evaluated the materials to ascertain whether sufficient protection was afforded to the extraterrestrial environment by the space community itself or by the current international legal and governance regime.

e) Having identified the current situation in respect of the space environment, inconsistencies and deficiencies in the existing technical data and governance framework were identified. This critical analysis was a crucial stage of the process as it provided what is known in management circles as a 'gap analysis' (an assessment of actual performance against potential or required performance).

The chapters of the Central Work (as outlined in section 4.3 of this commentary), and indeed the bulk of the publications forming the Submitted Works, have been developed using the process described above. The hypothetical scenarios or case studies that form chapters 7-9 of the Central Work (Williamson 2006, pp201-238) were founded on an inductive reasoning method analogous to legal reasoning, as described *inter alia* by McConville & Hong-Chui (2007, pp16-46).

In terms of methodology, then, the Submitted Works do not adhere to a single, easily identified research procedure, but constitute a hybrid of desk-based critique and inductive reasoning. The process identified above has, as a result of this methodology and a rigour in its execution, produced a coherent body of academic work that has been broadly accepted by the space community.

The following section reviews the rationale for the selection of the Submitted Works and considers the works themselves in three contiguous time periods: those published prior to the Central Work, the monograph itself, and the works published thereafter.

4. Submitted Works

4.1 Selection Rationale

The published work selected as a centrepiece for this thesis - an 80,000-word monograph entitled “Space: The Fragile Frontier” - both consolidates a decade or so of earlier work on space environment issues and extends it by building a case for the sustainable use and partial protection of that environment.

The body of work considered here also includes a number of supporting published texts in the form of peer-reviewed papers. References to the Submitted Works are emboldened in section 4 for easier reference to the Submitted Works associated with this commentary (submitted separately as PDF files).

The overriding rationale behind the choice of these texts was one of subject relevance and academic standing: this meant including only peer-reviewed works that supported the hypothesis (that space activity is potentially damaging to the space environment and that this is not sufficiently recognised) and specifically avoiding magazine articles and commentaries. It was also decided to avoid co-authorship of papers to retain author originality and ownership, and thereby maintain a coherent style and theme across the body of work. The possibility of bias beyond the allowable norms of professional opinion was mitigated by the official peer review process inherent in the body of work and by the author’s personal system of ‘preliminary peer review’ (by requesting professional comment).

The majority of the supporting works were presented as papers to the International Astronautical Congress (IAC) – a major annual space meeting organised by the International Astronautical Federation (IAF), a leading professional body in the space community. All papers are peer-reviewed by session coordinators and formally approved for inclusion at an annual meeting in Paris.

As mentioned earlier, the IACs are organised under the auspices of two organisations associated with the IAF: the International Academy of Astronautics (IAA) - which deals predominantly with science and engineering subjects, but also runs sessions on space policy, education and history – and the International Institute of Space Law (IISL), which specialises in the legal aspects of space exploration and development.

The earlier papers were published in hard copy (by the American Institute of Aeronautics and Astronautics, AIAA), but in recent years the IAF has migrated to an electronic format. The IISL publishes its papers in the annual Proceedings of its *Colloquia on the Law of Outer Space* (see **Williamson, 1990a, 1997, 2000a**). In addition, some of the papers listed below have, on recommendation, been republished in academic, peer-reviewed journals such as *Acta Astronautica*, *Advances in Space Research* and *Space Policy* (see **Williamson, 2000b, 2003, 2004a, 2005)**. Further background to the long-term academic study of the issues covered by these papers is provided in section 2 on Professional Context.

The following subsections provide an overview of the submitted texts published prior to the Central Work (4.2); the Central Work itself (4.3); and Subsequent Works (4.4) which build on the Central Work.

4.2 Antecedent Works

This subsection reviews the submitted texts published prior to the Central Work, showing how the author's initial research into existing space law treaties led to the formulation of a case for protecting the space environment. Over a number of years, this research base evolved towards a 'critical mass' that would prompt the creation of the Central Work considered in the following subsection.

As explained in subsection 2.3 (Research Journey), the first work relevant to this commentary was a paper – entitled 'Protection of the Space Environment under the Outer Space Treaty' - presented at the 40th Colloquium on the Law of Outer Space, held as part of the 48th IAF Congress in Turin, Italy (**Williamson, 1997**). The paper analyses the Articles of the Outer Space Treaty (OST) of 1967 with relevance to the space environment and concludes that the OST makes "insufficient provision" for protection of the space environment, especially considering the creation of additional orbital debris that “will undoubtedly accompany future developments and exploitation” [a pessimistic assessment borne out in January 2007 when China destroyed its own Feng Yun 1C weather satellite in an anti-satellite missile test, creating some 1600 trackable debris objects (Liou, 2007)].

The paper was intended as an original and somewhat provocative work designed to stimulate discussion and not as a catalogue of existing opinions. In this sense, it succeeded in providing the author with an ‘injection point’ into the orbit of experienced law professionals. It was among the first papers to analyse the OST in the context of environmental protection and to identify the inadequacies in relation to current and future activities (essentially because the space law treaties were designed to protect astronauts and their spacecraft rather than the space environment – there being no significant orbital debris problem in 1967). By recognising the potential damage to the space environment and pointing to the lack of recognition among space professionals, this first paper supported the hypothesis inherent in the research journey described here.

Although the paper conducted a well-reasoned analysis of the relevant Articles of the OST, it appears in retrospect to be naïve in its call to amend or supplement the Outer Space Treaty. While many authors have and, indeed, still call for such amendments, it has become clear that such treaties, drafted under the auspices of a United Nations Committee and adopted by the UN General Assembly, are not easily amended. In fact, it was this realisation that prompted the author to conclude that the solution for protecting the space environment was not to be found in the existing body of space law, but in some other mechanism, such as space industry guidelines or perhaps eventually an internationally agreed policy.

Importantly, in terms of a pragmatic approach to policy formulation, this paper introduced a central theme of the Submitted Works in recognising the need for “a sustainable balance between the productive activities of mankind and the desire to retain the purity of the space environment”.

Despite the observed inadequacy of space law to ensure sustainable development in space, the analysis conducted for the paper provided a useful demonstration of the status quo and was developed further to form chapter 5 of the Central Work. This included further consideration of the Moon Agreement of 1979, a discussion of sovereignty and ownership issues and a note on environmental conferences by way of terrestrial analogy. The chapter was fully referenced to reflect the legal context in which it was written and corrected any naivety in the original paper.

Within a few months, the second of the Submitted Works considered here was published in *Space Policy*, the leading peer-reviewed space policy journal, as a Viewpoint contribution, entitled ‘Protecting the Space Environment - Are We Doing Enough?’ (**Williamson, 1998**). Among other things, the paper extended the discussion of the space law treaties, highlighting the lack of powers of enforcement inherent in the current body of space law.

Although the *Space Policy* paper was designed to promulgate the analysis and conclusions of the above IISL paper to a wider audience (specifically in the space policy fraternity), it was also the author’s first peer-reviewed paper to properly address the issue of lunar impacts, the (continuing) practice of crashing spacecraft onto the lunar surface “ostensibly in the name of space science”. This was to be a continuing theme throughout the body of work which supported the hypothesis presented here; the analysis was developed further in the following paper and eventually formed chapter 4 of the Central Work.

From a knowledge of the structure and content of IAF congresses, it was evident that an opportunity to take the research further and promulgate the results existed in the form of the IAA/IISL Scientific/Legal Round Table, an annual multidisciplinary colloquium held at the congress. As explained in subsection 2.3 (Research Journey), this led to the author’s proposal for a Round Table on ‘Protection of the Space Environment’, which was accepted.

In addition to coordinating the event, the author presented a paper entitled ‘Planetary Spacecraft Debris – The Case for Protecting the Space Environment’ (**Williamson, 1999**), which was one of six presented at the 18th IAA/IISL Scientific/Legal Round Table, held at the 50th IAF Congress in Amsterdam. The aim was to assemble a multidisciplinary group of authors, which included an astronomer, a space scientist specialising in orbital debris, a space law academic, another lawyer specialising in planetary protection issues and a researcher in space ethics. Along with the author's contribution, the intention was to avoid the professional parochialism of some of the other conference sessions.

The author's paper introduced the Round Table by presenting data regarding spacecraft impacts on planetary surfaces and made the case for protecting the space environment. Its inclusion in an IAA/IISL Scientific/Legal Round Table is a significant issue in itself, not least because it was only the 18th Round Table organised under the auspices of two of the leading academic bodies in the space community, but also because the author's proposal was approved less than two years after his first paper on protecting the space environment was published. Other subjects covered since the first Round Table in 1977 have included important topics such as "energy from outer space", "space telecommunications" and "space debris" (Rohner-Willsch, 2011), but this was the first to be *dedicated* to protection of the space environment (the 8th Round Table in 1984 had considered some aspects in relation to "present and expected uses of outer space", but did not develop the subject further).

The Round Table paper was pivotal in the author's research on the topic of protection of the space environment and its progression towards the Central Work presented here. Firstly, it extended the discussion of spacecraft impacts from the Moon to Venus, Mars and Jupiter and published an initial impact catalogue; secondly, it included a reasoned statement of "the case for protection"; and thirdly, it highlighted a need to raise awareness of the issues among space professionals (once again supporting the hypothesis of the work). These three themes were developed further in chapters 4 and 10 of the Central Work.

The proceedings of IAA/IISL Scientific/Legal Round Tables are published in 'special addenda' to the annual Proceedings of the IISL Colloquia, which meant that, in addition to its publication as an IAA paper, the author's (**1999**) paper was co-published by the IISL (**Williamson, 2000a)**. Selected papers are also republished in the leading space journal *Acta Astronautica*, as was the case for the author's IISL paper the year after the Round Table took place (**Williamson, 2000b**).

The Submitted Works summarised above were presented to audiences in which law and policy practitioners predominate. It was clear, however, that since the subject was multidisciplinary (and the problems were the unintended consequences of advances made by the technical community), the wider community should be included.

As a result, a paper entitled ‘Exploration and Protection - A Delicate Balance’ (**Williamson, 2001**) was presented at an IAA symposium on ‘International Moon/Mars Exploration’, held as part of the 52nd IAF Congress in Toulouse, France. The symposium itself was tasked with investigating the ‘Rationale for Human Exploration of Space…’, and this gave the author an opportunity to extend his audience towards scientist and engineers.

Having presented some of the problems for the space environment in previous papers, this paper sought to present some options for solutions, suggesting either an ethical code for space exploration or at least a set of guidelines (or the type already formulated for the mitigation of debris in Earth orbit). The methodology of presenting problems and solutions (see subsection 3.3.2) was especially relevant in the context of an audience composed predominantly of engineers.

Also, as the subtitle (A Delicate Balance) suggests, the paper introduced one of the central themes of the collected works, which is the need to strike a balance between commercial development and environmental protection. This was developed further in chapters 9 and 10 of the Central Work.

Shortly after the 2001 IAF Congress, the author decided to propose a monograph for publication, which became the Central Work on space sustainability and protection of the space environment discussed here (**Williamson, 2006a**). This meant, of course, that papers on the subject published from 2002 were inextricably linked to the Central Work which, to some extent, represented a codification of the general body of work on the topic.

The 2nd World Space Congress - held in Houston, Texas, in 2002 – offered a useful platform for the following two papers discussed here. This meeting combined the International Astronautical Congress (IAC) and the Scientific Assembly of the Committee on Space Research (COSPAR), an international body formed in 1931 and tasked with the advancement of international cooperation in science. As such, it was an important meeting for the space community.

The first paper, entitled ‘Space Ethics and Protection of the Space Environment’ (**Williamson, 2002a**), was presented in an IAA symposium dedicated to space ethics. It further developed the discussion of an ethical code for space and defended the hypothesis that a code of ethics was required. It concluded that: “Had an ethical code for space been ‘in force’ in the late 1950s, much of the damage to the space environment might not have occurred in the decade that followed”.

Whereas much of the writing on space ethics is concerned with posing theoretical problems, the author’s stance throughout the Submitted Works is that of ‘pragmatic space practitioner tasked with providing solutions’. Recognising the existence of ethical codes in various branches of medicine and engineering, and the success of terrestrial environment summits and resolutions, the paper investigates the extension of this ‘collective responsibility’ to the sustainability of the space environment.

The paper was later republished in *Space Policy* (**Williamson, 2003**) and subsequently expanded to form chapter 6 of the Central Work. In retrospect, the paper proved to be not only a key progenitor of the Central Work, but also an important influence on the work of others. As shown in subsection 5.2 - Citation Analysis – this paper is one of the author’s most regularly cited works, being widely quoted in an academic text on ‘The Environmental Element in Space Law’ (Viikari, 2008) and in a chapter (Campion, 2015) contributed to a text on ‘Commercial Space Exploration: Ethics, Policy and Governance’.

The paper also introduced another sub-theme of the collected works, namely that ‘space assets’ have a value and thus, pragmatically speaking, are worth protecting. One of these assets is the set of specified positions for commercial communications satellites in geostationary orbit (GEO): satellites in GEO are, by definition, stationary with respect to the Earth, which makes it possible to specify, allocate and regulate their orbital positions (under the auspices of the International Telecommunication Union). This ‘asset value’ sub-theme, coupled with an analysis of how different stakeholders view the space environment, formed the basis of chapter 2 of the Central Work.

The second paper presented at the 2nd World Space Congress - entitled ‘Protection of the Space Environment: the First Small Steps’ (**Williamson, 2002b**) - was part of a joint IAC/COSPAR session. It extrapolated the orbital debris issue from low Earth orbit to geostationary orbit, noting specifically the temporary nature of the graveyard solution (a practice of boosting defunct satellites to an orbit 250-300km above GEO); it is considered temporary because - as detailed in the paper - in 50 years or so, there could be up to a thousand uncontrolled satellites in the graveyard orbit, which would represent an increased collision risk. This point specifically addresses the hypothesis that space activity is potentially damaging to the space environment. The paper concluded with the proposal that an international consultative body be formed to develop a policy for protection of the space environment (a notion expanded upon in chapter 10 of the Central Work).

The paper was republished in 2004 in *Advances in Space Research*, a COSPAR publication (**Williamson, 2004a**). The peer-reviewed recommendation to publish in ASR is a sign of professional recognition of the research.

The call for the development of a policy was further pursued in a paper presented at an IAA symposium on space policy, law and economics at the 55th IAF Congress in Vancouver (**Williamson, 2004b**). The paper – entitled ‘Protection of the Space Environment - Time for a Policy’ - reviewed planetary protection measures for biological contamination and highlighted the fact that no equivalent measures existed for “non-biological contamination”. Using examples of future potential environmental contamination (from space tourism and mining activities, for example), it outlined the process for the development of an environmental protection policy. Reflecting an increasing sense of urgency - resulting from announcements of such plans for commercial applications - the paper struck a forthright tone, suggesting that “the space profession needs a new model or ‘ethic’ of environmental awareness”. It thus specifically addressed the hypothesis that environmental issues are not sufficiently recognised by the space community.

A second paper at the 55th IAF Congress – entitled ‘Lunar exploration and development - a sustainable model’ (**Williamson, 2004c**) - was targeted at an IAA symposium on space exploration called “Strategies to Establish Lunar Colonization”. It represented a further attempt to influence science and technology stakeholders in the space community (as opposed to law and ethics professionals). In line with the subject matter of the symposium, it concentrated on the Moon, calling for the development of a sustainable model for any future exploration and development there. Interestingly, this concept of lunar sustainability was later developed by Newman (2015a) in his paper on ‘embedding sustainability in lunar exploration policy’.

The ‘sustainable model’ paper (**Williamson, 2004c**) was republished, by peer-reviewed recommendation, in *Acta Astronautica* the following year (**Williamson, 2005**). In common with the policy paper (**Williamson, 2004b**), it was written more or less in parallel with the Central Work (**Williamson, 2006a**), which had to be delivered for publication in 2005, and thus reflected some of its themes. In effect, they set the scene for the release of the Central Work, “Space; The Fragile Frontier”, which is discussed in the following section.

The decade of research that produced the Antecedent Works was crucial in developing the themes presented in the Central Work: i.e. the technical elements, the legal and ethical elements and, above all, the theme of space sustainability and the need for environmental protection that pulls the other elements together. Moreover, as the Citation Analysis in subsection 5.2 and the Citation Database in Appendix A will show, these works have influenced, and continue to influence, the work of other academics.

4.3 Central Work

This subsection discusses the content of “Space; The Fragile Frontier”, referred to here as the Central Work (**Williamson, 2006a**).

As implied above, an 80,000 word monograph requires time for planning and execution, as well as for peer review and the formal process of publication. In fact, the production of the monograph was a roughly three-year process, beginning in 2003 with the planning and formal proposal (discussed with the AIAA commissioning editor at the Bremen IAC in September 2003). Writing, peer review and contractual matters were undertaken in 2004 and 2005 – with contract signature in March - and the manuscript was delivered to the publisher in late 2005 for publication in May 2006. Professor James A. Van Allen contributed a Foreword dated September 2005 and sadly passed away in August 2006, a few months after publication.

It should be noted that the author considers himself extremely fortunate in securing the agreement of Prof. Van Allen to write a Foreword to the Central Work. It seems unlikely that a man with his professional reputation would do so if he felt the work had failed to make a worthwhile and original contribution to the professional literature. As a celebrated and widely respected scientist, the discoverer of the Earth's radiation belts (which were named in his honour) had a life-long interest in the physics of the space environment. In accepting the invitation to write a Foreword, he wrote "I am keenly interested in the subject…of your manuscript. (…) My congratulations on your important work".

In the Foreword itself, Van Allen wrote:

> "This important book provides an authoritative dose of prudence to the flourishing fields of space exploration and space technology. (…) The four concluding chapters of this comprehensive book are obligatory reading for every person who has a responsible role in space operations and/or space policy."

The three-year planning and production process meant that the research embodied within the Central Work had a degree of overlap with the foregoing Antecedent Works and, naturally, there was some interplay between them. What this meant in practice is that the Antecedent Works 'fed into' the Central Work and the latter 'fed out’ to Subsequent Works (subsection 4.4), effectively forming the coherent single body of work presented here.

It is also worth mentioning, in this context, that the author conducted his own preliminary form of peer review by asking recognised experts in respective chapter-topics to review the contents prior to manuscript delivery.

The monograph itself was organised within a ten-chapter structure, the content of which is summarised below.

Chapter 1 – ‘Space as a Frontier’ - begins by placing the exploration of space in the context of mankind’s inherent desire to explore new frontiers. There follows a short history of space exploration, decade by decade, providing an overview of key events and accomplishments. This allows the subject to be placed in a cultural and historical context, introducing readers to what has been done in space and indicating what might happen in the 21st century as ‘exploration’ becomes ‘development’. It also explains the importance of space exploration to society and the inevitability of space development (from communications satellites to space tourism).

The chapter was written using the author’s operational knowledge of space issues, but also with reference to a text on the history of space technology - entitled “Space Technology: The Early Years” (Williamson, 2006d) – which was being prepared in parallel for publication in 2006.

Chapter 2 – ‘Space as an Environment’ - moves from characterising space as a frontier to describing it as an environment. It does so by analogy with the better-known terrestrial environment, with which readers would associate, thereby assisting their appreciation that the space environment could be ‘at risk’ and, ultimately, could be protected to some degree.

The chapter defines ‘space’, its conditions as revealed by science spacecraft, and the orbital resources it provides. It then compares and contrasts the viewpoints of scientists, engineers and users of the space environment and introduces the concept of ‘value’, which was first introduced in the widely cited Space Policy paper

(**Williamson, 2003**). In addition to considering the planetary bodies as objects of scientific study, it highlights their potential as places to develop and exploit, thus introducing a key theme of the works: the need for balance between development and protection.

Although this chapter is more technical in terms of defining the environmental conditions of space and orbital resources, it was written as a second introductory chapter using similar methodologies and resources to chapter 1. Thus, in addition to the technical aspects, it references cultural aspects of space, as embodied in ethical discussions and lay publications on space produced both before the Space Age and during its formative years.

Chapter 3 – 'The Earth's Orbital Environment' - considers Earth-centred orbits as a resource for commercial and scientific applications and describes the threats to this resource. It introduces the problem of orbital debris, discussing sources of manmade debris, the evidence from recovered spacecraft and ground-based tracking systems, and its effects on individual spacecraft and the orbital resource as a whole. Actual and possible debris mitigation solutions are discussed. It then considers the evolution of the debris population and the difficulties of international debris mitigation policies. The chapter is fundamental in its support of the central hypothesis that space activity is potentially damaging to the space environment.

The chapter was written with reference to a wide variety of published material on orbital debris, both from space agencies and space industry experts. Key data on the evolution of orbital debris populations was obtained through personal contact with one of NASA's leading debris experts, who also contributed to the IAA/IISL Round Table coordinated by the author (see subsection 4.2).

Although not designed with this in mind, it is interesting to note that the contents of this chapter have proved useful to other students of the topic and have been cited in their theses (see 5.2 – Citation Analysis).

Chapter 4 – 'The Planetary Bodies' - extends the study of space debris beyond Earth orbit to the other planetary bodies, especially the Moon. It does so by considering the history of lunar spacecraft impacts and the potential for debris in lunar orbit. As mentioned earlier, this included the publication of a revised ‘lunar and planetary impact catalogue’ (again with the assistance of a NASA debris expert) which, once again, is fundamental in supporting the hypothesis.

The discussion then moves to the subject of ‘planetary protection’, reviewing NASA’s ‘probability of contamination formula’ and describing the COSPAR planetary protection policy (which categorises target bodies and the respective requirements for spacecraft decontamination). Noting the policy’s restriction to biological contamination, the chapter looks towards industrial development, space tourism and the possibility of terraforming (i.e. altering a planet’s environment to make it more like that of Earth) and the need to extend protection to physical or morphological environments (by analogy with Earth-based ‘geomorphology’).

The underlying themes throughout are the conflict between those who wish to study and those who wish to develop space, and the need to engineer a balance between protection and utilisation of the space environment. In addition to its technical aspects, the chapter draws heavily on published works in the fields of law, ethics, exobiology and cultural heritage.

Chapter 5 – ‘The Legal Dimension’ - presents the existing body of Space Law and analyses the 1967 Outer Space Treaty and the 1979 Moon Agreement in terms of protection of the space environment. It also discusses matters of sovereignty, reviews the ‘Common Heritage of Mankind’ principle and considers analogies with the terrestrial environment.

As mentioned in subsection 4.2, the analysis is extended from that performed for some of the Antecedent Works, with reference to multiple space law publications and some key terrestrial environmental conference declarations (in order to draw analogies for the space environment). It questions the degree to which the existing body of space law provides protection to the space environment and concludes that it is insufficient

Chapter 6 - The Ethical Dimension – conducts a similar analysis with reference to space ethics publications, defining ‘space ethics’ (Williamson, 2006a, p182) and returning to the ‘value’ question, that is since “space activities provide employment and opportunities for wealth creation…the concept of value must be applicable to the space environment” (Williamson, 2006a, p183). The chapter reviews professional opinion on the need for an ethical code or policy for space and includes discussion of how much control should be exerted, and by whom, stressing the international nature of space exploration and development throughout. It concludes that an ethical code, guidelines or policy might provide what is lacking in terms of environmental protection.

Chapters 7, 8 and 9 present three scenarios for the future development of space exploration and space exploitation to illustrate the ramifications of:

(a) allowing developments in space without control;
(b) controlling all developments in space under a strict regulatory regime;
(c) engineering a workable compromise that allows both scientific exploration and commercial development under internationally-agreed policies and using environmentally-friendly methods.

The three chapters employ a variety of literary devices (broadly classed as fictional) but are, effectively, engineering case studies presented in an accessible manner. The justification for the style of these three chapters is perhaps best provided by quoting directly from the book’s preface (Williamson, 2006a, p. xiii):

> “The majority of the book takes a standard form and style – presenting facts, arguments and possible solutions (all duly referenced) - but in recognition of the power of predictive fiction it includes three short chapters that present opposing scenarios for the future of space exploration and development. They are written, in fictional style, from the perspective of the year 2057 – the centenary of the Space Age – offering three different views of our future in space. I make no apology for including fictional accounts in an otherwise serious book. It is clear that there are limitations to how far we can extrapolate what we know now into the future. Borrowing the methods of a different genre

> releases us from the burden of absolute proof, while liberating our minds to consider the 'what-if scenarios' we might otherwise ignore."

It is worth repeating, in this regard, that Professor James Van Allen wrote in the Foreword to the Central Work: "The four concluding chapters of this comprehensive book are obligatory reading for every person who has a responsible role in space operations and/or space policy", which strongly implies that he appreciated the fictional methodology employed in chapters 7, 8 and 9.

The final chapter - Chapter 10: 'The Case for Protection of the Space Environment' – presents the case already made in some of the Antecedent Works in three sections entitled 'Recognition', 'Need For Action' and 'The Way Forward'. The first summarises the environmental concerns, while stressing a need for balance between development and protection; the second highlights the need for action with reference to orbits and planetary surfaces; the third makes recommendations for the formation of an international consultative body and considers how any resulting policies might be enforced. The chapter returns to the central hypothesis of the works and specifically addresses the central question on sustainability: "whether it is possible to establish an optimal balance between expansion of activity in space and protection of the fragile space environment."

In comparing the issues for the space environment with those faced by early proponents of the terrestrial environmental movement, it notes that changing attitudes is a long-term effort but warns that if the "laissez faire policy" is allowed to continue "until the second generation of lunar explorers is making footprints on the surface" it might be too late. The overall conclusion is that space sustainability can best be assured by the development of an internationally agreed policy regime.

As shown in subsection 5.2 (Citation Analysis), the Central Work is currently the most regularly cited part of the body of work presented here.

The following subsection features Submitted Works published after the Central Work was completed.

4.4 Subsequent Works

The concept of environmental sustainability, widely used in the terrestrial realm, was introduced specifically into the author's work on the space environment as the Central Work was under development. It was natural, therefore, that subsequent published works should highlight both 'sustainability' and the subtitle of the monograph itself. Interestingly, the two papers published in the year of publication of the Central Work (2006) were written and presented in the context of space agency plans to return astronauts to the Moon, which gave the general thesis on environmental protection a greater and nearer-term relevance.

The first paper – entitled 'Sustainable Development of "The Fragile Frontier"' (**Williamson, 2006b**) - was presented at the 57th IAF Congress in Valencia, Spain. It discussed scientific exploration, industrial development and space tourism in terms of sustainability, arguing that each of these aspects requires a sustainable approach to succeed.

The second paper – entitled 'Protecting "The Fragile Frontier" - The Need for a Policy' (**Williamson, 2006c**) – was also presented at the 57th IAF Congress. It returned to the requirement for an internationally accepted and enforceable policy, arguing that experience of space exploration has shown that protection of the space environment is unlikely to be "addressed automatically as part of any development plan".

An opportunity arose, following publication of the Central Work, to contribute a chapter on 'Sustainable Development for the Space Environment' (**Williamson, 2007**) to a monograph on sustainable development in general. While other chapters covered topics such as farming, forestry, oil extraction and terrestrial habitats, the author considered it useful to include the 'space sustainability agenda', not least as a thought-provoking extension of the sustainability concept. The author's chapter positions the space environment as part of mankind's "business and cultural realm" and argues that the advent of space tourism will increase its use, but warns that the concept of sustainability has "yet to be fully recognised by the space community" (an important part of the central hypothesis).

The following year, a paper entitled ‘Protection of the Space Environment: the advantage of an interdisciplinary approach’ (**Williamson, 2008**) was presented at the 59th IAF Congress in Glasgow, Scotland. The paper expands on the concept of an international consultative body included in the final chapter of the Central Work. It reviews the interdisciplinary nature of the space profession and the genesis of orbital debris guidelines by the Inter-Agency Space Debris Coordination Committee (IADC), an expert group developed by professionals in the space debris community; these guidelines are now increasingly (though not yet unanimously) observed by practitioners throughout the international space community. With reference to the IADC, the International Telecommunication Union (ITU) and terrestrial environmental ‘conferences’ on sustainability, such as Stockholm and Rio, the paper calls for a similar international and interdisciplinary approach.

The paper was written in the context of preparations for a major IAA ‘Cosmic Study’ entitled “Protecting the Environment of Celestial Bodies: the need for policy and guidelines” (see subsection 2.3) and provided input to that study, as explained below (see **Williamson, 2010a**).

A paper at the 60th IAF Congress in Daejeon, South Korea – entitled ‘Protecting the Space Environment: who decides?’ (**Williamson, 2009a**) - continued the discussion of the form of the proposed international consultative body, with reference to the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) as a possible forum or model for that body. It moved beyond the recommendations of the Central Work and, as with the previous paper, acted as a bridge between that monograph and the ongoing IAA Cosmic Study (**Williamson, 2010a**). Interestingly, the need for serious attention to the issues was highlighted by an in-orbit collision, in February 2009, between the Iridium 33 commercial communications satellite and the defunct Russian Cosmos 2251 spacecraft.

Following the publication of the Central Work (**Williamson 2006a**), the author was invited to present a paper at a conference organised by the European Space Policy Institute (ESPI) at its headquarters in Vienna in December 2007. The paper later formed a contribution to Chapter 2 of a monograph (entitled *Threats, Risks and*

Sustainability - Answers by Space) published in Springer's 'Studies in Space Policy' series (**Williamson, 2009b**). Along with meeting the brief of reviewing the role of space-based assets in assuring sustainability in a "knowledge-based society", the paper highlights the need to achieve sustainability in the space environment. So, although the contribution was not centred on protecting the space environment, it offered an opportunity to introduce the topic to an audience concerned more generally with sustainability issues.

As a direct result of the above-mentioned works, in particular the Central Work, the author was invited to contribute to and co-edit a prestigious International Academy of Astronautics (IAA) study on protecting the space environment. Its title was 'Protecting the Environment of Celestial Bodies: the need for policy and guidelines' (**Williamson, 2010a**). As its title implies, the study implicitly adopted the central hypothesis of the Submitted Works – in terms of the potential for damage to the space environment – and addressed the requirement for a balance between development and protection by way of internationally agreed policies and guidelines.

As mentioned above, such peer-reviewed studies are known in IAA parlance as "Cosmic Studies" and, in the Academy's words, are "carried out by specific Study Groups constituted by IAA experts". Once the two-to-three-year studies are completed and published, "they are distributed worldwide to Space Agencies and to UN organisations, as well as to relevant technical and international organisations interested in space activities" (see http://iaaweb.org/content/view/229/356/).

The author's contribution included a discussion of the interdisciplinary approach recommended in previous works and revisited the theme of how different users of the space environment possess differing viewpoints on its utility, sanctity and relevance to society. Following reminders of how the space debris community developed its guidelines for orbital debris mitigation and how the terrestrial environmental movement led eventually to international conferences for its protection, the contribution offered guidance on methodology for the subject's future development.

To some extent, this Cosmic Study could be seen as a culmination of the author's efforts to bring the issues of space environment protection to the notice of the professional space community. In the community served by the International Academy of Astronautics, a Cosmic Study is the highest accolade that can be accorded to the subject matter of a study; for the author, it represented the next step beyond the IAA/IISL Round Table and confirmation that protection of the space environment was worthy of consideration at a high level.

The final IAA paper in the series of Submitted Works presented here – entitled 'Protecting the Space Environment: A Policy Framework' (**Williamson, 2010b**) – was presented at the 61st IAF Congress in Prague, Czech Republic. It built on both the Central Work and the IAA Cosmic Study to develop a framework for a future policy that would offer some degree of protection to the space environment. It identified aspects "considered at risk" (which included orbital, surface and subsurface environments, atmospheres and the electromagnetic spectrum), expanded upon the risks and suggested a "holistic approach" towards the development of a space protection policy. It concluded that: "A carefully constructed policy for space environment protection will protect not only the environments themselves, but also our future ability to study and develop those environments in a sustainable way".

Again, based on the above-mentioned works, the author was invited to contribute to a panel at the 5th Eilene M Galloway Symposium [2] in Washington, DC, which discussed the "harmful contamination" concept in the 1967 Outer Space Treaty (the basic document of space law). This paper – entitled 'A Pragmatic Approach to the "Harmful Contamination" Concept in Art. IX of the Outer Space Treaty' (**Williamson, 2010c**) - was presented as part of the session on 'nonbiological contamination of the space environment' and included many elements covered in the Central Work (such as a balanced, pragmatic approach to protection policy, sustainability and inclusivity of the various stakeholders).

Interestingly, in the context of the published works presented here, it also

[2] http://www.spacelaw.olemiss.edu/events/notable/galloway.html

represented a return to the space law community (the target audience of the first paper reviewed above) and to analysis of the OST. This time, however, it sought to broaden the definition of ‘planetary protection’, ‘harmful contamination’ and other terms. It concluded that: “In the final analysis, space environment protection is not a legal nicety or an academic exercise; it is a requirement for the sustainable exploration and development of the solar system…and potentially beyond”.

In the context of the Submitted Works, the term “harmful contamination” (effectively, a legal recognition of the potential for damage to the space environment) also served to address the fundamental hypothesis of the works presented here (not only through the content of this final paper, but also the symposium of which it was a part). The following section considers the impact of these Submitted Works on the space community.

5. Impact

The impact of the Submitted Works within the space community (and to some extent beyond) is examined in this section. Subsection 5.1 (Literature Review) considers the professional publishing context in which the Submitted Works were performed; 5.2 (Citation Analysis) examines how other professionals have used the Submitted Works; and 5.3 (Evaluation) constitutes a critical appraisal of this contribution to the field.

5.1 Literature Review

As explained in subsection 2.3, the author's professional interest in protection of the space environment (in the context of the Submitted Works) dates from the 1989 International Astronautical Congress (IAC) and a paper (Eichler and Rex, 1989) on the risk of a self-sustaining 'cascade effect' increasing the orbital debris population in low Earth orbit (LEO). In fact, this 1989 paper was itself referencing a theory proposed by NASA scientist Donald J Kessler in 1978, known now as the 'Kessler Syndrome' (Kessler & Cour-Palais, 1978). The fact that, more than a decade after the original theory was published, the effect was still producing academic papers testifies to the long-term nature of some space-related issues, as explained in 1.3 (see also 5.3).

Thankfully, the Kessler Syndrome has yet to fully manifest itself throughout LEO, although the increase of the debris population observed as a result of two incidents this century gives cause for concern: namely, the deliberate destruction by the Chinese authorities of their Feng Yun 1C weather satellite in January 2007 and an unintentional collision, in February 2009, between the Iridium 33 commercial communications satellite and the defunct Russian Cosmos 2251 spacecraft.

An interesting indication of how long it can take for some concerns regarding the space environment to enter the public realm is the release of the Hollywood blockbuster 'Gravity' in 2013, which dramatises a debris chain reaction in LEO; that is, 35 years after the publication of Kessler's paper. His research remains relevant today.

The situation in LEO is, however, just one aspect of sustainability in the space environment. In researching the precursor works to the Central Work presented here, it became clear that several researchers had published papers on other aspects, including planetary protection, in both a biological and geomorphological sense, and the legal aspects of space settlement and industrial development.

Of particular note is the work by Hungarian Astronomer Ivan Almar and colleagues from the late 1980s, which provided early warnings (i.e. well before the technology existed) of the impact of mining operations on celestial bodies such as the Martian moon Phobos (Almar, Horvath & Illes, 1988; Almar & Horvath, 1989). These papers constituted 'early warnings' because it is only in recent years that serious commercial projects for off-Earth mining have been proposed and US law-makers have reacted by drafting a so-called Space Act (Foust, 2015; US Govt, 2015).

In parallel with the research described here, the author was working with Almar on a project concerned with multilingual astronautical terminology which led eventually to the publication of the IAA Multilingual Dictionary [3]. It transpired, in conversation, that Almar also had a professional interest in protecting the space environment and this led to his contribution (Almar, 1999) to the IAA/IISL Round Table coordinated by the author.

As a result of the author's own initial contributions to IISL sessions (2.3), the writings of two Arizona-based lawyers – Patricia Sterns and Les Tennen – on planetary protection were highlighted. These and many other publications formed the basis for some of the precursor papers reviewed in section 4.2 (Antecedent Works) and the Central Work itself (e.g. Sterns & Tennen, 1989, 1991; Cramer, 1997; Bohlmann, 2003).

Although, as explained above, the body of work presented here is multidisciplinary in nature, its ultimate intent is to educate and influence its professional/technical

[3] http://iaaweb.org/content/view/362/510

readership to be more receptive towards the development and international acceptance of a policy, or set of policies, that will provide enhanced protection for at least some parts of the space environment. These parts are, of course, very much still to be determined and agreed upon, but might include, for example, geostationary orbit, the lunar polar regions (where usable water-ice exists) and designated areas of scientific interest on Mars.

In retrospect, it is clear that the body of work has undergone an evolution of sorts, commonly referred to as a ‘research journey’. Most of the Antecedent Works presented above do not concern space policy for environmental protection, *per se*, because the field is in its formative stage; they are presented more in the field of space ethics (which was the reason the “ethical dimension” was covered as chapter 6 of the Central Work). This was because, until recently, the field has been focused on ‘what ought to be done, ethically speaking’ rather than ‘the policy that should be formulated’.

For this reason, a broad spectrum of ethical writing on space was referred to in chapters 6 and 10 of the Central Work and in Subsequent Works (e.g. Hargrove, 1986; Fogg, 1999; Pompidou, 2000; Arnould, 2001; Livingstone, 2002; Mendell, 2002). It is interesting to note that, at the time of the research, the French space agency CNES employed a philosopher and theologian, Jacques Arnould, to advise on the ethical, social and cultural dimensions of space activity.

However, in recognition that further development in the research topic should move away from theoretical ethics towards the pragmatic matter of policy, the later chapters of the Central Work, and most of the papers that form the Subsequent Works section here, concentrate on the policy aspects: the need for such a policy, the forum for the development of the policy, the rationale for including a broad selection of stakeholders, and so on. In effect, the research considered here has evolved from theory towards practice.

As a result of the author’s wide interests in space exploration and development, and because a serious study of sustainability of the space environment demanded it, the body of work presented here was influenced and enhanced by interaction with a range of professionals and their writings (as represented by the chapter reference sections in the Central Work). The continuation of this research beyond the Submitted Works is discussed in section 6.

5.2 Citation Analysis

A database of citations of the author's work relevant to the research question under consideration here has been compiled for this commentary and is included as Appendix A. In terms of year of citation, it extends from 1999 to 2017, appearing to peak first (in terms of number of citations) in 2007, based largely on a paper published in *Space Policy* journal, 'Space Ethics and Protection of the Space Environment' (Williamson, 2003); another more extended peak in citations occurs between 2009 and 2014, based predominantly on the Central Work, *Space: The Fragile Frontier* (Williamson, 2006a). In terms of work cited, the most frequently cited is Williamson 2006a, with 39 citations found, and the second most cited is Williamson 2003 (at 34). The fact that both works were still being cited in 2016 testifies to the long-term relevance of the research.

Several authors appear to have been influenced sufficiently by the body of work presented in this commentary to cite it multiple times within the same document. One example is Butler's 2007 paper in the Georgia Law Review, 'Unearthly Microbes and the Laws Designed to Resist Them' (Butler, 2007). He cites the author's work more than 40 times in his 40-page paper, literally from the first page to the last, initially regarding the subject of contamination [pp.1356-7] and later the inadequacy of the space law treaties in providing protection [pp.1358, 1360, 1374]. He also quotes the author on ethical issues [p.1367].

On page 1388, quoting from p.119 of the Central Work, the author is referred to directly in the text as follows:

> Scholar Mark Williamson has written, "[it] seems fair to conclude that [NASA's] limitation of decontamination measures was a result of financial concerns rather than an application of the scientific method."

Later, on page 1394, he quotes from p.175 with reference to the author's analysis of terrestrial environment conferences:

> "[A]ll... the space environment has going for it, in terms of protection," Mark Williamson has written, "is a catalog of analogies."

Because the topic of interest in Butler's paper is biological planetary protection, the majority of the citations are on this subject.

However, in her 2008 book "The Environmental Element in Space Law", Viikari (2008) concentrates more on the ethical and sustainability arguments presented in four of the author's Submitted Works (Williamson 2000b, 2003, 2005 and 2006a). For example, on page 15, she mentions the author's proposal for "an ethical code for space exploration and development" (in 2006a) and, on page 149, a four-page section of the Central Work (pp.137-141) on "the prospects of industrial development on the Moon and other celestial bodies". She also refers her readers, on pages 45 and 51 respectively, to the author's "more detailed account of lunar orbital debris" and "more detailed account of spacecraft decontamination" (in 2006a). It would appear, therefore, that she found the author's work useful in writing her own monograph.

In a paper on sustainable space exploration, Reiman (2010) cites the Central Work in her introduction, and even appears to adopt its title:

> "As Mark Williamson (2006) has noted, environmental ethics (of which space ethics can be seen as one subcategory) is, and should be, practical ethics…
>
> "Space, and any possible ecosystems on other planets, may represent a fragile frontier (Williamson, 2006)".

She continues to cite Williamson 2006a and 2004a throughout (though she refers to the latter as "2003"), using the author's observations to begin her sections 5 and 6 on space exploration and the sustainability approach, respectively.

Moreover, in her 2011 paper to the Mars Society, Reiman (2011) introduces section 1 with the headline quote:

> “Space is a fragile frontier” – Mark Williamson.

She then goes on to quote the author as saying “space is the ‘fragile frontier’ where harm done is often more permanent and more difficult to repair than the harm caused on Earth”, which refers to the author’s point that, in contrast with the Earth, the Moon has no atmosphere, no weather and thus no “ability to repair itself” (Williamson, 2006a, p.105).

Campion’s chapter on ‘The Moral Philosophy of Space Travel’ in Galliott’s 2015 book on ‘Commercial Space Exploration: Ethics, Policy and Governance’ (Campion, 2015) cites the author’s 2003 *Space Policy* paper on ‘Space Ethics and Protection of the Space Environment’ several times. First of all, he uses it to introduce his discussion by quoting the author’s argument that “space demands a somewhat different [ethical] philosophy, based on detailed knowledge of the space environment” (in fact, the author’s name appears no less than six times on his first page). He goes on to use the author’s definition of ethics and analysis of differing viewpoints of the space environment: “Williamson highlighted the core problem of a successful space ethics policy”, he writes, “…how is it possible to persuade people who see space as either empty or dangerous that it needs protecting?”.

Another author to cite the Central Work and the 2003 Space Policy paper in recent years is Newman, who uses the issue of lunar orbital debris and the permanence of surface impacts highlighted by the author (in Williamson, 2006a) to further develop the theme of sustainability in terms of lunar exploration (Newman, 2015a). In his subsequent work on space ethics (Newman, 2015b), he uses the author’s discussion of definitions and advocacy for the development of a code of space ethics to highlight some of the difficulties in establishing an ethical paradigm for space activities; in an apparent reference to the title of the Central Work, he even uses the phrase “how best to protect the fragile environments in space”. Newman (2016) also mentions that “Williamson (2006) and Viikari (2008) both explore the fragility of the extra-terrestrial environment and conclude that human activity has contributed to the degradation of the space environment threatening its sustained use"; as shown above, Viikari herself was heavily influenced by the author's work.

Although academics such as Campion, Newman, Reiman and Viikari appear to be building on the author's work as intended, for some citations the linkages are less clear cut. For example, Henry and Taylor's 2009 contribution to a 'Special Issue' of the Sociological Review Monograph Series on 'Space Travel & Culture' (Henry & Taylor, 2009) uses the Central Work in support of a thesis about space imagery and environmentalism. Citing page 11 of *Space: The Fragile Frontier*, it states: "Mark Williamson posits that 'the most significant legacy of the Space Age is the image of the Earth rising above the surface of the Moon' (although, in fact, the statement was prefaced with the word "perhaps"). Later in the chapter, the author's fragility argument picked up by Reiman is introduced as a route towards a discussion of art as an education tool: "Williamson suggests that this education could 'perhaps tak[e] the line of the 19th century wilderness painters (2006: 257)". However, they then point to an apparent omission: "Williamson does not transfer this potential to space artists, however. Rather he seems to privilege photography over art in raising environmental awareness…Williamson seems both to forget how Bonestell's art captivated the popular imagination and to minimize the effects that space art can have".

So, while recognising that the author includes space art in his book, he is criticised for "not giv[ing] it adequate attention (2006: 274)". It is worth mentioning, in this context, that *Space: The Fragile Frontier* was not a book on the potential of space art and did, in fact, use several examples to depict the space environment (although admittedly preferring to depict the true, rather than imagined, beauty of the space environment through actual photographic images where available). There has been extensive discussion, beyond the purview of the Central Work, regarding the impact of Earthrise upon humanity; see, for example, the work of Cosgrove (1994, 2001) on the legacy of the Apollo space photographs, and Lazier (2011) and Poole (2010) on the impact of Earthrise in particular.

The Central Work has been cited as a convenient source of information on orbital debris, even though it was included only as an introductory topic in the wider discussion of the space environment. In his detailed 2011 paper for the Vanderbilt Journal of Transnational Law, Imburgia (2011) cites chapter 3 of the Central Work extensively throughout, while Hollingsworth (2011) makes a similar use of the text for his Master of Strategic Studies degree thesis, “The Space Debris Crisis: time for an international treaty”.

Further, while it might be expected that a Submitted Work (i.e. Williamson, 2003) could be cited in a book dedicated to space tourism, it is interesting to note citations in two books on *earthbound* tourism: ‘Codes of Ethics in Tourism’ (Fennell & Malloy, 2007) and ‘Introduction to Tourism Transport’ (Gross & Haz, 2014).

Possibly the most surprising citation, however, was one in the Journal of Integrative Agriculture in a paper (Kadim et al, 2015) on ‘Cultured Meat from Muscle Stem Cells’ (section 7: ‘Ethics, public health and animal welfare’) which stated: “Consumers worldwide have a growing interest in food ethics along with animal ethics and the ethics of other human activities (Williamson, 2003)”. The reference section quoted the journal as “Science Policy” rather than “Space Policy”, but the other citation details were correct.

The fact that Williamson 2003 and Williamson 2006a were still being cited in 2015 and 2016 reflects the long-term nature of the subject and its continuing relevance to the space community and, at least to some extent, the academic community beyond. This relevance is evaluated further in the following section.

5.3 Evaluation

The previous subsection has shown that the body of work considered here has had a significant impact within and beyond the space community. However, the ultimate importance of the work and its impact within the professional international space community, which was the target audience, can only be measured in the long term, because protection of the space environment is a long-term goal.

From general observation of society we can see that some types of research have an impact in the short term. For example, if a small town's major employer closes, making hundreds of local workers redundant, it is likely that research into the economic impact will return meaningful results within a year, perhaps sooner. Likewise, media studies research into the influence of a leading popular band or singer on up-and-coming artistes is likely to be able to draw conclusions on impact within two or three years.

On the other hand, the impact of research into new drugs can take at least 10 years, because of the trials required before they are allowed to enter the health system. Moreover, in astronomy and cosmology research, for example, there can be an even longer gap between the initial observations and the acceptance of a theory, because of the high levels of probability required for acceptance in the scientific community.

More specifically in the context of this study, most developments in space technology have a long-term nature: it typically takes three years to build a commercial communications satellite; a government-owned weather or climate satellite can take six or seven years; and US military programmes are renowned for even longer schedules. Solar system exploration spacecraft may take more than a decade to reach their target planet and, although exceptional, the Voyager probes are still operating after nearly 40 years en route to the edge of the solar system.

Missions with human crews are at least as long-term: the US Space Shuttle was in development for about a decade before its first launch, and a promised crew-tended Mars mission is, today, considered to be at least 15 years away. Thus those concerned with space environment protection must take a long-term view, both in gathering data from the 60-year history of space exploration and in casting forward to a time of sustainable development of that environment.

This means that publications in the field tend to have greater longevity, remaining relevant over a longer period than, say, hard scientific or engineering publications, because the issues raised have not been addressed by the community or the technology it develops.

Detractors might ask why one would seek to develop a policy of sustainable development for a lunar mining facility, or a Mars transport hub, when no-one has ventured beyond low Earth orbit since 1972. Indeed, some criticism of the Central Work from the ‘space enthusiast’ end of the space community spectrum, reflecting concern that development might be curtailed before it got a foothold, characterised the protection message as “too early” (Ashworth, 1998).

That said, no difficulties were experienced in publishing the precursor works or the Central Work itself in respected academic fora. Indeed, as implied earlier, the contribution of a foreword to the book by James Van Allen was a part of the peer review process (Van Allen, 2006). Published contributions to the field which followed the Central Work, most notably the co-editorship of a prestigious IAA Cosmic Study (Williamson, 2010a), provided further confirmation of the validity of the research topic.

Perhaps predictably, the impact among the professional space community was not always the intended one, largely because environmental protection – whether on Earth or in space - is viewed by some as a threat to commercial development (Glass, 1998). However, the Central Work was careful to recommend a balance between protection and exploitation of the space environment. Recommendations included setting up an international consultative and, later, regulatory body under the auspices of the United Nations; it would be analogous to the International Telecommunication Union (ITU) which is, effectively, already charged with protection of the ‘frequency-space environment’ (i.e. the radio spectrum).

Beyond citations in academic texts (e.g. Cockell & Horneck, 2014; Viikari, 2008; Newman, 2015), it is difficult to provide evidence that the published works under consideration have influenced members of the space profession who are actually involved in exploring and exploiting space. However, it is possible to detect a cultural change within the broader space community.

The Preface of the Central Work stated at the time of publication: “The protection of the space environment - for the study of and use by successive generations of explorers and developers - is an important concept that has yet to enter the collective consciousness of the space community, let alone the wider terrestrial community” (Williamson, 2006a p. xiii).

Today, this is not the case, as the concept has gained some recognition within the space community. One reason that awareness of space as a fragile environment has improved in recent years is the increase in major debris-creating incidents in LEO mentioned above, but also because of plans for commercial development in space (from mining to tourism).

As stated previously, the debris situation in LEO has been discussed in the space community for several decades; it is the issue most in need of a short-term solution and, because LEO is relatively close to Earth, the easiest solution to provide using existing technology. For this reason, a number of space agencies and private companies are investigating technology demonstrators for satellite servicing (e.g. refuelling to extend life) and debris removal (Werner, 2016). In parallel, the rise of proposals for constellations of various-sized satellites (including so-called nanosats of 1kg or less) has caused some concern about the potential increase in orbital debris. Although there is some indication that the concern will be extended to geostationary orbit, its relative inaccessibility (being further from Earth) means that progress is slower.

In general, however, the language or terminology used with respect to space resources (again, predominantly LEO) has been developing over the past decade or so. Phrases such as ‘space situational awareness’ (which effectively means tracking satellites and debris objects), ‘space traffic management’ (so far restricted to compiling object databases and issuing warnings when two objects get close), and even ‘space sustainability’ (though mainly restricted to the sustainability of LEO satellite systems) are becoming common.

Although further research would be required to confirm the point, it appears that a cultural change is in progress among the space community and that the author’s work is in the vanguard of this change.

Increasingly, symposia and conference sessions are dedicated to sustainability topics; private organisations such as the Secure World Foundation have been founded (ostensibly to promote sustainable development [4]); and, as recently as November 2015, the US Government has passed the Space Resource Exploration and Utilization Act that *inter alia* promotes “the right of U.S. citizens to engage in commercial exploration for and commercial recovery of space resources” (US Govt, 2015). Moreover, the Act’s specific mention of asteroids brought it to the attention of the media (Foust, 2015), because it states that “A U.S. citizen…shall be entitled to any asteroid resource or space resource obtained, including to possess, own, transport, use, and sell it according to applicable law…”.

In addition, a small sample of published news and comment gives a flavour of the relevant topics under discussion in the ‘space press’:

- Quote from US State Department: “There have been subsequent [anti-satellite] tests by China, but none of them have been debris generating. At the State Department, we like to attribute that to the huge international outcry” (Stewart, 2016)
- Article on the lack of regulation for satellites in geostationary orbit: “At last count, there were some 1,400 objects in geostationary orbit, half of them drifting uncontrollably around the arc” (de Selding, 2016)
- Article on commercial lunar exploration: The US Federal Aviation Administration (FAA) is “trying to establish temporary rules to govern private space exploration of…the Moon” (Pulatrov, 2016)
- A call to designate the FAA office of commercial space transportation as “the

[4] Established in 2002 as a privately funded foundation, the Secure World Foundation’s mission statement is “to work with governments, industry, international organizations, and civil society to develop and promote ideas and actions to achieve the secure, sustainable, and peaceful uses of outer space benefiting Earth and all its peoples” [http://swfound.org/about-us/who-we-are/].

lead agency for space traffic management" and regulation (Bridenstine, 2016)

- Article on a UN COPUOS working group on the "Long-Term Sustainability of Outer Space Activities, whose main objectives are to identify areas of concern…propose measures that could enhance sustainability and elaborate a set of guidelines…" (Volynskaya, 2016).

The UN COPUOS working group mentioned in the final example was established under its Scientific and Technical Subcommittee and dates back to work done in 2010. More recently, Leiden University in the Netherlands established The Hague Space Resources Governance Working Group, the first "face-to-face" meeting of which was held in April 2016. The published objective of the Working Group is to "assess the need for a regulatory framework for space resource activities and to prepare the basis for such regulatory framework". Where the need is established, the Working Group will encourage states to "engage in negotiations for an international agreement or non-legally binding instrument" (Leiden University, 2016).

A final example from within the space community is provided by the Joseph P. Loftus Space Sustainability Award, which recognises individuals, organisations and/or institutions that have "championed preservation and sustainability of the space environment for the greater good of the future generation and the whole mankind" (Anz-Meador, 2016). So far, in line with the space community's understandable predilection for orbital debris mitigation, the award has tended to recognise work in this field, but one might expect this to evolve in future.

It appears that the topic of space sustainability and environmental protection has support beyond the space profession: according to the results of the first 'Citizens' Debate on Space for Europe', organised by ESA in November 2016, feedback from the 2000 participants included the conclusion that "84% think space should be protected from polluting and potentially harmful human activities" (ESA, 2016).

It can be seen from the above sample that the topics covered by the Submitted Works are very much of interest and under discussion across a variety of space fora. It is also noteworthy that the work itself remains extant within a professional community that is exhibiting an increased appreciation of sustainability and protection of the space environment, which implies that the conclusions of the work are validated and continue to have relevance. Arguably more important, however, is the fact that a cultural change is in progress which, if successful, will ultimately produce the sustainability of the space environment advocated by the body of published works considered here.

The rationale behind the selection of the works submitted here was explained in subsection 4.1. Any selection is, by definition, a judgement of appropriate material: in this case it involved selecting peer-reviewed works that best portrayed the research journey undertaken while also illustrating coherence as a body of work. This resulted in the consideration of Submitted Works spanning a period from 1997 to 2010, but as previous sections of this commentary have shown, this was undertaken in the context of a larger body of academic work including contributions in space history and space lexicography. Some of this work informed the Submitted Works considered here and some of it was informed by the Submitted Works.

In terms of the Submitted Works alone, it was always intended that the Central Work – 'Space: The Fragile Frontier' (4.3) – should provide a compact summary of the issues of space sustainability and space environment protection. In effect, its publication, in 2006, made this summary available for the space community to consider, critique and develop further; the publication of the Subsequent Works (4.4) was designed to assist this process by further dissemination of the ideas.

In the context of the body of work presented here, one might ask whether part of the submission has been superseded by the work of others. Indeed, one would hope that it *had* been superseded in some ways; otherwise the Submitted Works would represent nothing more than an interesting dead-end. In fact, thankfully, the work has been utilised and extended by academics such as Viikari (2008) in her work on the environmental element in space law and Newman (2015a) in his writings on lunar sustainability (see 5.2 Citation Analysis). More generally, however, the author's work has not been superseded in terms of the development of (i) practical measures to limit debris beyond LEO and (ii) ethical policies of sustainability with regard to operations on the Moon and other planetary bodies. For these reasons, the Submitted Works retain their relevance and originality today.

It is clear that space sustainability is an ongoing issue that deserves further attention from both academics and practitioners. The following section considers the evolution and continuation of the research journey, both for the author and for others**.**

6. Continuing Research

6.1 Towards a Sustainable Policy

For the author, the period of peer-reviewed publication considered here has been followed by a further research phase which has included, inter alia, a period of observation. As such, the author has maintained a 'watching brief' on matters of space sustainability (as portrayed in 5.3) in preparation for the next stage of contribution, while continuing collaboration with academics in related issues.

In the area of telecommunications law, for example, continuing collaboration with a Luxembourg-based co-author of the IAA Cosmic Study (see 4.4) resulted in the author presenting a paper on 'Technical Issues and Empowerment of the ITU' at a workshop on 'International Regulations of Space Communications' in May 2012. This was published the following year as part of a monograph of the same title (Williamson, 2013).

Additional related issues were presented in a paper to a 'Space Risk and Liability' workshop at Durham University in June 2015 entitled 'Space Risks and Satellite Insurance', which is due to be published in a monograph ('Frontiers of Space Risk: Natural Cosmic Hazards & Societal Changes') edited by Richard J Wilman (Durham University) and Christopher J Newman (Sunderland University). Academic works on topics including, but certainly not limited to, the role of the ITU and the function of space insurance are relevant to the space sustainability issue in terms of providing potential solutions (as explained throughout the Central Work).

In parallel, the author has maintained contact with the wider academic community concerned with researching space sustainability issues, engaged in relevant conferences and monitored the work of official bodies - such as the European Space Policy Institute (ESPI) and the United Nations - on space sustainability. One of the suggestions in the Central Work was that an international consultative body should be formed "under the auspices of the United Nations" (Williamson, 2006a pp261-2). Although no direct impact in terms of cause and effect is claimed, it is interesting to note that the United Nations Office for Outer Space Affairs (UNOOSA) has a ‘Working Group on Long Term Sustainability of Outer Space Activities’ which, in June 2016, published the first draft of its ‘Guidelines’ on the subject (UN OOSA, 2016b). As with other UN working groups, contributions are made via so-called National Focal Points, such as space agencies or other government departments. The author has established a link with the Foreign and Commonwealth Office (FCO) in London (along with the UK Permanent Mission to the UN in Vienna) and provided background information and advice which, it is hoped, will influence the guidelines.

In terms of relevant publishing, the author is also collaborating with Christopher Newman of the University of Sunderland on a paper for *Space Policy* journal. This marks the continuing evolution of the author’s body of work in that Newman (see 5.2) is one of the academics influenced by author’s research (having further developed the concept of lunar sustainability in Newman, 2015a) and is now working with the author to develop the issues beyond their current status.

The proposed paper is entitled “Space Sustainability: Reframing the Debate”. It recognises that the term ‘space sustainability’ has risen in prominence within the space community over the past decade, but notes that its applicability has narrowed to a limited part of the space environment: chiefly low Earth orbit (LEO). In other words, ‘space sustainability’ increasingly relates to the future sustainability of government, military and commercial spacecraft operations in LEO and is often closely linked with other phrases such as ‘space situational awareness’, ‘space traffic management’ and ‘space safety’.

While it is considered laudable that issues such as debris mitigation and removal are at last being taken seriously for LEO, and at least considered for higher orbits such as geostationary orbit (GEO), the current debate appears to have become limited to the Earth’s immediate space environment. The proposed paper highlights what is being lost in the debate: consideration of the long-term sustainability of activities and operations in the wider space environment, particularly with reference to the Moon and Mars. Within the next decade or two, if current plans come to fruition, there will be teleoperated rovers, scientific bases and perhaps even space tourists on the

Moon; meanwhile, space entrepreneur Elon Musk has announced plans to establish a colony on Mars (Williamson, 2016).

The long-term nature of the issue is a key consideration. Warnings of a possible ‘collisional cascade effect’ in LEO, known as the Kessler Syndrome, were first aired as long ago as 1978, but it was not until the formation of the Inter-Agency Space Debris Coordination Committee (IADC) in 1993 that guidelines for debris mitigation began to take shape. Significant collisions observed in the past decade have made the Kessler Syndrome seem increasingly plausible, but orbital debris is still being created faster than it can be removed (either naturally or by human intervention).

It is clear that policies need to be agreed well in advance of the utilisation of specific parts of the space environment. The paper seeks to reframe the debate concerning protection of that environment by extending the space sustainability discussion beyond the current pragmatic, but arguably parochial, concerns about Earth orbit.

It is also clear – particularly from a reading of the current UN guidelines - that there is still more work to do in terms of ensuring the sustainable development of the space environment and developing the appropriate policy regime. Research is, therefore, expected to continue.

6.2 Towards an Ethical Policy

While the majority of the body of work considered here supports a pragmatic approach to developing a policy for sustainable development of the space environment – in which pragmatic is an operative word – there is plenty of scope for development of the more theoretical and philosophical aspects of the subject.

One of these aspects is the ethical dimension, discussed initially in the author’s Space Policy paper (Williamson, 2003) and more extensively in chapter 6 of the Central Work (Williamson, 2006a). In terrestrial society, ethical codes are embedded within medicine and various branches of engineering - predominantly because they involve people, their safety and their rights - and are recognised as pragmatic and indispensable components of those ethical codes. This is not currently the case for putative codes of conduct mooted for sustainable development of the space environment, but as humankind extends its operations beyond Earth a body of space ethics will become increasingly important. As the published works show, there have been some attempts to embed an ethical approach into space-related development, but more work needs to be done.

Two areas of academic research that have the potential to influence the ethical dimension of space development are (i) aesthetic and cultural considerations of the space environment and (ii) the extension of the Anthropocene concept beyond the Earth.

6.2.1 Aesthetic and Cultural Considerations

Aesthetics as a discipline has yet to assert itself among the broader space community, arguably because an appreciation of concepts such as beauty, line and form require direct experience…and, so far, direct experience of the space environment has been limited to a cadre of 500 or so spacefarers. However, a number of those travellers have become well known for their aesthetic appreciations: the Russian cosmonaut Alexei Leonov, for example, was the first to draw in space, where he produced a coloured pencil sketch of an orbital sunrise [Stott, 2017]; Apollo astronaut Alan Bean paints pictures of lunar exploration using actual moondust; and the second man to walk on the Moon, Buzz Aldrin, famously described his first impressions of the Moon with the words “magnificent desolation”.

Of course, many others have gained a vicarious appreciation of the aesthetic aspects of the space environment (as described in chapter 6 of the Central Work) and have a keen awareness of its inherent beauty, but the space community as a whole is arguably more concerned with overcoming the difficulties of exploring space and developing its resources than protecting the environment for its own sake. This relates to space ethics by way of the simple definition of that subject proposed by the author (in Williamson, 2002a): “what we should and shouldn’t do in space”; specifically, a mature appreciation of the ‘value’ (both pragmatic and philosophical) of the space environment is required before that question can be sensibly addressed.

Several authors have taken the lack of appreciation of the value of extraterrestrial environments to the extreme in their proposals to terraform Mars (that is make the planet artificially Earth-like); see, for example, McKay, 1990. To many, this well-developed science-fiction scenario is “merely an entertaining thought-experiment [that] may become technically and economically achievable in coming centuries” (McMahon, 2016). On the other hand, the intrinsic beauty of parts of the Martian landscape have been recognised by proposals for a “planetary park” system analogous to the national park entities here on Earth (Cockell & Horneck, 2004). Unfortunately, as McMahon (2016) points out, such recognition would become largely academic if terraforming were to take place, but he believes that future exploration may bring Martian forms of beauty to public consciousness well before terraforming becomes feasible. In terms of aesthetics, he concludes that “Aesthetic responses to Mars will shift unpredictably in the decades and centuries to come, as the planet is transformed from a remote and quasi-mythical space into a familiar, humanly intelligible place - even a home”.

It has already been identified that the published works considered here draw upon the scientific and technical expertise of the author to both balance competing solutions posed by threats to the space environment and evaluate governance mechanisms to protect that delicate environment. It is acknowledged, however, that any discussions regarding the inherent value of any environment, terrestrial or extraterrestrial, should be conducted within the wider discipline of natural cultural and heritage studies and undertaken with due regard to the appropriate academic techniques for identifying and analysing such values.

Although the ‘Ethical Dimension’ chapter in the Central Work provides a starting point for such discussions, an analysis of the issues was not a central aim of the published works. Discussions such as ‘*The cultural landscape of interplanetary space*’ (Gorman, 2005) and broader academic works on identifying intrinsic value in cultural and heritage sites would enhance analysis of cultural values in relation to protection of the space environment (see, for example, Ahmad (2006), Aplin (2007) and Bond & Worthing (2016)). Similarly, the work of Conroy and Peterson (2012), Gratani et al (2016), Mikkelson (2017), and Plumwood (2001) may be useful in augmenting the discussion on the notion of natural values of the space environment.

As stated, such detailed academic analysis requires immersion in the issues of cultural values well beyond the remit of the published works and the expertise of the author. Such works would, however, undoubtedly complement and enhance consideration of the Submitted Works when it comes to the formulation of an ethical policy for sustainable development of the space environment.

6.2.2 The Anthropocene and the Space Environment

Consideration of whether the relatively new concept of the Anthropocene – also known as the ‘Age of Man’ - can be extended beyond the Earth provides another interesting avenue of academic research. Although the word Anthropocene had been used before, it was promoted by atmospheric chemist Paul Crutzen (2002) as recently as 2000 as a new geological epoch characterised by observable chemical, biological and climatic signatures of human activity on the terrestrial environment (Zalasiewicz, 2017). It is, at present, not fully defined and thus not uniformly recognised as distinct from the Holocene epoch (which began about 12,000 years ago) and different authorities consider the Anthropocene to have begun anywhere from the dawn of the industrial revolution to the initiation of nuclear weapons testing in the 1940s.

In essence, the theory asserts that a global layer termed the technosphere – a human-induced development of the biosphere – might exist around the world and might be detectable, for example, in layers of Antarctic ice. To formalise the definition, a globally-identified layer in the rock strata above which the geology changes – colloquially known as the ‘Golden Spike’ – must be identified (Waters et al, 2014). Although the science is in its formative stages, it is hypothesised that markers of the technosphere could include changes in the nitrogen cycle (Galloway & Cowling, 2002); deposits indicating the use of fossil fuels; and a layer showing an increase in the elements plutonium and caesium. As palaeobiologist Jan Zalasiewicz opined on a recent episode of BBC’s Radio 4 programme ‘The Life Scientific’, these indicators are “not yet geology, but will become geology” (Zalasiewicz, 2017).

Geology is, by definition, the study of the origin, structure and composition of the Earth (from the Greek for Earth, ge, which also forms the root of words such as geomorphology, geodesy and geostationary), but it is also customary to extend the concept to the scientific study of other planets and minor bodies rather than invent new terms. One day, lunar geologists may distinguish their studies by referring to selenology and communications satellites serving Mars may be based in areostationary orbit, but for the foreseeable future we are likely to use the recognised, parochial terminology.

Such developments do, however, broach the question of whether a putative Anthropocene will be extended beyond Earth to the space environment. In fact, some authors believe the Anthropocene “cannot be understood without reference to space” (Gorman, 2014), because the Earth is subject to the gravitational and electromagnetic environment of space and because terrestrial technology has already made its mark (on both orbital and frequency space). Indeed, the detection and mapping of the technosphere might be more applicable to the developing discipline of space archaeology than to geology. And although its specific literature and methodologies are necessarily beyond the purview of the works under consideration here, such a discipline may be well positioned to instil an ethic of conservation in future space-based societies (see, for example, Capelotti, 2010; Darrin & O’Leary, 2009; O’Leary & Capelotti, 2015).

In the next millennium, will each of the major planetary bodies in the solar system have its own detectable technosphere? The possibility of this relates directly to considerations of space ethics and the formulation of an ethical policy for sustainable development of the space environment. The issue of what we ‘should and should not do’ in space seems likely to be of interest for the foreseeable future.

6.3 Beyond the Fragile Frontier

As the foregoing subsections indicate, the topics summarised, extended and introduced in the Submitted Works provide the foundations for a wide variety of further academic study. It is clear from an analysis of existing works and current activity that the central topic of space sustainability is most definitely a work in progress (see for example Rathgeber et al, 2010; O'Leary & Capelotti, 2014).

An interesting aspect of this observation is that a broad spectrum of researchers and practitioners are involved, from scientists and engineers to lawyers, policy makers, archaeologists, ethicists and artists. In fact, what is generally termed 'the space community' can potentially include professionals from any discipline – because ultimately the space environment will become an extension of our terrestrial business, domestic and cultural environment.

Indeed, perhaps more than any other subject of interest to humankind, the study, exploration and development of the space environment can benefit from a transdisciplinary approach (see 3.3). By working together in an open-minded and pragmatic fashion, professionals from different disciplines can create something that is more than the sum of their individual bodies of knowledge and secure a sustainable future for the space environment.

7. Conclusions

The body of work presented here is believed to be an original and coherent contribution to the space profession in the general subject areas of space policy and environmental sustainability.

The Submitted Works described in this thesis commentary are centred on a monograph entitled “Space: The Fragile Frontier”, which is the first academic text to draw together the recognised issues of Earth orbital debris and planetary protection, set them in the context of space law and ethical policies, and encourage a balance between desirable expansion into space and protection of the space environment. In essence, it calls for a sustainable and environmentally-friendly approach to space exploration and development (4.3).

This monograph - known here as the Central Work - is supported by a number of peer-reviewed Antecedent Works (4.2) and Subsequent Works (4.4). The research embodied in these peer-reviewed texts was designed to address the question of whether it is possible to establish an optimal balance between expansion of activity in space and protection of the fragile space environment. It did so by investigating existing and potential future threats to the space environment, considering how related legal, ethical and policy-related issues have been addressed by the space community and, ultimately, how the sustainable development of the space environment might be assured.

The research was undertaken using scientific and engineering methodologies to produce a published body of work that is accessible to a wide range of professional readers and also useful for other researchers. As explained in section 3.3, the research also benefitted from the author’s active participation in the professional community, which extended the research element from inherently limited desk-based methods to information collection ‘in the field’, while also allowing the author to make a real-time contribution to the space community.

The section of this commentary on Impact (section 5) shows that the Submitted Works have been widely cited within the space community, and in some cases beyond, and continue to feature in academic publications. Because of the long-term nature of space-related developments, the body of work is expected to guide and influence workers in the field for some time to come.

Looking to the future, the space community is witnessing a shift from government- and established industry-dominated programmes to commercial projects proposed and funded by space entrepreneurs and wealthy individuals in what has come to be known as the ‘NewSpace’ community. For example, in recent years, NASA has transitioned from funding industrial contractors to design and manufacture space shuttles to transport cargo to and from the International Space Station to buying logistics services provided by the space industry. This is expected to be extended to crew delivery and return services in the near future and represents a new paradigm in space development both in and beyond Earth orbit.

Indeed, while some of these new developments feature constellations of relatively small satellites in low Earth orbit, which may one day add to the orbital debris population, others have set their sights at the Moon, Mars and the minor bodies such as asteroids. This evolution makes the call for sustainable development espoused in the Submitted Works increasingly relevant and any future work in the field must continue to address the risks to the environment presented by these projects.

Ideally, as suggested in the Submitted Works, an international consultative body would be formed to consider the relevant issues and raise awareness of the subject among the growing body of space professionals and practitioners. Given that much of the interest in the subject currently resides within the academic sector, there is no reason why this sector should not continue to make an important contribution.

In many ways the issues are long term, but promised developments suggest that time is of the essence. As the closing sentence of *Space: The Fragile Frontier* suggests: “In another 20 years or so – when the second generation of lunar explorers is making footprints on the surface – it might be too late”.

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(NB. References in **bold** are Submitted Works)

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Appendices

Appendix A: Citation Database

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Appendix B: Background Texts (non-Submitted Works)

Progenitor papers, commentaries and magazine articles

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Williamson, M. (1996) 'The Early Development of Space Science Satellites and Planetary Probes', Institution of Electrical Engineers 24th Weekend Meeting of PG S7 (History of Technology), University of York, July 1996

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Williamson, M. (1997) 'Are We Trashing the Solar System?', *Space News* (Commentary), Dec 1-7, 1997, p15

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Williamson, M. (1998) 'Protecting the Space Environment', *Spaceflight* (Into Space), Vol.40, no.4, April 1998, p135

Williamson, M. (1999) 'Planetary Spacecraft Debris – The Case for Protecting the Space Environment', *Earth Space Review* Vol 8 No 3 1999

Williamson, M. (2000) 'Protecting the Space Environment', *Earth Space Review* Vol 9 No 4 2000

Williamson, M. (2006) 'Space: The Fragile Frontier', *Space News* (Commentary) June 26, 2006 p19

Books as sole author:

1990: *The Communications Satellite*, Institute of Physics Publishing
1990: *Dictionary of Space Technology*, Institute of Physics Publishing
2001: *The Cambridge Dictionary of Space Technology*, Cambridge University Press
2006: *Space Technology: The Early Years*, IEE Publishing
2006: *Space: The Fragile Frontier*, AIAA
2007: *50 Years of Space Exploration: A European Perspective*, Maxhill Publishing Ltd
2010: *The Cambridge Dictionary of Space Technology*, CUP (paperback)

Contributions to other texts including:

1988: Chapter 1, ‘Broadcasting by Satellite: Some Technical Considerations’ In Negrine, R. (ed) *Satellite Broadcasting - the Politics and Implications of the New Media*, London: Routledge, pp23-48

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