Contents

Abstract			i
Acknowledgements			ii
Contents			iii
1	Introduction		1-1
	1.1	Space Debris	1-1
		1.1.1 Debris sources and sinks	1-2
	1.2	Debris Environment Characterisation and Modelling	1-4
	1.3	Debris Particle Characteristics	1-5
		1.3.1 Debris size, mass	1-5
		1.3.2 Debris shape	1-5
		1.3.3 Debris Albedo	1-6
1.4	Structure of Thesis		1-8
2.	Topocentric Angular Speed of Space Debris		2-1
	2.1	Topocentric and geocentric angular speed	2-1
	2.2	Observing at the zenith	2-3
		2.2.1 Definition of ω_{top} - general 2D case	2-3
		2.2.2 Extremes of topocentric angular speed	2-5
		2.2.3 Three-dimensional case: i≠0, zenith-looking observatory at latitude L≠0, and circular orbit.	2-7
	2.3	Away from the zenith	2-10
		2.3.1 Trajectory through zenith (2D)	2-10
		2.3.2 Non-Zenith Pass (3D)	2-12
	2.4	Conclusions	2-17
3	Sky Pattern of Space Debris Detectability (“SkyPlot”) – Introduction		3-1
	3.1	Introduction	3-1
	3.2	Code Structure	3-2
	3.3	Program Execution - Overview	3-2
	3.4	Program Execution - In Detail	3-5

3.4.1 Abort Scenarios 3-5
3.4.1.1 Geometric Effects 3-5
3.4.1.2 Twilight Latitudes 3-6
3.4.1.2.1 Twilight Window Calculation 3-6
3.5 Summary 3-10

4 SkyPlot Program Detail 4-1
4.1 Dual Time Increments (Time Steps) 4-1
4.2 Homing 4-4
4.3 Coordinate system 4-5
4.4 Equations of satellite motion 4-6
4.4.1 Orbit terminology 4-6
4.4.2 Position in the orbit 4-7
4.5 Orbital Perturbations 4-9
4.6 Position of Observer 4-11
4.6.1 Geocentric to geodetic alt/az correction 4-14
4.7 Earth Shadow 4-17
4.8 Topocentric Angular Velocity 4-25
4.8.1 Observer velocity 4-25
4.8.2 Geocentric debris velocity 4-26
4.8.3 Topocentric angular velocity 4-27
4.8.4 Topocentric Angular Velocity Binning 4-28
4.9 Solar Motion 4-28
4.10 The Moon 4-28
4.10.1 Sky Brightness due to Moonlight 4-28
4.10.2 Lunar Motion 4-29
4.11 Milky Way 4-31
4.12 Zodiacal Light 4-33
4.13 Refraction 4-33
4.14 Debris Signal-to-Noise Ratio (SNR) 4-35
4.14.1 Debris Flux Calculation 4-36
4.14.1.1 Debris Brightness 4-36
4.14.1.2 Optics transmission 4-38
4.14.1.3 Plate Scale 4-38

4.14.1.4 Streak Image Dimensions 4-38
4.14.1.5 Penumbra Shading 4-41
4.14.2 Galactic and Ecliptic Background 4-41
4.14.3 Night Sky Contribution 4-41
4.14.4 Scattered Moonlight Contribution 4-41
4.14.5 Readout Noise Contribution 4-42
4.15 Summary 4-42

5 SkyPlot Results and Analysis 5-1
5.1 Orbit/Observing Site Selection 5-1
5.2 Orbit Selection 5-2
5.3 Output Description 5-4
5.4 Results 5-5
5.4.1 MIR Orbit Skyplots 5-6
5.4.2 IRIDIUM Constellation Skyplots 5-11
5.4.3 GPS Constellation Skyplots 5-16
5.4.4 Molniya Constellation Skyplots 5-21
5.5 Analysis 5-26
5.5.1 Mir Skyplots 5-26
5.5.2 GPS Skyplots 5-26
5.5.3 Molniya Skyplots 5-28
5.5.4 Iridium Skyplots 5-28
5.5.5 Relative visibility 5-28
5.6 Effect of Debris Size on Skyplots 5-29
5.6.1 Introduction 5-29
5.6.2 Discussion 5-29
5.6.3 Skyplots of Debris of Varying Sizes 5-31
5.6.4 Summary 5-33
5.7 Conclusions 5-33

6 Point Target Detection System for Space Debris 6-1
6.1 Introduction 6-1
6.2 Requirements of such a detection system 6-3
6.2.1 Real Time Response through the FOV 6-3

6.2.2 Highest Sensitivity Possible - Dwell Time 6-5
6.2.3 Determination of Orbital Characteristics 6-6
6.2.3.1 Effects of Errors on Downrange Predictions 6-8
6.3 Herstmonceux Camera System 6-10
6.3.1 Herstmonceux camera system “front end” 6-10
6.3.1.1 Telescope 6-11
6.3.1.2 Camera 6-11
6.3.1.3 Computing equipment available 6-11
6.3.2 Image processing details 6-11
6.3.2.1 Thresholding 6-11
6.3.2.2 Centroiding 6-12
6.3.2.3 Run Length Encoding 6-12
6.3.2.4 Resulting system restrictions 6-12
6.4 Summary 6-12

7 Debris Detection Program Details 7-1
7.1 Program Initial Ideas 7-1
7.2 Program Final Form 7-1
7.3 Search Area & Predicted Position Theory 7-4
7.3.1 Reason for Search Area 7-4
7.3.2 Search Philosophy & Creation Of Active Border 7-5
7.3.3 Search Area Geometry 7-6
7.3.4 Predicted Positions 7-9
7.4 Extra considerations 7-10
7.4.1 Star Background 7-10
7.4.2 Noise (camera/sky - twilight) 7-11
7.5 Implications on minimum height detectable 7-11
7.6 Implementation 7-12
7.6.1 Choice of C over Fortran 7-12
7.6.2 Picture data I/O 7-12
7.6.3 Search Area Scanning 7-13
7.7 Algorithm code 7-15
7.8 Summary 7-15

8 DDT Testing and Image Analysis 8-1
8.1 Static Noise Tests 8-1
8.1.1 Noise Test Results 8-2
8.1.2 Static Noise Test Analysis 8-3
8.2 South Africa Image Testing 8-4
8.2.1 Introduction 8-4
8.2.2 Image manipulation 8-5
8.2.3 Results 8-6
8.3 Minimum Detectable Size of Debris 8-9
8.3.1 Minimum altitude 8-9
8.3.2 Minimum Debris Size 8-10
8.4 Conclusions 8-17

9 Conclusions and Further Suggestions 9-1
9.1 SkyPlot 9-1
9.1.1 Further suggestions 9-1
9.2 Debris Detection (DDT) Program 9-2
9.2.1 Further suggestions 9-3
9.2.1.1 Asteroid detection with the DDT 9-4

Appendix 1: Penumbra Transit Duration, Preliminary Calculation A1-1
A1.1 Introduction A1-1
A1.2 Radial Transit A1-1
A1.3 Tangential Trajectory A1-2

Appendix 2: Volume of Gaussian Curve A2-1

Appendix 3: SkyPlot Code A3-1

Appendix 4: DDT Program Code A4-1

References R-1