Ka Band
Propagation Experiments on the Australian Low Earth Orbit Microsatellite ‘FedSat’

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A Thesis Submitted for the Degree of
Doctor of Philosophy

2008
Certificate of Authorship/Originality

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Sydney, September 2008

________________________
Thorsten Kostulski
Für meine Eltern.
Acknowledgements

There are several organisations and countless people to thank who have supported and accompanied me during the course of my doctoral candidature, and even well before.

I am very grateful for the opportunity to contribute to the challenges of the ‘FedSat’ Mission — a research project otherwise rarely found in a university environment. Therefore, I would like to thank the Australian Cooperative Research Centre for Satellite Systems (CRCSS) for providing me with such a unique research platform with the capability of conducting truly original, experimental space engineering research. It has been a pleasure cooperating with the other CRCSS partners, especially with Mr Terry Kemp from the Operations Control Centre in Adelaide and with CSIRO researchers in Sydney.

However, this involvement in the CRCSS would not have been possible without the trust by the Australian Government (DEST) in my research capacity, by sponsoring me through the 'International Postgraduate Research Scholarship’ at the University of Technology, Sydney (UTS). I express my deep gratitude towards this confidence in my past (and hopefully future) contributions to Australian research.

The UTS Faculty of Engineering has been instrumental in providing an excellent research environment, for example laboratories, equipment, manufacturing support, an extensive computing infrastructure and office space. I would also like to mention the financial support I have received from the Faculty during a difficult period, which is gratefully acknowledged.

It is natural that the greatest contribution to the success of my thesis comes from the principal supervisor, A/Prof Sam Reisenfeld. In this case, the support I have received from him over all those many years, both professionally and personally, goes beyond explanation. Over the past years I have not only benefitted from his profound expertise in satellite systems design, but he has also provided very substantial financial support during my candidature through the CRCSS, despite a difficult budget situation. His qualities as a supervisor are outstanding, and without his subtle, constant motivation, encouragement and commitment of his time to me – especially before submission – this goal would have been much harder to achieve. I am sincerely grateful for that, Sam!
Going back to 1999, I first came to UTS as an undergraduate student when I participated in the exchange program between UTS and the University of Applied Sciences and Research, Aachen, Germany. That year changed my life fundamentally and clearly laid the foundations for my continued work with UTS, culminating in today’s achievement. I would like to thank the staff of the International Office (UAS Aachen), particularly the Director, Mr T. Lex, as well as Prof M. Trautwein and Prof P.M. Schoedon from the Faculty of Electrical Engineering and Information Technology for their flexibility and tremendous support for my aspirations.

Dealing with the many practical and experimental aspects of the thesis would have been unthinkable without the much earlier dedication of a few amateur radio enthusiasts, many of them with a notable background in radio frequency engineering. During my high school years, they had already recognised my interest in electronics, became my mentors and taught me countless lessons of theory and practical experimentation, resulting in my amateur radio licences DL1BF and VK2BF. People to thank in particular are Mr Horst Jackisch (DL1BQ), Mr Rolf Steins (DL1BBC), Mr Ullrich Piggen (DF3BU) and Mr Manfred van Kampen (DH5BAL).

In the absence of family, I was lucky to be cheered up and encouraged by a large circle of reliable friends in Australia. There are too many names to mention, but you all know who you are and how much I value your company. I would especially like to point out the close friendship with Heinz von Hollander, Dr Peter West and Minnie Fabiansson over all those years. However, the main reason for my persistence has been the tremendous understanding and moral support by my partner Lam Ly. A big thanks to all of you!

Finally, my parents, Martin and Christine, deserve great respect for their support of my chosen personal and professional ambitions, but I know very well that my absence from home has never been easy for them. I can always count on your unconditional love and support, especially under difficult circumstances. I regret we have rarely seen each other during the candidature, but the circumstances may change in future. My dedication of this thesis to you is just a small sign of my gratitude for what you have sacrificed for my education and wellbeing over so many years.

Thorsten Kostulski, September 2008.
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Nomenclature

Roman Symbols

- $A$: Attenuation
- $a_E$: Equatorial Earth Radius
- $c$: Speed of Light
- $C/N$: Carrier-to-Noise Ratio
- $D$: Antenna Reflector Diameter
- $d$: Distance
- $dB$: Decibel
- $dBm$: Decibels of Milliwatts
- $dBZ$: Decibels of $Z$
- $e_E$: Earth Eccentricity
- $El$: Elevation
- $f$: Frequency
- $G$: Gain
- $GHz$: Gigahertz
- $h$: Hour, Satellite height above Sea Level
- $H_0$: Earth Station Height above Sea Level
- $H_E$: Rain Height above Sea Level
- $hPa$: Hectopascal
NOMENCLATURE

\begin{itemize}
\item \textit{Hz} Hertz
\item \textit{K} Kelvin
\item \textit{k} Regression coefficient, Boltzmann’s Constant
\item \textit{kHz} Kilohertz
\item \textit{km} Kilometres
\item \textit{L} Loss, Attenuation
\item \textit{Lat} Latitude
\item \textit{Lon} Longitude
\item \textit{M} Link Margin
\item \textit{m} Metres
\item \textit{MHz} Megahertz
\item \textit{min} Minutes
\item \textit{P} Transmit Power
\item \textit{P_n} Polynomial Coefficient
\item \textit{R} Vector from the Centre of the Earth
\item \textit{R_{0.01}} Rainfall Rate for 0.01\% Probability
\item \textit{s} Seconds
\item \textit{SSP} Sub-Satellite Point
\item \textit{V} Volts
\item \textit{v} Velocity
\item \textit{W} Watts
\item \textit{X} X-axis (pedestal)
\item \textit{Y} Y-axis (pedestal)
\item \textit{Z} Reflectivity Unit (in \(\mu m^3\))
\end{itemize}
Greek Symbols

\( \alpha \)  
Elevation, General Angle

\( \epsilon \)  
Angular Error

\( \gamma_R \)  
Specific Attenuation

\( \lambda \)  
Wavelength

\( \varphi \)  
Compensation Angle, Feed Offset Angle

\( \rho \)  
Vector between Earth Station and Satellite, Water Vapour Density

\( \theta \)  
Tracking Pedestal Angle, Squint Angle

Subscripts

\( d \)  
Downlink

\( ES \)  
Earth Station

\( H \)  
Horizon

\( Lat \)  
Latitude

\( Lon \)  
Longitude

\( M \)  
Motor

\( P \)  
Position

\( Rx \)  
Receive

\( S \)  
Satellite

\( tot \)  
Total, Overall

\( Tx \)  
Transmit

\( u \)  
Uplink

\( Z \)  
Zenith

Other Symbols

\( ^\circ \)  
Degrees
### NOMENCLATURE

#### Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>ACS</td>
<td>Attitude Control System</td>
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<tr>
<td>ACTS</td>
<td>Advanced Communication Technologies Satellite</td>
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<td>ADAM</td>
<td>Advanced Data and Messaging</td>
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<td>ADC</td>
<td>Analog-to-Digital Converter</td>
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<tr>
<td>ADEOS</td>
<td>Advanced Earth Observation Satellite</td>
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<td>AEDST</td>
<td>Australian Eastern Daylight Savings Time</td>
</tr>
<tr>
<td>AEST</td>
<td>Australian Eastern Standard Time</td>
</tr>
<tr>
<td>AMSL</td>
<td>Above Mean Sea Level</td>
</tr>
<tr>
<td>AOS</td>
<td>Acquisition of Signal</td>
</tr>
<tr>
<td>AWGN</td>
<td>Additive White Gaussian Noise</td>
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<tr>
<td>AWM</td>
<td>Average-Worst-Month</td>
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<td>BBP</td>
<td>Baseband Processor</td>
</tr>
<tr>
<td>BOM</td>
<td>Bureau of Meteorology (Australia)</td>
</tr>
<tr>
<td>bps</td>
<td>bits per second</td>
</tr>
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<td>BTU</td>
<td>British Thermal Units</td>
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<td>C band</td>
<td>4-8 GHz frequency band</td>
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<tr>
<td>CDF</td>
<td>Cumulative Density Function</td>
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<td>CDMA</td>
<td>Code Division Multiple Access</td>
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<tr>
<td>COTS</td>
<td>Component off-the-shelf</td>
</tr>
<tr>
<td>CP</td>
<td>Communications Payload</td>
</tr>
<tr>
<td>CRC</td>
<td>Cooperative Research Centre</td>
</tr>
<tr>
<td>CRCSS</td>
<td>Cooperative Research Centre for Satellite Systems</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
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<tr>
<td>---------</td>
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<tr>
<td>CSIRO</td>
<td>Commonwealth Scientific and Industrial Research Organisation</td>
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<td>DAC</td>
<td>Digital-to-Analog Converter</td>
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<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DDS</td>
<td>Direct Digital Synthesizer</td>
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<td>DHS</td>
<td>Data Handling System</td>
</tr>
<tr>
<td>DL</td>
<td>Downlink</td>
</tr>
<tr>
<td>DPLL</td>
<td>Digital Phase Locked Loop</td>
</tr>
<tr>
<td>DSP</td>
<td>Digital Signal Processor</td>
</tr>
<tr>
<td>FedSat</td>
<td>Federation Satellite</td>
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<tr>
<td>FPGA</td>
<td>Field-Programmable Gate Array</td>
</tr>
<tr>
<td>GEO</td>
<td>Geostationary Earth Orbit</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
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<tr>
<td>GSM</td>
<td>Global System for Mobile Communications</td>
</tr>
<tr>
<td>HF</td>
<td>Frequency band below 0.1 GHz</td>
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<tr>
<td>HPA</td>
<td>High Power Amplifier</td>
</tr>
<tr>
<td>HPCE</td>
<td>High Performance Computing Experiment</td>
</tr>
<tr>
<td>IF</td>
<td>Intermediate Frequency</td>
</tr>
<tr>
<td>IJK</td>
<td>Inertial Coordinate System</td>
</tr>
<tr>
<td>IST</td>
<td>Integrated Systems Test</td>
</tr>
<tr>
<td>ITR</td>
<td>Institute for Telecommunications Research, Adelaide</td>
</tr>
<tr>
<td>ITU</td>
<td>International Telecommunications Union</td>
</tr>
<tr>
<td>JAXA</td>
<td>Japan Aerospace Exploration Agency</td>
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<td>JPL</td>
<td>Jet Propulsion Laboratory, USA</td>
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<td><strong>Ka band</strong></td>
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<td><strong>Ku band</strong></td>
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<td><strong>L band</strong></td>
<td>1-2 GHz frequency band</td>
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<td><strong>LCP</strong></td>
<td>Left-Hand Circular Polarisation</td>
</tr>
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<td><strong>LEO</strong></td>
<td>Low-Earth Orbit</td>
</tr>
<tr>
<td><strong>LNA</strong></td>
<td>Low Noise Amplifier</td>
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<tr>
<td><strong>LO</strong></td>
<td>Local Oscillator</td>
</tr>
<tr>
<td><strong>LOS</strong></td>
<td>Loss of Signal</td>
</tr>
<tr>
<td><strong>MEO</strong></td>
<td>Medium-earth orbit</td>
</tr>
<tr>
<td><strong>MMIC</strong></td>
<td>Monolithic Microwave Integrated Circuit</td>
</tr>
<tr>
<td><strong>MPA</strong></td>
<td>Medium-Power Amplifier</td>
</tr>
<tr>
<td><strong>N</strong></td>
<td>Coaxial RF Connector (up to 11 GHz)</td>
</tr>
<tr>
<td><strong>NASA</strong></td>
<td>National Aeronautics and Space Administration</td>
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<td><strong>NASDA</strong></td>
<td>National Space Development Agency</td>
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<td><strong>NCU</strong></td>
<td>National Central University</td>
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<td><strong>NewMag</strong></td>
<td>Name of the Magnetometer Experiment onboard FedSat</td>
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<td>Nanyang Technological University</td>
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<td><strong>OSCAR</strong></td>
<td>Orbital Satellite Carrying Amateur Radio</td>
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<tr>
<td><strong>PCI</strong></td>
<td>Peripheral Component Interconnect</td>
</tr>
<tr>
<td><strong>PCS</strong></td>
<td>Power Conditioning System</td>
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<tr>
<td><strong>PDF</strong></td>
<td>Probability Density Function</td>
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<tr>
<td><strong>PID</strong></td>
<td>Proportional-Integral-Derivative</td>
</tr>
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<td><strong>PLL</strong></td>
<td>Phase Locked Loop</td>
</tr>
<tr>
<td><strong>PWM</strong></td>
<td>Pulse-Width Modulation</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Definition</td>
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<tr>
<td><strong>Q band</strong></td>
<td>36-46 GHz frequency band</td>
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<td><strong>QAM</strong></td>
<td>Quadrature Amplitude Modulation</td>
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<tr>
<td><strong>QPSK</strong></td>
<td>Quadrature Phase Shift Keying</td>
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<td><strong>QUT</strong></td>
<td>Queensland University of Technology</td>
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<td><strong>RCP</strong></td>
<td>Right-Hand Circular Polarisation</td>
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<tr>
<td><strong>RF</strong></td>
<td>Radio Frequency</td>
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<tr>
<td><strong>ROCSAT</strong></td>
<td>Republic Of China Satellite</td>
</tr>
<tr>
<td><strong>rpm</strong></td>
<td>Revolutions per minute</td>
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<tr>
<td><strong>S band</strong></td>
<td>2-4 GHz frequency band</td>
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<tr>
<td><strong>SEZ</strong></td>
<td>Topocentric Horizon Coordinate System</td>
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<td><strong>SGP4</strong></td>
<td>Simplified General Perturbations Satellite Orbit Model 4</td>
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<td><strong>SIL</strong></td>
<td>Space Innovations Ltd.</td>
</tr>
<tr>
<td><strong>SNR</strong></td>
<td>Signal-to-Noise Ratio</td>
</tr>
<tr>
<td><strong>STRAP</strong></td>
<td>Satellite Transmission Rain Attenuation Project</td>
</tr>
<tr>
<td><strong>TDM</strong></td>
<td>Time-division Multiplex</td>
</tr>
<tr>
<td><strong>TDMA</strong></td>
<td>Time-division Multiple Access</td>
</tr>
<tr>
<td><strong>TIP</strong></td>
<td>Telecommunications and Industrial Physics</td>
</tr>
<tr>
<td><strong>TLE</strong></td>
<td>Two-Line Elements</td>
</tr>
<tr>
<td><strong>TT&amp;C</strong></td>
<td>Telemetry, Tracking and Control</td>
</tr>
<tr>
<td><strong>UHF</strong></td>
<td>0.3-1 GHz frequency band</td>
</tr>
<tr>
<td><strong>UL</strong></td>
<td>Uplink</td>
</tr>
<tr>
<td><strong>UTC</strong></td>
<td>Universal Time Coordinated</td>
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<tr>
<td><strong>V band</strong></td>
<td>46-56 GHz frequency band</td>
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<tr>
<td>WR28</td>
<td>Waveguide Size (26.5-40 GHz)</td>
</tr>
<tr>
<td>WR42</td>
<td>Waveguide Size (18-26.5 GHz)</td>
</tr>
<tr>
<td>WRESAT</td>
<td>Weapons Research Establishment Satellite</td>
</tr>
<tr>
<td>X band</td>
<td>8-12 GHz frequency band</td>
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Abstract

The emergence of the 20/30 GHz Ka band in satellite communications in recent decades has seen systems designers faced with the problem of severe signal attenuation though atmospheric effects, especially rain. Previous experimental missions, such as ACTS and OLYMPUS, have succeeded in collecting large amounts of propagation data, which has led to the development of various semi-empirical models for link design. However, all these experiments were carried out over geostationary satellites, and with a recent tendency towards constellations of low-earth orbit satellites for true global coverage and increased system capacity for real-time services, these models are in need of adaptation for variable elevation angles and the effects of rapid satellite movement.

The work contained in this largely experimental thesis presents the Australian ‘FedSat’ LEO microsatellite, carrying a Ka band beacon and a bent-pipe mode transponder, as an ideal research platform for such investigations. The in-house design, deployment and operation of a very low-cost, fast-tracking earth station is examined in-depth, and particular attention is paid to systems design aspects involving numerous hardware and software technologies, which interact with each other in a highly complex manner, for example Doppler frequency tracking, pointing accuracy control and precise signal power measurements. Prior to and during the operational phase, several crucial design improvements are discussed, implemented and verified. Successful and reliable tracking by using pointing coordinates derived from two-line elements, as opposed to GPS data, is experimentally proven.

The design of the earth station prototype is validated by the collection of Ka band propagation data in both beacon and bent pipe modes. After post-processing of the data, attenuation results for various weather conditions and down to elevation angles well below 10° are illustrated and interpreted in conjunction with the prevailing weather conditions. While a comparison with the measurements from geostationary satellites widely confirms the validity of the
results, other interesting phenomena are unveiled that require further investigation. In particular, the extent of low-angle scintillation appears to be wider band than previously reported in published literature, which is a potentially important finding.

Finally, the experience gathered during the late-stage design and the operation of the earth station gives rise to several recommendations for further design improvements and operational strategies, which may be helpful for future research groups in this field wishing to conduct similar LEO Ka band propagation experiments on a low budget.