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

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Doctor of Philosophy

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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.

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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

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

Greek Symbols

α	Elevation, General Angle
ϵ	Angular Error
γ_R	Specific Attenuation
λ	Wavelength
φ	Compensation Angle, Feed Offset Angle
ρ	Vector between Earth Station and Satellite, Water Vapour Density
θ	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

Acronyms

AC	Alternating Current
ACS	Attitude Control System
ACTS	Advanced Communication Technologies Satellite
ADAM	Advanced Data and Messaging
ADC	Analog-to-Digital Converter
ADEOS	Advanced Earth Observation Satellite
AEDST	Australian Eastern Daylight Savings Time
AEST	Australian Eastern Standard Time
AMSL	Above Mean Sea Level
AOS	Acquisition of Signal
AWGN	Additive White Gaussian Noise
AWM	Average-Worst-Month
BBP	Baseband Processor
BOM	Bureau of Meteorology (Australia)
bps	bits per second
BTU	British Thermal Units
C band	4-8 GHz frequency band
CDF	Cumulative Density Function
CDMA	Code Division Multiple Access
COTS	Component off-the-shelf
CP	Communications Payload
CRC	Cooperative Research Centre
CRCSS	Cooperative Research Centre for Satellite Systems

CSIRO	Commonwealth Scientific and Industrial Research Organisation
DAC	Digital-to-Analog Converter
DC	Direct Current
DDS	Direct Digital Synthesizer
DHS	Data Handling System
DL	Downlink
DPLL	Digital Phase Locked Loop
DSP	Digital Signal Processor
FedSat	Federation Satellite
FPGA	Field-Programmable Gate Array
GEO	Geostationary Earth Orbit
GPS	Global Positioning System
GSM	Global System for Mobile Communications
HF	Frequency band below 0.1 GHz
HPA	High Power Amplifier
HPCE	High Performance Computing Experiment
IF	Intermediate Frequency
IJK	Inertial Coordinate System
IST	Integrated Systems Test
ITR	Institute for Telecommunications Research, Adelaide
ITU	International Telecommunications Union
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory, USA
K band	18-24 GHz frequency band

NOMENCLATURE

Ka band	24-36 GHz frequency band
Ku band	12-18 GHz frequency band
L band	1-2 GHz frequency band
LCP	Left-Hand Circular Polarisation
LEO	Low-Earth Orbit
LNA	Low Noise Amplifier
LO	Local Oscillator
LOS	Loss of Signal
MEO	Medium-earth orbit
MMIC	Monolithic Microwave Integrated Circuit
MPA	Medium-Power Amplifier
N	Coaxial RF Connector (up to 11 GHz)
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency
NCU	National Central University
NewMag	Name of the Magnetometer Experiment onboard FedSat
NTU	Nanyang Technological University
OSCAR	Orbital Satellite Carrying Amateur Radio
PCI	Peripheral Component Interconnect
PCS	Power Conditioning System
PDF	Probability Density Function
PID	Proportional-Integral-Derivative
PLL	Phase Locked Loop
PWM	Pulse-Width Modulation

Q band	36-46 GHz frequency band
QAM	Quadrature Amplitude Modulation
$QPSK$	Quadrature Phase Shift Keying
QUT	Queensland University of Technology
RCP	Right-Hand Circular Polarisation
RF	Radio Frequency
$ROCSAT$	Republic Of China Satellite
rpm	Revolutions per minute
S band	2-4 GHz frequency band
SEZ	Topocentric Horizon Coordinate System
$SGP4$	Simplified General Perturbations Satellite Orbit Model 4
SIL	Space Innovations Ltd.
SNR	Signal-to-Noise Ratio
$STRAP$	Satellite Transmission Rain Attenuation Project
TDM	Time-division Multiplex
$TDMA$	Time-division Multiple Access
TIP	Telecommunications and Industrial Physics
TLE	Two-Line Elements
TT&C	Telemetry, Tracking and Control
UHF	0.3-1 GHz frequency band
UL	Uplink
UTC	Universal Time Coordinated
V band	46-56 GHz frequency band
VHF	0.1-0.3 GHz frequency band

$WR28$	Waveguide Size (26.5-40 GHz)
$WR42$	Waveguide Size (18-26.5 GHz)
$WRESAT$	Weapons Research Establishment Satellite
X band	8-12 GHz frequency band

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.