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Optimization of a Global Network for Satellite Operations

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Unterschrift

Kurzfassung

Seit mehr als einem Jahrzehnt stellt der nichtkommerzielle Weltraumflug eine stark wachsende Disziplin dar. Die Technologie der Kleinstsatelliten erlaubt Universitäten und anderen akademischen Einrichtungen die Konstruktion, den Start und den Betrieb kostengünstiger Satelliten für eine Vielzahl unterschiedlicher Forschungsaufgaben. Um das Volumen der vom Satelliten transferierbaren Daten zu erhöhen werden Netzwerke entwickelt, welche Bodenstationen an verschiedenen geographischen Positionen miteinander verbinden und dadurch das Zeitfenster zur Kommunikation zwischen Boden und Satelliten vergrößern.

Diese Dissertation konzentriert sich auf die Optimierung großer Bodenkontrollstationsnetzwerke, inbesondere des "Global Educational Network for Satellite Operations" (GENSO), welches von ESA, NASA und JAXA koordiniert wird, durch die Vorhersage der Qualität zukünftiger Satellitenkommunikationsvorgänge als Planungskriterium. Hierfür wurde ein neuartiger Ansatz gewählt, welcher Methoden des maschinellen Lernens dazu verwendet, den Einfluss von mehr als 25 verschiedenen Umweltfaktoren auf die Qualität von Satellitenlinks zu analysieren. Das dadurch gewonnene Vorhersagemodell ermöglicht erstmals den Ansatz von Qualitätssicherung bei nichtkommerzieller Satellitenkommunikation.

Da es bisher keine Methoden zur Messung von Satellitenlinkqualität unter Verwendung der im akademischen Umfeld eingesetzten Kommunikationshardware gegeben hat, wurde im Zuge dieser Dissertation eine neuartige Methode entwickelt, um Messungen auch trotz unterschiedlicher Hardwarevoraussetzungen miteinander vergleichbar zu machen. Des weiteren wird mit Hilfe der entwickelten Methodik das wissenschaftliche Potential und die neu entstandenen Möglichkeiten zur Auswertung weltweit verteilter Qualitätsmessungen aufgezeigt und diskutiert.

Um die durch Hardwarelimitierungen vorhandenen Einschränkungen bei der Messpräzision aufzuheben, wird ein Kleinstsatellit für die hochgenaue Determinierung der Sende- und Empfangsqualität von Bodenstationen vorgestellt. Dieser Satellit eröffnet neuartige Möglichkeiten zur Ermittlung der Bitfehlerrate für Satellitenlinks in nichtkommerziell genutzten Frequenzbändern und schafft dadurch die Basis für eine Forschung mit hochpräzisen Signalqualitätsmessungen.

Um das Optimierungspotential angewandter Linkqualitätsvorhersagen evaluieren zu können, wird ein neuartiger Algorithmus zur Satellitenkommunikationsplanung präsentiert, welcher in ein speziell entwickeltes Simulations-Framework eingebettet ist. Die Simulationen bestätigen den starken Anstieg der kommunizierbaren Datenvolumina mit erdnahen Satelliten unter Einsatz von Bodenstationsnetzwerken. Darüber hinaus kann ein signifikanter Anstieg im möglichen Datentransfervolumen nachgewiesen werden, wenn das neu entwickelte Qualitätsvorhersagemodell zum Einsatz kommt.

Die vorgestellte Forschungsarbeit optimiert großangelegte Bodenkontrollstationsnetzwerke und infolgedessen auch das mögliche Datentransfervolumen von und zu nichtkommerziellen Satelliten. Diese Arbeit demonstriert daher nicht nur das große wissenschaftliche Potential derartiger Netzwerke, sondern verifiziert und erhöht auch deren maßgeblichen Anteil am Erfolg heutiger und zukünftiger Weltraummissionen.

Abstract

Non-commercial space-flight is an emerging discipline for more than one decade. Small satellite technology allows universities and other institutions to construct, deploy, and operate low-cost satellites for manifold educational and research purposes. In order to raise the data return of academic space missions, ground station networks have been developed. Its purpose is to interconnect satellite ground stations on different geographical locations and thereby extend the communication duration between ground and space.

This thesis focuses on the optimization of large-scale ground station networks, especially the Global Educational Network for Satellite Operations (GENSO) supervised by ESA, NASA, and JAXA, by applying satellite radio link quality prediction. A novel approach utilizing machine learning techniques to identify correlations between radio channel quality and 25 different features covering both surface and space weather is presented. The developed prediction model enables the provision of communication quality assurance for non-commercial space missions.

As no research on measuring satellite link quality using amateur radio ground station hardware has been performed prior to this thesis, a novel methodology is presented to collect and compare such measurements in heterogenous ground station hardware environments. Furthermore, the scientific potential and the novel possibilities of global satellite link sensing by aggregating the data from several nodes of a ground station network are identified and discussed.

Although the passive measurements collected using the developed methodology are sufficient for the investigations performed in this thesis, their precision is limited by hardware constraints preventing further model refinements. In order to compensate these limitations, a small satellite for active, high-precise link quality measurements is presented. The proposed satellite offers a novel possibility to estimate bit error rates in both transmission directions for academic satellite communication links and allows for a manifold of new investigations based on fine-grained quality measurements.

In order to evaluate the optimization possibilities when applying link quality prediction to large-scale ground station networks, a novel satellite range scheduling algorithm and simulation framework is presented. The simulations performed verify the strong gain in mission data return when establishing ground station networks for academic missions in general and especially the significant increase of data return when applying radio channel quality prediction to satellite range scheduling.

The research work presented in this thesis significantly optimizes large-scale ground station networks and consequently improves the data return from non-commercial satellites. This thesis not only demonstrates the strong scientific potential of these networks but also verifies and increases their huge impact on current and future academic space missions.

Acknowledgements

I would like to thank Lars Mehnen for his outstanding supervision at all phases of my thesis and for introducing me to the fascinating domain of space sciences. Without him and his catching enthusiasm I would have never get the chance to participate an ESA project nor meet all the great people working voluntarily for getting ideas into space! I'd also like to thank Prof. Frank Rattay for his unprecedented support during my thesis and for always being there and helping. I also thank Prof. Jens Frederik Dalsgaard Nielsen from Aalborg University who invited me to his department and supervised my research stay abroad. His support exceeded by far what I've anticipated. I particularly thank Sebastian Krinninger who has significantly supported my research work and is still a very active part in our team. Furthermore I thank Kresten Kjær Sørensen and the whole AAU-SAT II team for providing knowledge and support and last but not least the measurements being fundamental for this thesis. I'd also like to express my gratitude to the whole GENSO team, especially to Neil Melville from ESA, Phil Beavis from VEGA, and Ivo Klinkert, Graham Shirville, Dave Johnson, and John Rivett from AMSAT-UK. I also thank Thomas Scheller and Markus Karolus for their great support and development work on the Vienna part of GENSO. I especially want to say thank you to Martina, who is always there, no matter which daytime it is or which problems I have. She is my greatest support in all aspects. And I'd also like to thank my family for their tireless support and for always being there. Thank you!

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Contents

Chapter 1

Introduction

Over the last decade academic space-flight became more and more popular as a tool for research and space education. Driven by miniaturization and global knowledge exchange, satellite technology was drastically downsized enabling academic institutions to launch low-budget satellite projects. Discovering the various advantages of micro-satellites led to a rapidly growing industry focusing on this emerging market. But long before universities and other academic institutions started to develop and launch their own spacecrafts, radio amateurs already deployed and operated their own radio relay stations in orbit.

As amateur radio communication bands are free of charge and the technology used has matured for years, universities operate their spacecrafts in the same bands using the same technology as radio amateurs. As a consequence thousands of amateur ground stations all over the world can communicate with and downlink data from spacecrafts launched for educational and research purposes.

This kind of distributed downlink becomes more and more important as the amount of collected data increases continuously as technology advances, but the communication bandwidths drag behind. To resolve this bottleneck, radio amateur and university ground stations are becoming interconnected by ground station networks.

1.1 Research Objectives

This thesis focuses on the optimization of global satellite ground station networks, especially the non-commercial Global Educational Network for Satellite Operations (GENSO). Global ground station networks are a novel appearance in the last couple of years whereas no network has yet exceeded a couple of interconnected ground stations on a limited geographical area. GENSO is the first approach supported by all major space agencies (NASA, ESA, JAXA, and others) and is projected to be released in spring 2010. The medium-term intention of GENSO is to interconnect one hundred globally distributed ground stations and more than 20 non-commercial space missions.

When interconnecting several ground stations in order to track one or more satellites, communication conflict avoidance is a requirement, otherwise the satellite would become inoperable and the ground stations unusable. Large-scale ground station networks require a specific approach on satellite range scheduling, as usually more than one satellite is in the range of one ground station and one satellite is in the range of more than one ground station. Additionally, scientific and, especially, educational space missions have a limited power budget compared to large, commercial satellites. As a consequence the communication time of a satellite is limited and onboard power shall be preserved, adding requirements to the scheduling algorithm and other kinds of optimization.

When having additional information about satellite passes in advance, especially their communication link quality, weak passes can be filtered out and passes promising a high amount of data receivable can be prioritized. As the discipline of ground station network optimization is very young, the topic of link quality assurance and prediction has never been investigated yet in this context. Additionally, the determination and comparison of link quality has never been scientifically evaluated. When aggregating precise satellite link quality information with environmental data like surface and space weather, their correlations and interdependencies can be studied. Compared to traditional link budget calculations as used in communication engineering, an approach using machine learning methods for model derivation allows for consideration of all kinds of environmental and other data and the determination of their specific impact on link quality.

By predicting the link quality of a future satellite pass and having a scheduling system considering this information, the optimization potential on the overall mission return in large-scale ground station networks can be investigated.

1.2 Outline

The emerging field of satellite ground station networks and their optimization offers a huge potential for scientific investigations. As a consequence this thesis focuses on one specific topic. Whereas a complex hybrid peer-to-peer network can be optimized in various aspects, this thesis investigates the aspect of satellite link quality prediction and its impact on non-commercial space missions. As the coordination of heterogenous ground stations using a hardware setup of different vendors is a young area of research, this work may be considered as the first of its kind in the field of global ground station network optimization.

In order to enable research on link quality, a comparable and sufficiently precise link quality metric for non-commercial missions is identified. This constitutes the foundation for measurement collection and analysis.

A dedicated link quality metric enables the automated evaluation of quality measurements which in turn allows for advanced investigations. Using a standard radio amateur ground station and a CubeSat satellite deployed in orbit, a sufficient amount of measurements is collected using the developed measurement method. Measurement evaluation possibilities are investigated and possible application scenarios are developed. Afterwards, environmental data possibly influencing satellite links like space weather, surface weather, astronomical conditions, and others are collected from external data sources and aggregated in order to derive a precise link quality prediction model using both machine learning classification and regression. Based on the research results on link quality evaluation, a measurement instrument is proposed for actively measuring high-precise link quality information for future research.

Finally, a simulation framework is designed and developed for the evaluation of the optimization potential of ground station networks. Especially the impact of satellite link quality prediction on the optimization of large-scale ground station networks is inspected. For this purpose a novel scheduling algorithm is proposed and benchmarked.

1.3 Overview

Chapter 2 introduces the reader to the history of non-commercial space-fight and provides a decent background of the ground and space segment as well as satellite communication. Chapter 3 (cf. [Preindl et al., 2008]) describes the Global Education Network for Satellite Operations in detail. In chapter 4 (cf. [Preindl et al., 2010a]) the determination and comparability of link quality is discussed, chapter 5 (cf.[Preindl et al., 2009d]) discusses the possibilities of large-scale ground station networks based on the investigations in chapter 4. Chapter 6 (cf. [Preindl et al., 2009b], [Krinnigner et al., 2010]) aggregates the previous investigations and applies methods of machine learning to develop a novel satellite link quality prediction model. In order to enhance the precision of the prediction model, chapter 7 (cf. [Preindl et al., 2009c], [Preindl et al., 2009a]) provides the feasibility study of an orbital measurement instrument for gaining high-precise link quality information. Chapter 8 (cf. [Preindl et al., 2010b]) describes a sophisticated scheduling and simulation framework for mission return optimization aggregating the previous investigations on satellite link quality and large-scale ground station networks.

Appendix A is a survey of support vector machines in space applications, appendix B provides the implementation of an AX.25 packet decoder, appendix C provides detailed measurements of the radio equipment used for collecting link quality data and D explains the data format used for storing the measurements.

Chapter 2

Small Satellite Operations

The following chapter provides a decent introduction into the basics of both the space and ground segment and satellite communication in non-commercial environments. Practically, non-commercial missions in space differ from commercial ones in the same orbit height by their goals, the used hardware, and the used communication frequencies. Hence, all theories and fundamentals applying for non-commercial missions in space are also true for commercial missions. As a consequence the optimization of amateur, educational and other academic missions and their operation can also be applied to commercial missions when keeping in mind that the optimization goals may differ.

2.1 History of Non-Commercial Space Missions

Non-commercial space flight is not as new as the CubeSat standard introduced in 1999 (see section 2.2), on the contrary, amateur space missions have been launched into orbit since the early 1960's. From the wish of radio amateurs of using orbiting satellites as communication relays for Citizens' Band radio (CB)[Durkin, 1982] the Amateur Satellite Radio community (AMSAT) has been founded [Baker and Jansson, 1994].

The first satellite designed, constructed and operated by radio amateurs was Orbiting Satellite Carrying Amateur Radio (OSCAR) 1 and has been launched in 1961. Figure 2.1 illustrates the simplicity of the satellite compared with nowadays satellites. Until 2009 AMSAT has projected 64 satellites with amateur radio payload on board, the largest counting 450kg (OSCAR-40) and the oldest one operating since 1974 (OSCAR-7).

Nowadays the amateur satellite radio communication is much more than only analog CB radio communication. It is - amongst many other tasks - a vehicle for space engineering education [Newport, 2005] and the advancement of space technologies. Following the example of the AMSAT satellites countless universities all over the world have started space engineering projects targeting on their own satellite in space. Was the amount of AMSAT members decreasing over the last decades also because of the Internet making the need for alternative ways of long-distance communication obsolete, the educational space flight has refreshed the community and revitalizes the requirement for non-commerical experts,

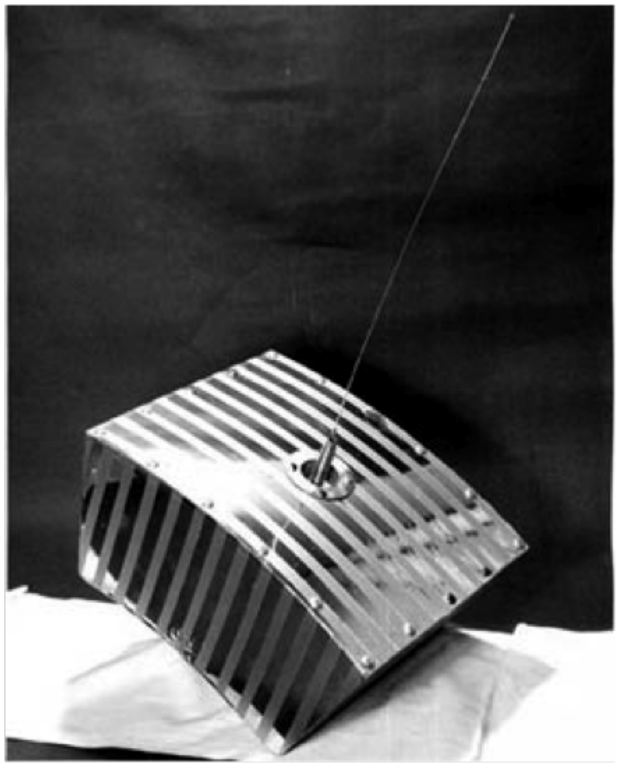

Figure 2.1: OSCAR 1 - The first amateur satellite deployed in 1961 (picture is courtesy of AMSAT-UK)

networks and communication frequencies. Nowadays radio amateurs support both commercial and educational missions with their valuable know-how and found the precondition for a new generation of space engineers [Ratcliff, 1988].

In addition to the large amount of radio amateur satellites deployed in orbit over the last decades, a large amount of educational (student) satellites and space probes have been constructed and deployed [Swartwout, 2006]. This again has not been initialized, but heavily powered by the development of the CubeSat standard. But not only nano-sized satellites, also larger platforms have been deployed in orbit. One of the most famous student satellites and the first one planned and constructed by teams distributed all over Europe was SSETI Express, which has been launched in 2004 [Alminde et al., 2005]. The mission had several sister and follow-up projects, like the European Student Earth Orbiter (ESEO) [Arana and Troncoso, 2003], the European Student Moon Orbiter [Coletti et al., 2009] and the Young Engineer's Satellite 1 (YES) and 2 (YES2) [Fujii et al., 2007].

Many of the satellite missions intended to educate space engineering and sciences are sponsored by the European Space Agency (ESA), the National Aeronautics and Space Administration (NASA), the Japan Aerospace Exploration Agency (JAXA) and others like CNA and CNES. All major space agencies have joined forces in the International Space Education Board (ISEB). For universities, the development and operation of student satellites is also an educational instrument as space engineering is a strongly interdisciplinary field teaching students to combine and apply knowledge from various technical disciplines [Zhou et al., 2009] [Nakasuka et al., 2009].

By the end of 2009 more than 100 educational satellites were under construction or have already been deployed in space. Most of them follow the CubeSat standard, elucidated in the following section.

2.2 The CubeSat Standard

Figure 2.2: The CubeSat CP3 (picture is courtesy of Californian Polytechnical University, San Louis Obispo)

The CubeSat standard [Hutputtanasin and Toorian, 2005], originally defined by Stanford University and the Californian Polytechnical University, defines a small satellite having the size of 10x10x10 centimeters (see figure 2.2) and a maximum weight of 1 kg. A majority of the current academic small satellite projects rely on the CubeSat design proposal as it standardizes also the orbit deployment unit of the satellites [Nugent et al., 2008].

The payload of CubeSats can be educational, scientific (earth quake detection, radiation measurements, optical and infra-red sensors, biologic experiments, particle counters) and also industrial (SOS signal relaying, prototype platform). Latest industry-driven approaches in satellite development have been towards small satellites (also referred to as pico satellites) as they are cheap in design and construction, standardized and easy to deploy. Instead of designing full-sized satellites for very high costs these are more and more substituted by redundant small satellite constellations.

When using a CubeSat as a prototype platform, virtually all subsystems of the satellite can be tested, plus new communication technologies, all kinds of micro-propulsion technology (tethering, solar sails, ion thrusters,...), miniaturization in general and swarm theories as well (satellite cluster technologies).

The basic components of any satellite, but especially CubeSats, are a mechanical frame structure (often sold as a barebone), a system communication bus, a power subsystem (including solar panels and usually a battery), an onboard computer taking over the housekeeping tasks, one or more communication modules for sending and receiving data from earth and other satellites, sometimes an active or passive attenuation determination and control system (ADCS), communication antennas and usually one or more payloads.

Due to their design small satellites are equipped with comparable weak communication facilities [Klofas et al., 2008] as their production of energy is limited by the small area of solar panels (the maximum of a one unit pico satellite is usually around 1W). These limits cause the up- and downlink to be very vulnerable to environmental influences and imprecise ground antenna calibration. It also causes low horizon passes to be very error-prone as the distance between the satellite and the ground station is highest at that constellation. This makes many satellite passes unusable and restricts the valuable passes to ones with a high elevation.

In addition to the typical 1U CubeSat standard as seen in figure 2.2 also two and three unit CubeSats (2U and 3U) have been constructed and launched. They provide more space for payload and more areas for solar panels. Hence their power budget is about twice or three times as large as the budget of 1U satellites.

2.3 Launch and Orbit Deployment

Academic and small scientific satellites are usually additional payloads of larger commercial and scientific missions, which makes launches very cheap and the amount of satellites deployable in orbit comparable high (the current maximum is 10 deployed missions during one rocket launch). Several nations respectively organisations provide launches for non-commercial payload. The most important are:

- ESA (Guiana Space Centre, Kourou, French Guyana)
- NASA (Kennedy Space Center, Cape Canaveral, USA)
- JAXA (Tenagashima Space Center, Mazu, Japan)
- Russian Federal Space Agency (Russia Baikonur Cosmodrome, Tyuratam, Kazakhstan)
- Indian Space Research Organization (Shar Space Launch Center, Sriharikota Island, India)

For the CubeSat standard, the most widely used form factor for small non-commercial satellites, specific launch pods, also referred to as Poly Pico-Satellite Orbital Deployer (P-POD), are mounted to the rocket payload frame together with other payload. A typical CubeSat launch pod may carry three units of CubeSats, so any combination is valid (e.g. three single unit satellites or one 3U satellite). When the launch vehicle arrives in the final orbit, the launch pods deploy the satellites using a simple spring mechanism. The different, specific impulses given to each payload let the different satellites spread out over time and change the orbit continuously.

Launch costs are a function of size and weight and the target orbit. A general rule for low orbits counts 10.000 USD for one kilogram of payload excluding all extra costs like insurance and tests, whereas this is a rule of thumb for larger payloads. The costs for test, transport, insurance, launch, and deployment of a 1U CubeSat satellite add up to 70.000 USD at the time of writing. High orbits (like geostationary orbits) cost approximately ten times as much as low orbits due to the more expensive and complex deployment procedure.

2.4 Orbit Characteristics

An orbit describes the position of a specific object at a specific time in relation to another object. It is usually representated as Keplerian elements and encoded as two-line-elements (TLEs). Earth Satellites are orbiting - as the name implies - our planet. When talking about earth orbits, the following orbits have been established in literature (see figure 2.3):

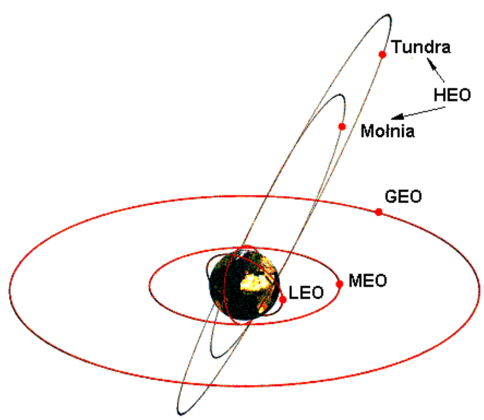

Figure 2.3: The different types of orbits.

- Low Earth Orbit (LEO): LEO ranges from 200km to 1200km above earth surface. Earth and space observing missions, space shuttles and space stations like the International Space Station (ISS) are located in LEO.

- Medium Earth Orbit (MEO): MEO covers the range between LEO and GEO in between the both Van Allen belts [Horne et al., 2005] and is usually used for navigation services like GPS or Gallileo.

- Geostationary Orbit (GEO): GEO has a radius of 36.000km and is synchronous to earth rotation. It is used for so-called fixed services which allow antennas on earth having a fixed pointing as the relative satellite position never changes. Typical applications are broadcast and communication.

- Highly Elliptical Orbits (HEO): HEOs have a low perigee and a very high apogee. Satellites in HEO are able to cover high inclination areas like north and south pole not covered by GEO satellites for several hours a day in order to establish semi-fixed services.

In contrast to orbiting objects, (deep) space probes leave earth's gravitation field for other planets, stars or even galaxies. Even though there is already an amateur space probe in construction (P5B) by AMSAT Germany, the typical target orbit for nano- and pico-sized satellites is the Low Earth Orbit (LEO). LEO provides several advantages over other orbits, e.g.

- Short communication distance: The very low power budget of nano and pico-sized satellites limits their communication range. In LEO the distance to the ground station is the lowest possible, hence communication with earth is possible with very little power consumption.

- Radiation: When being deployed in MEO or GEO, satellites have to cross the inner and, probably, also the outer Van Allen belt which exposes the hardware to critical radiation.

- Deployment costs: The higher the orbit, the more expensive launch and deployment become. Hence, LEO is the cheapest orbit.

- Space debris: The lower the orbit, the earlier satellites are entering earth's atmosphere and are consequently burnt to dust (in case of very small satellites). Space debris is a serious problem and becomes more and more harmful to manned and unmanned space flight. As small satellites typically only operate for not more than a couple of years, they should enter the atmosphere as little time after shutdown as possible. As too low orbits cause too short communication time frames, even educational satellites stay in an orbit of at least 600km above earth's surface. Consequently, the satellites remain for several decades - still a short time frame compared to satellites in MEO or even GEO.

Still, LEO has also disadvantages satellites deployed there have to face. The most impacting disadvantage is the short communication timeframe between a satellite and a specific ground station caused by the following rule: The closer a satellite is deployed to earth (given the initial impulse to keep the object relatively stable in orbit), the faster it is moving in relation to the earth's surface. As a consequence, the average satellite in LEO orbits earth 18 times a day with a speed (in relation to ground) of more than 27.000km/h.

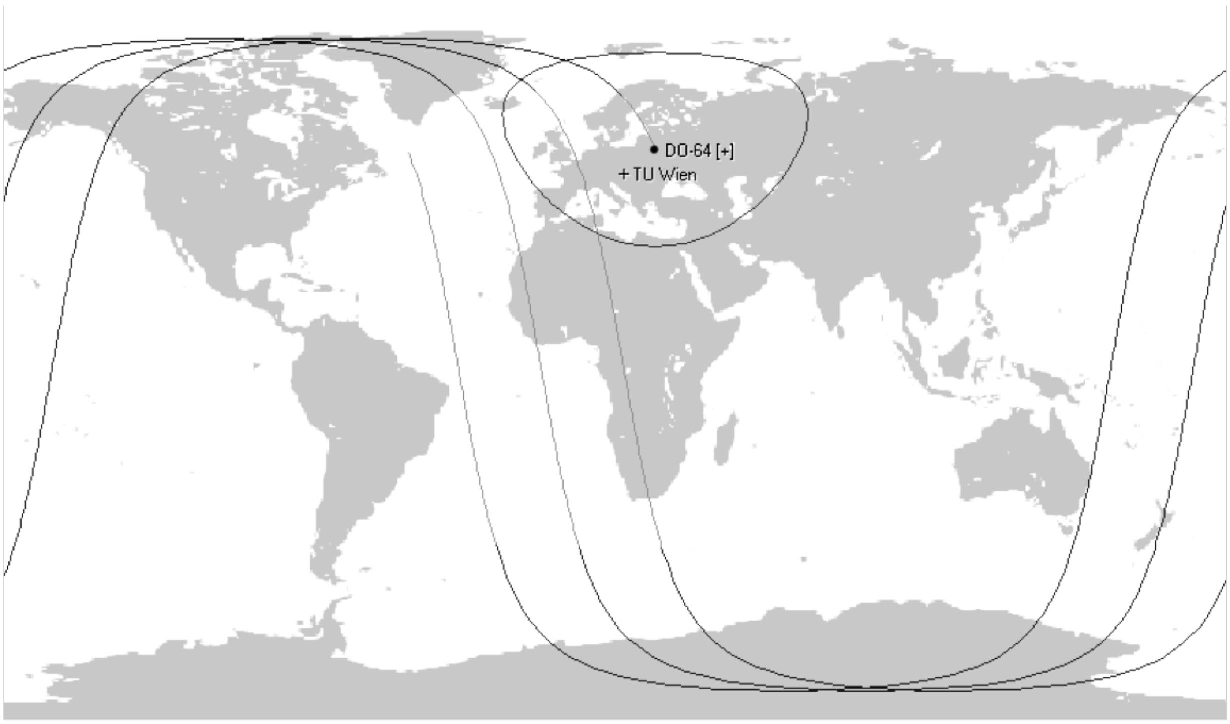

Figure 2.4: The communication horizon and ground track of a typical satellite in a LEO polar orbit.

A consequence is the comparable small communication horizon of a single ground station, namely only a few thousand kilometers. This leads to very short communication time frames with a minimum of some seconds up to a maximum of 15 minutes, if the satellite passes a ground station in an elevation of 90°. As - in typical polar orbits - the ground track of a satellite changes on each orbit (as earth rotates while the satellite orbits), not each orbit brings the satellite in range of its ground station. The average overall communication frame of a single satellite and a single ground station is approximately one hour a day, whereas not the full time can be used for communication due to low elevations of the satellite (the lower the elevation, the longer the signal has to run between satellite and ground station and the higher the atmospheric signal attenuation). Figure 2.4 illustrates the change of the ground track due to earth's rotation and the limited communication horizon of a typical LEO satellite.

Each contact of sight between a ground station and a spacecraft (whenever a spacecraft "passes" a ground station) is called a "pass" and is - for the satellites in focus of this thesis - limited by the following boundaries: A pass has a minimum length of 1 second and a maximum length of 900 seconds and a minimum elevation of 1° and a maximum elevation of 90°.

2.5 Satellite Communication

The field of satellite communication is very large and complex. [Elbert, 1999a] and others provide in-depth knowledge for general and commercial satellite communication. This section only touches the subject by providing the key data of amateur radio communication.

The satellite frequency allocation in the radio amateur bands is a task of the International Amateur Radio Union (IARU). The following frequency bands are currently available for non-commercial satellite communication and of interest for nano- and pico-sized satellites:

- High Frequency (HF): 7, 14, 21, 28MHz
- Very High Frequency (VHF): 145MHz
- Ultra High Frequency (UHF): 435, 1260, 2400MHz (S-Band)
- Super High Frequency (SHF) - Microweave: 3.4GHz, 5.6GHz, 5.8GHz, 10GH, 24GHz

The most widely used (baseband) digital modulation techniques in amateur radio frequency bands are (in FM):

- FSK: Frequency Shift Keying, as well as AFSK (Audible FSK)
- MSK:Minimum Shift Keying
- PSK: Phase Shift Keying, BPSK (Binary Phase Shift Keying) and QPSK (Quadruple Phase Shift Keying)

Typical baud rates range - depending on the used frequency bands - from 300bps up to 19400bps and the most widely used protocol is AX.25 [Parry, 1997].

2.6 Ground Segment

In order to enable a satellite operator to communicate with the deployed satellite a specific ground station is required. Every hard- and software on ground is covered by the term "ground segment" and is exhaustively covered, amongst others, by [Elbert, 2001]. This section only focusses on the requirements and limits of ground stations as they are of interest for communication in radio amateur bands in order to use them for communication with non-commercial spacecrafts.

In general a ground station consists of the following components (for further details refer to [Tuli et al., 2006]):

- A radio covering specific frequency bands, implemented whether in hardware (e.g. [Lorek, 2001]) or in software [Buracchini, 2000] and usually controllable by software.

- An AD/DA converter, similar to a modem, implemented wether in hardware (called a Terminal Node Controller (TNC)) or in software.

- One or more antennas optimized for the specific frequency band (e.g. YAGI antennas for UHF and downwards and a dish antenna for S-Band and upwards).

- A two-axis rotor (elevation and azimuth) in order to be able to track a satellite during its pass.

- Filters, (low noise) amplifiers (LNA), and other high frequency (HF) components to interconnect the antennas with the radio.

- A COTS personal computer for controlling the hardware and/or running the software.

Figure 2.5 illustrates the interconnection of the different components.

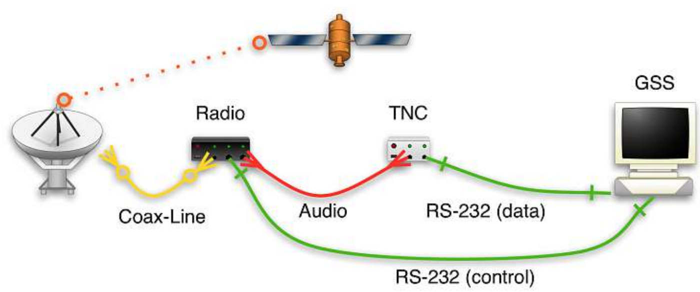

Figure 2.5: The wiring of a typical, automated amateur radio ground station

Problems which have to be considered when installing and operating any kind of ground stations are:

- Antenna calibration: A mispointing antenna can add up several dBs of attenuation to sent and received signals

- Tracking precision: The pointing of the antenna has to be accurate over the full azimuth and elevation in order to guarantee an optimal transmission of signals in each satellite position.

- Antenna dead spot: A typical antenna setup has a "dead-spot" which is caused by the wiring of the antenna. Ignoring the dead spot can lead to serious hardware damage due to broken cables.

- Interferences: Electrical sources nearby the antenna setup can add a strong, additional background noise to the signals. Such sources are usually stronger when the ground station is located close to cities.

- Cabling: Attenuation, shielding and connectors are important factors for a proper functionality of HF communication. Cabling problems were a major source of packet loss in past satellite missions.
- Wear-out: The antenna rotors are sensitive to corrosion and overheating. Both has to be considered in order to protect the expensive hardware.
- Environmental harms: (Thunder-)storms can cause serious harm to the hardware. As a consequence the antennas and the auxiliary hardware has to be protected against thunderbolts and strong winds.
- Antenna oscillation: Both wind and the usually applied step motors can cause an antenna to oscillate. This affects the accuracy of the antenna pointing and can lead to a loss of signal strength.
- Doppler effect: Due to the orbit characteristics of LEO satellites the Doppler Shift effect has to be considered (frequency auto-adjustment).

Nowadays most ground stations enable a full automatization of their hard- and software components. As a consequence the problems as listed above become even more important as no human interaction in case of problems may be possible.

2.7 Ground Station Networks

One of the obstacles of LEO satellites is their limited number of passes and the resulting narrow communication time window with the ground station (see figure 2.6). Ground station networks aim at using synergy effects by connecting ground stations over the internet. The idea is to use the resources of ground stations that were built to track a limited number of satellites and are idle most of the time. By building up a network of ground stations located at geographically different positions, the number of visible passes for each satellite increase (as seen in figure 2.7).

The currently most popular approach for fostering a ground station network is the Global Educational Network for Satellite Operations (GENSO). Preceding analogical but non-global approaches include Stanford University's Mercury network [Cutler and Kitts, 1999] and the Japanese GMS (Groundstation Management Service) network.

Assuming all ground stations operating independently from each other and tracking only their own missions, they have and idle time of 95%—most of the payload data collected by an amateur satellite nowadays is lost because it cannot be transmitted back to earth. When aggregating the horizon of all ground stations, the possible communication timeframe between satellite and earth is increased by more than one dimension.

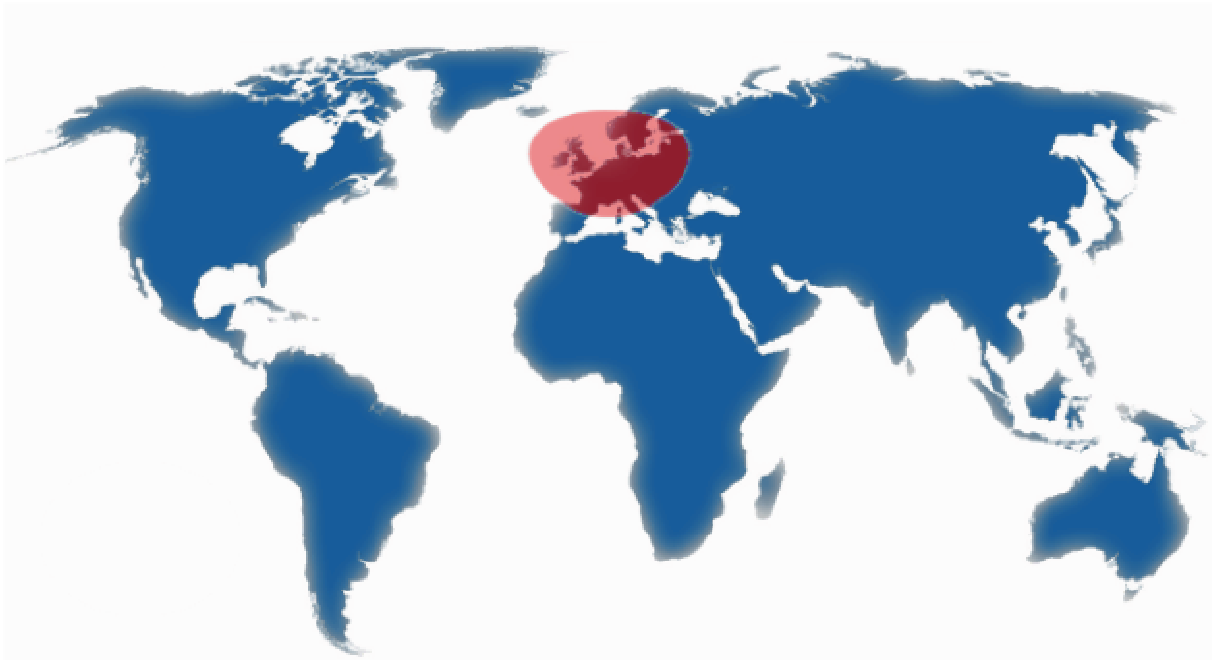

Figure 2.6: The average LEO communication horizon of a single ground station.

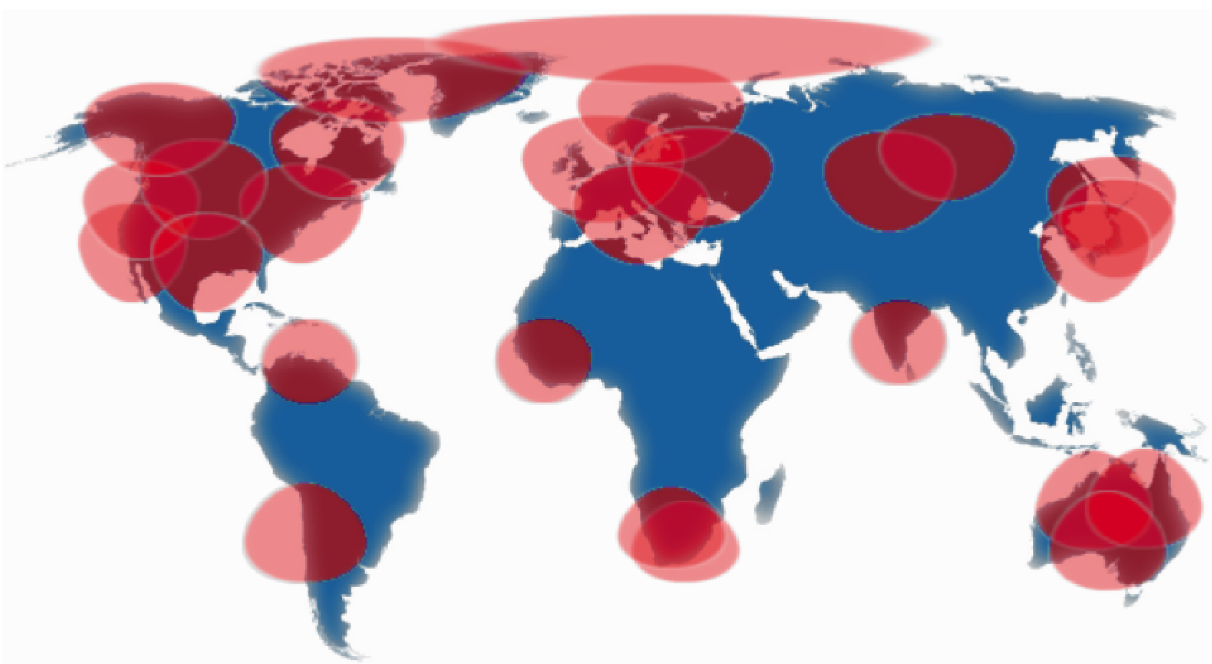

Figure 2.7: The predicted average communication horizon of a ground station network.

Chapter 3

GENSO

3.1 Introduction

The Global Educational Network for Satellite Operations (GENSO) aims to foster a world-wide community of educational institutions by developing and utilising ground segment tools and standards which can dramatically improve access to orbital educational space-crafts.

Educational space missions are often hampered by the relatively small communication windows offered by their typically low orbits and local ground stations. By developing a software standard which allows these ground stations to communicate with non-local spacecraft, sharing the data with the spacecraft controllers via the internet, it will be possible to alleviate this highly restrictive problem.

With over 80 educational spacecrafts currently (as in 2009) planned (mostly CubeSats) there is a very large demand for such a project. Since educational ground stations exist in many different locations around the globe, and since educational spacecraft are found in a variety of orbits, it is very often possible for single ground stations to track many different spacecraft without encountering any significant scheduling conflicts. This is also made feasible by the common adherence to radio amateur frequencies and protocols, rendering the ground stations largely compatible.

Therefore, by way of carefully implemented scheduling algorithms, educational ground stations can track each others' spacecraft in addition to their own, in each case streaming mission data to the appropriate controllers via the internet. If such cooperation can be highly automated, removing the need for inefficient human-interaction, then this local, limited and underused resource can be turned into a distributed, shared and highly utilised resource.

The compatibility foreseen with the radio amateur community will also serve to involve a large user-base (several hundred), maximising the network resources available. Once a large enough number of ground stations participate in the cooperative scheme, almost world-wide coverage will be potentially possible. Additionally, GENSO offers the unique possibility to obtain information meta information on satellite links for various scientific purposes.

The design and implementation work is being carried out by a distributed set of student and radio amateur teams worldwide, coordinated by the ESA Education Department.

The project is endorsed by the International Space Education Board (ISEB). This board consists of representatives from the education departments of CSA, CNES, ESA, JAXA and NASA.

3.2 System Description

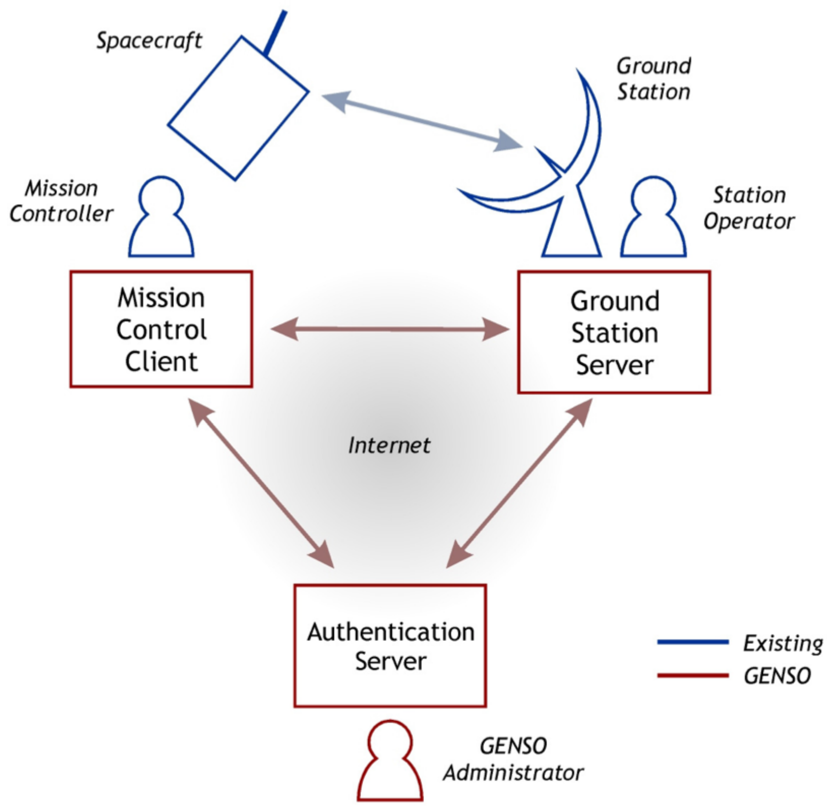

Figure 3.1: The basic architecture of GENSO.

GENSO is being developed as a hybrid peer-to-peer network between ground stations and mission control centres, which is supervised by an authentication server (see figure 3.1).

GENSO will handle two different types of satellite passes: active and passive. Passive passes (or bookings) involve only the downlink of telemetry (Rx) and can be scheduled autonomously by any ground station. Active passes involve both Rx and the uplink of telemetry (Tx) and have to be requested by mission controls and negotiated between mission controls and ground stations.

In the case of passive downlinks the downloaded data is cached in the ground station and forwarded to the mission control client on request. In case of a active passes a direct point to point connection between the satellite and the mission control is established by tunneling through the ground station server (GSS) software application.

3.2.1 Authentication Server (AUS)

The purpose of the authentication server is to control and supervise the network of ground stations and mission controls. It continuously receives status messages from the mission controls and ground stations, is informed about bookings scheduled by ground stations and mission controls and about past and ongoing satellite passes. It provides the ground stations and mission controls with up to date information about other entities in the network, needed for negotiation between them to arrange bookings.

Another purpose of the authentication server is to orchestrate the scheduling of passive and active pass bookings. A manifold of algorithms are applied to guarantee fair and optimized ground station and satellite scheduling. Quality prediction algorithms are applied to give ground stations an idea about the probability of low bit error rates on upcoming passes.

The authentication server also forms the hub between the GENSO operators and the participating entities. It detects network abuse and anomalies, is able to intervene if needed and provides the community and the operators with statistics about the networks, the participating missions and the ground stations.

3.2.2 Ground Station Server (GSS)

The ground station server (GSS) is the software application which is installed on the computer controlling the ground station hardware (radio, TNC, antenna rotors). Since it is completely developed in Java, it is - to a large extent - platform-independent and therefore not restricted to a particular operating system (although certain drivers may require a specific platform).

Each instance of the GSS has to be registered with the GENSO network to be able to receive information about participating spacecraft and provide its services to the network. Once registered and running, a GSS automatically calculates upcoming passes based on the available TLEs of the spacecraft, optimises the schedule and starts to track all compatible spacecraft participating in GENSO. The Rx data received from spacecraft is stored locally and the authentication server is informed about a newly-received pass (the GSS sends a pass report). The information is then forwarded to the Mission Control Client (MCC) client by AUS (see section 2.3).

When requested, a GSS will forward all the recorded data to the relevant mission control. The GSS not only stores the pass report itself but also meta information about the pass, such as S-Meter readings, bit error rates and others.

If an active pass for a specific spacecraft is requested by a mission control, the GSS checks whether the configurations are compatible, what the quality of the Rx/Tx is predicted to be and - in case of concurrency - if no other mission is discriminated against by the booking. The AUS provides decision support. Seconds before the active pass takes place, a secured full duplex communication channel is established between the MCC and the GSS concerned and maintained throughout the pass. Every byte coming from the satellite is directly forwarded to the mission control centre and vice versa. After an active pass has taken place, a pass report is again submitted to the AUS for statistical purposes.

A ground station may always manually prefer to operate one particular satellite over others. Thus, if a university has its own CubeSat and its own ground station, GENSO will always prioritise the local or ÔaffiliatedÕ spacecraft.

Depending on the configuration of the spacecraft and the ground station, a ground station is able to forward data from and to the spacecraft on one of the following layers:

- Audio (or raw baseband)
- Binary (including all protocol overhead)
- Decoded (only binary payload)

The payload itself is never touched nor inspected by any of the GENSO entities - data is always directly exchanged between mission controls and their spacecrafts.

The GSS communicates with the ground station hardware using a hardware abstraction layer (HAL) and a so-called pipeline configuration. A ground station operator defines the local hardware constellation and how it is interconnected with the controlling computer. The GSS calculates all hardware pipelines and also their (in-)dependencies. As a consequence of this, a machine with two separate hardware constellations, such as two radios and two rotors, can serve two passes simultaneously.

A Ôwall plugÕ interface is provided to connect common satellite and ground station applications to the GSS software, in order to track the ongoing communication.

At any time, a ground station operator can simply disable the GENSO software (even during a pass) and utilize his own hardware as usual. The GSS software ensures in particular that ground station hardware and resources are never overstrained.

3.2.3 Mission Control Client (MCC)

The Mission Control Client (MCC) application forms the counterpart of the GSS, providing an interface between local satellite applications and the GENSO network.

Like the GSS, it has to be registered (together with a mission) with the AUS. A wall plug interface is provided to interconnect local applications with the network via virtual ports. Utilizing this interface, a local application sees no difference between communicating with a spacecraft through a tunnel provided by a GENSO GSS and communicating directly via local hardware.

The MCC application is also developed in Java and therefore platform-independent. Amongst the provision of the wall plugs, its purpose is to receive passive pass reports and book active passes. There is no need for an MCC to run constantly. Transmissions from satellites are collected unattended (e.g. beacons) and delivered to an MCC on request.

3.2.4 Message Exchange Between the Network Entities

Both ground stations and mission controls continuously exchange control and status messages with the authentication server, however the content of the communications is not centrally saved. All network traffic is digitally signed and strongly encrypted using state of the art SSL/TSL techniques.

The network protocol is open and utilizes XML to structure the data. As a consequence it is possible not only to extend the applications after GENSO been publicly released as open source, but also to develop applications acting as GSS or MCC in different languages.

3.3 Summary

The current problem of all missions operating in LEO is that the spacecraft is above the horizon of a ground station for only a few minutes each day. For the rest of the time, missions rely on manually collected beacons from other ground station operators or simply have to wait for the spacecraft coming overhead again.

GENSO extends the timeframe for communication with a LEO satellite from a maximum of half an hour up to a theoretical maximum of 24 hours a day not only for Rx, but also for Tx, by tunneling the traffic over the internet.

While the dramatically-increased communication timeframe is one of the major benefits of GENSO, the network will also offer many other advantages to the operators of small educational satellites, such as:

- Spacecraft orbit deviation measurements
- Access to a satellite within minutes in case of emergency, no matter where the satellite is located in its orbit
- A significantly lowered bit error rate in Rx by aggregating multiple pass reports to statistically detect bit errors
- Automated ground station decalibration detection
- Pass quality prediction for avoidance of low quality passes with hardly any or no payload outcome and therefore optimization of resource utilization
- A manifold of statistics on link quality, spacecraft communication ability, spacecraft transmit power, ground station communication facilities, and much more

- Rapid orbit determination after launch, long before institutions such as the North American Aerospace Defense Command (NORAD) are able to provide reliable orbit information

- Significantly extended mission lifetimes and returns on investment, due to increase frequency of downlinks, faster TLE determinations after launch and the possibility to contact the satellite independently of its position.

GENSO has the potential to offer many additional services for participating missions and ground stations through the application of novel scientific approaches as presented in the following chapters.

Chapter 4

Satellite Link Quality

A required precondition for predictions of any kind are measurements of quality, otherwise it can't be proved if the optimization was successful. To be able to measure quality, it has to be defined what quality in the context of satellite communications means, especially in the context of educational satellites.

In comparison to commercial satellites, small educational and research satellites focus mainly on size and development costs, so they usually lack of link quality feedback facilities [Cuevas and Rehwinkel, 1995]. Another problem is that the network supports several different protocols, modulations, frequencies and ground station hardware configurations, covering antennas, rotors, radios, amplifiers and demodulators respectively decoders.

As most of the satellites in focus of the network are operating in lower earth orbit (LEO) [Cakaj et al., 2007], the distance between satellite and ground-station varies continuously during a pass. This has two different impacts on measurements: The longer the distance between sender and receiver (the smaller the angle between horizon and spacecraft), the weaker the signal. And the shorter the distance between sender and receiver (the larger the angle between horizon and spacecraft), the larger is the Doppler-shift effect [Ali et al., 1998].

To achieve comparable measurements between different pass durations and spacecraft and ground station configurations, these circumstances have to be taken into account and measured data has to be normalized.

4.1 Link Quality Metrics

Depending on the communication layer a measurement's focus lies on, the following quantities can be identified as quality indicators for digital radio communications (as applied by spacecrafts and ground-stations in focus of the network):

- Radio Layer: The Signal to Noise Ratio (SNR, S/N) [Elbert, 1999b] defines the strength of the received signal compared to the noise added to the signal. The larger the SNR, the better the quality of the received signal. The SNR is expressed in dB.

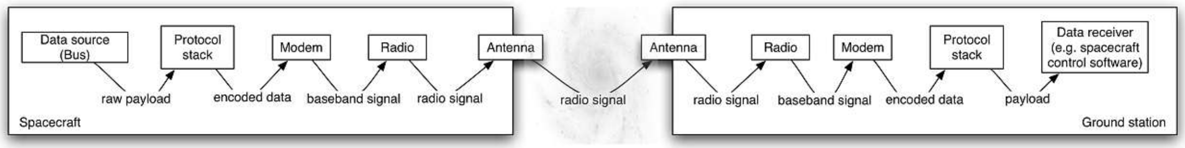

Figure 4.1: Stages within a communication link between a spacecraft and a ground station: The payload data from the spacecraft (1) is going to be encoded (framed) into a data link layer protocol (2) like AX.25, modulated (3), amplified and transmitted(4,5). On the ground station side the received signal is amplified and downmodulated to baseband (6,7), demodulated (8) and decoded (9) for further processing. SNR information can be gained from (7) and (8) and PLR information from (9). A TNC covers both (8) and (9).

- Modulation Layer: The Bit Error Ratio (BER) [Pratt et al., 2003a] describes the average amount of (mean distributed) bit errors within a specific time or amount of data. The lower the BER, the higher the correctness of the received data.
- Data Link Layer: Packet Loss Rate (PLR) describes the amount of lost packages (frames) within a sequence of sent or received packages (frames). The lower the PLR, the higher the amount of correctly transferred packets and therefor the better the quality of the link. It is expressed in the percentage of lost packages.

The dependencies between these quality metrics depend mainly on the applied modulation algorithms and utilized protocols. The BER is usually an artificial value which cannot be directly measured without running a dedicated bit error ratio test (BERT) nor knowing the received data beforehand.

Based on the measured PLR the BER can be expressed as equal or greater than a calculable value, depending on the error detection and forward error correction (FEC) [Pratt et al., 2003b] capabilities of the applied protocol. Based on the SNR the BER can be expressed as equal or lower than a calculable value, based on both the quality of the modulation algorithm and the error correction capabilities of the protocol.

So consolidating the SNR and the PLR measurement provides the following artificial quality information:

- The calculated Bit Error Ratio
- The Burst Rate (BR) of a specific communication link

The BR provides additional information about the origin and nature of link perturbations as different ascendancies result in different burst rates or different perturbation signatures. Depending on the FEC capabilities of the applied data link protocol a higher burst rate is generally preferred over a constant worse SNR in respect to an equal BER. A protocol with low or no FEC capabilities will flag a frame containing a (detected) bit error as erroneous anyways and throw it away or re-request it (if automatic repeat request (ARQ) technologies apply) [Chu et al., 1997]. Having bit errors poorly distributed in bursts is an advantage in that case, as the PLR decreases in contrast to well distributed bit errors, unlike protocols providing FEC. In case of FEC-protocols well distributed bit errors can lead to less PLR, as long as the BER doesn't exceed a protocol-specific threshold.

Recapitulatory having all discussed quality metrics available and gaugeable is the best precondition for determining the link quality of a satellite communication. To achieve suitable and comprehensive evidences at least the SNR and the PLR should be obtainable as the other values can be derived at least in an approximate fashion.

The optimal situation – retrieving all possible quality indicators – is practically only possible when being aware of the exact sequence of data to be retrieved or when having the ability to create test data to be transmitted to the satellite and received again after being replied. This is certainly only the case when being able and permitted to transmit data to the spacecraft and the spacecraft supports the relay of the received data back to the sender.

4.2 Current Situation

The nature of both an open ground station network and the unrestricted participation of different spacecrafts with different missions and configurations eliminates the possibility of being aware of the received data a priori, no matter if the data originates from the receiving station or not. One reason is that, referring to the architecture of GENSO, the ground-stations their-self act as a data aggregator and relayer so they are never aware of the transmitted payload content and meaning nor are they allowed to create content their-selves.

These circumstances reduce the link quality measurement possibilities to purely passive observations and the retrievable values to the SNR and the PLR.

Fig. 4.1 shows the generic constellation of a communication link between a spacecraft and a ground station. Every stage between the data source and the data receiver can be origin of noise and bit errors. On the receiving end every processing step removes valuable information about the signal quality so the perfect precondition is direct access to the raw sampled data stream. Unfortunately the common hardware for ground stations doesn't provide full access to all needed data.

4.2.1 Ground Station Environment

The traditional approach for measuring the signal quality amongst radio amateurs is to read the S-Meter value on the radio device [Dinger and Paine, 1947]. The S-Meter indicates the strength of the received signal. Traditionally the S-Meter scales from S1 to S9 (S1 = very weak signal, S9 = very strong signal) and proceeds with S9+dB, whereas dB is added to the dBs the value S9 represents. The S-Meter-stepwidth is non-linear (see figure 4.2). Although there are recommendations for the physical values they represent, it may vary among manufactures and builds what the correspondent dB value to an S-Meter value is in fact.

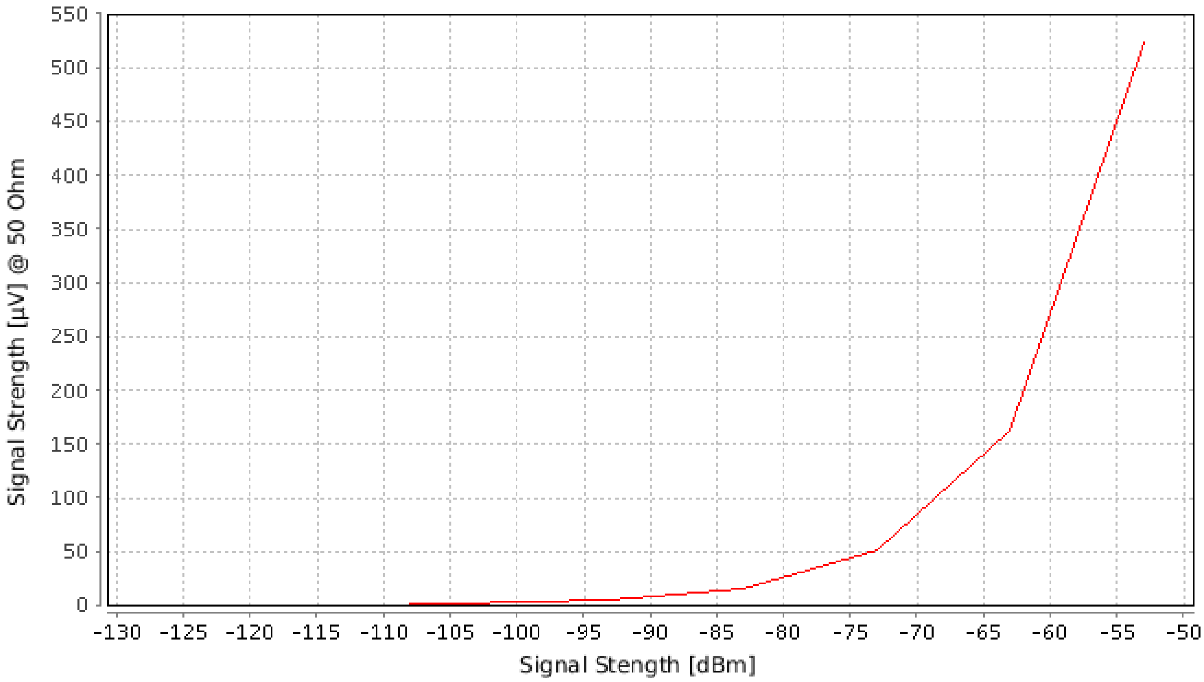

Figure 4.2: The non-linear relation between signal strength in μV and dBm

Reading the S-Meter provides the operator with a signal strength, but provides no information concerning the noise during data transmission. When reading the S-Meter when no data is transferred provides the current noise level of the channel. Comparing the S-Meter readings during transmission and during interruption provides both signal-strength and noise-strength and makes the SNR calculable.

Retrieving the PLR is not so straight-forward in the case of common radio amateur communication. There exist mainly two different approaches providing an acceptable outcome:

- The traditional method: In that case a satellite pass is recorded and the retrieved frames are counted and compared with an approximate maximum account of retrievable frames.

- The precise method: Retrieving communication and packet loss statistics from the decoding hardware device or software system

Whereas the second method is more precise, it's not always applicable. Depending on the utilized terminal node controller (TNC) the possibility of reading out the packet loss rate in form of Rx statistics is given or not. In case of software decoders the ability is practically always given.

A precondition for utilizing the traditional, (automatic) packet counting and comparing method is that the exact amount of packets and their length is known beforehand.

Spacecrafts provide telemetry data encapsulated in radio beacons, which size and interval is predictable.

When having the spacecraft in transmission mode, initiated by a command sequence from an authorized groundstation (e.g. by being utilized for an active spacelink within the GENSO network), the transmission of beacons is substituted by transmission of mission data. Knowing the exact amount of data transferred in a specific timeframe and the exact frame-length of the data packets permits the statistical approach on PLR-retrievement also during a spacecraft's transmission mode.

The current and future spacecrafts supported by the network will use different beacon configurations, baudrates and transmission modes as much as protocols, supplying both hard- and software decoders. As a consequence an approach for a hybrid PLR measurement has to be taken, which requires not only the protocol and its characteristics to be known but also the exact spacecraft's transmission behaviour.

4.2.2 Hard- and Software Limitations

For a digital, software-based and -controlled aquisition of quality information, specified interfaces have to be available to retrieve both the SNR and the PLR. The common ground station configuration utilizes a hardware-radio and a hardware-demodulator and -decoder (the TNC) [Wickramanyake, 2006]. From the perspective of quality measurement this can be considered as being the worst-case scenario compared with software radios and software decoders, as the hardware capabilities and the applying standards are more or less random (as a contrast to this situation refer to [Arsinte, 2006] as the by far easier precondition for quality measurements). Heading for the largest possible amount of groundstations being able to collect quality information, the focus lies on configurations with hardware-radio and hardware-TNC.

The usual interface between the ground station PC, to be referred to as ground station server (GSS), is an RS-232 connection. The connection is required to automatically configure the radio for the transmission frequency and mode. The GSS interfaces with available driver libraries like HamLib[1], the Mercury project driver library [Cutler and Kitts, 1999] and the GMS driver library. Depending on the capabilities of the radio the digital read-out of the S-Meter value during transmission is possible, whereas the values theirselves are not standardized and vary by model and manufacturer. So the equivalent absolute Integer value of an S-Meter reading of S9 on an Icom 910 is probably not equal to the same reading provided by another radio model. Additionally the S-Meter readings may be imprecise depending on the method the radio uses to derive the signal strength [Dinger and Paine, 1947].

Not only the radio control interface has to be capable of the digital S-Meter readout but also the software driver has to be able to read and provide the value. There is currently no reliable information available about the percentage of supported radios in respect to the S-Meter reading, but the majority seems to be capable of both in hardware and driver

[1] http://hamlib.sourceforge.net/

support. Not only the values theirselves differ from model to model and driver to driver but also the sample rate can be different.

The usual interface between the TNC and the GSS is also an RS-232 interface. In contrast to the radio connection the RS-232 line transfers both data and control commands. Some TNCs, e.g. the TNC3S [Zieliński, 2009], are able to provide packet loss statistics. The disadvantage of using one serial line for both data and commands is that only one of both modes can be active at one time. Therefor the only possibility of statistical readouts is whether before or after a satellite pass has taken place. As discussed in a later chapter, the PLR information should be of a higher granularity than once after a pass.

As the majority of TNCs doesn't support the provision of packet loss statistics at all and nor do many drivers, the PLR has to be retrieved using the statistical approach when running a hardware TNC configuration. Software decoders provide detailed information about PLR in common and the network's protocol transcoder libraries (which have been implemented from scratch in Java to fit the need for a platform-independent solution) do also. Unfortunately hardly any hardware TNCs can operate in a "real" raw mode, so precise PLR information will most often be lost when using a hardware TNC.

Depending on the applied layer 2 protocol, more or less information about the link quality can be provided (mainly when using software modems). The AX.25 protocol [Parry, 1997], as an example, provides no FEC but a CRC (CRC-16 CCITT). Therefor the only information it can provide is if one or more bit errors occured. The passive assumption is that if an AX.25 frame of an assumed specific size has been dropped the BER was at least 1 devided by the packet length [Zieliński, 2008]. Other protocols with more sophisticated error detection and correction mechanisms provide different information when dropping a packet. If a 3/4 FEC protocol is applied and a packet is dropped, a BER of approximately 0.25 can be assumed.

Nowadays most student satellites use the AX.25 protocol for communication rather than a more sophisticated protocol using FEC, which would deliver more fine-grained BER information, but on the downside would cause more problems regarding the compatibility in heterogenous ground station networks.

4.2.3 Spacecraft and Antenna Particularities

As the main focus of GENSO lies on small satellites in LEO which needs the ground station antenna to be mounted on a rotor able to track a satellite on its pass from horizon to horizon, quality measurements like signal strength face four different problems:

1. Antenna calibration: As the spacecraft transmission (Tx) signal gain is due to power limitations low compared to many commercial satellites, slight miscalibrations of the receiving (Rx) antenna adjustment lead to significant Rx signal strength losses.

2. Rotor control precision: Compared to professional, high priced antenna rotor drives the effortable rotors for educational and amateur ground stations provide a less precise tracking by having coarser antenna moves and therefore possible reverbarations

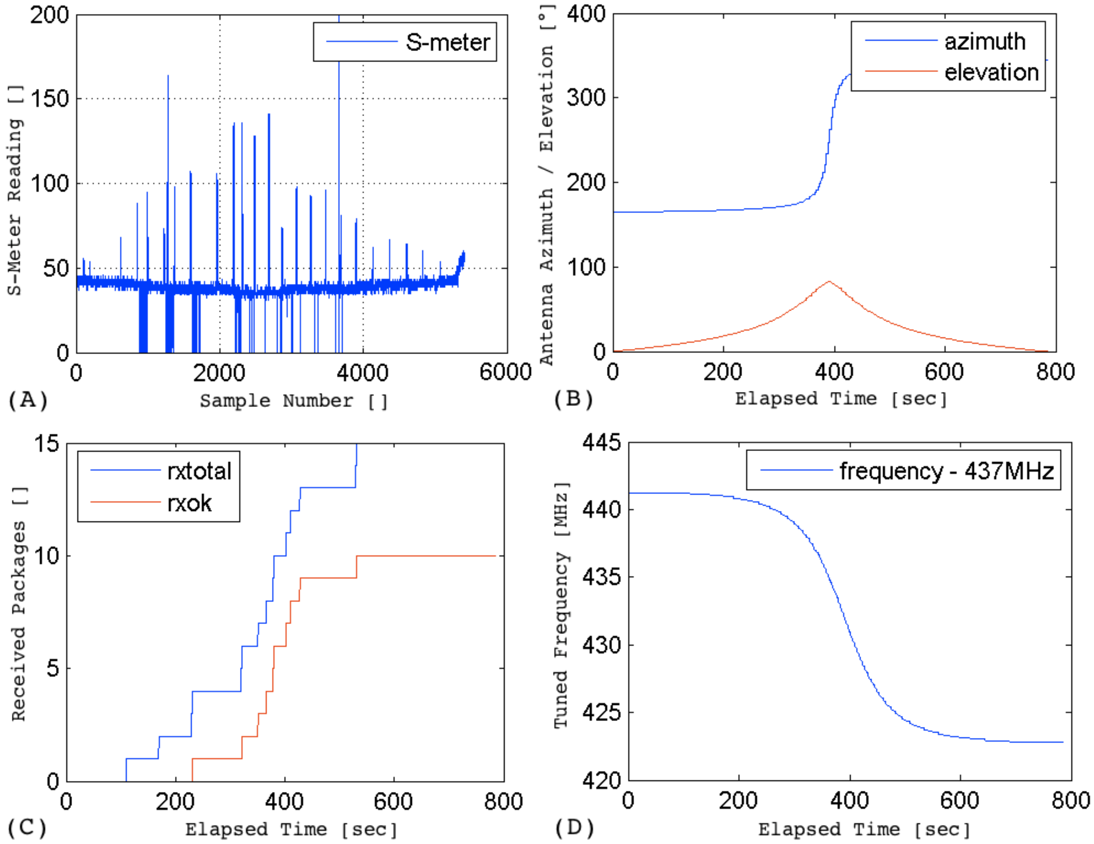

Figure 4.3: Plot of the raw data recorded during a single satellite pass of 10 minutes: (A) shows the plot of the raw signal strength measurement per sample, (B) shows the antenna azimuth and elevation, (C) shows the amount of overall received packets and how many passed the CRC check, and (D) shows the change in carrier frequency as a consequence of the Doppler shift effect [Ali et al., 1998]

of the antenna causing strength oscillations. Vibrations on the antenna can also be caused by strong winds.

3. Spacecraft tumbling motion: Satellites which don't carry an attitude determination and control system (ADCS) [Larsen et al., 2005] with them, and many of the small satellites education is focussed on don't, tend to tumble in an undeterminable fashion. So signal strength oscillates during a pass depending on the spinning axis and speed of the spacecraft.

4. Imprecise spacecraft orbit information: Orbital elements, whether being calculated or determined [Chouraqui et al., 2003], e.g. by NORAD[2], may be inexact which results in tracking the wrong spacecraft orbit and leads to frequency offset errors.

[2] http://www.ncdc.noaa.gov/oa/gsod.html

This causes the signal strength to be below the expected value and therefor causes higher BERs.

Both (1) and (4) result in a constantly lower SNR and therefore in an increased BER. As a matter of principle it cannot be determined apart from external information like comparable measurements from different GSS. The intracacies caused by (2) and (3) can be at least deflated by adjusting the sampling rate.

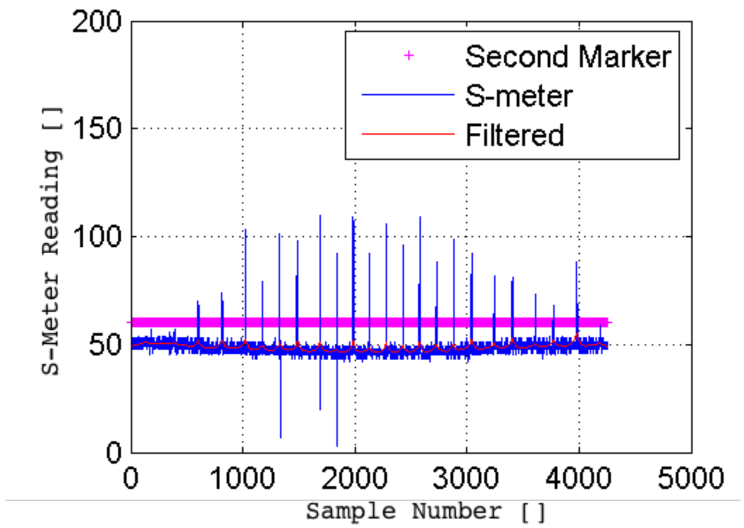

Figure 4.4: This diagram shows the course of the S-Meter levels of a typical satellite pass. The noise floor can be separated from the actual signal in order to gain the SNR.

4.2.4 Communication Parameters

The major amount of academic satellites uses the AX.25 protocol or at least parts of the high-level data link control standard (HDLC), only a few use more advanced protocols, like SRLL. Usually the frequency shift keying (FSK) or audio FSK (AFSK) are applied as modulation schemes with symbol rates of 1200 and 9600 baud. The most comprehensive collection about small satellite communication facilities provides Klofas et. al. in [Klofas et al., 2008].

Common TNCs support primarily AX.25 protocol processing, other protocols require special firmwares or software decoders. TNCs can usually operate in different modes, the most common is the so-called KISS mode. The KISS mode only applies the CRC inspection and generation and bit stuffing operations of the HDLC part of the AX.25 protocol. Against common presumptions the KISS mode does not only forward the raw incoming and outgoing data but also processes the forwarded frames. It is therefor impossible to operate protocols not according to the HDLC standard regarding the frame check sequence (FCS), the bit stuffing process and the packet delimiters with KISS TNCs.

KISS also describes a simple intermediate protocol for data exchange between the host machine and the TNC - after HDLC frame preprocessing the data is encapsulated in the so-called KISS frame which replaces the original HDLC frame. Protocols different from standard AX.25 can be applied as long as the HDLC frame persists. This constraint limits the error detection to the CRC-algorithm of HDLC and eliminates the possibility of FEC. SMACK represents an enhancement to KISS as it adds a CRC checksum also for the communication between TNC and host machine.

A simple KISS and SMACK frame counter in the ground station transcoder framework makes it possible to precisely count the amount of received packets.

4.2.5 Retrievable Values

As a preliminary conclusion the following values from the common educational or amateur ground station are possible to retrieve without further investigations:

- Hardware-dependent S-Meter readings during transmission
- Hardware-dependent S-Meter readings while no transmission takes place (= noise reading)
- Amount of properly received data link packets

4.3 Measurement and Postprocessing

For gaining comparable and usable quality information the values have to be measured, preprocessed and compiled.

For the SNR the driver libraries are going to be utilized and abstracted by the GSS software to retrieve the S-Meter readings of the radio. Fig. 4.3-A shows a single pass of AAU-SAT II over Aalborg university recorded with an ICOM IC-910H radio [Lorek, 2001] using a sample rate of 8 samples per second. The values collected between the beacon transmissions are used to determine the current noise level. Depending on the intended kind of investigations the measurements can be combined to different levels of average. For example, elevation-dependent investigation like tumble rate determination require more fine-grained consolidations whereas more abstract investigations like link quality prediction require overall mean values.

For the PLR the retrieved data frames are counted and compared to the theoretical maximum amount of transferable packets during the pass. At a typical baud rate (e.g. 1200) the packet rate is very low and the usage of beacons instead of constant streams of data decreases the amount of transmitted packets additionally. The proposed sampling rate for the packet count is therefor at least one minute, 60,000ms. The reason why one overall count for one pass is not recommended is that it disables the possibilities for angle-based normalization, what is also a reason why the data transmission statistics provided by some TNCs cannot be used. Figure 4.3-C shows the received amount of packets and the

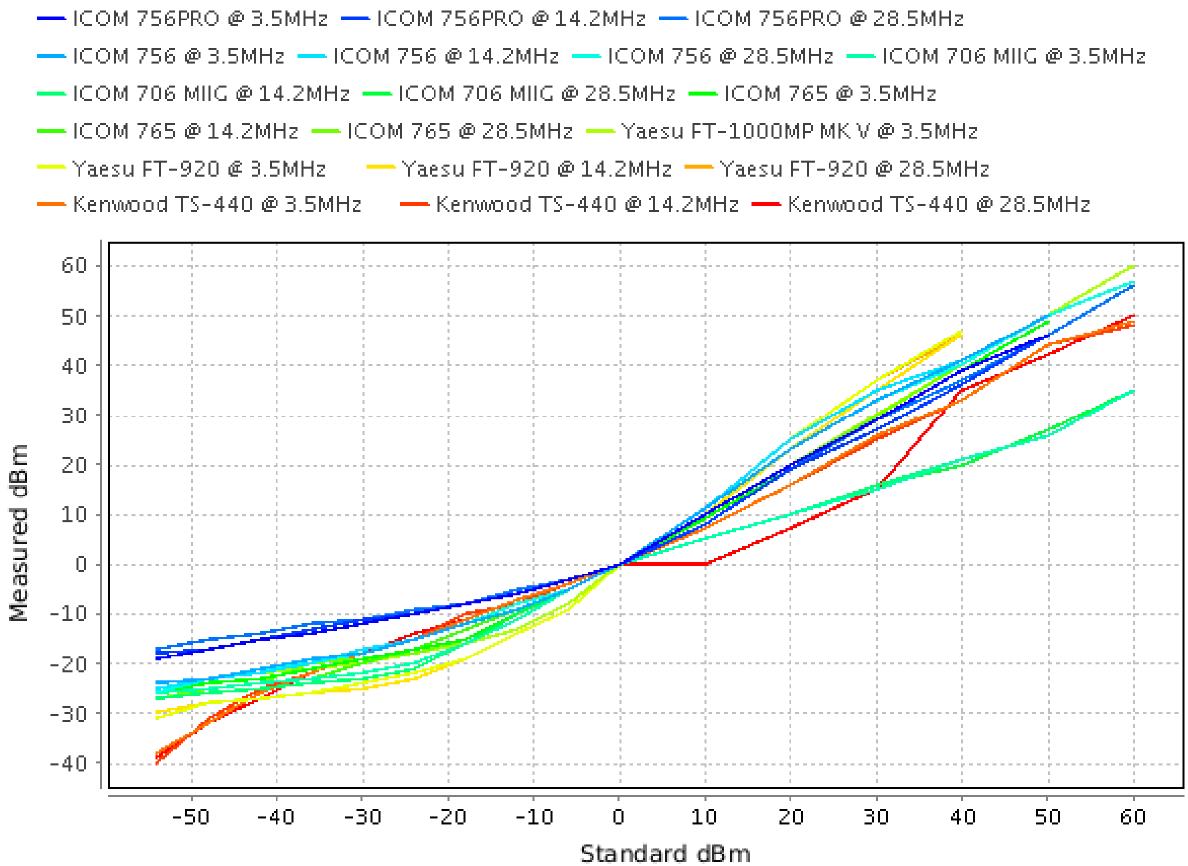

Figure 4.5: Differences between analog (visual) S-Meter readings on different radios in different HF frequencies (measurements collected by Greg Ordy)[3].

PLR for the same pass as the signal strength recording. Based on the information which is provided for every spacecraft about baud rate, protocol, beacon length and interval the mean PLR can be calculated.

The remaining problem is that - in case of transmitted beacons or discontinous transmissions - the measured S-Meter values range from the noise strength to the actual received signal strength indication (RSSI). As a consequence the average value adducted for quality assertions over a certain amount of time would be in-between the noise level and the factual RSSI. Hence the values have to be devided into two categories, one containing values above an arithmetic mean value, representing the presumed RSSI values, and one containing the values below the arithmetic mean value, representing the noise level. Figure 4.4 shows the noise floor separation and peak detection using a two-class clustering algorithm as applied in [Preindl et al., 2009d].

By analyzing the samples located in the RSSI category for continous oscillations presumptions about the thumbling behaviour of the spacecraft can be extracted, which can be a valuable information for the spacecraft operator.

Further investigations concerning the noise level exhibiting artificial, continous patterns

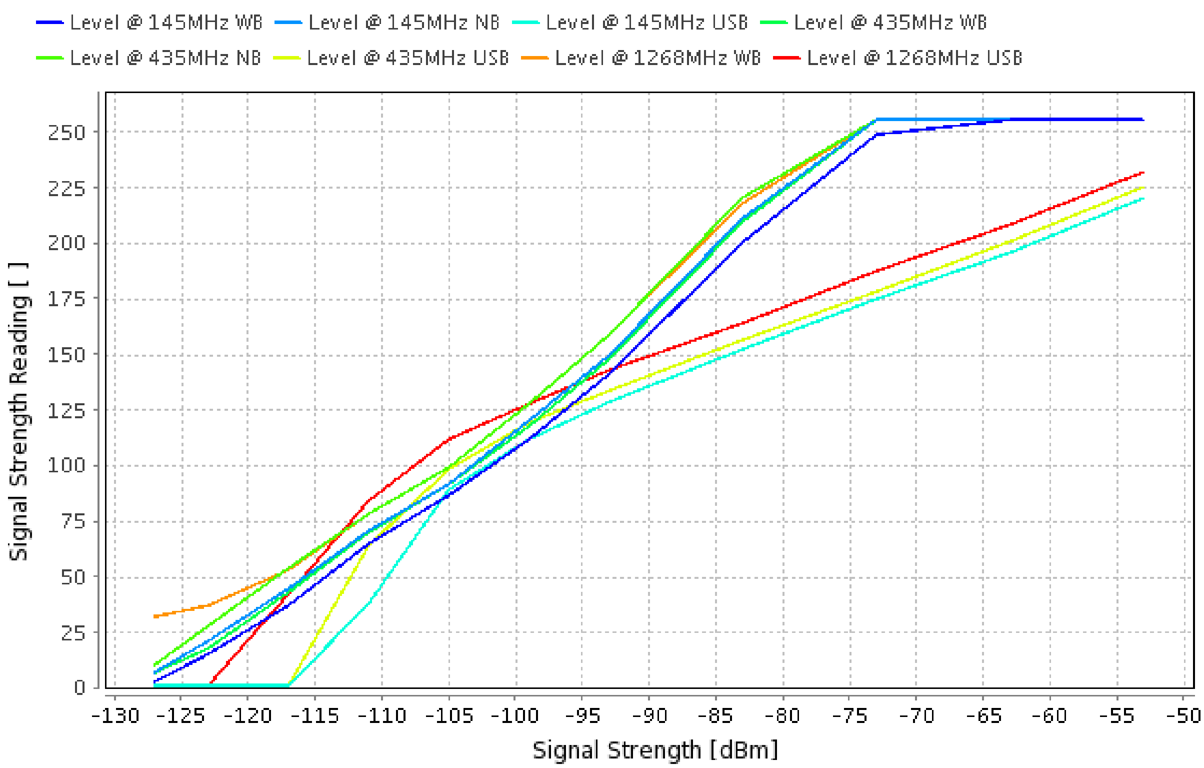

Figure 4.6: Differences between digital S-Meter readings on an ICOM IC-910H in different frequencies and modes (FM narrow band (NB), FM wide band (WB) and upper side band (USB)). In the middle strength regions the readings are nearly linear.

could lead to assumptions about radio interferences, as an example. Although these investigations are not yet part of the current evaluation they can provide valuable information for future calculations and predictions (refer to [Preindl et al., 2009d] and [Preindl et al., 2009b] for further applications).

4.4 Comparability

The S-Meter values differ depending on hardware, mode and frequency. Figure 4.5 shows the differences on readings on several COTS radios in HF frequencies whereas figure 4.6 shows the differences on an ICOM IC-910H in VHF and UHF. The values on the ICOM radio differ significantly based on the tuned frequency and band (narrow, wide or upper side band). Even more surprising are the strong differences between the theoretical standard values and the displayed values and their frequency dependencies (see figure 4.7). But even though the values may differ strongly we've observed that the relation between noise and signal strength itself as a factor is largely unaffected by that circumstance in the main signal strength areas (see figure 4.8). As a consequence the digital measurements collected using such COTS radios, even though the radio's S-Meter reading facility is not calibrated,

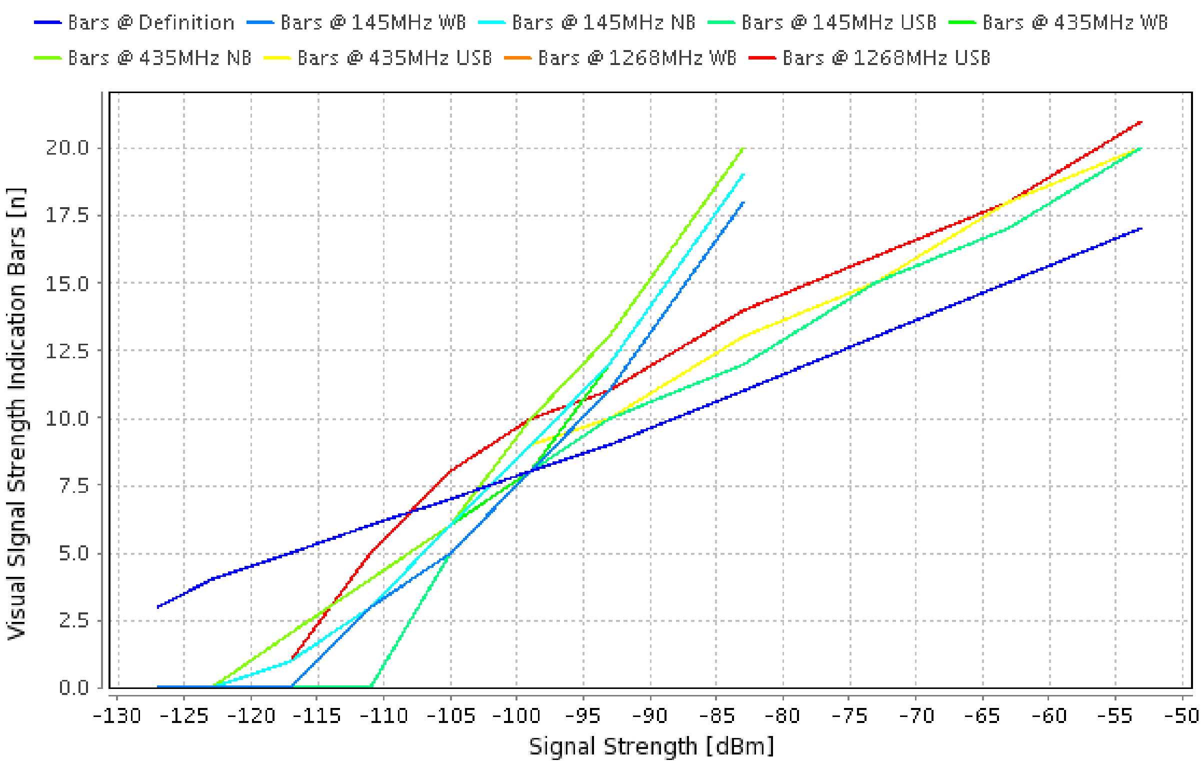

Figure 4.7: Differences between analog (visual) S-Meter readings (amount of displayed bars) on an ICOM IC-910H in different frequencies and modes. The definition reflects the IARU standard at VHF/UHF.

leads to usable and comparable signal to noise recordings. Refer to Appendix C for the detailed measurements of the ICOM 910.

4.5 Summary

Heterogeneous ground station hardware environments, a wide range of different spacecraft communication facilities and the utilization of different protocols form together one of the worst possible scenarios for obtaining meaningful, comparable quality measurement results. We have identified what link quality means in respect to non-commercial satellite communication and which possibilities are provided to collect raw information concerning the quality of an established space link. Furthermore we've demonstrated how the collected raw measurement data has to be sampled and processed to achieve normalized, comparable information. The introduced procedure establishes the required foundation for further investigations and novel approaches on long-term link quality recordings and predictions. As integral part of the Global Educational Network for Satellite Operations link quality measurement facilities will offer both science and education the possibility of a distributed and accurate collection of communication meta information. Additionally, link quality

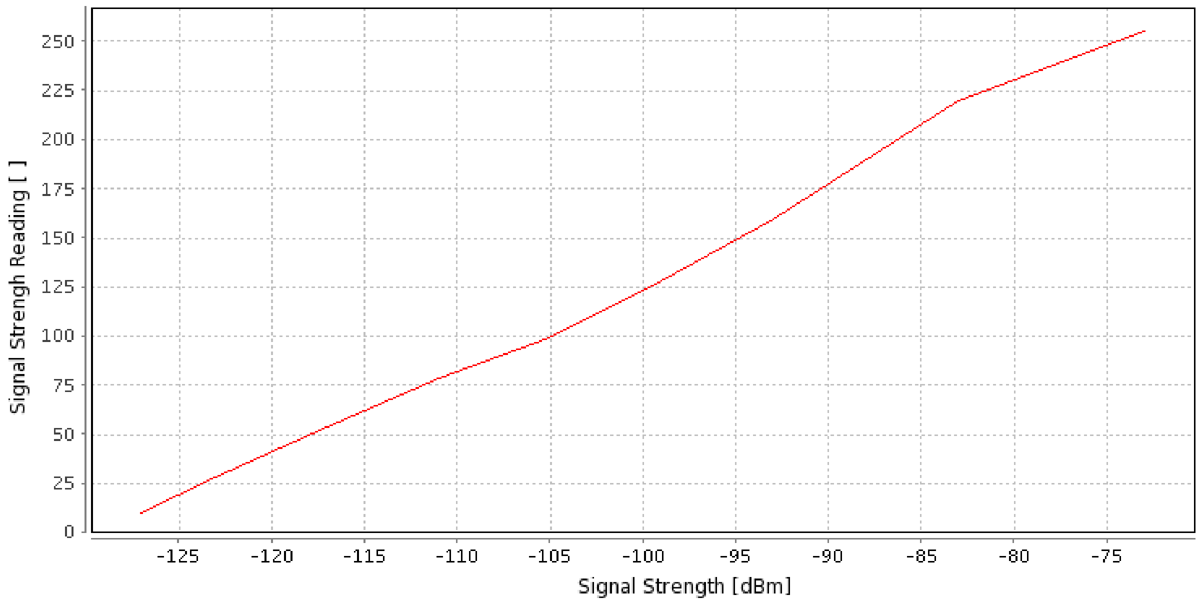

Figure 4.8: The relation between the digital signal strength readout and the measured dBm at 435MHz narrow band. A nearly linear dependency can be seen. Of special importance is the precision at lower signal strength, as this is the typical signal strength region of satellite links.

information can be used to identify whether problematic ground stations or degrading satellites by aggregating the measurements of several stations.

The granularity and precision of the measurements based on a hardware radio S-Meter are reliable enough to investigate on several applications of the gained quality information. It enables the application of data mining and machine learning techniques to consolidate environmental and weather information for satellite pass quality prediction. Other applications can be spacecraft health and status determination. By utilizing the possibilities of a software defined radio (SDR) like GNU Radio including a sophisticated DSP board the measurement precision and sample rate could probably be increased, but although the distribution of SDRs within the radio amateur community is continuously growing, the ratio is still low. Future investigations will nevertheless include SDRs and the possibilities they offer in respect to link quality determination.

Chapter 5

Global Satellite Link Sensing

Ground station networks like Global Educational Network for Satellite Operations (GENSO) can also be used to collect signal strength data during satellite passes. The collected measurements can be used for a manifold of scientific investigations. In the time between April 2008 and April 2009 a test scenario took place at Aalborg University in Denmark. As a precursor to possible future investigations 2454 signal strength measurements collected during passes of the Danish AAU-SAT-II CubeSat over the universities' ground station have been analyzed and interpreted. In the following chapter the experimental setup of the measurements will be described in detail, the analytical interpretations will be discussed and possible scenarios of remote satellite link sensing are described.

5.1 Experimental Setup

The underlying measurements have been performed by recording the continuously transmitted beacon signals and the background noise between beacons as indicated by the radio equipment's signal strength meter. While this is considered to be a stand-alone configuration, the utilization of a ground station network would allow for a multiplication of the recorded measurements. Figure 8.1 illustrates the triangular measurement setup between several ground stations, a mission control entity and the tracked satellite.

Although the measurements being subject of this paper have been recorded by a specific ground station hardware, recordings collected on a distributed base from ground stations all over earth's surface are kept within the same format and grade of sensitiveness. The methods described in [Preindl et al., 2010a] allow for receiving comparable values even though the hardware itself differs by model and manufacturer.

The amount of measurements which can be collected linearly depends on the amount of ground stations and spacecrafts connected to the network. The approximate amount of satellite passes over a single ground station is six per day. The amount of spacecrafts and ground stations multiply the amount of possible passes (if the ground stations are not co-located). Taking the future goal of GENSO having 100 ground stations and 20 participating spacecrafts as an example and assuming that all entities have conflict-free

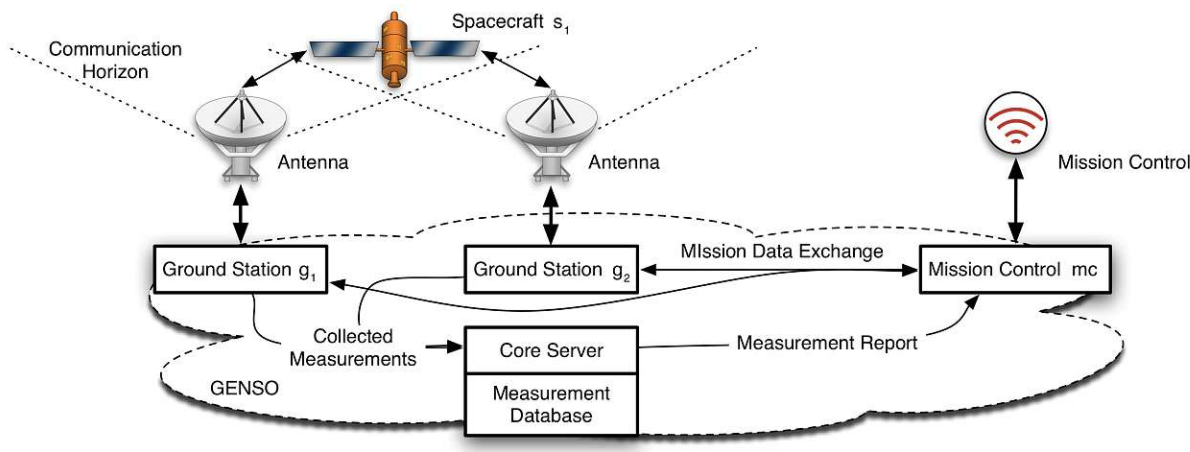

Figure 5.1: Parallel to a direct data exchange between the mission control and the ground stations signal quality measurements are recorded by the ground stations and communicated to the core server. The core server stores all collected measurements for scientific investigations and to create reports for the mission controller.

ground-tracks and are compatible with each other the network will be able to collect more than 4,000,000 measurements each year.

5.1.1 Ground Station Hardware

The ground station hardware operating at Aalborg University (57°02'N, 9°54'E) consists of two typical YAGI antennas as they are used for receiving and sending within the radio amateur frequency band at 434-437 MHz (UHF). The movement of the antenna is degree-wise (each change in a satellites elevation or direction of more than one degree triggers the antenna rotors to move towards the current satellite position by one degree). An important factor for gaining comparable values is the tracking accuracy of the antenna rotor. The higher the carrier frequency, the more important the pointing accuracy (receiving in UHF requires less accuracy than for example receiving in S-Band (2,4GHz) – an inaccuracy of at most 5° is tolerable for UHF). As a consequence antenna pointing deviations have been taken into account for measurement normalization.

The radio hardware used for receiving the beacon signals is a common and very popular ICOM IC-910 [Lorek, 2001].

The signal strength reading has been performed by reading out the S-Meter indication value [Dinger and Paine, 1947] via the RS-232 control connection of the radio. The sample rate was 8 samples per second.

5.1.2 Measured Satellite

The satellite which has been tracked and sensed was Aalborg University's AAUSAT II CubeSat which has been launched April 28th 2008. The measurements taken into account when creating the models described on the following pages have been recorded between May 2008 and May 2009.

AAU-SAT-II and most of all other academic spacecrafts [Klofas et al., 2008] operate within the radio amateur UHF frequency band around 437 MHz and use (Audio) Frequency Shift Keying (AFSK) respectively a modification (like Minimum Shift Keying (MSK) [Pasupathy, 1979] in case of AAUSAT II). The most common transport protocol, although it is not important for the kind of measurements currently performed, is AX-25 [Parry, 1997]. The beacon length of the satellite is 1.6 seconds and is transmitted every 30 seconds at 437.432 MHz (MSK 1k2 1200Hz/1800Hz, FM). The satellite is equipped with an omni-directional antenna. Doppler shift [Ali et al., 1998] can be up to 25KHz and requires continues frequency adjustments during the pass (see figure 6.1-D).

The satellite is operating in Low Earth Orbit in a height of 615 to 634 kilometers and orbits earth almost 16 times a day. As a consequence the maximum communication timeframe during one pass is less than 15 minutes and the amount of beacons which can be recorded is about 30 during each pass.

5.2 Measurement Analysis

All recorded signal strength measurements have been filtered, normalized and analyzed using various scientific methods including methods from the field of machine learning [Preindl et al., 2009b] and used to create models of various kinds. The following sections describe the further analysis performed.

5.2.1 Background Noise Map

Whereas the signal to noise ratio is an important indicator for satellite link quality and constitutes the base for investigations in prediction models, the noise-floor itself offers various possibilities for further investigations.

One very interesting approach is the creation of full-coverage noise floor maps. They show in a highly detailed manner the average strength of the background noise at the different elevations and azimuths on the hemisphere around a ground station. Figure 5.2 shows the noise hemisphere around Aalborg ground station by aggregating the noise-floor of all collected measurements.

One potential area of application for such noise floor maps is when a ground station within a network of stations has to decide between two satellites if both are in range and compatible for tracking. The satellite passing over a part of the hemisphere providing a lower noise floor could be the one being preferred in respect to the expected link quality. Another one are full-coverage noise maps, as described later.

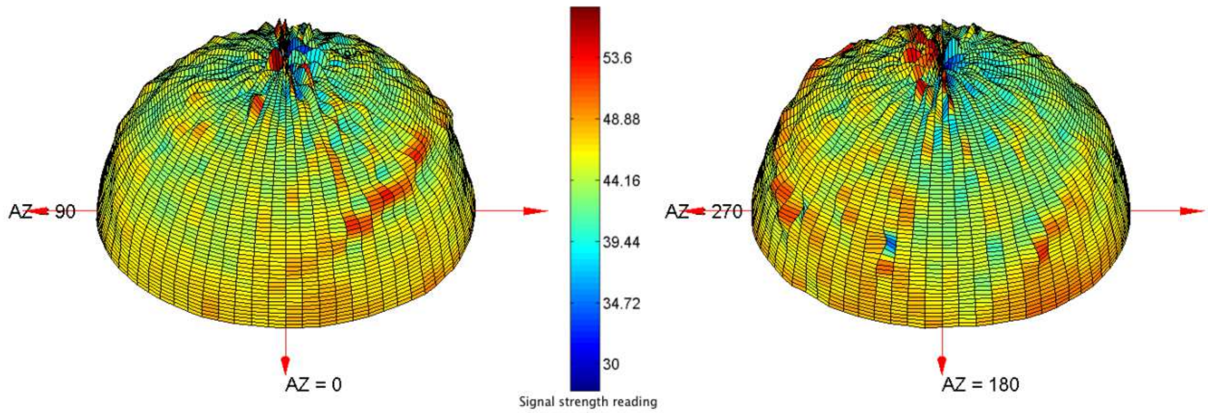

Figure 5.2: Two 3D background noise plots (noise maps) calculated from 2500 passes covering the full 360° hemisphere around the Aalborg ground station. Azimuth resolution: 5° Elevation resolution: 1°

5.2.2 Satellite State Analysis

In contrast to noise floor maps which are used to inspect the ground, the signal strength reading of uninterrupted data transmissions can be used to gain more knowledge about the state of a satellite. One novel application is the determination of the tumbling rate of satellites from ground by applying FFT to the recorded signal strength curve (see figure 5.3).

Gaining information about a satellite's onboard power system degradation or a decrease of its effective isotropic radiated power (EIRP) is possible when performing long-time observation of the signal strength a satellite provides. When aggregating pass measurement data collected over a specific timeframe and calculating a linear mean SNR as a function of time, serious problems can be discovered and intervention is possible before the communication with the satellite becomes impossible.

Satellite state analysis from ground may also be used for dynamically selecting communication parameters like baud rate, protocol and package length to compensate degradation of a satellite's communication facilities.

5.3 Prospective Remote Sensing Scenarios

What we have seen in the last sections were possible measurements and interpretations driven by one ground station and one satellite. Ground station networks like GENSO [Preindl et al., 2008] offer the novel possibility to aggregate those measurements and a satellite link sensor network all over earth's surface. The following scenarios are already projected and are just a small excerpt from the possibilities given in future.

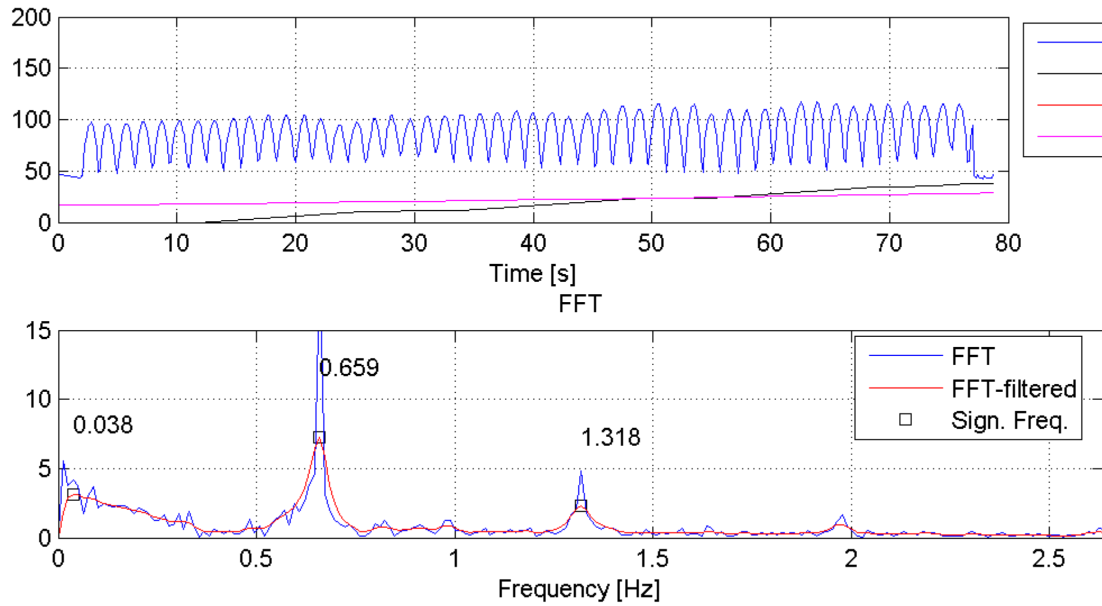

Figure 5.3: The analysis of the signal strength measurement during permanent data transmission shows the tumbling interval of AAUSAT II (here: 0.66Hz).

5.3.1 Measurement Satellite

The signal strength readings constituting the base for the investigations discussed in the last chapter perform well for initial models and feasibility studies, but due to the nature of communication beacons and the sensitiveness of radio hardware their precision is limited. To countervail the lack of precision a dedicated measurement satellite is currently developed [Preindl et al., 2009c]. The main purpose of the satellite is to transmit and receive continuous and predefined bitstreams to and from ground stations with a symbol rate of nearly 10.000 bits/second. As a consequence the precision will be a multiple of the current and the sample rate will grow a thousand times (refer to chapter 7 for details).

Not only precision is increased significantly, also the amount of ground stations capable of performing measurements is raised as the measurement analysis is hardware-independent. Additionally new remote sensing scenarios become possible like the sensing of dense objects in the view of the ground station (see figure 5.4). Such “coverage window maps” could for example influence the pass scheduling decision in networks of ground stations so that only ground stations are selected for a specific, continuos series of passes which provide the required azimuth angles.

5.3.2 Full-Coverage Noise Maps

Noise floor maps give deeper insights into the behavior and the electromagnetic emisson of earth’s surface and can be used for various applications. Using only one ground station’s

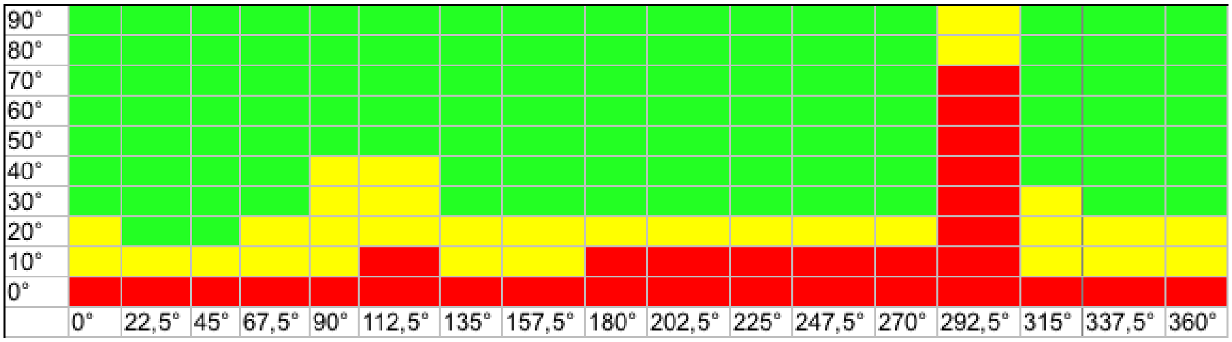

Figure 5.4: The graphical evaluation of a hypothesized coverage window matrix with a very rough degree resolution (Green = high SNR, Yellow = low SNR, Red = no signal).

noise map allows for detecting and avoiding specifically noisy directions for pointing antennas to during passes, but it does not provide any information about the distance to the noise emitting area or object.

When applying classical triangular position determination using the noise maps of several ground stations within the same geographic grid square a consistent noise map layer can be calculated which allows for precise identification of noise sources. The more ground stations provide their maps, the more precise the maps become. This is especially interesting in very populated areas where the amateur ground station density is comparatively high and noise sources are more common than elsewhere. This maps could be aggregated example given with with projects for noise pollution visualization [Paolino et al., 2001].

5.3.3 Rapid Orbit Determination

The principle of a triangular antenna pointing can also be used to determine the position of a satellite autonomously without the need of periodic radar scans of the orbit [Lee et al., 2003]. By aggregating the link quality measurements of different ground stations within the satellite's ground visibility at the same time orbit deviation can be determined. Existing techniques for orbit determination using low cost ground stations [Sakamoto, 2000] may be applied and improved, but also novel approaches like an individual, orchestrated and deliberated change in the current orbital elements in order to scan for a satellite's strongest signal could be implemented.

Using the potential of ground station networks for remote sensing the link quality of a satellite could lead to a strong shortening of the time required for orbit determination. This is especially interesting in situations where a satellite's orbit is yet to be determined and time is short because the satellite is within a critical state in its mission (e.g. immediately after launch and deployment from the carrier).

5.3.4 Signal Strength Amplification

By combining several ground stations to track the same satellite and record the same downlinked data, the overall bit error rate can be lowered significantly [Stolarski, 2006]. By doubling the amount of downlinking ground stations, a gain in the overall bit error rate of 3dB can be achieved. This is especially interesting for satellites with a very low power and link budget or with communication problems of any kind (antenna deployment failure, solar cell and battery degradation, attitude stability problems like tumbling).

A properly located cluster of ground stations can be - in theory - viewed as a permanent link. When at each time several ground stations track one satellite, its output power can be lowered which results in a significantly extended communication time. Additionally, the problem of tumbling fading, a problem on most satellites without attenuation control systems, could be eliminated.

5.4 Summary

Ground station networks like GENSO establish a manifold of novel science investigation possibilities in many different research fields. By not only collecting payload data during satellite passes but also measuring signal levels, an unprecedented amount of global measurements can be performed waiting for the scientific community to be analyzed.

Performed measurements on a single ground station in 2008 have been evaluated and interpreted. The resulting interpretations like signal to noise filtering, satellite condition derivation and 3D noise floor maps demonstrate the possibilities of aggregated measurements performed within a global sensor network.

The amount of possible future recordings is high and provides the preconditions for the establishment of large-scale noise floor maps, novel approaches on rapid orbit determination and the creation of signal quality prediction models.

Chapter 6

Link Quality Prediction

The collection of satellite link quality information performed by the measurement and comparison method developed in chapter 4 enables the derivation of a satellite link quality prediction model. The applications of a prediction model are various, as discussed in the following, but a precondition for any application is a high precision accuracy. This chapter's focus lies on the development and improvement of both a link quality prediction model using both classification and regression.

6.1 Applications of Link Quality Prediction

Each of the following applications can support both current and upcoming space operations. All applications focus on the reduction of resource and energy consumption to enhance the outcome of space missions drastically.

6.1.1 Identification of Environmental Correlations

The collected information about satellite link quality can be set into relation with environmental data to identify correlations between environmental conditions and their impact on link quality. The ground station network can therefore be utilized as very large distributed sensor cluster.

Environmental variables which will be taken into account cover:

- *Space weather*: Solar bursts, ion storms and similar space weather conditions do have a heavy impact on space communication links. Large ground-bounded sensor clusters and satellite missions for measuring space weather provide detailed information about the current situation in space.

- *Earth weather*: Rain, humidity, snow and other well-known earth weather conditions also do affect radio communication. Not only the weather on ground but also the conditions within the stratosphere, mesosphere and ionosphere have to be taken into account.

- *Atmospheric effects* : Atmospheric gases in different layers can have impact on radio links whereas higher frequencies are more susceptible. Effects like ice crystals in higher atmospheric layers are taken into account.
- *Astronomical circumstances*: The positions of sun and moon play an important role amongst other geographical and temporal circumstances in the condition of radio links. Therefore their relative positions have to be taken into account.

Actually not being an environmental variable but having perhaps the largest influence on link quality are communication parameters like carrier frequency, bandwidth, applied modulation and encodings, filters and many others.

The resulting calculation model establishes the base for further investigations on environmental impacts on one hand and quality predictions on the other hand.

6.1.2 Rapid Orbit Determination

When new spacecrafts are exposed into their designated orbit by a launch vehicle, their exact position and even the orbit is not known. It can take up to several days until institutions like the North American Aerospace Defense Command (NORAD) have clearly identified the new spacecraft in orbit and provide the exact orbital elements (the Keplerian Elements) defining the position and attenuation of an object in space. The worst situation is that no communication can be established to the spacecraft during that time. The first hours and days in orbit are the most important ones since most problems occur during that time [Chouraqui et al., 2003]. A significant amount of space mission failures have been a consequence of no communication possibilities between ground station and spacecraft causing enormous losses of investment, both time and resources.

Taking these circumstances and the fact that institutions like NORAD are under governmental control into consideration points to the need for an independent, reliable process for rapid orbit determination.

An algorithm shall be proposed, modeled, simulated and approved for the automated orbit determination by utilizing the ground stations participating in GENSO and the model derived from former quality considerations. The algorithm is intended to reduce the time for gaining a precise orbit from several days to a couple of hours and therefore significantly support future space mission.

6.1.3 Optimization of Mission Data Return

Based on the aggregated information of satellite link quality and current environmental conditions a short-term prediction model will be designed. Not only the useful booking of ground stations is going to be optimized but also the probability of successful space links is dramatically raised.

This raises the amount of retrievable satellite data during nominal operation significantly and can even play a major role in the success of a whole mission in critical situations wherein time is the most important factor.

6.1.4 Identification of Imprecise Ground Stations

By reversing the model for short-term prediction of the link quality and investigating on differences between the predicted and effective link quality after the pass of a spacecraft has taken place, ground stations with receiving and transmitting capabilities below the predicted level can be identified.

The ground station operators are informed about problems with their communication hardware which offers the possibility of having a low-cost calibration facility for non-commercial ground stations. In parallel the ground stations are downgraded within the network to avoid the use of broken or imprecise ground stations in critical situations.

6.1.5 Determination of Spacecraft Condition

Based on the model for prediction of the satellite link quality anomalies in a spacecraft's behavior and its health status can be (indirectly) identified and counter-measured. Not only signal weaknesses and anomalies can be identified but also orbit deviations. The orbit information can be automatically re-adjusted by applying a prediction algorithm as for the rapid orbit determination after a spacecraft launch.

6.2 Feature Vector Composition

Due to their design, small satellites are equipped with comparable low-powered communication facilities as their production of energy is limited by the small area of solar panels. These limits cause the up- and downlink to be very vulnerable to environmental influences and imprecise ground antenna calibration. It also causes low horizon passes to be very error-prone as the distance between the satellite and the ground station is highest at that constellation.

All in all, it can be said that communication time with the satellite at a decent quality is very valuable. Therefore it would be interesting for a ground station operator to know which factors are responsible for a bad link quality and which link quality can be expected for a future pass. With this information, the efforts of tracking unpromising passes can be saved. These questions become particularly important when several ground stations share their hardware and the ground station's ressources could be used in a more efficient way in the mean time.

Therefore, we want to find out which environmental factors have an impact on the quality of the communication link between a satellite and a ground station. For this purpose, surface and space weather information, as well as the data of over 1800 satellite passes is analyzed. Furthermore, we attempt to create models for the link quality to be expected of a satellite pass knowing the environmental conditions. We do not take into account quality differences due to different hardware (e.g., better antennas) or software (e.g., better communication protocols). In fact, only one satellite and one ground station were used to obtain data for the analysis of the link quality. The hardware and software environment of the satellite and the groundstaion were kept fixed, except for non-intentional wear of the equipment. The observed satellite sends in the ultra high frequency (UHF) band.

In this section we define the setting and the goals of the link quality prediction problem. We specify how the signal strength measurements were recorded and preprocessed and how the link quality information was extracted from them. Furthermore, a description of the available environmental variables, i.e., surface weather and space weather, is given. We also report on the scientific approach we use to solve the problem.

6.2.1 Measurements

We measure the quality of the communication channel between a satellite and a ground station. The satellite regularly emits peaked, so-called *beacon signals* in short intervals which can be received by the ground station. Besides the satellite's signals, the ground station also receives background noise. Thus, the link quality can be measured with the signal-to-noise ratio. For this purpose, the strengths of the received signals are recorded for every pass of the satellite during the observation period. In total, we analyzed the measurements of approximately 1800 passes between June 2008 and April 2009.

The satellite which has been tracked and sensed was Aalborg University's AAUSAT-II CubeSat which has been launched in April 2008. AAUSAT-II and most of all other academic spacecrafts [Klofas et al., 2008] operate within the radio amateur UHF frequency band around 437 MHz and use (Audio) Frequency Shift Keying (AFSK) respectively a modification (like Minimum Shift Keying (MSK) [Pasupathy, 1979] in case of AAUSAT-II). The transport protocol currently driven, is AX-25 [Parry, 1997]. The beacon length is 1.6 seconds and is transmitted every 30 seconds at 437.432 MHz (MSK 1k2 1200 Hz/1800 Hz, FM). The satellite is equipped with an omni-directional antenna. Doppler shift [Ali et al., 1998] can be up to 25 KHz and requires continues frequency adjustments during the pass. The satellite is operating in low Earth orbit in a height of 615 to 634 km and orbits Earth almost 15 times a day. As a consequence the maximum communication timeframe during a pass is less than 15 minutes and the amount of beacons which can be recorded is about 30. A peculiarity of the measured satellite is its rotation around itself, which can be described as 'tumbling'. AAUSAT II is still operating for more than 20 months at the time of writing and the battery and solar cell degradation is minor. The overall signal loss following the link budget calculation is 17,2dB.

The ground station hardware operating at Aalborg University (57.01°North, 9.99°East) consists of two typical CP-30 circular YAGI antennas [Stearns, 2008] (14,2dB gain) as they are used for receiving and sending within the radio amateur frequency band at 434–437 MHz (UHF). The radio hardware used for receiving the beacon signals is an ICOM IC-910 [Lorek, 2001]. During a pass, the antenna tracks the satellite degree-wise by changing its azimuth and elevation angles such that it is always pointing at the satellite. In the middle of a pass, the distance to the satellite reaches its minimum and the elevation angle of the antenna is at its maximum. The signal strength over the course of a pass is determined by reading out the S-Meter indication value [Dinger and Paine, 1947] via the RS-232 control connection of the radio. The sample rate is 8 samples per second.

6.2.2 Preprocessing

For every recorded satellite pass, we separate the beacon signals from the background noise in the S-Meter readings. Each recording sample indicates the current signal strength as measured by the radio. During 'silent' periods, i.e., between two beacon signals, the recorded samples reflect the background noise in the direction the antenna points at the specific moment.

We use k-means clustering (with $k = 2$) to separate the data into two subsets according to a threshold for the S-Meter value that is individual for every measurement (see Sect. 6.3.7 for details about clustering). We initialize the first cluster (noise) with the minimum value of the data and the second cluster (signal) with the maximum. This separation allows to determine the mean noise level of a measurement. We further determine the peaking values of the measurement by locating the local maxima of the separated signal. The application of these steps to a raw measurement can be seen in Fig. 6.1.

This figure also illustrates the 'tumbling' of the satellite. Usually, one would expect that the strength of the signal increases as the distance to the satellite decreases until the middle of the pass and then decrases as the distance increases again. However, due to the rotation of the satellite, the satellite is not always transmitting directly in the direction of the ground station with its own antenna, as it is actually supposed to be. This means that the signal strength at some peaks is lowered by the amount of signal that gets lost due to the deviations of the sending satellite.

In signal processing, the signal-to-noise ratio in dB is usually given by

$$\mathrm{SNR[dB]} = 10\log_{10}\frac{P_{\text{signal}}[dBm]}{P_{\text{noise}}[dBm]} = L_{P_{\text{signal}}[dBm]} - L_{P_{\text{noise}}[dBm]} \quad . \tag{6.1}$$

where P denotes the power of the signal. The power of the noise is given by the mean noise level. For the power of the signal we pursue a different approach. The average signal strength is not an adequate measure for the signal strength—we are actually interested in the highest possible signal strength during a pass. However, the maximum signal strength would not be a fair estimate of the amplitude since the satellite's 'tumbling' might lower the signal strength at a local peak. We therefore estimate the amplitude of the signal by the mean of the c highest peaking values. The choice $c = 5$ turned out to be appropriate for a smoothed estimate.

In our machine learning context, we prefer a different representation of the signal-to-noise ratio, namely the direct quotient

$$\mathrm{SNR} = \frac{P_{\text{signal}}}{P_{\text{noise}}} \quad . \tag{6.2}$$

We suppose that it is more transparent for our machine learning process if both influences to the compound quantity are treated in a linear manner. We have verified that this representation does not worsen our results. To the contrary, we recognized that classification results are marginally better using our representation.

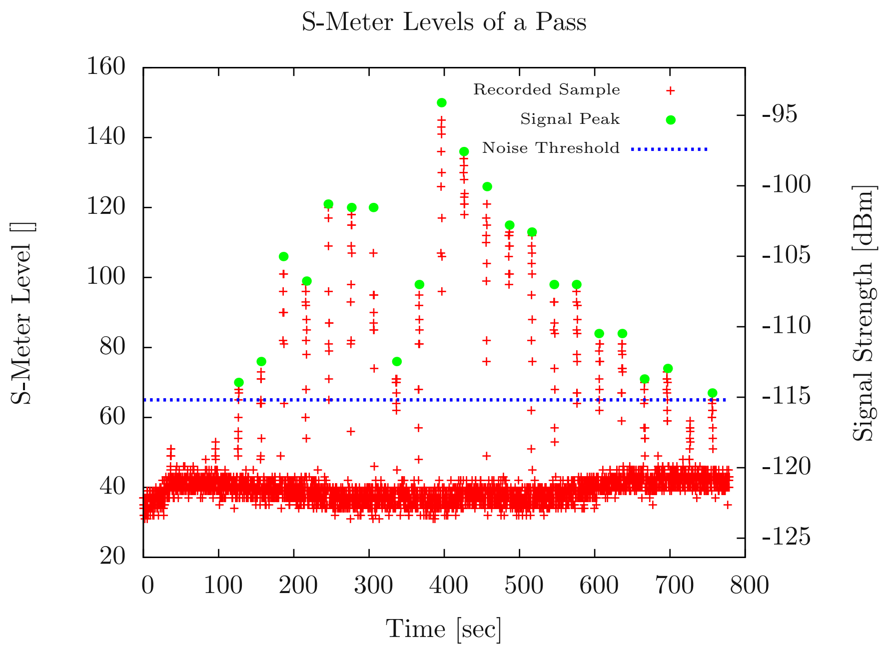

Figure 6.1: This diagram shows the course of the signal strength in S-Meter levels (left) and as dBm (right) of a typical satellite pass consisting of 5900 S-Meter samples. The noise floor can be separated from the actual signal. Also, the peaks of the signal can be determined.

6.2.3 Shortcomings

Some of the measurements have to be excluded because of measurement errors. In some cases it is not possible to determine a meaningful boundary between noise and signal. Those are also excluded. This mostly concerns measurements where the maximal elevation of the antenna was very low and therefore adds a minor bias to our experiments. However, this should not affect the overall results of our work. It must also be noted that the observed satellite rotates around its axis and therefore shows a tumbling behavior that got stronger towards the end of the observations. This results in a periodical change in the signal strength.

Fig. 6.2 shows the SNR measurements over the course of the measurement period. It can be noticed that in the middle of the measurements the SNR values are significantly lower than the others with the exception of a sudden peak. These irregularities can be attributed to hardware changes in the ground station that were performed at that time. Such influences cannot be handled in principle with our models. For this reason we split the data into two datasets. The first data set contains the measurements from the beginning until the middle of October '09 and contains 553 measurements. The second data set starts in the middle of January '09 and goes until the end. It contains 739 measurements. The measurements in between are excluded from our analysis.

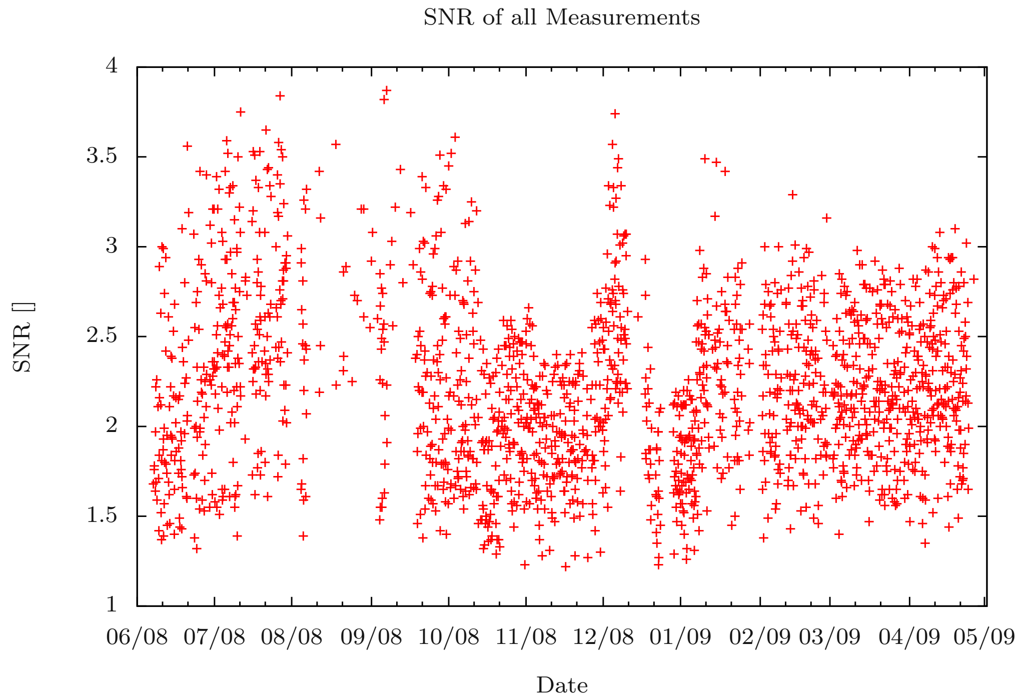

Figure 6.2: The development of the artificial SNR over the course of the measurement period. Each marker represents one single pass.

6.2.4 Attributes

For our learning tasks, several attribute values of features are available to the learner. These attributes give information about side conditions of a pass that might influence the link quality. We included measurements of the surface weather because it is a common experience that certain weather conditions lead to better or worse radio link quality. We also believe that weather-like conditions above the atmosphere in the environment of the satellite could play a similar role which is why we also included space weather information. A third group of attributes deals with the location of the satellite. Table 6.1 lists all attributes and gives a short description for each. The type of the attribute is also given: 'c' stands for continuous (real-valued), 'n' for nominal and 'b' for binomial. In total, we collected 41 attributes.

The surface weather information is taken from observations at Aalborg airport with a measuring interval between 10 to 60 minutes taken from the METAR data from the National Weather Service[1].The attributes rain and fog were taken from the National Climatic Data Center's (NCDC) Global Surface Summary of Day data for Aalborg[2].

With the notion of space weather, several changing environmental conditions in near-

[1]http://weather.noaa.gov/weather/metar.shtml
[2]http://www.ncdc.noaa.gov/oa/gsod.html

Earth space are aggregated. We think that it seems plausible that influences from the sun like solar wind, particles coming from the sun, changes in the interplanetary magnetic field and sunspot activity have impact on the radio communication for LEO satellites. The space weather data ist taken from the Space Weather Prediction Center (SWPC). We use the Real-Time Solar Wind (RTSW)[3] data which is available hourly. These measurements were taken by the Advanced Composition Explorer (ACE)[4] spacecraft which has several instruments on board . Furthermore, we use the Daily Solar Data and the Daily Particle Data[5].

For every pass, we determine the corresponding attribute values by finding those measurements and observations that are temporally closest to the pass. Unless noted otherwise, all attributes—except the classification and regression labels—are normalized beforehand by Mahalanobis scaling (see Sect. 6.3.3).

Location		
minimal distance	c	minimal distance between the satellite and the ground station during the pass according to the satellite's Keplerian elements and the ground station's location
maximal elevation	c	maximal elevation angle of the observing antenna during the pass
day	b	indicates if the measurement was taken at night or during the day, i.e., on which side of the Earth relative to the sun the satellite was located
Surface Weather		
temperature	c	measure of the kinetic energy of the air
dew point	c	temperature at which at which vapor condenses into water
humidity	c	relative amount of water vapor in the air
sea level pressure	c	weight of air above the surface, normalized to sea level
visibility	c	distance at which an object or light can be clearly discerned
wind speed	c	speed of the movement of air
conditions	n	describes the overall weather condition, e.g. 'partly cloudy'
fog	b	indicates whether there was fog on the same day
rain	b	indicates whether there was rainfall on the same day

[3]http://www.swpc.noaa.gov/ftpmenu/lists/ace2.html
[4]http://www.srl.caltech.edu/ACE/
[5]http://www.swpc.noaa.gov/ftpmenu/warehouse.html

Space Weather hourly		
differential electron flux	c	differential electron flux at 38–53keV and 175–315 keV, measured by ACE's Electron Proton and Alpha Monitor
differential proton flux	c	differential proton flux at 47–65 keV, 112–187 keV, 310–580 keV, 761–1220 keV and 1060–1910 keV, measured by ACE's Electron Proton and Alpha Monitor
anisotropy index	c	measures the degree of the anisotropy (i.e., 'directedness') of the flux measurements
IMF value	c	position of the interplanetary magnetic field in GSM coordinates (X, Y, Z, latitude, longitude) and the component magnitude, measured by ACE's Magnetometer
integral proton flux	c	integral flux of high-energy solar protons at >10 MeV and >30 MeV, measured by ACE's Solar Isotope Spectrometer
solar wind	c	proton density, bulk speed and ion temperature, measured by ACE's Solar Wind Electron Proton Alpha Monitor
Space Weather daily		
proton fluence	c	daily integrated particle flux for protons of energies >1 MeV, >10 MeV and >100 MeV, measured by GOES-11
electron fluence	c	daily integrated electron flux for electrons of energies >0.6 MeV and >2 MeV, measured by GOES-12
neutron monitor	c	relative amount of neutrons compared to the background particle flux, measured with a neutron monitor
radio flux	c	solar radio flux at a wavelength of 10.7 cm
sunspot number	c	the Space Environment Services Center (SESC) sunspot number is an estimate for the number of sunspots
sunspot area	c	sum of the area of all observed sunspots measured in millionths of the Sun's visible hemisphere
new regions	c	number of new sunspot groups (regions)

Table 6.1: Overview of Attributes

6.2.5 Methodology

We aim at predicting the expected link quality of a pass given a set of attributes that describe the side conditions of each pass. We assume the quality to be given by the SNR. We consider both, a regression and a classification task. The regression task consists of finding a function that approximates the SNR. For the classification task, a class label is created out of the SNR values by performing a clustering with a fixed number of clusters in order to get a natural partition of the data. This nominal value of the class label is the target to be predicted. For the evaluation of a model's performance we use 10-fold cross-validation. We compare regression performance with the root-mean-square error (RMSE) and classification performance with the accuracy. We further want to find out which features are important by feature selection.

In some cases, a special kind of preprocessing is applied to the SNR, namely a distance correction which is described in detail in Sect. 6.4.1. This 'normalized' SNR will be denoted as SNRn and is used in experiments that demonstrate the effectiveness of the approach regardless of the linear influence of the distance.

6.3 Machine Learning Techniques

In the following, we describe the techniques from the field of machine learning as well as statistics that we apply for the impact evaluation and prediction of the link quality. In particluar, we specify the concepts of regression, classification and clustering and describe the corresponding algorithms we use for our task. The concepts introduced in the following are taken from [Bishop et al., 2006].

6.3.1 Statistical Measures

In the following, we recapture some empirical statistical measures of data sets to clarify our notation and arguments. Let $x = (x_1, \ldots, x_n)$ and $y = (y_1, \ldots, y_n)$ be n observed values of two features. The (arithmetic) mean of x is given by

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \ . \tag{6.3}$$

The variance of x is

$$\sigma_x^2 = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2 \tag{6.4}$$

and the standard deviation is given by

$$\sigma_x = \sqrt{\sigma_x^2} \tag{6.5}$$

and measures the average deviation from the mean value.

The covariance of the two features x and y is given by

$$s_{x,y} = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y}) \ . \quad (6.6)$$

and is a measure of how much two variables change together.

A normalized form of the covariance is the correlation coefficient of which is given by

$$r_{x,y} = \frac{s_{x,y}}{\sigma_x \sigma_y} \ . \quad (6.7)$$

The correlation coefficient is a statistical measure for the degree of linear dependency between two random variables. Furthermore it holds that $r_{x,y} \in [-1, 1]$. The absolute value of $r_{x,y}$ is 1 if the pairs (x_i, y_i) $(1 \leq i \leq n)$ lie on a straight line in the two-dimensional x-y space, regardless of the slope of the line. If the line is ascending, the coefficient is 1 and if the line is descending the coefficient is -1. The smaller the absolute value gets, the more noise is present in the measurements or the smaller is the linear dependence.

6.3.2 Simple Linear Regression

Simple linear regression is a method to exploit the linear dependency between two features which allows to predict the value of the second feature when only the value of the first feature is known. Let $x = (x_1, \ldots, x_n)$ and $y = (y_1, \ldots, y_n)$ be two features that show a linear dependence of the form $y \approx \beta_0 + \beta_1 x$. Our goal is to approximately find the line on which the data points lie in the x-y space. The offset of this so-called regression line is given by β_0 and the slope by β_1. The function $y(x_i) = \beta_0 + \beta_1 x_i$ then gives us the approximation of y_i given x_i.

We can model this situation with

$$y = \beta_0 + \beta_1 x + \varepsilon \quad (6.8)$$

where $\varepsilon = (\varepsilon_1, \ldots, \varepsilon_n)$ is the error term that measures the deviation of the approximation from the target value.

In our choice of parameters β_0 and β_1 we want to minimize the error due to the linear approximation with regard to an error function. We choose the sum-of-squares error function given by

$$E(\beta_0, \beta_1) = \sum_{i=1}^{n} \varepsilon_i^2 = \sum_{i=1}^{n}(y_i - (\beta_0 + \beta_1 x_i))^2 \ . \quad (6.9)$$

Geometrically, this choice of error function means that the regression line should fit the points in the x-y space as close as possible.

We can obtain the minimum of the error function by setting its derivates to zero:

$$\frac{\partial E(\beta_0, \beta_1)}{\partial \beta_0} = 0 \qquad \frac{\partial E(\beta_0, \beta_1)}{\partial \beta_1} = 0 \quad (6.10)$$

The solution to this problem is given by

$$\beta_0 = \bar{y} - \beta_1 \bar{x} \tag{6.11}$$

and

$$\beta_1 = \frac{s_(x, y)}{\sigma_x^2} = r_{x,y} \frac{\sigma_y}{\sigma_x} \quad . \tag{6.12}$$

The least-squares approximation obtained from our choice of the sum-of-squares error function corresponds to the maximum-likelihood model. The idea of simple linear regression can be enhanced to more than one attribute. In this case the target y is approximated by a linear combination of features $x^{(1)}, \ldots, x^{(m)}$:

$$y \approx \beta_0 + \beta_1 x^{(1)} + \ldots \beta_m x^{(m)} \quad . \tag{6.13}$$

However, the maximum-likelihood approach for regression is sensitive to outliers. Therefore it is often considered as a baseline method for regression tasks.

6.3.3 Mahalanobis Scaling

With Mahalanobis scaling [Mahalanobis, 1936] we perform a kind of normalization to transform the values of a feature $x = (x_1, \ldots, x_n)$ into $x' = (x'_1, \ldots, x'_n)$. The corresponding formula is

$$x'_i = \frac{x_i - \bar{x}}{\sigma_x} \tag{6.14}$$

which gives $\bar{x'} = 0$ and $\sigma_{x'} = 1$. Mahalanobis scaling is a necessary preprocessing step in order to have comparable magnitudes for the different components of the feature vector. This is a requirement for most machine learning algorithms in order to allow for equal treatment of the different features.

6.3.4 Regression

We are given N observations of x together with observations of t. We wish to find a functional dependency between x and t, i.e., a continuous function y that approximates t given x. An optimal regression function always provides the correct prediction, i.e., $y(x_i) = t_i$. The divergence of a single prediction from the real value is given by $t_n - y(x_n)$.

The root-mean-square error of such a function y is given by

$$E_{\mathrm{RMS}} = \sqrt{\frac{1}{N} \sum_{n=1}^{N} (y(x_n) - t_n)^2} \quad . \tag{6.15}$$

The RMSE gives the average error, i.e., the magnitude of the difference to the actual value, that can be expected when relying on the predictions of y. The lower the RMSE, the better is the approximation of the target value t by the function y. In contrast to other error measure, like for example the sum-of-squares error, the RMSE is measured on the same scale as the target value.

6.3.5 Classification

In a classification task, we are given N observations of x together with class labels t. We wish to find a classifier that decides in favor of one of the classes given x. An optimal classifier always outputs the correct class for an observation.

For the performance evaluation of a classifier, it is first trained on a training set of data. After that, its class predictions on a distinct test set are determined. The accuracy is ratio between the number of correct classifications and the size of the test set. An accuracy of 100% means that the classifier could perfectly predict the target values of the test set.

If the classes to predict are not equally distributed in the data, the accuracy might be biased towards the larger class. More insight can be gained by looking at the confusion matrix that allows the evaluation of the classifier for each class separately. The confusion matrix is given by the number of samples for every possible combination of the actual class label and the predicted class label. The typical layout of such a matrix is given in Table 6.2 where the two classes C1 and C2 are considered. C1 is referred to as the positive class in this example.

Table 6.2: Confusion Matrix

		true class	
		C1	C2
predicted class	C1	tp (true positives)	fp (false positives)
	C2	fn (false negatives)	tn (true negatives)

With this matrix, the measures precision and recall can be defined for each class. The precision of a class is the ratio between the number of samples that were predicted as class members and really belong to this class and the total number of samples that were predicted as class members. The recall gives the ratio between the number of samples that are actual class members and correctly predicted and the total number of samples that actually belong to this class. This means that the precision is computed for the rows of the matrix and the recall is computed for the columns. In our example, the overall accuracy and the precision and recall for C1 are given by:

$$\text{Accuracy} = \frac{\text{tp} + \text{tn}}{\text{tp} + \text{tn} + \text{fp} + \text{fn}} \tag{6.16}$$

$$\text{Precision} = \frac{\text{tp}}{\text{tp} + \text{fp}} \tag{6.17}$$

$$\text{Recall} = \frac{\text{tp}}{\text{tp} + \text{fn}} \tag{6.18}$$

6.3.6 Cross-Validation

In machine learning, generalization, i.e., a good performance on data that has not been previously available to the learner, is a general goal. For this purpose, the performance of a learner is usually reported on a test set that is distinct from data set that was used to train the model. For the evaluation of the performance of our models in the learning tasks, we use the technique k-fold cross-validation.

For k-fold cross-validation, the data set is split into k distinct subsets of equal size. The following validation process is then repeated k times: In the i-th run, the i-th subset is used as the test set. The other $k-1$ subsets are used as the training set. After training, the predictions of the learner on the test set are determined and stored. After k runs, every data point was used for testing exactly once. The overall classification or regression result is given by the accumulated results of every run.

In the case of regression, we use shuffled sampling which means that the assignment to the subsets is randomly (and not according to the temporal order of the data points). In the case of classification we use stratified sampling to determine the partition of the data set which means that in addition to randomness every subset has the same distribution of classes. The choice $k = 10$ seems reasonable for our data set as it ensures that the training set is always large enough and makes random successes of a learner improbable.

6.3.7 Clustering

In contrast to classification, the objective of clustering is to find structure in data without the a-priori knowledge of a class label. In this context, a *cluster* is a group of data points. Usually, the goal is to assign clusters in a 'natural' way, i.e., the similarity of data points within a cluster should be high and the similarty to data points outside a cluster should be kept small. Often, as in our application, the number k of clusters that should be determined is fixed. If the data points are feature vectores, a common measure for similarity is the Euclidian distance.

One of the popular clustering algorithms is k-means. The idea of k-means is to constantly change the cluster assignment such that every data point is assigned to the cluster to which it is nearest until the cluster assignment does not change any more. Algorithm 1 shows in more detail how k-means works. Due to the randomness involved in the initialization of the algorithm, it is a common practice to run the algorithm several times with different initializations.

We use k-means with $k = 2$ to separate the signal from the background noise in the S-Meter readings. In that case, the initialization of the first cluster with the minimum value of the data and the second cluster with the maximum turned out to work well. For determining class labels from the SNR values, we also use k-means with $k = 2$ and $k = 3$.

6.3.8 Support Vector Machines

Support vector machines (SVM) are based on the idea of separating two classes by a hyperplane such that the margin of the hyperplane to the data points is maximal. Those data points that have the least distance to the separating hyperplane are called support vectors. If the data points are not linearly separable, the data points can be transformed to a higher-dimensional so-called feature space. Due to the kernel trick it is usually not

Input: data $X = \{x_1, \ldots x_n\}$, number of clusters k
Output: partition $S_1 \cup \ldots S_k$ of X

```
t ← 0
m^t ← initialize(X)
while m^t ≠ m^{t-1} do
    foreach 1 ≤ i ≤ k do
        S_i^t ← ∅
    end
    foreach x_j ∈ X do
        c ← arg max_{1≤i≤k} ||m_i^t − x_j||
        S_c^t ← S_c^t ∪ x_j
    end
    t ← t + 1
    foreach 1 ≤ i ≤ k do
        m_i^t ← mean(S_i^t)
    end
end
S_i ← S_i^t
```

Algorithm 1: This is the k-means algorithm for partitioning a set of data into k clusters. Note that we operate on multisets which allow multiple entries of the same value. The set of cluster centers for a step t is denoted by $\mathbf{m}^t = (m_1^t, \ldots m_k^t)$ and the assigned clusters are given by the partition $S_1^t \cup \ldots \cup S_k^t$. Every data point is assigned to the cluster for which the Euclidian distance to the cluster center is the smallest. After the assignment, the new cluster centers are computed as the mean of the newly assigned clusters. The initialization of $\mathbf{m}$ is done by randomly choosing k distinct values from the data set.

necessary to explicitly give the transformation function. Instead, it is sufficient to define an appropriate kernel function that directly measures the similarity that two vectors of the input space have in the feature space. Popular kernel functions are the linear, polynomial, Gaussian (RBF) and sigmoid kernels.

Another approach to deal with non-linearity is to allow misclassification as well as data points within the margin, which yields a so-called soft margin. These ideas are implemented in C-SVM and ν-SVM where C and ν are penalty terms that quantify the degree of misclassification that should be allowed.

It is possible to adapt the idea of SVMs to regression problems. The interested reader is referred to the literature [Bishop et al., 2006] and to appendix A for an introduction to ε-SVM and ν-SVM for regression.

In general, SVMs proved to perform better than other paradigms, such as neural networks or decision trees, for the classification and regression tasks on our data sets. In the case of regression, ν-SVM showed the best performance (with $\nu = 0.5$), whereas C-SVM performed best for classification. Furthermore, the linear kernel, which is basically the dot product in the input space, and the RBF-kernel appeared to be the best choices. The corresponding formulas for these two kernels are

$$k_{\text{lin}}(x, y) = x^T \cdot y \tag{6.19}$$

and

$$k_{\text{RBF}}(x, y) = e^{-\gamma \|x-y\|^2} \ . \tag{6.20}$$

For the RBF-kernel we relied on the heuristic formula

$$\gamma = \frac{1}{N} \tag{6.21}$$

where N is the number of attributes. The parameter C was chosen in exponential steps until an optimum could be found. For the regression tasks we used $C = 10$, unless noted otherwise.

6.4 Results

The following results could be obtained for the first dataset. We report shortly on the results for the second dataset in Sect. 6.4.5. The machine learning experiments were carried out with RapidMiner (formerly YALE), an environment for machine learning and data mining experiments [Mierswa et al., 2006].

6.4.1 Feature Correlations

In this section we analyze some interesting correlations that can be found in the data. Naturally, some correlations among the surface and space weather attributes occur in the data set which are not of interest here. Also the high correlation between the minimal distance and the maximal elevation with a coefficient of -0.900 can be explained with the nature of orbital movements. More interesting are the weak correlations between the SNR and three of the surface weather attributes: temperature, dew point and wind speed. Further weak correlations can be found for the space weather attributes radio flux, sunspot number, sunspot area, IMF X and proton density. The correlation coefficients for the most correlating attributes are given in Table 6.3.

The strongest correlation, with a coefficient of -0.751, can be found between the minimal distance and the SNR. This allows the approximation of the SNR with a linear function of the minimal distance. We determine this function with simple linear regression taking the minimal distance as the x-value and the SNR as the y-value. The approximation presents itself as

$$\text{SNR} = 3.35 - 0.632 * d \tag{6.22}$$

where d is the minimal distance in 10^3 km. The corresponding regression line is shown in Fig. 6.3. Remarkable is the strong deviation of the single measurements to the approximation which indicates that other influences are subject to also have an impact on the SNR.

Table 6.3: Correlation Coefficients Between Selected Features and the SNR/SNRn

attribute	correlation with SNR	SNRn
minimal distance	−0.751	−0.002
maximal elevation	0.746	0.108
temperature	0.113	0.233
dew point	0.276	0.410
wind speed	−0.162	−0.182
IMF X	−0.149	−0.206
proton density	0.128	0.183
radio flux	−0.085	−0.152
sunspot number	−0.124	−0.186
sunspot area	−0.122	−0.190

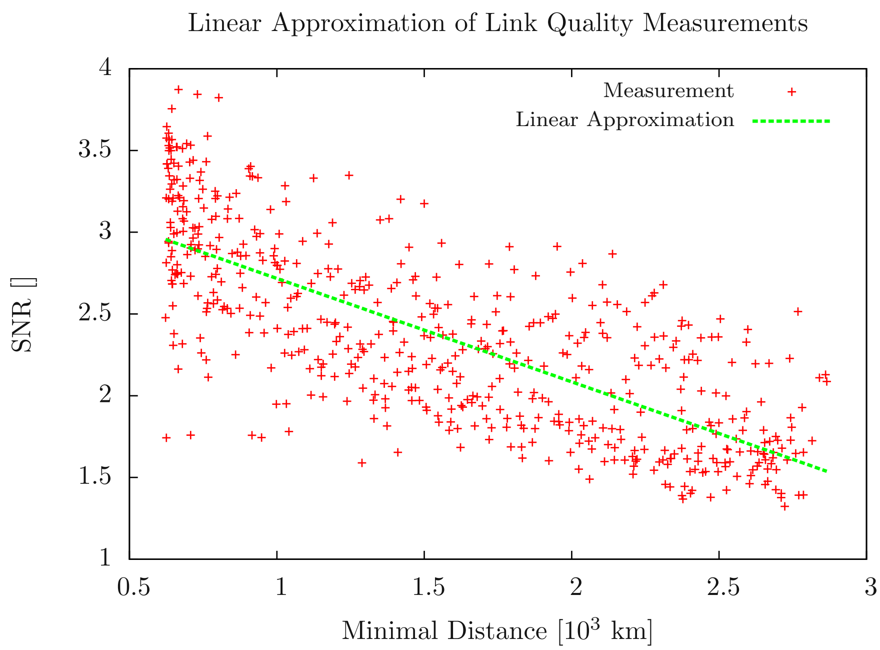

Figure 6.3: This diagram shows the relation between the minimal distance of a satellite pass and the corresponding artificial SNR. A linear, least squares approximation of the link quality is possible.

The linear approximation by the minimal distance can be seen as a baseline for more sophisticated models. Furthermore, the influence of the distance to the link quality can be factored out. The 'normalized' value is determined by the difference between the actual value and the prediction by the linear model:

$$t_i' = t_i - y(x_i) \ . \tag{6.23}$$

This distance corrected value will be denoted as SNRn. The surface and space weather attributes show higher correlations for the SNRn than for the SNR which can be seen in Table 6.3. The dependency between the two surface and space weather attributes with the highest correlations and the SNRn is visualized in Fig. 6.4.

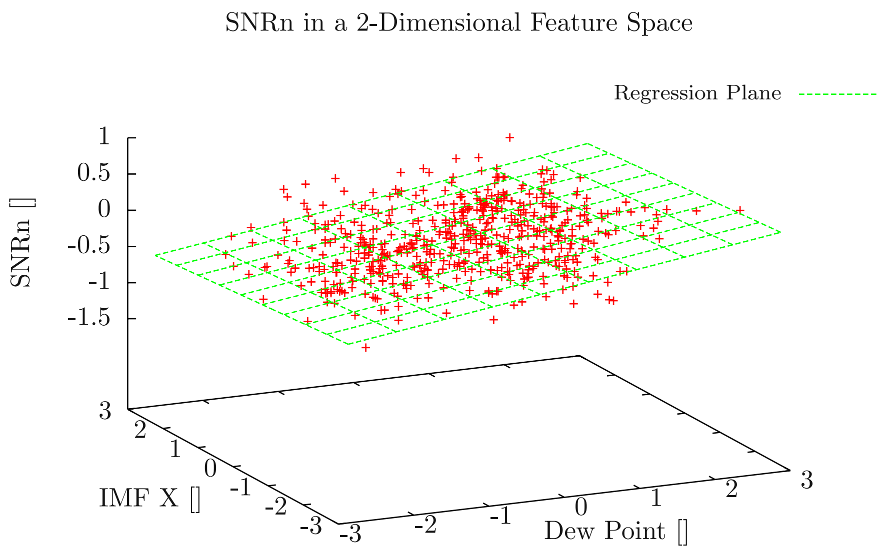

Figure 6.4: This diagram shows the dependency of the distance corrected SNRn on the most correlating surface weather and space weather attribute. The plane that approximates the SNRn given the two attributes according to multiple linear regression is also drawn. The two attributes are normalized with Mahalanobis scaling.

We also notice a correlation between the SNRn and the location of the ACE measurement satellite for the space weather which is given by its GSE coordinates. The coefficients are:

- X-coordinate: -0.144
- Y-coordinate: 0.493
- Z-coordinate: -0.186

This seems quite remarkable, however, no underlying cause that affects the SNR as well as the measurement satellite's coordinates could be found yet. As these coordinates actually do not represent a space weather condition, they have not been included in the set of attributes available for learning.

6.4.2 Clustering Results

We analyzed the SNR value we extracted from the measurements with the k-means clustering technique. Fig. 6.5 shows the distribution of the SNR. The SNR has a range of 1.323 to 3.873 with a mean of 2.357 and a standard deviation of 0.577. With a 2-means clustering we can separate the two clusters at the threshold 2.430. For the 3-means clustering the borders appear at 2.0825 and 2.7885.

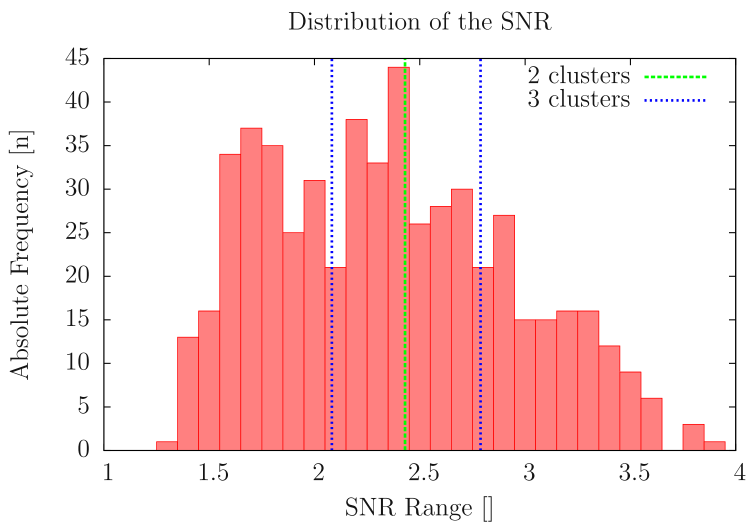

Figure 6.5: This diagram shows the distribution of the SNR value. The class boundaries resulting from clustering are also marked (green line for the case of 2 clusters, blue lines for the case of 3 clusters).

The same is done for the distance corrected SNRn value. The SNRn has a range of -1.210 to 0.980, a mean of 0 by construction and a standard deviation of 0.381. Fig. 6.6 shows the corresponding distribution. The two clusters occuring with 2-means clustering can be separated at the value 0.0175. In the case of three clusters the borders can be set at -0.133 and 0.314.

The resulting clusters are used as class labels to define classification tasks with two and three classes. The classes are labelled 'low' and 'high' in the case of two clusters and 'low', 'medium' and 'high' in the case of three clusters. The corresponding class distributions are shown in Table 6.4.

Table 6.4: Class Distributions

	2 classes		3 classes		
value	low	high	low	medium	high
SNR	318	235	197	223	113
SNRn	292	261	235	195	123

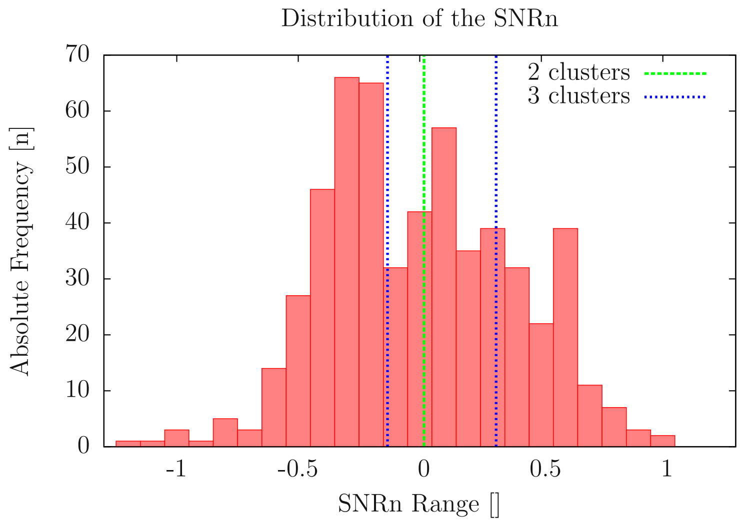

Figure 6.6: This diagram shows the distribution of the distance corrected SNRn value. The class boundaries resulting from clustering are also marked (green line for the case of 2 clusters, blue lines for the case of 3 clusters).

6.4.3 Regression Performance

Regression of the SNR.

First, we aim at finding a function that predicts the value of the SNR. The standard deviation of the SNR is 0.577 which corresponds to the RMSE that would be obtained by constantly giving the mean of the SNR as the prediction. This means that a predictive method should at least perform better (i.e. have a lower RMSE) than this naive approach.

Using the minimal distance as the only attribute, we obtain an RMSE of 0.382 with simple linear regression as described in Sect. 6.3.2.

Excluding the space weather attributes, we obtain an RMSE of 0.322 with a ν-SVM ($C = 10$). This corresponds to an improvement of 15.7% in comparison to the linear regression with the minimal distance.

The attribute dew point seems to be of special importance. Using only the dew point in combination with the minimal distance and the maximal elevation, we obtain an RMSE of 0.338 with a linear regression model. The corresponding linear combination for the full data set is given by

$$\text{SNR} = -0.2506 * d + 0.2022 * e + 0.1538 * p + 2.3569 \tag{6.24}$$

where d is the minimal distance, e the maximal elevation and p the dew point.

Under exclusion of the surface weather attributes, an RMSE of 0.335 is reached which is worse than for the exclusion of the space weather attributes. Using the full set of attributes, the RMSE is 0.308 which improves the result of the single-attribute linear regression by 19.4%.

Regression of the SNRn.

In a further experiment, we analyze the regression performance for the distance corrected SNRn value. The SNRn has a standard deviation of 0.381. First, the attributes minimal distance and maximal elevation are not available to the learner because their linear influences have already been factored out in the preprocessing for the SRNn. Excluding the space weather attributes, we obtain an RMSE of 0.333 with a ν-SVM. Using only the attributes dew point and humidity, the RMSE is 0.337 (with $C = 1000$ in this case). Under exclusion of the surface weather attributes, the RMSE is 0.348.

Taking both, space and surface weather, an RMSE of 0.323 can be obtained. With the full set of attributes, i.e., under inclusion of the attributes minimal distance and maximal elevation, an RMSE of 0.307 can be reached, thus taking into account nonlinear influences of these two attributes.

6.4.4 Classification Performance

In the following, we report on the experimental results for the classification task. We could observe that the accuracies are lower when using only the space weather attributes compared to using only the surface weather attributes. Furthermore, the classification performance could not be improved by using the full set of attributes compared to using only the surface weather attributes. Therefore, we do not report on the classification performance for the space weather attributes and consider only the surface weather attributes.

Classification of the SNR.

First, we perform the classification with two classes. A default learner that always decides in favour of the largest class reaches a classification accuracy of 57.50% for this task. With a simple decision rule that decides in favor of one of the two classes according to a certain threshold of the minimal distance, the highest accuracy is 80.12%.

The best classification result can be achieved with a C-SVM (linear kernel, $C = 1$), reaching an accuracy of 85.35%. The corresponding confusion matrix can be seen in Table 6.5.

Table 6.5: Confusion Matrix for 2-Class Classification of the SNR

	true low	true high	class precision
pred. low	283	46	86.02%
pred. high	35	189	84.38%
class recall	88.99%	80.43%	

Next, we consider the classification task with three classes. The classification accuracy of a default learner is 40.32% in this case. With a linear separation of the single attribute minimal distance by a SVM the accuracy is 63.68%.

Under exclusion of humidity and visiblity, the accuracy is 69.65% with a C-SVM (RBF-kernel, $C = 1$). The corresponding confusion matrix can be seen in Table 6.6. We notice that the class 'medium' leads to the biggest confusion in the classification. We also see that the two biggest mistakes possibly in the classification occur very seldomly: Only one example of the class 'high' was predicted as 'low' and only three examples of the class 'low' were predicted as 'high'.

Table 6.6: Confusion Matrix for 3-Class Classification of the SNR

	true low	true medium	true high	class precision
pred. low	151	49	1	75.12%
pred. medium	43	135	33	63.98%
pred. high	3	39	99	70.21%
class recall	76.65%	60.54%	74.44%	

Classification of the SNRn.

In a second step we performed the classification for the distance corrected SNRn value. For the two-class-problem the default classifier gives an accuracy of 52.80%.

Using only the attribute dew point and an SVM with RBF-kernel, the accuracy is 66.72%. The best result possible is 67.99% and can be obtained with a C-SVM (RBF-kernel, $C = 10$), excluding the attributes minimal distance, maximal elevation, daylight, dew point and conditions. A slight improvement with an accuracy of 70.16% is possible when the minimal distance and the maximal elevation are included for their non-linear influences. In this case the attributes day, dew point and rain have been excluded. The corresponding confusion matrix is shown in Table 6.7.

Table 6.7: Confusion Matrix for 2-Class Classification of the SNRn

	true low	true high	class precision
pred. low	216	89	70.82%
pred. high	76	172	69.35%
class recall	73.97%	65.90%	

Finally, we considered the three-class problem for the SNRn. Here, the accuracy of the default learner is 42.50%. Using only the attribute dew point, the accuracy of a SVM with RBF-kernel is 51.53%. With a C-SVM (RBF-kernel, $C = 10$) an accuracy of 52.27% is reached under exclusion of the attributes sea level pressure, minimal distance and maximal elevation

An accuracy of 54.27% is reached when the attributes minimal distance and maximal elevation are available for learning. The attributes day, dew point, rain and sea level pressure have been excluded in this case. The corresponding confusion matrix is given in Table 6.8. It can be seen that almost all examples of the class 'high' are predicted incorrectly. This leads to an extremely low recall of 6.50% of the class 'high' which can be improved on with other classifier paradigms, but not without lowering the overall classification accuracy.

Table 6.8: Confusion Matrix for 3-Class Classification of the SNRn

	true low	true medium	true high	class precision
pred. low	178	76	28	75.12%
pred. medium	53	114	87	44.88%
pred. high	4	5	8	47.06%
class recall	75.74%	58.46%	6.50%	

6.4.5 Second dataset

On the second dataset a regression performance of 0.204 for the SNR can be reached using simple linear regression with the minimal distance as the only attribute. The approximating function for the SNR is given as

$$\mathrm{SNR} = 3.02 - 0.467 * d \tag{6.25}$$

where d is the minimal distance in 10^3 km. The correlations between the SNR and the surface weather or the space weather are significantly smaller than for the first dataset. The regression and classification rates can only be improved marginally by providing the weather and space weather attributes. We assume that this independence of external influences could be gained with a change in the hardware setup. This would also explain the multiple structural changes of the link quality in the middle of the measurements as a side effect of the hardware being changed.

6.4.6 Discussion

It can be observed that the distance between the satellite and the ground station has the greatest impact on the link quality which coincides with the "inverse-square law" for electromagnetic waves. However, the regression performance using only this single attribute leaves space for improvement. This suggests that other influences are of importance for the link quality. Using surface and space weather information, the link quality is a learnable concept even after factoring out the influence of the distance. We find out that not all of our features are necessary to reach the best classification rates. The most important attribute concerning the surface weather turns out to be the dew point. However, we also observe that the absence of the dew point attribute can be compensated by the other attributes. The impact of the wind speed might be explained with the sensibility of the antenna of the ground station.

We see clear correlations between the space weather and the SNR. However, the benefits of the additional space weather attributes are limited. While it is possible to improve on the regression task, the performance for the classification tasks remains unchanged. A possible explanation for this effect is that the regression result improves for examples that lie far away from the decision boundary and are therefore easy to classify. We also notice that for the regression tasks, the surface weather has a higher impact on the performance than the space weather. One explanation for the higher impact of the surface weather compared to the space weather might be that the surface weather affects the SNR due to different levels of the background noise whereas the overall signal strength is influenced stronger by the distance than by space weather effects.

We see that besides the obvious linear influence of the distance to the satellite and the angle under which it is observed also non-linearities occur. Furthermore, the linear influence that we explicitly took care of with the distance correction of the SNR is adequatly presented in our learning models. The regression tasks for the SNR and the distance corrected SNRn show a nearly equal performance.

For our classification task, the class boundaries were defined by the naturally appearing clusters in the data. Of course, other definitions are also be possible and might lead to different accuracies. A possible scenario would be a simple binary decision whether the expected link quality is high enough or not. Then the ground station operator could set the threshold accordingly. However, this requires some sort of expert knowledge to decide on an appropriate threshold. The accuracy in such cases depends on the separability of the classes at the chosen threshold. Furthermore, it might be possible to modify the threshold to particularly reduce false positives or false negatives.

Still, the prediction of link quality has to take the specific EIRP of the satellite to be tracked and the performance of the tracking ground station into account. The proposed models are generally valid for satellites and ground stations similar to the ones observed and the relative impact of features is also valid for other setups, but the absolute impact of the different features on the SNR strongly relates on the link budget of the satellite.

Hence, it requires further knowledge of each satellite and ground station in order to predict the link quality accurately. The performance of ground stations can be evaluated and compared when observing the same satellite and comparing the SNR measurements. By observation of several satellites using one ground station, the different EIRPs of the satellites can be evaluated. As a consequence the application of link quality prediction in large-scale networks requires preceding observations on the different spacecrafts and entities.

6.5 Related Work

Several attenuation factors of radiowaves have already been investigated in the literature. In a survey by Panagopoulos et al [Panagopoulos et al., 2004], the attenuation factors for satellite communication in frequencies above 10GHz—namely Ku, Ka and V bands—are explained. Precipitation, gaseous absortion, clouds, the melting layer, sky noise increase, signal depolarization, tropospheric scintillations and intersystem interference are given as the main sources of attenuation. It is reported that these effects are often modelled stochastically. The importance of models that take the combined the effects of different attenuation factors into account is also emphasized.

A system which measures the link quality of satellites, called SPOCS, is introduced in [Cuevas and Rehwinkel, 1995]. The goal of the system is to make the commissioning, testing, operating, maintaining, and trouble-shooting of digital satellite links easier. The system consists of a spectrum analyzer, a digital signal analyzer and a weather monitor. With the spectrum analyzer, quality differences in the analog signal, like changes in the noise floor, can be detected. The digital signal is also analyzed for bit and block errors. The weather monitor captures several weather conditions at the ground station like temperature, humidity, amount of rainfall, wind speed and barometric pressure. It is stated that a decreased link quality can often be explained by weather conditions at the ground station. Equipment failures or operational problems are given as another source of impacts. The system also includes facilities for data management and analysis. After several weeks of measurements at a ground station, SPOCS can perform an analysis to characterize the quality of a satellite link.

6.6 Summary

The signal-to-noise ratio provided by LEO satellite passes in UHF was used to measure the link quality between a ground station and a satellite. In order to determine the impacts on the communication link quality the signal strength readings of more than 1800 satellite passes have been empirically analyzed. A linear dependency between the link quality and the distance between the satellite and the ground station during a pass has been observed, which seems kind of nature, but influences of surface and space weather conditions have also been recognized. Furthermore, machine learning techniques have been applied to create models that can predict the link quality that is to be expected given certain environmental circumstances. Models based on support vector machines showed the best performance, but simple linear regression models also showed a decent performance and have the advantage of high explanatory power. In general, the influences of the surface weather attributes for successful learning can be graded higher than those of the space weather attributes. The most important surface weather impact in this regard turned out to be the dew point.

In the evaluation of the created models it can also be seen that the current predictions still leave some room for improvement. This can be either explained with impacts not considered in the models or with the impreciseness of the link quality measurements. Further efforts could extend the set of attributes to consider other types of earth weather, e.g., stratosphere weather, atmospheric effects, e.g., ice crystals in higher atmosphere layers, and geographical cirumstances, e.g., the position of the moon that can disturb the signal for the receiver. With a special measurement satellite, which is proposed in chapter 7, a more precise quality feedback based on the bit error rate would be available for ground stations all over the planet. The actively measured bit error rate has the advantage of good comparability between heterogenous hardware and would therefore be well-suited for the proposed investigations.

The derived prediction models can also be used for reverse investigations on atmospherical and space weather conditions. When being aware of the expected link quality, other features used in first place for link quality prediction can be predicted. On a broad base this kind of passive atmospheric measurements can be performed globally using the scenario introduced in chapter 5.

Chapter 7

A Link Quality Measurement Satellite

7.1 General Overview

The proposed project introduced and discussed in detail in this chapter focusses on the design, construction, launch and operation of an orbital measurement instrument for satellite link quality. This chapter does not cover a detailed mission design and the process of system engineering as this is a very large area of itself, rather it develops a possible scenario taking the previous research results into account.

Whereas satellite link quality determination is possible when performed passively utilizing the functions of common off the shelf ground station hardware, the possibilities are limited and already exhausted. The consequential step following is the switch to active measurements. A precondition for active measurements is the control of both the facility sending and the facility receiving the measuring data sequences.

Currently no orbital measurement instrument is available focused on the active performance of satellite link quality measurements. This study is emphasizing the need for a dedicated measurement satellite and proves the feasibility of such a project.

The proposed platform for the measurement instrument is based on a standard CubeSat framework which has been launched and operated several times in the past. The minimum operational time of the measurement instrument is projected to three months, reserved for accomplishing the primary goals of the project (derivation of a high precise link quality prediction model, establishment of a measurement reference for autonomous measurements, investigating the impact of atmospheric gas concentration on satellite link quality and establishment of a link quality sensor network – see section 7.3.1). The remaining operational time of the instrument will be used, in parallel to the continuing generation of measurements for further investigations, to accomplish secondary goals and establishing several services for commercial and non-commercial operations (see section 7.3.2).

In order to perform the active link quality measurements using the proposed satellite, usual low cost COTS ground station hardware is sufficient and no expensive measurement equipment is required.

7.2 Setup

By designing a satellite which main purpose is to send and receive predetermined bit sequences for accurately evaluating the bit error rate against the time within a pass a multitude of quality parameters can be gained. In the following the design of such a satellite and its principles of function are described in detail.

7.2.1 Overview

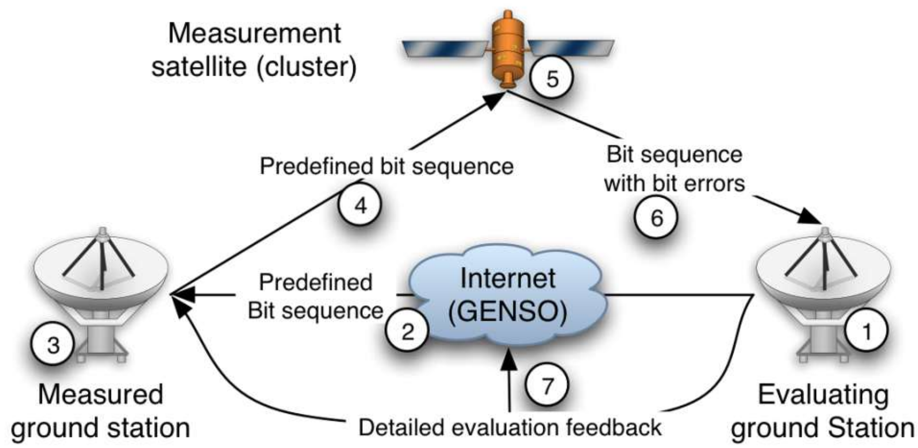

Figure 7.1: The schematic sequence of an uplink quality determination: The satellite controlling ground station (1) transfers a sequence of bits (2) to the ground station over the Internet using the GENSO system to the ground station to be measured (3). When the measurement satellite passes the ground station, the ground station continuously and repeatedly transmits the sequence of bits (4) to the satellite (5). When the satellite passes the controlling ground station (master station), it transmits the buffered bit sequences including any bit errors (6) to the station. The master station evaluates the received bits and sends a report to both the GENSO network and the measured ground station (7).

Fig. 7.1 and 7.2 draw the schematic data flow for precisely evaluating the bit error rate for a specific ground station and their up- and downlink capabilities.

In contrast to usual satellite beacons the bit sequence is sent continuously but with lower effective isotropic radiated power (EIRP). This way the satellite is able to effort the needed energy and the BER can be determined more precise when more data is going to be transmitted. For being able to synchronize and to determine start and end of a bit sequence, the satellite is not transmitting continuously but remains silent for a specific time between the transmission of the sequences.

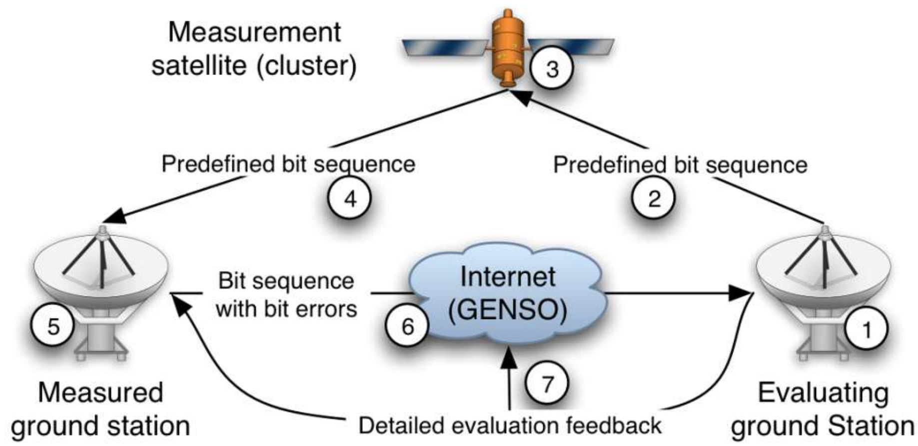

Figure 7.2: The schematic sequence of a downlink quality determination: The satellite controlling ground station (1) transfers a sequence of bits (2) to the measurement satellite when it passes the station. When the satellite passes the ground station to be measured, it continuously and repeatedly transmits the sequence of bits (4) to the station (5). The ground station then transfers the received sequences including any bit errors (6) to the control ground station (master station). The master station evaluates the received bits and sends a report to both the GENSO network and the measured ground station (7).

Due to the reduced EIRP the out-coming BER will be significantly higher as if data from common satellites is received - the same situation applies for the data sent to the satellite, as the amplification will be lower than usual. The lowered receive sensitivities and EIRP values come with a big advantage for precise measurements: Even ground stations performing very well will have a noticeable BER. If the EIRP would be higher, they would in any situation receive data with no bit errors at all, which would make their results incomparable. Lowering the threshold for significant BERs raises the limits for useful measurements significantly and will make them more precise.

The scheme remains the same for all different frequency bands, modes and also for different baud rates. For compatibility issues the application of common modulations and baud rates is recommended, whereas larger baud rates allow a more precise BER. A symbol rate of 1200 per second, a very common value for nano- and pice-sized satellite communication, with a presumed coverage of 90 percent of a pass of 5 minutes leads to more than 300.000 transmitted bits. In the next chapter it is assumed to measure in sections during a pass for more detailed reports on quality problems. If a division into, for example, 10 seconds for every measurement section is proposed, there are still about 10.000 bits for every measurement part left. This leads to a precision of 1/10.000 for the BER, which allows a very precise determination of quality. When heading for higher symbol rates, the BER becomes even more accurate.

As a matter of course no error detection or correction methods of any kind are applied on the measurement transmissions as it would be absurd. This also excludes by nature the usage of common TNCs not able to forward raw, unverified bit streams (this mode is often referred to as "modem mode" or "raw mode"). To stick to applicable rules for amateur frequencies a part of the bit sequence could be the amateur call sign of the ground station or the satellite.

In contrast to the measurements the bit sequence exchanges between the satellite and the controlling ground station (also referred to as "master ground station") take place at maximum EIRP and amplification and with added error detection or correction and at a high symbol rate. The receiving entities, both a ground station and a satellite, add additional information like time-stamps to the received data to map it to specific parts of a pass.

On a long run, when the satellite is used as ground station supervision instance in networks, the transmitted bit sequence should be changed on a regular base for avoiding a falsification of the measurement results (as it could take place to give the own ground station higher quality rates within a ground station network like GENSO, even if the outcome of such a cheating is somewhat ridiculous). For simplicity the bit sequence pattern could also be auto-generated based on a formal definition; for comparability with preceding measurements it has to be taken care for a Gaussian distribution of the different symbols and their repetition within the sequence.

As the satellite receives on only one frequency the uplink quality measurements have to be precisely scheduled to avoid overlaps but allow a high resource efficiency. In the GENSO network this can be accomplished by booking so-called active passes which support both data transmission and receiving. The master ground station transmits the bit sequences using the ground station to be measured and evaluates the data received from the satellite later on for the quality determinations.

The measurement of the receiving qualities of a ground station can take place on a broadcast basis as the master ground station can evaluate a theoretically infinite amount of measurement reports at the same time. So no scheduling of any kind has to take place but the ground station has to add additional information to the received bit sequences for advanced evaluations.

7.2.2 The Orbital Link Quality Measurement Instrument

Fundamental Design Decisions

To cover the majority of used frequency bands [Klofas et al., 2008] and therefore of available ground station constellations [Toorian et al., 2008] a design covering VHF, UHF or S-Band amateur frequency bands is proposed.

Instead of designing one small satellite carrying communication facilities for several frequency bands a growing cluster of pico-sized satellites (Cubesats [Waydo et al., 2002]) wherein each satellite covers one frequency band is preferred for several reasons:

- *Reduced costs*: The launch and deployment costs of satellites according to the Cubesat standard [Hutputtanasin and Toorian, 2005] are dramatically lower than the costs for larger satellites. Same applies to the construction costs. For the pico-satellite standard COTS components even up to bare-bones are available which significantly reduces costs for design and implementation of the satellites.

- *Approved designs*: The Cubesat standard has proven its robustness and usability in several successful missions, many of them still operating. There are tailored launch and payload facilities for pico-sized satellites making the design and deployment comparable easy. The wheel doesn't have to reinvented concerning several architectural parts - wherever possible approved components can be part of the implementation.

- *Redundancy*: Having a cluster of comparable simple satellites being responsible for quality assurance rather than only one, more complex satellite not only raises the reliability of the system but also establishes a redundancy of the service. Even if one satellite fails and has to be replaced, which typically takes a couple of months even if a substitution is already in place, the service itself (probably not covering all frequency bands any more which is a minor issue) remains stable and reliable.

- *Breakdown of complexity*: The larger a system grows, the more complex it gets usually. This rule also and particularly applies to satellite systems. Hence the use of several rather simple but robust small satellites also simplifies the complexity of the whole system. This in turn shortens the time needed for development and thus for deployment which reduces the overall risks of the project.

- *Subsystem independence*: The independent implementation of the cluster parts in form of pico satellites allows a construction in sequence whereas one large satellite would draw the need for a parallel development of its subsystems. A rather independent constellation of small satellites also easily allows the addition of further satellites to the cluster which enables the service to grow continuously.

As emerged from these arguments a very independent, growing constellation of satellites is proposed forming rather a logical cluster by their collective purpose than a physical one. All cluster nodes together have a central administration and one mission control center evaluating the data collected by both the cluster and the ground stations handing in measurement results.

The proposed measurement instrument is intended to be the first in a row, depending on the success of this project. Hence the projected instrument is designed to focus on the most common frequency bands in small satellite communication nowadays, UHF and VHF.

Basic Platform Design

The following subsystems are stated as must-have on the proposed measurement satellite:

- *Solar cells and battery*: The satellite needs a sufficient power supply also during eclipse to keep the payload communication system operational round-the-clock.

- *Command communication system*: The satellite is going to be equipped with a common system for transmitting housekeeping data and receiving tele-commands. It continuously sends beacons including system data in parallel to the communication system payload.

- *Attenuation control*: An ADCS system [Larsen et al., 2005] is part of the satellite architecture as the satellite should point its antennas towards earth to maximize the RSSI on ground and keep it constant.

Measurement Instrument (Satellite Payload)

The satellite payload covers the main purposes of the satellite:

- *Transmission of a predefined bit sequence*: The satellite is continuously transmitting a predefined sequence of bits on one frequency with one modulation type and one baud rate. The bit sequence and the transmit power has to be changeable.

- *Receiving and buffering of bit sequences*: The satellite is continuously listening for bit sequences from ground stations and buffers the incoming sequences. The sequences remain untreated and are later on forwarded to the controlling ground station of the satellite cluster for extensive evaluation. Alternatively the received bit sequences are evaluated in orbit for saving downlink bandwidth by downlinking only the resulting measurement reports. The receiving amplification has to be adjustable.

It therefore consists of an own, independent transmitter and receiver for sending and receiving the bit sequences and storage memory for the bit sequences to be sent on one hand and which are received on the other hand. It is not in scope of this proposal but investigations on specifics of the transmitted bit sequences will be required, e.g. by consideration of the Viterbi algorithm [Viterbi, 1967].

7.2.3 Evaluating and Operating Ground Station

The ground station performing the up- and downlink of measurement data and results and operating the satellite is intended to be a high-quality station following the GENSO reference ground station design which is similar to the design introduced in [Wickramanyake, 2006]. It requires to provide at least the following facilities:

- *Antennas and rotors*: At least two UHF respectively VHF YAGI antennas with a precisely calibrated rotor for tracking the satellite during the pass.

- *Radio hardware*: A digitally controllable radio supporting UHF respectively VHF radio amateur frequencies (437Mhz and 140MHz).

- *Controller (PC)*: A COTS PC running the software applications required to operate the satellite and to receive and transmit payload data.

7.3 Mission Goals

The goals of the proposed space mission are divided into primary and secondary goals. The primary goals are designed to be achievable within the predicted minimum life time of the measurement satellite. The primary goals focus on the achievement of new scientific insights whereas the secondary goals focus on support and enhancement of global ground station networks. During the second stage of the mission the hardware of the measurement instrument is also used to support the proposed business model.

7.3.1 Primary Goals

Derivation of a High Precise Link Quality Prediction Model

It has been demonstrated that based on satellite link quality measurements and surface weather measurements a sophisticated link quality prediction model can be derived when applying the methods presented in [Preindl et al., 2009b].When refining the current model using the high-precise and very fine-grained measurements which can be achieved with an active orbital measurement instrument, not only the prediction accuracy can be raised significantly. Moreover, new parameters from space weather, surface weather and other influences can be identified impacting link quality.

A high-precise quality prediction model will significantly raise the possible outcome of space missions and can even extend mission life times.Hence it raises the return of investment for all space missions operating in the measured radio frequency bands and gives advices for the optimization of current and future satellite and ground communication facilities.

Establishment of a Measurement Reference

As shown in the precedent chapters the models and consequences derived from passive measurements are very valuable and for special applications like noise floor maps they remain the only source of records to be evaluated. One of the main disadvantages of passive measurements is the lack of comparability caused by hardware differences (mainly caused by the different measurement facilities of the utilized radios, but also by different hardware like filters, amplifiers and cables).

When having one source of signals and high-precise reference measurements performed by calibrated reference ground stations, the application of proper conversion models (as available for most modulations and currently adopted by the authors) between BER and SNR would enable the precise calibration of ground station hardware equipment. Once calibrated, the equipment can be used for precise measurements also on other spacecrafts which are not equipped with special hardware for measurement performances.

When being able to calibrate ground stations using the reference orbital measurement instrument, the quality prediction model and other approaches engineered in the past could be easily corrected to be generically applicable. Those models may then found the base for refinement and further investigations.

Investigation of the Impact of Atmospheric Gas Concentration on Satellite Link Quality

Based on the derived model of dependencies between environmental conditions and the quality of satellite links the focus is set on the impact of specific magnitudes as they may play a large role within the global climate change. The different impacts on the different radio frequency bands, modulations and encodings are investigated and a long-term impact prediction on satellite communication based on current prognoses is developed.

The outcoming results will supposedly be a significant factor in future spacecraft and ground segment design as a possible outcome of the investigations identifies susceptible communication variables in respect of the predicted global climate change. This has to be taken into consideration when designing also commercial satellites which stay operational in orbit for a decade or more.

Establishment of a Link Quality Sensor Network

As discussed and confirmed with examples in [Preindl et al., 2009d] the full potential of satellite link quality measurements can only be gained when aggregating the satellite tracks of several ground stations, ideally distributed all around the world. An orbital satellite link measurement instrument will significantly help in establishing a global link sensor network by establishing a reference on one hand and one point of measurement evaluation on the other hand. Hence one of the main goals of the proposed measurement satellite is the installation of a global link sensor network (see chapter 5 for potentials of such a network).

7.3.2 Secondary Goals

After completion of the main goals the instrument will help on fulfilling the secondary goals as described in the following sections. In parallel the data up- and downlinked from the satellite will still be used for gaining further knowledge and refining the prediction models [Preindl et al., 2009b].

Ground Station Monitoring and Calibration

Letting ground stations continue to report the received measurement streams to the evaluating ground stations, deviations from the predicted quality can immediately be determined and reported back to the ground station operator. Being interconnected via a ground station network like GENSO the information can be immediately considered in the scheduling algorithms to ensure that broken ground stations or ones of bad quality are not used for mission critical communication. Moreover, the measurement satellite can deliver continuous information about the radio horizon of the ground station (refer to chapter 5) which can in turn be used for fine-tuning the scheduling decisions.

Using the uplink capabilities of the orbital measurement hardware the services for ground stations can even be further extended. One possibility is to test a ground stations uplink facilities before affiliated operations are launched or before mission critical commands shall be transferred to the spacecraft. Being aware of hardware and communication problems in advance can be of great value for every space mission as failover in serious situations is often complicated or even impossible (ground station networks relax the situations significantly, but they can never guarantee failover possibilities).

Optimization of Network Utilization

When being able to precisely predict the quality of a prospective satellite link the optimization of a satellite (full duplex) ground track coverage gains an extremely valuable input factor. The possibilities of fine-tuning the prediction models on one hand and identification of ground stations having communication problems on the other hand impact the overall mission data output of ground station networks and consequently all participating space missions significantly. By saving energy by avoiding satellite links which packet drop rate is exceeding a certain threshold, more power is available for links offering a better link quality.

Rapid Orbit Determination

Spacecrafts in low earth orbit (and orbits in general) are located by the United States NORAD [Sci, 2002] using radar propagation [Lee et al., 2003]. There are various alternative ways how orbit determination can be performed [Sakamoto, 2000]. One novel approach is to evaluate the link quality measurements derived from various ground station within a network like GENSO to determine orbit shifts and to locate new objects on a differential base.

A precondition for performing orbit determinations with ground station networks is a calibration scheme for each radio involved within the orbit determination constellation. Without calibrated hardware the differential position finding is falsified by wrong signal strength measurements.

7.4 Scientific Evaluation Process

The following section describes the multiple steps projected to evaluate the acquired measurements and derive prediction models and perform other scientific reasoning as well as reporting to the evaluated ground stations. Figure 7.3 illustrates the multiple steps discussed.

7.4.1 Mission Operating Ground Station

The ground station dedicated to operate the mission is also the ground station which downloads the recorded uplink measurements from other ground stations which have been buffered in the measurement instrument's onboard memory. It generates raw measurement data by downloading it from the instrument.

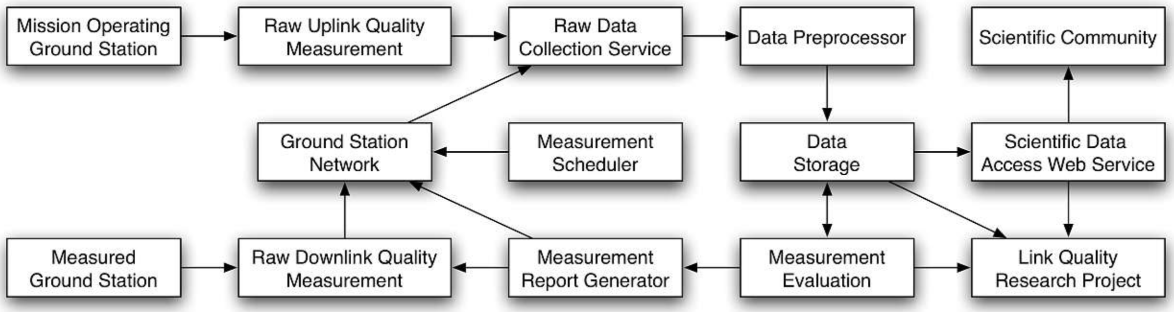

Figure 7.3: The multiple steps required for collection, evaluation and provision of the collected measurements

7.4.2 Raw Uplink Quality Measurement

The measurement is generated by the operating ground station and/or the measurement instrument and delivered to the raw data collection service.

7.4.3 Measured Ground Station

The measured ground station can be any arbitrary ground station connected to the ground station network. It generates raw downlink quality measurements.

7.4.4 Raw Downlink Quality Measurement

This measurement is generated by the evaluated ground station and is provided to the evaluation facility via a ground station network. In contrast to the uplink measurement only one predefined bit stream is stored in the onboard memory as the different measurements do not have to be stored in orbit.

7.4.5 Ground Station Network

The ground station network is used to both command ground stations to track the measurement instrument and receive and store the measurements bitstreams and to interchange the raw data with the evaluation facility operated by the project.

7.4.6 Measurement Scheduler

The scheduler is used to schedule ground stations to track the satellite and to avoid concurrent uplinks from different ground stations at the same time. The scheduler can be operated by the project or the ground station network.

7.4.7 Raw Data Collection Service

This service acts as a data aggregator within the ground station network and is similar to a usual mission control application. Both the operating ground station and the ground stations interconnected via the ground station network are providing their measurements to the data collection service.

7.4.8 Data Preprocessor

The data preprocessor analyses the provided measurements (whether audio or bit streams) and calculates the quality of the link on a fine-grained base. As a consequence the quality can be determined not only on a per-pass base but also on a per-elevation or per-azimuth angle base. The preprocessed data is then, together with the raw measurements for post-process purposes, stored in the data storage.

7.4.9 Data Storage

The data storage is a long-term storage for all mission data acquired and for all data generated being project-related. It provides the data to the measurement evaluation and can be directly accessed by the link quality research project also operating the instrument. Furthermore the data is provided to the scientific community for external research projects via a web service.

7.4.10 Measurement Evaluation

The evaluation aggregates external resources like space and surface weather, atmospheric gas concentration and several other potential quality influences with the preprocessed link quality measurement. Furthermore it performs time-based analytical tasks to identify time-dependent changes in link quality. Moreover several heuristic and statistical models are applied in order to gain all possible information from the measurements. The results of the evaluation are stored in the data storage, provided to the ground station network and the evaluated ground station operator and directly provided to the quality research project on demand.

7.4.11 Scientific Data Web Service

In order to enable other projects than the link quality research project operating the instrument to perform analysis and scientific investigations on the data collected by the instrument a web service is established providing access to the raw and processed, but anonymized measurement data.

7.4.12 Link Quality Research Project

The team of the research project is the primary entity working on and evaluating the collected measurement data. Hence they require direct access to all possible data sources.

7.4.13 Scientific Community

The scientific community is an important entity in the data evaluation process as not all possible data investigation can be performed by the project team due to limited resources. Consequently the collected data is provided to it after being anonymized to protect the ground station operators privacy and safety.

7.5 Business Model

The projected measurement instrument, after finishing the primary goal of collecting link quality measurements, is providing several other services which can also be of commercial interest. Even the collected data itself, once analyzed and used as input data for new prediction models respectively prediction model refinements, offers commercial usability. Hence, even though the primary focus of the project is to collect data for research on satellite links, the possible services offering commercial usability are described in detail in the following chapters.

7.5.1 Offering the Link Quality Prediction Model

The mission the measurement instrument is dedicated to is the collection of link quality measurements which are used as input vectors for new and refined link quality prediction models (see chapter 6). As the satellite power budget plays a major role on every satellite, especially small satellites, and as micro satellites become an emerging market in the space business, decent knowledge about the predicted bit error rate of one specific pass can save money and significantly increase the mission data return. But not only whole passes can be rescheduled or skipped due to low predicted error rates, also the radio characteristics can be changed according to the predicted circumstances.

For example the change of communication paradigms due to link quality predictions [Shaffer et al., 2009] or the change of routing strategies [Wang et al., 2005] are hot topics as well as channel hopping.

Whereas the scientific results of the project will be free for the scientific community, the professional implementation of the prediction model can be offered to industry customers as a service or a module for their scheduling subsystems. A possible service interface could take a satellite's communication parameters and a ground station location and configuration as input parameters and offer a predicted bit error rate or signal to noise ratio as a calculation result taking all available environmental conditions into account. Established as a professional web service customers could easily integrate it in their calculations and computation workflow.

7.5.2 Measuring Ground Station Performance on Demand

Both low-cost and professional ground stations and their equipment can fail due to several reasons. Whereas complete fall outs are easy to detect, degradations in both sending and receiving direction, but especially in sending direction, are sometimes hard to detect and can take weeks until being discovered and corrected. Whether one-time measurements of up- and downlink quality of specific, customer-related ground stations or even periodic measurements (e.g. once a day) can be performed using the measurement instrument's payload.

Each measurement (each pass) will create a highly detailed ground station link quality report for both RX and TX including conclusions regarding creeping and sudden degradations as well as conclusions regarding a satellite's communication signature if multiple reports from multiple ground stations are available. The created reports are delivered to the customer on an automated base. A possible business model includes the creation and storage of the detailed reports as well as the creation of one-time performance measurements to ensure that a ground station operates as expected before critical mission operations (e.g. launches) take place.

7.5.3 Visibility Window Determination on Demand

In urban and rangy environments the visibility window of a ground station is one of the most limiting factors regarding the stability and duration of satellite links. The more irregular the surrounding area of a ground station, the more complex is the task of defining a precise visibility window model. Chapter 5 demonstrates how the measurement instrument can be used in order to create precise visibility window maps. The resulting maps not only cover visible barriers but also invisible ones (like strong noise sources).

As the visibility windows do not differ between low-cost and professional ground stations and the visibility maps are even applicable for different frequencies than the ones provided by the measurement instrument, the instrument can be used to offer the automated measurement and assembling of high-precise window maps. In order to be able to quickly detect changes in the visibility of a ground station (which is even more interesting for unmanned stations) the measurements can be performed on a regular base. Like the ground station performance measurements the visibility maps are delivered to the customer in a highly detailed fashion. In contrast to the one-time measurements required for determining a station's performance, ground station visibility maps require several passes in order to be able to assemble a complete map. Hence duration and costs to create such maps differ from one-time measurements.

7.5.4 Offering Local Radio Background Noise Maps

As discussed in chapter 5 the collected link quality measurements can be aggregated and correlated in order to calculate 3D noise coverage maps. A precondition for a sensible degree of precision in the calculated maps is a high density of ground stations within the inspected area. As a consequence the provision of noise maps is only feasible in urban or sub-urban areas. But as a matter of nature those areas are also the areas with the highest amount of background (radio) noise, which is on its part again a major factor for link quality loss in urban areas.

As the background noise maps are a by-product of the continuously performed link quality measurements using a large amount of ground stations, the provision of noise coverage maps can be performed immediately on demand. As background noise has a serious impact on all radio links, especially on those with a low link budget, detailed information about "white spots" in the surrounding area of a ground station can be of great usability for mission operators. It helps on one hand to avoid passes which cross noisy areas in the hemisphere and helps on the other hand to adjust the transmission power level in order to compensate the increased noise level.

Not only satellite mission operators profit from detailed noise maps of specific areas, but also providers of other radio links (e.g. mobile phone services, wireless internet access, ...). Moreover, public institutions can also have a strong interest in noticeable sources of radio noise. Consequently the provision of noise maps can be offered on a one-time basis or also on a continuos base where a customer gets a detailed analysis and report every couple of days (depending on the amount of ground stations in the inspected area and the amount of passes).

7.6 Requirements

In order to successfully achieve a decent return of investment from the proposed project, a variety of requirements has to be satisfied. Those requirements are not only limited on resources like hardware but cover also human manpower, know-how and legal perspectives.

7.6.1 Scientific Requirements

The project proposed focuses on scientific investigations based on research work performed so far which proves the feasibility and sensibility of the approach. As the underlying research results show a significant impact of environmental conditions on satellite links and the various evaluations of present measurements have been successfully performed, the scientific requirements for a sensible accomplishment of the proposed project are completely fulfilled.

7.6.2 Measurement Platform Requirements

The underlying measurement platform, the small satellite, has to fulfill a couple of requirements in order to be able to carry the measurement instrument on one hand and in order to operate properly and provide decent measurement results on the other hand. The following sections state the detailed requirements.

Satellite Engineering Model

The engineering model is a flattened version of the real flight model, primarily reduced by solar cells, batteries and an ACDS system. It is intended to enable engineering and testing tasks on a decoupled framework which is similar to the one launched after the engineering and test phase has been successfully completed. Hence it requires to consist of the following parts:

- *Platform frame/structure*: A modular platform structure is required in order to be able to mount different modules on the satellite fulfilling the standard defined by the structure.

- *Main CPU/board*: A main CPU is required to interconnect the different modules and in order to take over house-keeping, power management, module intercommunication and failover tasks.

- *Control communication module*: One communication module with both up- and downlink capabilities is required in order to be able to control the satellite and to change respectively up- and downlink the measurement payload.

- *Measurement module*: The final measurement module requires to be part of the engineering model in order to be able to develop the measurement payload (software) and to test the payload and measurement behavior.

- *Battery*: A battery is required in order to test the power budget of the instrument framework and the transmission and receiving behavior (EIRP and RSSI) of the measurement instrument.

- *Antenna subsystem*: Fully functional antennas are required in order to test the antenna beam figure and the EIRP respectively RSSI.

The engineering model will furthermore be used as a spare model in case of tests required to be performed on ground during normal operation or in case of complete fails of the operating instrument and the requirement of a re-deployment.

Satellite Flight Model

The flight model will be deployed in orbit and carries the operational measurements instrument. Consequently it carries some additional modules on its frame required for orbital operation. The following lists shows all modules required on the flight model:

- *Platform frame/structure*: A modular platform structure is required in order to be able to mount different modules on the satellite fulfilling the standard defined by the structure.

- *Main CPU/board*: A main CPU is required to interconnect the different modules and in order to take over house-keeping, power management, module intercommunication and failover tasks.

- *Control communication module*: One communication module with both up- and downlink capabilities is required in order to be able to control the satellite and to change respectively up- and downlink the measurement payload.

- *Measurement module*: The final measurement module requires to be part of the flight model.

- *Battery*: A battery is required in order to operate also during eclipse phases.

- *Solar cells*: Solar cells are required to charge the batteries for eclipse operation and for normal operation in sunlight. Solar panel degradation is the main case of mission failures, hence high quality panels are required.

- *A(C)DS*: An attenuation (control) and determination system is required in order to correct the measurements in respect to the tilt of the satellite an, in case of a control system, to correct the tilt of the satellite in order to receive proper measurements.

- *Antenna subsystem*: Fully functional antennas are required.

Launch and Deployment

The launch is required to be performed during respectively in the middle of the overall project schedule in order to enable measurement evaluation during the operational phase of the instrument. Furthermore the launch vehicle requires to be equipped with proper launch pod for the measurement satellite.

The target orbit for measurement instrument deployment requires to be in a height allowing the instrument to operate for one or more years on one hand and to be able to measure with the provided power budget. Consequently an orbit between 600 and 800 kilometer is required. Furthermore to cover earth's surface and, consequently, as many ground stations as possible, a sun synchronous orbit is recommended.

Operation and Evaluation

For being able to properly perform and collect measurements from the orbital measurement instrument, at least one reference ground station is required which may also be used to take over house-keeping tasks with the satellite. For a broader and global measurement scenario a ground station network supporting the mission like GENSO is required.

In order to be able to properly evaluate the measurements performed and perform research tasks, a measurement collection, preprocessing and storage architecture is required. The architecture is required to be able to store, transcode and also backup all incidental measurements, data transformations and evaluation results. The measurements shall be made available to the scientific community for further investigations also after the operational phase of the instrument has been completed.

For being able to collect a sensible amount of data, the missions requires to be operating in a nominal way for at least 3 months. A proper operation extending that timeframe will add value to the overall mission outcome, but is not required in order to perform decent research on the collected data.

7.6.3 Measurement Instrument Requirements

The measurement instrument's main task is to transmit and receive bitstreams in at least one common frequency band. In order to be able to perform decent measurements in these bands, the measurement instrument is required to operate in UHF (437 Mhz) and/or VHF (140 Mhz).

Furthermore, the instrument requires to transmit and receive with a specific receive and transmit power. Those two values require to be set to a level which offers the measurements a maximum amount of bandwidth. Consequently the measurement instrument is required to provide an adjustable receive and transmit power which enables the instrument to be tuned and calibrated when set into operation.

The measurement instrument also requires an internal A/D-D/A converter in order to be able to transmit predefined bit sequences in space and to receive and demodulate received bit sequences in space. It also requires a proper amount of in-flight memory to store a decent amount of received measurement sequences from ground stations and to store the predefined bit sequences set by the reference ground station.

The measurement instrument moreover requires to be connected to a very well calibrated and measured antenna subsystem in order to be able to exactly calculate the EIRP of the satellite.

7.6.4 Software requirements

In order to be able to operate the satellite on one hand and to collect and evaluate measurements on the other hand respective software applications are required. For collecting a large amount of data from several locations world-wide, a global ground station network supporting the mission is required.

7.6.5 Ground Station Requirements

For the proposed measurement setup two kinds of ground stations are required: reference ground stations and measurement ground stations. The reference ground station is at the same time the controlling ground stations and calibrates the satellite in order to be able to compare measurements performed with independent measurement ground stations interconnected via a large-scale ground station network. Both kinds of ground stations face different requirements being discussed in the following subsections.

Reference and Operating Ground Station Requirements

The reference ground station requires to be equipped with a very well calibrated ($\leq$1 ° of elevation and $\leq$1° of azimuth) antenna and antenna control. Furthermore it requires to be able to move the antenna in 1 degree steps in both azimuth and elevation. Furthermore the reference (operating) ground station requires to be equipped with radio and HF hardware being able to receive and transmit in the respective frequencies (437 MHz for UHF, 140Mhz for VHF). The ground station is recommended to be connected to the global educational network for satellite operations.

Measurement Ground Station Requirements

The measurement ground station requires to be equipped with radio and HF hardware being able to both receive and transmit in all of the supported frequency bands (437 MHz for UHF, 140Mhz for VHF). The reference ground stations are required to be connected to the global educational network for satellite operations.

7.6.6 Legal Requirements

Due to Austrian space law issues the measurement instrument is required to be mounted on a satellite not registered in Austria but in a country which permits and insures launch and operation of spacecrafts.

7.7 Risk Analysis

A complex and long-term project as described in this study holds a lot of risks which require to be identified. All identified risks require proper counter-measurement plans to be applied in case.

7.7.1 Manpower Risks

In case of manpower failing due to any reason (health or personal) enough manpower requires to be in place to take over the work and to introduce new people to the project and the specific part of work. Moreover, possible fails should not impact the project timeline as some milestones require long-term planning (especially the launch of the instrument). To countermeasure these risks, the project has at least three people working on the project for the full project time whereas each person has at least one other person which is able to take over ones work.

7.7.2 Financial Risks

Even though all matter of expenses have been considered and well calculated in advance, an unexpected change in costs may occur at any time. To be able to countermeasure variations of fixed costs up to 5 percent, manpower budget calculations include appropriate overheads which can be used to balance additional costs.

7.7.3 Contractor Risks

Though our proposed contractors are companies with a stable order situation and deal with an emerging business, fail of a contractor can never be precluded. We identify the following detailed and their counterr-measurements:

- **Loss of satellite framework design and construction company**: In this case we have further offers from a competitor which may vary in costs but provide the same functionality and launch compatibility in short time. As a last resort the project team has the required skills, experience and facilities to construct the satellite with COTS components, even though its capabilities will drop behind a professional, tested framework.

- **Loss of measurement instrument construction company**: In this case we have at least one additional offer from a competitor which may vary in costs but provide the same functionality and launch compatibility in short time.

- **Loss of launch provider**: In this case we would have to take over the launch acquisition, payload tests and campaign ourselves, which is possible. No negative variations costs are expected.

- **Loss of operating and reference ground station**: In this case we have at least one backup ground station to be able to take over the main operation. No negative variations in costs are expected.

7.7.4 Design and Construction Risks

As the whole design and construction of the instrument framework is outsourced to a company, all risks regarding those tasks lay also at the contractor. In case of serious unexpected, short-term problems with the satellite framework, the engineering model is identical to the flight model and can take over all tasks of the flight model in short time.

In case of the measurement instrument itself also two models will exist: An engineering and a flight model. All engineering, development and payload test tasks are performed with the engineering model. Shortly before the launch campaign starts, the flight model measurement instrument is updated and tested with the software implementation from the engineering model. Consequently any serious problem with the flight model payload can be counter-measured by taking the engineering payload as a substitution for the flight payload.

7.7.5 Delivery (Schedule) Risks

in case of the project falling seriously behind the proposed schedule in a way that important waypoints like the launch campaign require postponing, additional launch dates have been identified to serving as alternative launch dates. As the primary goals of the mission can be achieved within only three months and the launch is projected to happen in the middle of the project timeline (one year before the project is finished), a maximum of three launch date shifts is possible.

No other serious schedule risks have been identified.

7.7.6 Deployment Risks

During launch campaign (delivery of satellite including payload, launch carrier assembly, launch, orbit deployment) several risks and counter-measurements have been identified:

- **Damage of satellite or payload (measurement instrument) during transport to launch site**: At the launch site the launch provider will perform proper tests in order to ensure the full functionality of all components. In case any problems occur, the components can be exchanged in time with components from the engineering model.
- **Damage of payload during carrier assembly**: No counter-measurement is possible at this stage of launch. As this equals a fail during operation before primary mission goals have been accomplished, an insurance would be the only possibility to lead the project to success.
- **Damage of carrier or other payload during launch or deployment**: The launch carrier insures the spacecraft and its components for this case.
- **Decay of batteries or solar panels due to launch delay**: In case of unforeseen launch delays which are damaging batteries and/or solar panels the launch contractor takes care of replacement parts and proper pre-launch replacement.
- **Launch failure**: No counter-measurement is possible at this stage of launch. As this equals a fail during operation before primary mission goals have been accomplished, an insurance would be the only possibility to lead the project to success.
- **Deployment failure**: This is the case if the deployment facility (pod) malfunctions. No counter-measurement is possible at this stage of launch. As this equals a fail during operation before primary mission goals have been accomplished, an insurance would be the only possibility to lead the project to success.
- **Antenna deployment failure**: In case of the antenna not deploying correctly in orbit the measurement instrument may stay operational and may be able to accomplish the primary goals. The consequences of an antenna deployment failure rely

mainly on the kind of deployment failure (full failure or partial failure). In any case the transmitting signal strength and the receiving signal sensitivity will be lowered. In case of a partial failure the instrument may be able to fully compensate the damage, in case of a full failure the mission will most probably fail. As this would equal a failure during operation before primary mission goals have been accomplished, an insurance would be the only possibility to lead the project to success.

7.7.7 Operational Risks

During operation several risks have been identified and counter-measurements have been designed:

- **Fail of set-in operation**: This is the case when the satellite never starts to operate properly after deployment in its orbit. No counter-measurement is possible, an insurance would be the only possibility to lead the project to success.

- **General failure of measurement instrument**: In this case the house-keeping communication facility is able to take over most of the measurement instrument tasks. The caveat is a reduced operability as no parallel performance of communication and measurement is possible any more.

- **General failure of satellite during operation**: In this case the operation has failed if the failure occurred before the primary goal was accomplished. No counter-measurement is possible, an insurance would be the only possibility to lead the project to success in that case.

- **Failure of one channel of the measurement instrument (whether up- or downlink)**: In this case the measurements in one direction can still be performed and measurements in the other direction can be performed using the house-keeping communication module (as in case of full failure of the measurement instrument).

- **Failure of one channel of the measurement instrument and a contrary channel on the house-keeping communication module**: Both modules can substitute the failing abilities of each other module as the satellite platform allows for dynamic in-fight rewiring of the communication data flow.

- **Failure of both uplink channels**: The system will continue to transmit the last uploaded bit sequence or, in case of a failure in the beginning of the mission, a default bit sequence will be transmitted. Uplink measurement will be not possible any more, but measurements in the downlink direction can take place, with the lack of power adjustments.

- **Satellite battery failure**: The satellite is still fully operational in sunlight but shuts down during sun eclipses.

- **Satellite solar panel failure**: The system voltage will continuously drop until the satellite stops operation (refer to the case of general failure). In case of sudden digressions (caused by e.g. space debris) of one or two panels, the satellite and the measurement instrument is still fully operational but with restrictions on its duty cycle (no 24h operation possible any more).

- **Any other power problems**: The satellite architecture is possible to shut down devices consuming too much power as a consequence of failures. Depending on the module which requires to be shut down the satellite whether remains fully operational, remains partly operational or has to stop operational tasks.

- **Attenuation control and/or determination problems**: In case of control problems, the satellite's determination system delivers the required information to normalize measurements in respect to the attenuation of the satellite. In case of the determination instrument failing, the satellite's attenuation can be determined passively using the calculation models available for passive measurements.

- **System bus failure**: The measurement instrument remains operating by itself but cannot be maintained (adjusted) any more. Depending on the kind of failure the power bus can also be affected. In that case the result is similar to a general failure.

- **Transmit or receive power calibration failure**: Depending on the power set the satellite remains fully operational or becomes partly operational. In second case primary mission goals can still be accomplished but may require changes of the reference ground station hardware.

- **In-space collision**: In case of an in-space collision the launch carrier respectively the launch contractor take over full responsibility.

- **Ground Impact**: In case of a ground impact the launch carrier respectively the launch contractor take over full responsibility.

- **Radio hardware malfunction**: In case of the radio affecting other reserved frequencies or operating on too high power levels following a malfunction, the radios can be deactivated remotely. If this affects both transmitting radios, the satellite becomes in-operational.

7.7.8 Measurement Risks

When performing link quality measurements, the following possible risks have to be considered:

- **Ground station deficiencies**: Each measured ground station can have different deficiencies, like wrong calibrated antennas, weak radio or antenna equipment. In order to be able to computationally eliminate these deviations, a calibrated reference ground station delivers reference measurements which can be set into relation to the gaugeable, external influences. When taking the environmental conditions of the measured ground station, the deviations between the reference station and the differing ground station can be isolated and taken as a correction value for the specific station. Moreover, the correction value is an indicator for problems of the ground station and can be reported to the operator.

- **Loss of the Global Education Network for Satellite Operations**: The experiment strongly relies on the availability of GENSO for global measurements. In case of GENSO becoming inoperable or stopping to support the mission, a switch to the complementary, Japanese network GMS/GROWS is a possible option. Even in the case of no ground station network being able to support the mission, all required measurements can be collected using the reference ground stations. Additional support is usually provided by the AMSAT community also providing satellite pass recordings to other satellite missions.

7.7.9 Evaluation Risks

When evaluating the collected measurements the following risks have been identified:

- **Derivation of wrong coherences**: Calculation and methodological errors can never be eliminated. As a consequence the possibility is given that the models and results derived from the evaluation of the measurement data are wrong or erroneous. To counter this possibility, a very large amount of measurements is performed and the derived models are compared with the underlying models which have been derived from other measurements using different references. Moreover, the derived deductions are compared with traditional models and experiences and checked for general plausibility. Continuous scientific publications of the derived results shall also help to identify errors and recalculate the models in case of faults being detected.

- **Corruption or loss of measurement data**: The underlying measurement results which are used for scientific investigations, model refinements and commercial applications (refer to the proposed business model in chapter 7.5) could be destroyed or manipulated in case of soft- or hardware errors. As a consequence all operations on the collected data are only allowed to be performed in a read-only fashion. By not altering the measurement data in any way a large amount of data is generated on the downside, but no harm can be caused to the measurements by software. In order to avoid data loss caused by external faults (hardware or underlying software errors), continuous backups are performed.

- **Erroneous external data**: The different model developments not only require the measurement data but strongly rely on the correlation with external data like surface and space weather information. This information is derived from external sources, like web services, and it cannot be obviated that the provided external measurements are wrong. In order to counter this possibility, more than one source for a specific value is used. In specific cases no alternative sources are available (e.g. space weather). In this case the validity of the information is taken as given as the source is professional (e.g. ESA or NASA).

Chapter 8

Satellite Range Scheduling

The amount and the quality of data received from a satellite is a measure for the success of a pace mission. Large-scale ground station networks like GENSO interconnect a multitude of ground stations worldwide in order to share their resources for raising the amount of data retrievable from non-commercial LEO satellite missions. A satellite range scheduling framework for large-scale ground station networks helps to *improve the overall data output* of satellites by increasing their visibility periods to various ground stations and hence their communication time frames.

For ground station operators the join of such a network leads to a *better usage of their hardware* which would be idle otherwise. Ground station hardware is expensive and the more the hardware is utilized, the higher is the return of investment. By providing the ground station to all network members, the resources of all other members are potentially available in return.

In this chapter a scheduling architecture for large-scale ground station networks is proposed in order to utilize the ground stations to their maximal capacity, to increase the satellites' communication time window and the overall outcome of space missions.

8.1 Scheduler Design

In the following, the input expected by the scheduling framework, the resulting schedule, as well as the constraints which must be considered are discussed. Finally, the section is concluded with a comparison of related work.

8.1.1 Definitions

The formal functionality of GENSO is depicted in Figure 8.1. First, a mission control mc which operates a spacecraft s_1 registers at the central GENSO server which contains a scheduling component. When it has successfully joined the network, it may request for ground station resources. The GENSO scheduler integrates the request in the current flight schedule considering numerous constraints and assigns ground station capacity if possible.

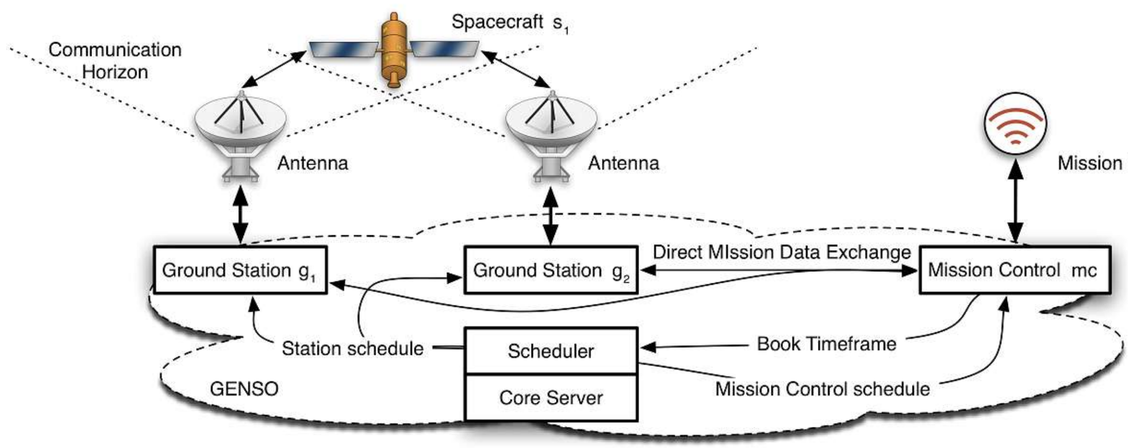

Figure 8.1: Operation sequence of GENSO.

When later s_1 passes the assigned ground station g_1, g_1 contacts mc, and forwards the data received from s_1 to mc. If s_1 is in the scope of another ground station g_2 which has been granted to mc too, g_2 also contacts mc to send data from s_1. Currently, scheduling in GENSO follows the first-come-first-serve paradigm, resulting in an unbalanced working load with unused resources.

8.1.2 The Scheduling Problem

Let $\mathcal{S} = \{s_i | 1 \leq i \leq m\}$ be the set of all satellites and $\mathcal{G} = \{g_j | 1 \leq j \leq n\}$ be the set of all ground stations in GENSO. By $\mathcal{P}$ we denote the set of all possible passes. Based on the location of a ground station and the orbit of a spacecraft, the exact time frame of a pass and the exact angle and elevation between the ground station and the satellite at a specific time can be predicted [Vallado and Crawford, 2008].

A pass is a tuple of the form (s_p, g_p, t_p, d_p) where $s_p \in \mathcal{S}$, $g_p \in \mathcal{G}$, t_p is the starting time, and d_p is the duration of the pass. The set $\overline{\mathcal{P}} \subseteq \mathcal{P}$ contains all admissible passes which are reduced to the passes fulfilling the constraints defined in the next section.

A booking is a tuple (mc, s_b, t_b, d_b) indicating that a mission control mc requests a communication time frame $(t_b, t_b + d_b)$ where the tracking of the satellite s_b by different ground stations should be as continuous as possible. The set of all collected bookings is named B. A pass $p \in \overline{\mathcal{P}}$ occurs within a booking $b \in \mathsf{B}$ iff $t_b \leq t_p \leq t_b + d_b$ and $s_p = s_b$. The set of all passes within a booking $b \in \mathsf{B}$ is denoted as $\overline{\mathcal{P}}(b)$.

A *schedule* (also flight plan) $\mathcal{F}_\mathsf{B}$ for a time frame (t_s, t_e) is a subset of $\overline{\mathcal{P}}$ such that for all $p \in \mathcal{F}_\mathsf{B}$, there exists a booking $b \in \mathsf{B}$ with $p \in \overline{\mathcal{P}}(b)$ and $\forall p_1, p_2 \in \mathcal{F}_\mathsf{B}$ with $p_1 = (s_{p_1}, g_{p_1}, t_{p_1}, d_{p_1})$ and $p_2 = (s_{p_2}, g_{p_2}, t_{p_2}, d_{p_2})$ and with $s_{p_1} = s_{p_2}$ or $g_{p_1} = g_{p_2}$, the intervals $(t_{p_1}, t_{p_1} + d_{p_1})$ and $(t_{p_2}, t_{p_2} + d_{p_2})$ do not overlap. Furthermore, $\forall p \in \mathcal{F}_\mathsf{B}$ with $p = (s_p, g_p, t_p, d_p)$ it holds that $t_s \leq t_p \leq t_e$.

An exemplary instance of the problem is visualized in Figure 8.2 with 10 ground stations and 8 spacecrafts for a one hour duration. By reducing the pass space by one dimension

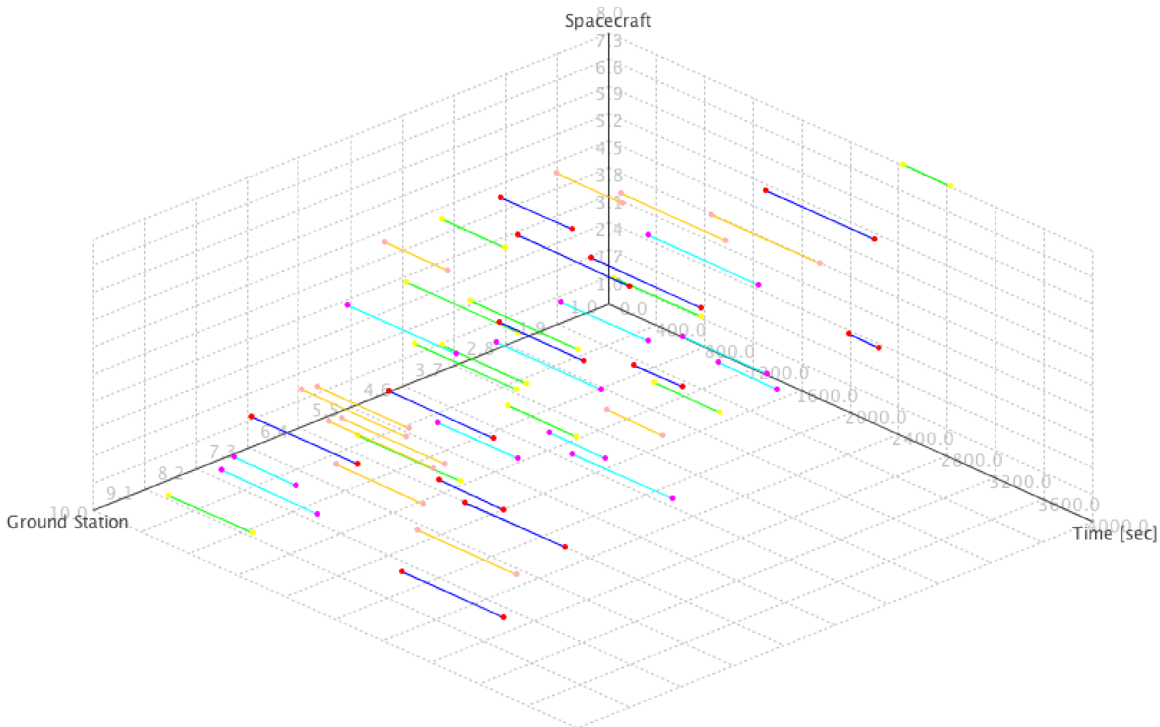

Figure 8.2: The Satellite Pass Space: The 3D plot shows all passes within one hour above 10 ground stations with 8 spacecrafts orbiting in LEO. Each color represents the passes of one spacecraft.

the overlapping passes and hence the conflicts which require resolution become visible (as seen in Figure 8.3). Each overlapping pass visualizes that the two spacecrafts are passing the same ground station at the same time. Physical constraints force the ground station to decide for one (or no) pass. Making this decision is the task of a satellite range scheduling algorithm,

8.1.3 Constraints

The scheduling architecture has to take the following constraints into account.

- *Hardware Compatibility.* The scheduling framework has to decide which ground stations' and which satellites' radio equipments are compatible and hence can establish a valid communication link between each other.

- *Hardware Usage and Maintenance.* Ground station installations have different constraints regarding their duty cycles and degree of wear. Hence specific idle times between utilization for cooling and specific maintenance time slots have to be taken into account.

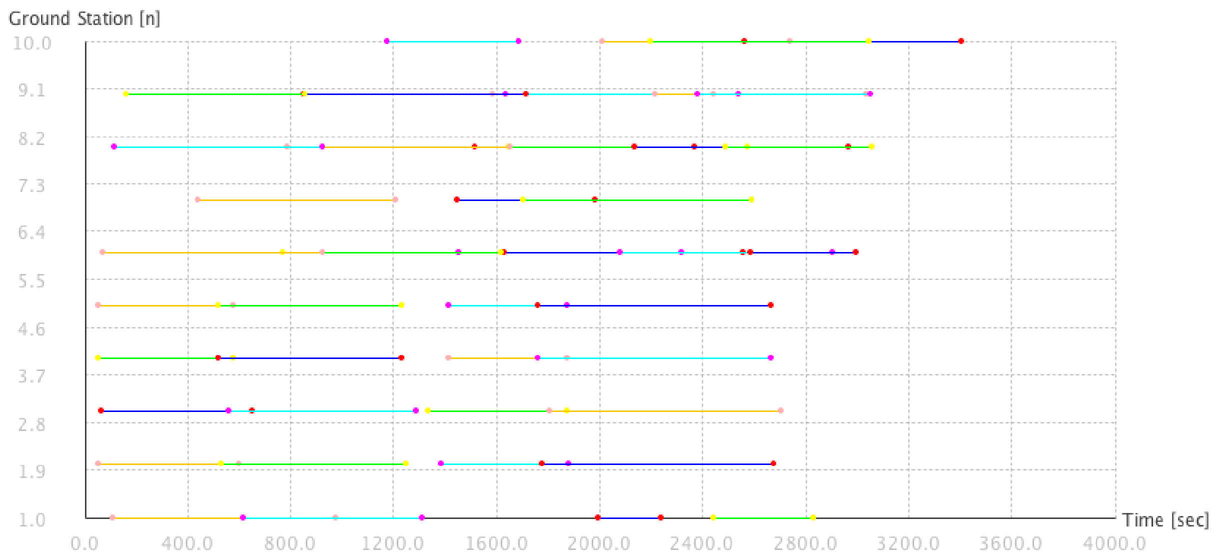

Figure 8.3: The Ground Station Conflict Table: The overlapping between the passes shows when a ground station has more than one spacecraft in range. Each color represents the passes of one spacecraft.

- *Avoidance of Uplink Collisions.* In case of bidirectional transmissions the scheduling framework has to take care of uplink collisions. Cases in which two or more ground stations uplink to the same spacecrafts or to different spacecrafts within a specific horizon or angle (depending on the frequency bands) must be avoided.

- *Security Considerations.* In heterogenous mission and ground stations environments specific mission data may be not allowed to pass specific ground stations for political reasons, reasons of law, or reasons of trust. To avoid data safety risks the scheduling algorithms has to take specific rules into account to filter passes being a potential security risk.

- *Fairness of Output and Utilization.* In ground station networks consisting of non-commercial ground stations and missions the provided hardware and the participating missions assume a fair utilization of their hardware and a fair amount of transferred mission data.

- *Priorization.* Satellite missions may have different priorities according to their operation state or unforeseen emergency situations.

- *Optimization of Flexibility and Reaction Time.* The prioritization possibilities of a ground station network judge its flexibility to react on specific events like priority changes. Also its reaction time to changes within the network is important for several reasons (e.g. failover).

8.1.4 Output

The scheduling framework is expected to deliver the following results.

Ground Station Scheduling Plans. Every participating ground station shall be provided with a specific view of the overall scheduling decisions telling the ground station which satellite to track, which communication mode shall be used, and at in timeframe the track takes place.

Mission Control and Satellite Scheduling Plans. Every mission control shall be provided with a specific view of the overall scheduling decisions telling the mission control which ground station to connect to at which timeframe with the correct communication mode.

Statistics. The scheduling framework shall report about the degree of optimization (the difference between a theoretical schedule without any ground station network and the actual schedule in respect to hardware utilization) and the amount of discharged booking requests. Furthermore, general statistical information about the passes which have been scheduled and the scheduling process itself shall be provided.

8.1.5 Related Work

Satellite range scheduling is an important research topic since the first satellites have been deployed in space over fifty years ago. Dynamic approaches [Taylor, 1977] are researched since computer hardware became powerful enough. Numerous artificial intelligence techniques are applied like genetic and evolutionary algorithms [Globus et al., 2003; Li et al., 2007], dynamic constraint satisfaction [Plaunt et al., 1999], local search algorithms [Barbulescu et al., 2002], heuristic algorithms [Wong and Melliar-Smith, 1990] and others. Schmidt [Schmidt and Schilling, 2008] has recently presented an algorithm for scheduling educational ground station networks satisfying some of the special constraints of those kinds of networks but neglected pass booking requests.

Almost all of the previous approaches are based on the assumption that one ground station has to decide between two ore more satellites but does not take into account that one satellite may be in view of two or more ground stations at the same time. This new scenario becomes more important with the establishment of large ground station networks. Furthermore commercial and military ground station networks, which are the common focus of research in this domain, are usually limited to bidirectional connections whereas upcoming large ground station networks can distinguish between bidirectional passes and unidirectional communication only harvesting downlinked data. This requires the design of a multi-step scheduling approach novel in this domain. Another requirement is multi-criterial scheduling to support input parameters like the predicted pass link quality [Preindl et al., 2009b] and fairness. At the time of writing no general simulation and scheduling

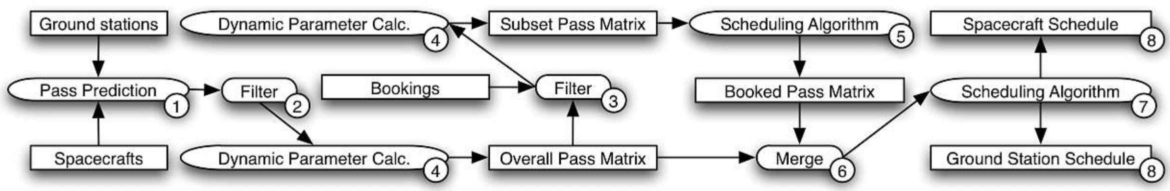

Figure 8.4: The different steps of the scheduling process.

framework for LEO satellites taking the special constraints of non-commercial ground stations into account has been made publicly available.

8.2 Architecture

The proposed scheduling architecture includes a multi-step approach for input data aggregation, data preprocessing, schedule calculation, and result output. Figure 8.4 visualizes the process steps. For the proposed scheduling architecture access to all aggregated information of the ground station network is required. Hence the architecture is described as a *centralized scheduling algorithm*.

The following steps have to performed in order to prepare the data for the scheduling algorithm:

1. *Calculation of All Possible Passes.* First all astronomically possible passes for each ground station and for each spacecraft for a specific timeframe are calculated. For each pass required details are added about the tracked spacecraft, the tracking ground station, the start time of the pass, end time of the pass and the detailed spacecraft track. The calculation is performed using a spacecraft visibility prediction algorithm like NASA's SGP4 [Vallado and Crawford, 2008] or SGP8.

2. *Pass Filtering.* All for any reason (communication hardware, legal aspects, pass length) incompatible passes are filtered.

3. *Booking Consideration.* All received bookings for specific spacecrafts are used to filter the overall pass matrix and gain a pass subset only including passes which could possibly be used to satisfy the booking requests. The detailed filtering rules are stated in the next chapter.

4. *Dynamic Parameter Calculation.* Non-static parameters like fairness or the predicted satellite link quality require the dynamic calculation for a specific pass. The resulting values are added to the profit function of each pass used as weighting criteria for the scheduling algorithm. Parameters and profit function may vary for booked and non-booked passes.

5. *Booked Pass Scheduling.* An optimized schedule for satisfying the booking requests is derived. The scheduling algorithm is described in detail in the next chapter.

6. *Pass Matrix Merge.* The resulting schedule is merged back into the overall pass matrix.

7. *Downlink Pass Scheduling.* The passes not conflicting any booked passes are optimally scheduled for downlink-only satellite tracks to optimize hardware utilization and mission data return.

8. *Individual Schedule Plan Derivation.* For each spacecraft and for each ground station an individual view of the overall schedule is derived and provided.

8.3 Realization

In the following we present the realization of the scheduling architecture presented in the last section. After the input data has been preprocessed, the actual search algorithm is applied.

8.3.1 Data Preprocessing

In order to prepare the data for the scheduling process, the following steps are necessary:

1. Create a subset of passes from the general pass matrix by applying the following filtering rules:
   - Remove all passes with a spacecraft not related to a booking
   - Remove all passes with a booked spacecraft being not within the requested communication timeframe
   - Remove all passes with ground stations not trusted for data uplinks
   - Remove all passes with ground stations not equipped with hardware capable of doing a data uplink to the specific spacecraft
2. Predict tranmission link quality for the remaining passes.
3. Calculate the initial score (based on the predictions and other constraints) for each pass.

8.3.2 Scheduling Algorithm

In order to enable the optimization of the schedule based on dynamic decisions (like favoring one pass over another) a scoring function is introduced. For each pass two different scores exist: The spacecraft score and the ground station score. The ground station score of a

SCHEDULE($\mathcal{G}$, $\mathcal{S}$, $\overline{\mathcal{P}}$, B, t_s, t_e)
Require: $\mathcal{G} \neq \emptyset, \mathcal{S} \neq \emptyset$
Ensure: a conflict-free schedule $\mathcal{F}_\mathsf{B}$ starting at t_s and ending at t_e

for all entities $e \in (\mathcal{G} \cup \mathcal{S})$ **do**
  create directed, weighted graph $\mathsf{G} = (V, E)$ where
  ... V are the nodes v_0 ... v_{n+1}
  ... v_1 accords to p_1, ..., v_n accords p_n
  ... v_0 represents an artificially introduced pass at t_s
  ... v_{n+1} represents an artificially introduced pass at t_e
  ... E are the edges of the form (v_1, v_2, d) with $v_1, v_2 \in V$ and distance $d \in \mathbb{N}$
  ... $\forall v \in V$, e is involved in v, i.e., v is associated with $p \in \overline{\mathcal{P}}$, $p = (e, \_, \_, \_)$ or $p = (\_, e, \_, \_)$
  ... $\forall (v_1, v_2, d) \in E$, v_2 does not start before v_1 is finished
end for
$\mathcal{F}_\mathsf{B} = \overline{\mathcal{P}}$
while getConflictingPasses($\mathcal{F}_\mathsf{B}$)$\neq\emptyset$ && $\neg$*externallyInterrupted* **do**
  $\mathcal{F}_\mathsf{B} = \emptyset$
  for all graphs G **do**
    e = entityOf(G);
    $\mathcal{F}_\mathsf{B}$= $\mathcal{F}_\mathsf{B} \cup$ findBestPassesFor($v_0 \in \mathsf{G}$, e);
    if $e \in \mathcal{G}$ **then**
      for all $p \in \mathcal{F}_\mathsf{B}$ **do**
        increaseSpacecraftScore(p);
      end for
      for all $p \notin \mathcal{F}_\mathsf{B}$ **do**
        decreaseSpacecraftScore(p);
      end for
    end if
    if $e \in \mathcal{S}$ **then**
      for all $p \in \mathcal{F}_\mathsf{B}$ **do**
        increaseGroundstationScore(p);
      end for
      for all $p \notin \mathcal{F}_\mathsf{B}$ **do**
        decreaseGroundstationScore(p);
      end for
    end if
  end for
end while
return $\mathcal{F}_\mathsf{B}$

Algorithm 2: The scheduling algorithm.

findBestPassesFor(node v, entity e)

minimum cost $c_{min} = \infty$
cheapest node $v_{next} = null$;
for all edges r with $r = (v, v_2, d)$ **do**
  if $e \in \mathcal{S}$ **then**
    cost $c = f_S(v_2)/d$;
  else
    cost $c = f_G(v_2)/d$;
  end if
  if $c < c_{min}$ **then**
    $v_{next} = v_2$;
    $c_{min} = c$;
  end if
end for
if $v_{next} \neq null$ **then**
  return $\{v\} \cup$ findBestPassesFor(v_{next}, e);
else
  return $\{v\}$
end if

Algorithm 3: A greedy algorithm for the pass selection within one scheduling iteration.

pass is defined as a function $f_{\mathcal{G}} : \mathcal{P} \mapsto \mathbb{R}$ and the spacecraft score is defined as $f_{\mathcal{S}} : \mathcal{P} \mapsto \mathbb{R}$. An entity $e \in \mathcal{G}$ applies $f_{\mathcal{S}}$ and an entity $e \in \mathcal{S}$ applies $f_{\mathcal{G}}$ in order to score a specific pass. This ensures that no entity directly effects its own decisions by prior decisions (which would result in an immediate over-saturation of the passes which have been scored in the first iteration).

The scheduling process is a dual-layer process which uses a graph-based cost minimization algorithm to find a local maximum and a kind of round-robin algorithm which iterates through the different graphs until all selected passes are conflict-free. Algorithm 2 describes the different steps performed by the scheduling algorithm.

The functions for finding an optimal path can be implemented for example using a standard greedy algorithm as presented in algorithm 3 but the framework allows for performance and optimization evaluation of several different algorithms. The local maximization functions score a pass up in order to “convince” the counterpart of their decision and scores all passes not selected in a specific iteration down.

Note that the algorithm is well suitable for concurrent and distributed processing because the single graphs, i.e., the optimization problems for single bookings/ground stations may be handled independently.

8.4 Performance

The presented algorithm has been implemented in Java and exhaustive performance measurements have taken place under the Java Runtime Environment 1.6. During the process of development and testing, a decent optimization process took place.

We've investigated that it is fundamental for the algorithm to deliver an appreciable performance that not only a positive scoring takes place but also a penalty is introduced. Hence, in each scoring turn each node an out-going edge points to which is not considered by the algorithm is negatively scored. We furthermore investigated that there is no need for different scoring functions for different entity types. It is also remarkable that even a very little penalty function is sufficient in order to gain a very good scheduling performance. We've discovered that a relation between the positive and negative scoring value of 100, e.g. a positive value of 10 and a negative value of -0.1, provides the best results.

In order to be able to benchmark the presented algorithm we've defined the average communication time between one satellite and one ground station as the maximum possible communication time without any kind of optimization (it reflects the typical stand-alone ground station scenario). This communication time is represented as 100%. We've furthermore implemented a simple first-come-first-serve greedy algorithm reflecting the current scenario wherein each satellite operator tries to occupy as much resources as possible. Our algorithm has been put into competition with the greedy algorithm in order to emphasize the possible optimization when applying a more sophisticated approach.

Our testing scenario is a pre-calculated set of satellite passes taking place within 24 hours. 40 ground stations are fairly distributed over earth's capitol cities in order to reflect the reality of increased occurrences of non-commercial ground stations in congested areas. A set of 20 LEO Satellites with real orbital elements is acting for space craft simulation. A maximum of 18.000 passes has been calculated for that time and has to be scheduled by the presented algorithms. For demonstrating the scalability of the algorithms, not only the maximum amount of passes had to be scheduled but all possible constellations from 1..n ground stations and 1..n space crafts. Hence, each algorithm had to perform a schedule 800 times. All single results have been aggregated and are presented below.

It has to be noted that the following benchmarks only take active passes into account. Hence, one satellite may only be tracked by one ground station at a time. This reflects the scenario of a bidirectional (command) communication with the spacecraft. The results vary strongly when this rule is annihilated. Furthermore, it has to be noted that we assume that all possible passes shall be scheduled. In reality, the amount of passes is radically pruned by the fact that satellite operators prefer shorter times of active communication—on one hand due to satellite power limitations, on the other hand for the simple reason of the availability of human resources.

8.4.1 Greedy Algorithm Performance

The greedy algorithm tries to occupy passes without respecting any of their characteristics. The first space craft selected for occupying its passes has naturally the largest amount of

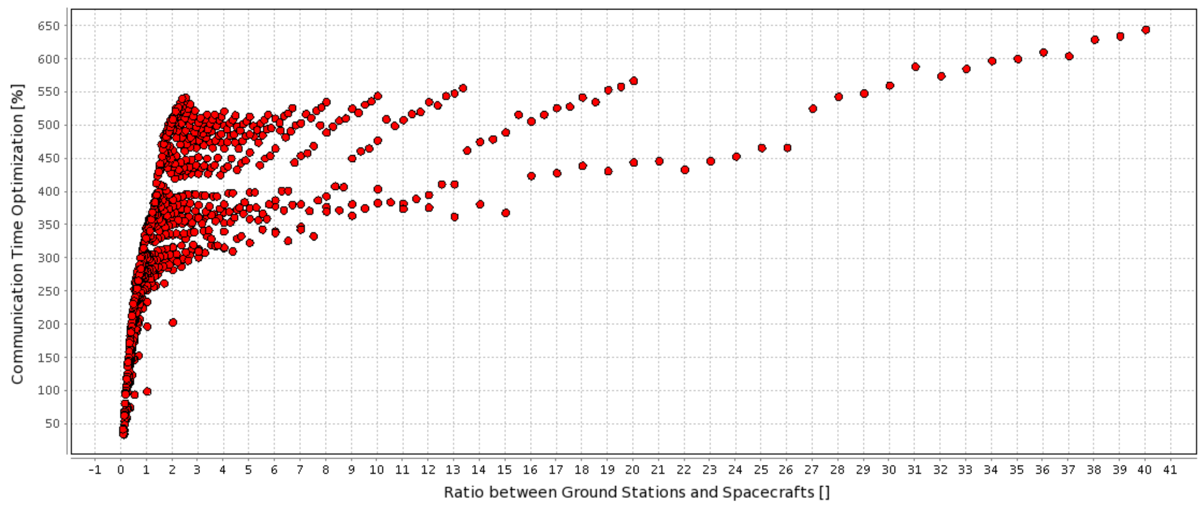

Figure 8.5: The optimization performance of the first-come-first-serve greedy algorithm in relation to the ratio of ground stations and spacecrafts.

passes as ground stations can only track one satellite at a time. The later a space craft is allowed to choose passes, the less it is able to occupy. The algorithm is not optimized for the maximum amount of time nor a maximum of uninterrupted communication. As a consequence it is very cheap in respect of both time and memory consumption. Apparently the algorithm also doesn't handle fairness, which is an important topic in a real-world scenario.

Figure 8.5 shows the performance of the greedy algorithm in relation to the theoretical maximum stand-alone performance of 100%. It can be seen that a realistic maximum optimization possibility lies at 550% and the average optimization levels off between 250% and 500%. Both memory and time consumption were negligible.

8.4.2 Performance of Proposed Algorithm

Figure 8.6 shows the performance of the proposed algorithm. The distribution of the optimization is quite similar to the simple greedy algorithm with a ratio below 2, but above the advantage compared to the common solution lies at 30-40%. The maximum optimization possibility lies above 700% and the average levels off between 400% and 700%. The degree of optimization is further raised when the look-ahead time raises. Noncompetitive, a schedule for 72h hours, as shown in figure 8.7, results in a maximum optimization possibility of over 850%.

As our proposed algorithm not only aims for the maximum amount of pass time for each spacecraft in respect of fairness but also focusses on keeping the maximum amount of time between two passes low (which in turn enable operators to continuously communicate with their spacecraft) the maximum distances in time between two passes have also been

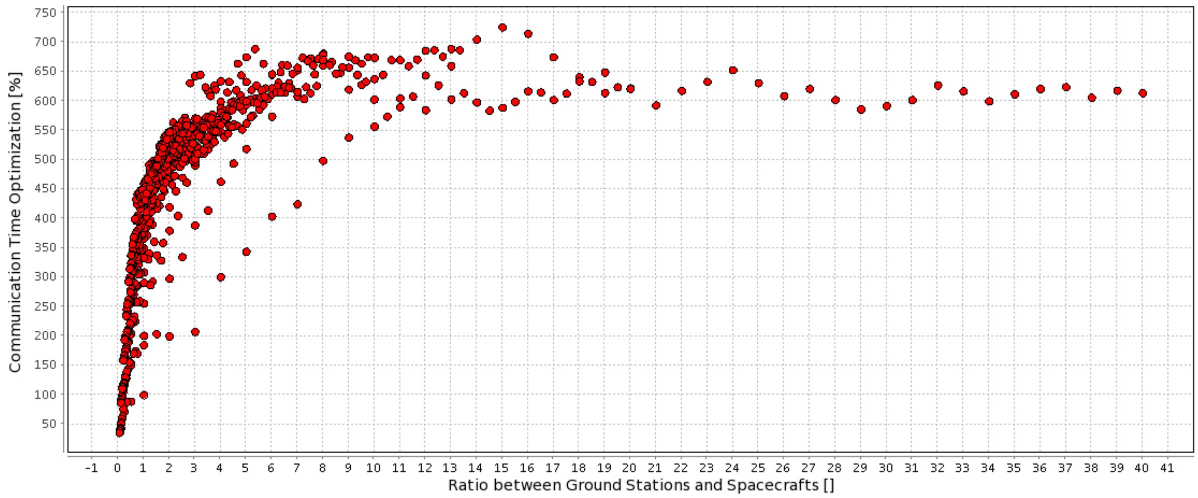

Figure 8.6: The optimization performance of our proposed algorithm in relation to the ratio of ground stations and spacecrafts.

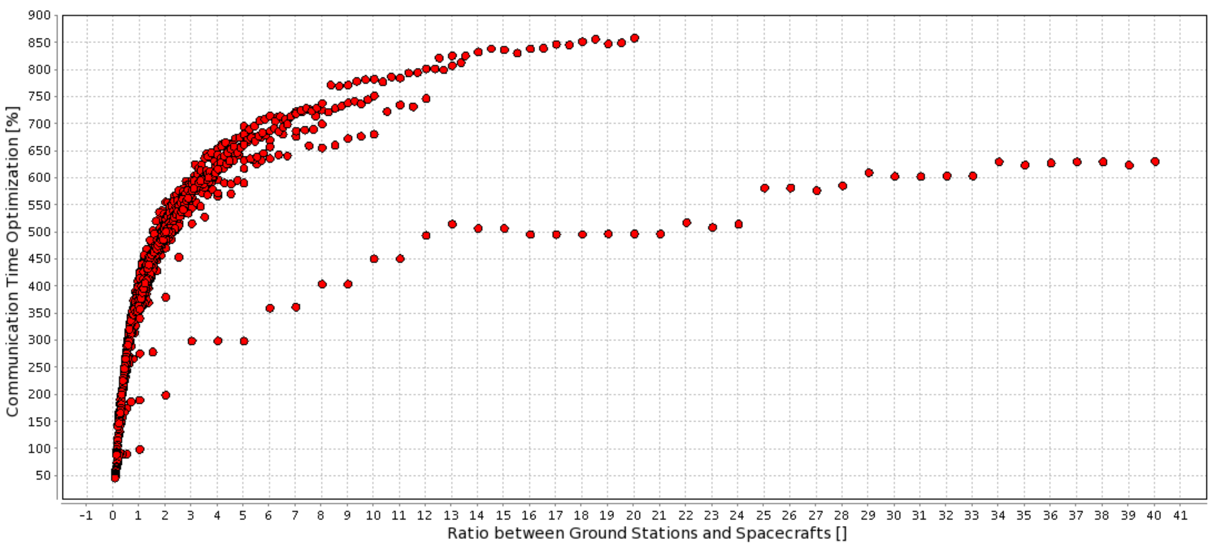

Figure 8.7: The optimization performance of our proposed algorithm in relation to the ratio of ground stations and spacecrafts for a 72h calculation.

observed. Whereas the behavior for spacecrafts acts perfectly fair, the pass gaps for ground stations are remarkable. Figure 8.8 illustrates how the maximum graph edge lengths of behave in respect to the ratio between ground stations and space crafts. Above a ratio of 3, the amount of completely unconsidered ground stations raises significantly. This is a result of ground station over-saturation compared to the amount of scheduled spacecrafts. Hence, we can identify an optimum ratio between spacecrafts and ground stations for the utilization of ground stations of 1 and, in respect to mission return, of 10. Still, in reality

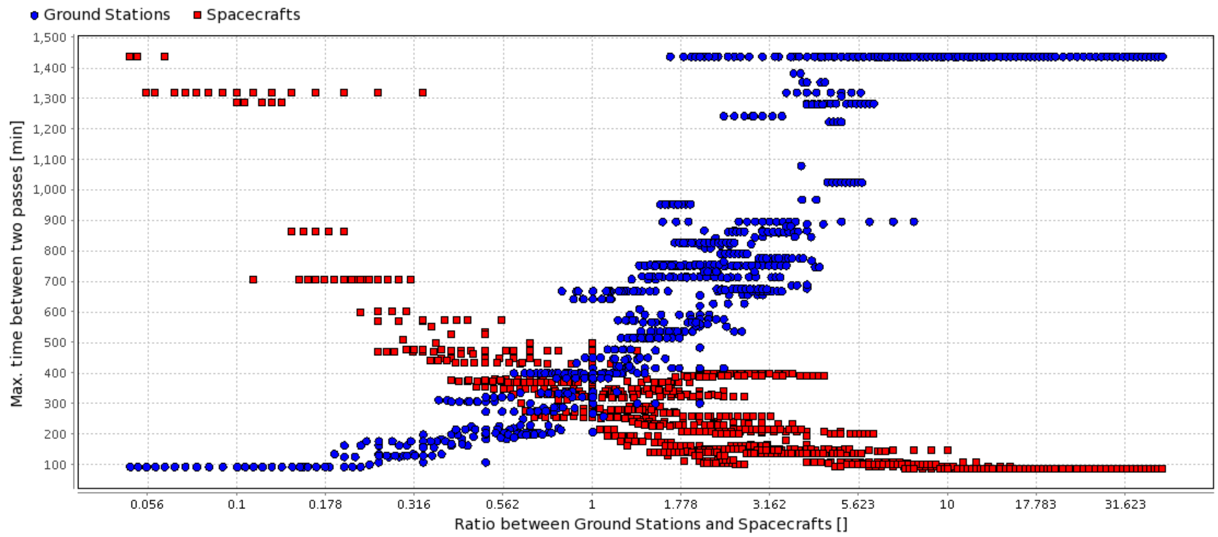

Figure 8.8: The longest time between two passes for ground stations and space crafts in minutes in relation to their ratio.

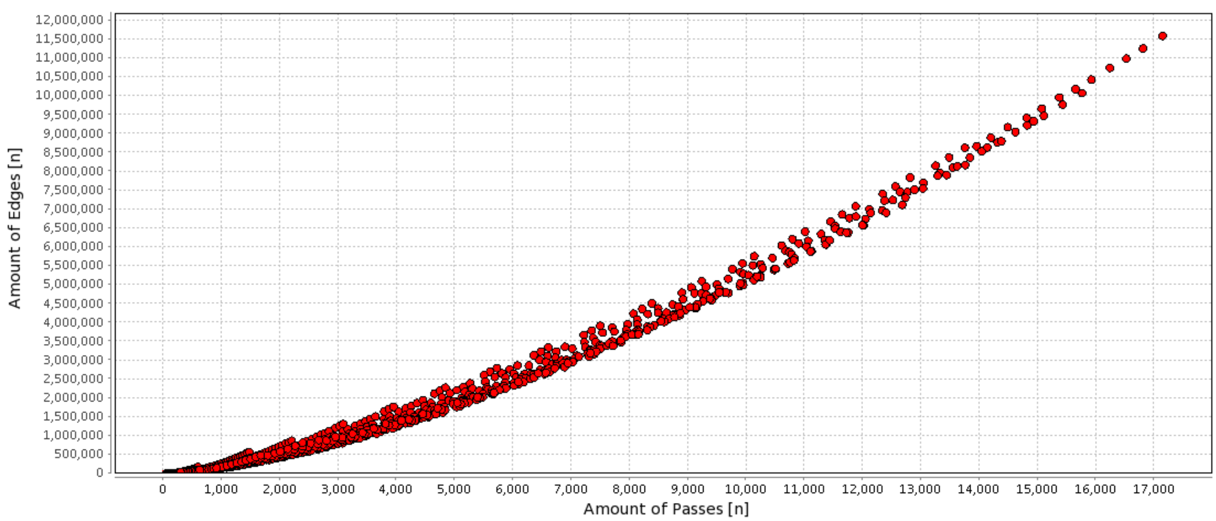

Figure 8.9: The amount of graph edges in relation to the amount of passes to be scheduled.

the distribution of ground stations may vary significantly and not each ground station is compatible with each spacecraft, hence an oversupply of ground stations has only positive effects.

8.4.3 Resource Consumption

We have shown that our proposed algorithm significantly outperforms simpler algorithms regarding its raw pass time optimization capabilities. Certainly, its scheduling performance

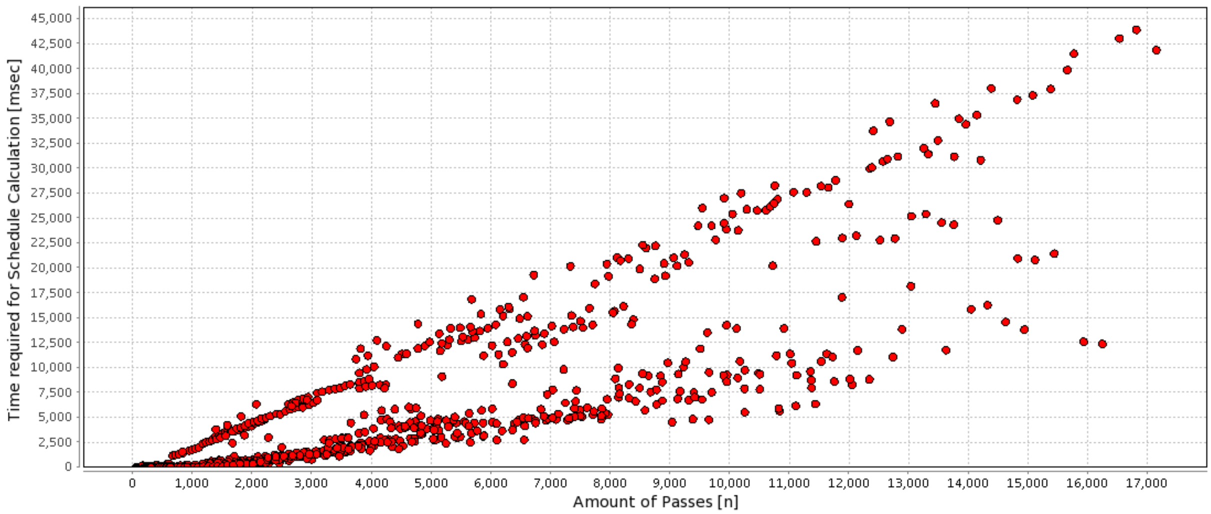

Figure 8.10: The time required for scheduling in relation to the amount of passes. The nonlinearity is explained by the different amount of iterations required to calculate a conflict-free schedule.

is paid at the cost of resource consumption. Memory costs are non-linear and currently limit possible scheduling scenarios. Figure 8.9 shows the amount of edges in relation to the amount of passes to schedule. We see that the graph size required for scheduling of 18.000 passes requires 12 million edges. In the domain of small amounts of entities the resource effort stays cubic in relation to the amount of space crafts and ground stations. Still, the largest graph in this benchmark required nearly 1 gigabyte of memory which limits the theoretical application possibilities to about 100 entities.

However, in a real scenario a 24h look-ahead schedule is not required and the graph will be drastically pruned by selective bookings of time slots. Hence, we anticipate that the proposed algorithm is able to handle the typical appearance of scheduling tasks in large ground station networks with several hundred ground stations and several dozen missions.

Not less important is the amount of time required to create a schedule of a specific size. Figure 8.10 illustrates the time required to schedule in relation to the amount of passes which have to be scheduled. It can be derived that the costs of time behave linear to the amount of passes to schedule.

8.5 Impact of Satellite Link Quality Prediction

All yet performed measurements only focused on the optimization of pass time, in particular on the optimization of communication continuity between ground and space. We now investigate on the mission data return optimization potential of the satellite link quality prediction model introduced in chapter 6.

In order to enable for mission data return optimization, the prospective data output of each pass must be predicted preliminary to the schedule process. A simplified prediction

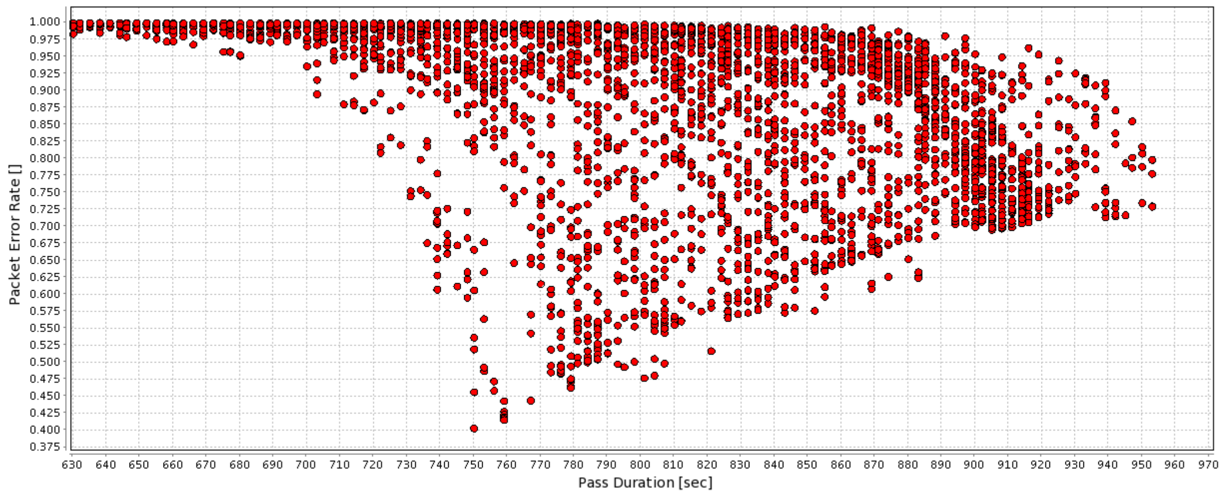

Figure 8.11: Relation between packet loss rate and pass duration for the simulation test set.

model was taken based on the approximated linear dependency between communication distance and the signal to noise ratio. A typical academic satellite mission's optimal packet loss rate of 0.5 has been assumed for the inspected spacecrafts.

A new test set of 100 ground stations distributed over the world and 25 space crafts with different orbital positions has been used to calculate more than 18.000 passes for a 24h schedule. The average duration of a pass is 711 seconds with a standard deviation of 181 seconds. The average amount of received data is 92KByte and the average packet error rate is 0.907. The very high packet error rate may look unrealistic, but academic missions face such high rates when using the default AX.25 protocol without forward error correction and the satellite isn't in an optimal condition. Figure 8.11 shows the relation between pass duration and packet error rate and demonstrates that even though the packet error rate depends on the pass duration, there is still a strong bias between different spacecrafts as their distance varies.

In order to respect both pass duration and the predicted amount of mission data downlink, our algorithm has been extended accordingly. In order to illustrate the gain in duration respectively data compared to a scenario without ground station networks, a reference calculation with spacecrafts only being tracked by one ground station each has been performed. Figure 8.12 illustrates the gain in mission data return for both an algorithm optimizing for communication duration and an algorithm optimizing for mission data return.

Not surprisingly the algorithm aiming on a maximum communication duration between space and ground is outperformed by the algorithm aiming for data outcome. Additionally, the gain in data return can be accomplished within a significantly shorter amount of time, as figure 8.13 illustrates.

It can be reasoned that it's not only possible to fairly raise the amount of data which can be transferred between satellite and ground station and hence raise the overall mission

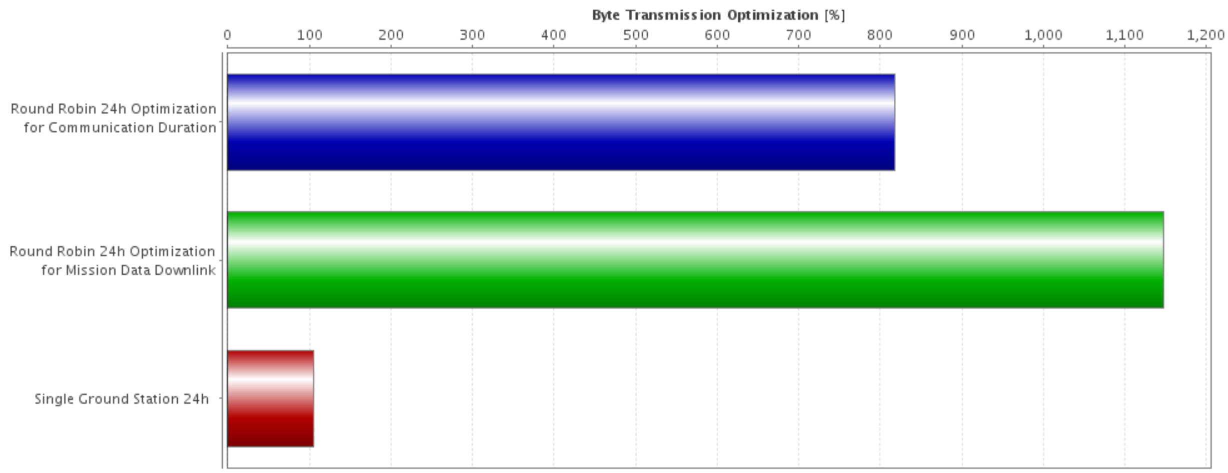

Figure 8.12: Gain on mission data return with different optimization targets.

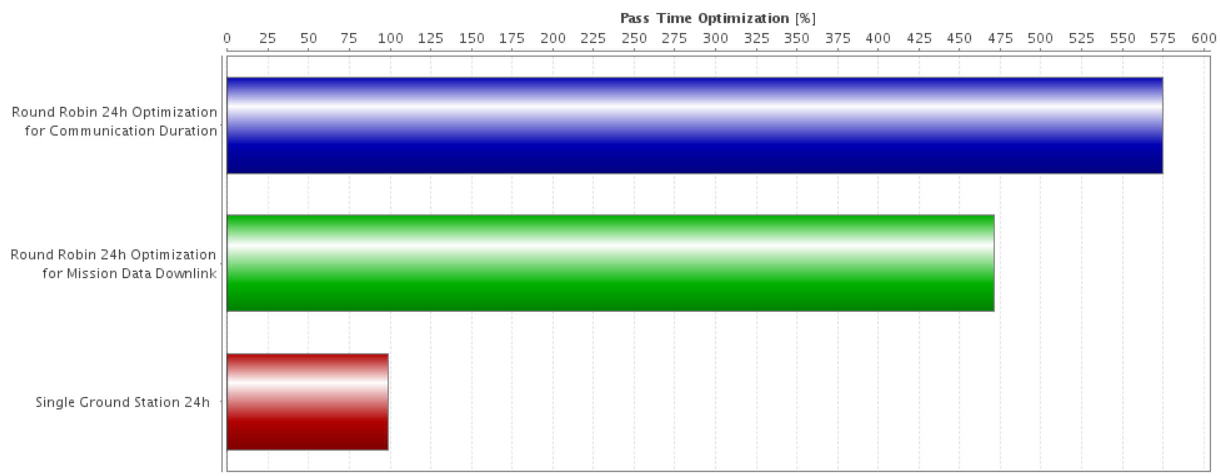

Figure 8.13: Gain on communication duration with different optimization targets.

data output, but also the amount of time required for transferring the data can be lowered when applying link quality prediction as input factor for satellite range scheduling. As a secondary outcome both satellite onboard energy and ground station hardware is preserved by up to 20%.

8.6 Summary

The proposed scheduling architecture and algorithm solve the multi-dimensional problem of scheduling large satellite ground station networks by providing a solution optimized by several constraints including conflict management and fairness under consideration of all possible input constraints. It establishes an ideal testbed for different optimization algorithms and the application of latest accomplishments in the field of satellite communication research including link quality prediction and fast orbit determination. The proposed solution enables all kinds of ground station networks to optimize their hardware utilization and as a consequence gain a significantly higher mission return from low earth orbit missions. It has furthermore been demonstrated that the impact of signal link quality on mission data return is significant.

Future investigations will focus on several topics. The implementation will be integrated in GENSO and its behavior in a real environment will be monitored and optimized. Stepwise the profit will be improved and more input parameters will be added to the profit calculation. Further scenarios are subject to be supported including network utilization for fast orbit determination [Sakamoto, 2000], synchronized up- and downlinks for bit error reduction and overlapping passes for seamless satellite communication over a long period of time. On a long-term perspective also spacecrafts in higher orbits and interstellar probes shall be supported. Furthermore it will be investigate on parallelizing the schedule algorithm to support multi-processor environments and significantly lower the overall runtime requirements.

Chapter 9

Conclusion

In this thesis several optimization possibilities for large-scale ground station networks have been investigated and developed. Special focus was set on the introduction of satellite link quality assurance into non-commercial space-flight by the development of a link quality prediction model and its impact on satellite range-scheduling.

First, the architecture of the Global Educational Network for Satellite Operations has been analyzed and components required for data collection and centralized scheduling have been developed. In his role as software and system engineer on the project, the author was also able to establish the required interfaces for a future application of the research results of this thesis.

As a prerequisite for detailed link quality measurements and scientific evaluations, the possibility of link quality determination and comparison required detailed investigations. In this thesis, a sophisticated method for passive satellite link quality measurement, evaluation, and comparison using the digital signal strength facilities of low cost COTS satellite radio components has been developed and applied. Using the developed methodology, 2500 measurements have been collected and evaluated in collaboration with Aalborg University, Denmark, and its CubeSat AAU-SAT II, a satellite transmitting in UHF and orbiting in LEO.

Several applications for scientific link quality investigation have been studied in this thesis, including link quality state analysis and the calculation of background noise maps. Additionally, further possibilities have been identified and drafted, for example the application of link quality information on satellite orbit determination.

The collected measurements have been preprocessed and analyzed for the determination of their signal to noise ratio and 1800 measurements have been chosen for the development of a novel satellite link quality prediction model. Air traffic, scientific and governmental databases have been used to gain detailed and fine-grained surface and space weather information. 24 different parameters aggregated from four different data sources have been correlated with the link quality measurements to form an input vector for machine learning algorithms. The performance of several common machine learning algorithms has been compared for both classification and regression. Support Vector Machines turned out to perform best on the given classification and regression task using the provided input vectors. A binary classification precision of 85% and a regression performance 0.307 (RMSE) could be obtained. In general, the influences of the surface weather attributes for successful learning are higher than those of the space weather attributes. The most important surface weather impact in this regard turned out to be the dew point.

Even though the prediction quality was unexpectedly high, it can be significantly improved if the precision of the link quality measurements is raised. One possibility is the active measurement of link quality requiring both, a dedicated sender and receiver. This thesis provides the design of an active link quality measurement satellite which could significantly raise measurement precisions and enables bidirectional measurements. Additionally, it enables for quality assurance of ground station networks like GENSO by continuous evaluating a satellite ground stations' link quality in both receiving and transmitting direction. In addition to the scientific improvements possible with such a satellite, a business model has been developed for commercially using the facilities of such an instrument.

To demonstrate the possible improvements of mission data return using large-scale ground station networks, a simulation framework for satellite passes has been developed in this thesis. In order to be able to simulate realistic scenarios, real orbital and geographical location data has been used. It has been demonstrated that the application of ground station networks compared to nowadays situation provides a gain in communication time of more than five times if no orchestrated scheduling takes place, simulated by a first-come-first-serve pass selection algorithm. For maximizing both the communication duration with and mission data return from satellites on the one hand and enhancing the continuity of communication sessions on the other hand, a novel scheduling algorithm for the multi-dimensional problem of satellite range scheduling has been designed, implemented and benchmarked in this thesis making a gain in communication duration of more than factor nine possible.

For evaluation of the gain in mission data return when considering the predicted link quality of a pass, a simplified prediction model has been integrated into the simulation framework and the developed scheduling algorithm has been modified in order to respect the data outcome of satellite passes to be scheduled rather than their duration and continuity. An average gain of more than ten times in mission data return compared to nowadays situation with single ground stations and a gain of more than 30% compared to optimizations aiming on communication duration could be measured.

The research carried out in this thesis enforces the need for global ground station networks for non-commercial space-flight. It demonstrates the scientific and economic possibilities given when investigating on satellite link quality analysis and prediction. It furthermore demonstrates the strong impact the consideration of link quality can have on mission data return. For future investigations the establishment of an active, orbital measurement instrument is proposed as high-precise, fine-grained measurements a requirement for more precise link quality prediction models. Taking the aspect of link quality assurance introduced in this thesis into low power satellite communication will significantly enhance both the mission success rate and the mission data return from all kinds of satellite missions: educational, scientific, and commercial.

Appendix A

Support Vector Machines

A.1 History of SVMs

Compared to classification algorithms like for example the Bayesian Networks, Neural Networks, or Tree-Learners, Support Vector Machines are a quite young approach to tackle the classification problem. It was introduced in August 1995 by Vladimir Vapnik, a Russian computer scientist, in the Journal of Machine Learning after a nearly two year lasting acceptance period. The publication "Support Vector Networks" [Cortes and Vapnik, 1995] presents the concept of mapping input vectors to a very high-dimension feature space where a linear decision surface is constructed.

After Vapnik's first publication the community soon started to investigate the possibilities and performance of SVMs. Where the original SVM was a binary classifier, investigations have been undertaken to apply the SVMs to numerical classifications called nowadays Support Vector Regression [Smola, 1996]. Also methods to allow multi-value classification have been introduced.

In 1996 the community started to publish the first results of the performance of SVMs when being applied to practical applications. These applications also covered a lot of "traditional" Neural Network domains where SVMs in many cases outperformed traditional approaches. First application domains were text categorization [Joachims, 1998], natural speech recognition [Schmidt, 1997], and image classification (e.g. face recognition [Osuna et al., 1997]). SVMs were also used for spam detection from the very beginning on [Drucker et al., 1999] when spam-filtering using machine-learning algorithms became a hot topic in the late 90's.

Nowadays SVM is a well-proven, very good performing machine learning algorithm which is applied to a myriad of classification and regression problems. So it was only a matter of time until also the field of space sciences would jump on the bandwagon.

A.2 SVMs in Space Science

At the time were others already published first results on practical SVM applications, the field of space applications didn't pay a lot of attention to it. In 1996 Berenji wrote about the computational intelligence and soft computing in space applications [Berenji, 1996] and focussed primarily on (fuzzy) rule-set-based methods for derivation and implementation of knowledge and pattern. He identifies well the possibilities of computational intelligence for space applications and writes about its potentials, but it will take another couple of years until machine learning approaches, in particular SVM, will be introduced to the applications he writes about (space engineering itself rather than space-supported sciences like weather predictions).

In 1999 SVMs are applied to a space-related field for the first time: Satellite image processing. In [Brown et al., 1999] SVMs are used for the optimal classification and the spectral unmixing of satellite images. They are compared to traditional approaches like linear spectral mixture models and neural networks and outperform both. The paper claims SVMs to be a "relatively new technique" at a time when it has already been applied in other scientific fields for a couple of years.

A big step has been made in 2001 when Gavrishchaka introduced SVMs to the prediction of space weather [Gavrishchaka and Ganguli, 2001], more detailed to the prediction of solar wind-driven geomagnetic substorm activity characterized by the auroral electrojet (AE) index. For the first time SVMs have been applied to space physics and to predictions in space sciences in common. The SVMs have been trained on a feature vector consisting of encoded AE index time series to classify between supercritical or subcritical geomagnetic substorms. This kind of prediction, although it's binary, can be compared to classical weather forecast prediction as performed for every day's weather forecast. Again the SVM performance has been claimed to be superior to the one neural networks delivered. It is also expected that SVMs will be more often applied in future space weather forecasting models where high-dimensional, multi-scale input data needs to be processed once the information will be available in real-time. Indeed SVMs became more common for space weather prediction, e.g. for ionospheric forecasting.

After the application of SVMs to image compilation they have also been applied to image analysis and pattern recognition. One approach is to utilize SVMs to classify clouds. As there are several kinds of clouds, a multi-classification extension to classical binary-classification support vector machines is needed. [Lee et al., 2004] uses a multicategory support vector machine (MSVM), which extends the binary SVM to the multicategory case, to efficiently detect and classify clouds for use in earth observing system models. In comparison to the treatment of multicategory problems as a series of binary problems, as it was very common at that time, MSVMs are claimed to deliver a better classification performance. The model is trained to detect clouds, the type of clouds, ice, water, and other surface types. The authors believe that MSVMs will be a very useful tool for classification problems in atmospheric sciences.

Gavrishchaka may have introduced SVMs to space physics, but not until 2005 they have been applied to avionics and communication optimization. [Dan et al., 2005] introduces a novel support vector machine fuzzy network for digital modulations in satellite communication. Modern satellite communication utilizes different modulations like frequency shift keying (FSK), two-binary-phase-shift-keying (BPSK) or quad-shift-keying (QPSK) to be able to deliver more information in a specific time between spacecraft and ground station. Different modulation types on one hand and different error correction methods on the other hand deliver different bit error rate thresholds for making an error-free-communication possible. [Dan et al., 2005] applies SVMs as error correction instance to provide a sophisticated forward error correction (FEC) algorithm. Thus it allows the signal to noise ratio (SNR) to be lower as with common forward error correction methods which allows w.g. mobile satellite phones or digital television receivers to work under worse weather or interference conditions as it was usual by that time.

Finally [Preindl et al., 2009b] combines some of the previous approaches like surface and space weather prediction to on his part predict the quality of space links as input size for a link scheduling system. Space links are, depending on the operation frequencies, modulations, baud rates and error corrections, sensible to a variety of environmental influences: surface weather, space weather, ionosphere gas concentration, astronomical constellations (e.g. sun and moon). [Preindl et al., 2009b] Êtakes these environmental conditions as input sizes for a feature vector to predict the communication link quality of upcoming satellite passes. Unlike geostationary satellites, who always stay at the exactly same position relative to earth's surface to make e.g. satellite television broadcast possible, satellites in low earth orbit (LEO) travel very fast relative to the earth's surface. This leads to a very small communication window between ground station and satellite. Predicting the quality of upcoming communication links enables a scheduling system to reschedule satellite passes to different locations with a higher predicted link quality than others and consequently increase the transferrable amount of data.

A.3 Summary

Support Vector Machines have helped to significantly optimize several applications in the field of space sciences. They became common and have been applied a couple of years after other disciplines discovered them as well performing classification and regression algorithms, but in the meanwhile the SVMs also caught up in this discipline. SVMs are utilized in various different problem areas, for example satellite image processing, surface and space weather forecasting and even the optimization of communication and avionics. It is beyond all questions that also other, even more complex tasks, can be optimized by the utilization of machine learning approaches and SVMs in particular and we may curiously and excitedly look towards the future.

Appendix B

An AX.25 Transcoder in Java

B.1 Background

The AX.25 protocol is the most widely used protocol for digital radio amateur communication. In order to be able to count the amount of packet losses on a radio transmission when using a Java application for controlling the radio (as it is the case when using GENSO for collecting satellite data), a Java implementation of the HDLC framing of AX.25 is required. The implementation as described in this chapter became part of the official GENSO project codebase.

Only the decoding procedure which is required for data analysis is described in this chapter. The encoding procedure reverses the described steps.

B.2 Implementation

The detailed specification of AX.25 can be found in [Parry, 1997]. In principle the following steps are applied to AX.25 encoded, demodulated data streams in order to gain the unframed AX.25 packet:

- Frame detection (Packet separation)
- Bit unstuffing
- CRC check and checksum removal

B.2.1 General Algorithms

Bit operations in Java are - due to the lack of unsigned primitive types - more tricky than in other, less abstract languages. Hence the following methods help to perform bit operations:

```
public final class ByteUtilities {
    private static final String SPACE = " ";
    private static final String ZERO = "0";
    private static final int BITS_8 = 8;
    /**
     * Converts a <code>List</code> of <code>Integer</code> to an array of <code>int</code>.
     *
     * @param bytes the list in integers
     * @return the array of bytes
     */
    public static int[] listToByteArray(final List<Integer> bytes) {
        final int[] byteArray = new int[bytes.size()];
        for (int i = 0; i < byteArray.length; i++) {
            byteArray[i] = bytes.get(i);
        }
        return byteArray;
    }
    /**
     * Converts binaries to bytes
     *
     * @param binary Binary to be converted
     * @return Byte value
     * @throws NumberFormatException
     */
    public static int binaryToByte(final int[] binary) throws NumberFormatException {
        if (binary.length != BITS_8) {
            throw new NumberFormatException("Byte Array for Binaries has not 8 digits");
        }
        int finalByte = 0;
        final int[] bitMask = new int[8];

        for (int i = 0; i < BITS_8; i++) {
            bitMask[i] = 1;
            bitMask[i] <<= i;
        }
        for (int i = 0; i < BITS_8; i++) {
            if (binary[i] == 1) {
                finalByte |= bitMask[i];
            }
        }
        return finalByte;
    }
    /**
     * Converts bytes to binaries
     *
     * @param token Byte to be converted
     * @return Array of bits
     */
    public static int[] byteToBinary(final int token) {
        final int[] otherOne = new int[BITS_8];
        final int[] bitMask = new int[BITS_8];
        for (int i = 0; i < BITS_8; i++) {
            bitMask[i] = 1;
            bitMask[i] <<= i;
        }
        for (int i = 0; i < BITS_8; i++) {
            otherOne[i] = token;
            otherOne[i] &= bitMask[i];
            otherOne[i] >>= i;
            if (otherOne[i] < 0) {
                otherOne[i] = otherOne[i];
            }
        }
        return otherOne;
    }
```

```
    /**
     * Converts an integer array to a byte array
     *
     * @param frame Frame to be converted
     * @return Byte array
     */
    public static byte[] intArrayToByteArray(final int[] frame) {
        final byte[] array = new byte[frame.length];
        for (int i = 0; i < array.length; i++) {
            array[i] = (byte)(0x000000FF & frame[i]);
        }
        return array;
    }
    /**
     * Reverse a given array (required for LSBF data)
     *
     * @param array Array to be reversed
     * @return Reversed array
     */
    public static int[] reverseArray(final int[] array) {
        final int[] tempArray = new int[array.length];
        for (int i = 0; i < tempArray.length; i++) {
            tempArray[tempArray.length - 1 - i] = array[i];
        }
        return tempArray;
    }
}
```

B.2.2 Frame Detection

Detecting an AX.25 frame is simple (whenever the bit sequence 01111110 is detected, a new frame starts). The following method removes the start/end bytes:

```
public static int[] cropStartEndBytes(int[] frame) {
    int[] newFrame = new int[frame.length];
    System.arraycopy(frame, 0, newFrame, 0, frame.length);
    if (Integer.toHexString(newFrame[0]).matches(HEX_7E)) {
        newFrame = Arrays.copyOfRange(newFrame, 1, newFrame.length);
    }
    if (Integer.toHexString(newFrame[newFrame.length - 1]).matches(HEX_7E)) {
        newFrame = Arrays.copyOfRange(newFrame, 0, newFrame.length - 1);
    }
    return newFrame;
}
```

B.2.3 Bit Unstuffing

When a single frame has been extracted from the data stream, the following code performs the bit unstuffing (former stuffing has been required in order to avoid the start/end bit sequence within a packet).

```
public static final int[] unstuff(final int[] frame) throws FrameCorruptException {
    final List<Integer> boolList = new ArrayList<Integer>();
    for (int i = 0; i < frame.length; i++) {
        final int token = frame[i];
        final int[] binary = ByteUtilities.byteToBinary(token);
        for (int j = 0; j < binary.length; j++) {
            boolList.add(binary[j]);
        }
```

```
    }
    int oneCounter = 0;
    int bitCounter = 0;
    int bytenum = 1;
    boolean remove = false;
    final List<Integer> unstuffedList = new ArrayList<Integer>();
    for (Integer digit : boolList) {
        System.out.print(digit);
        if (digit == 1) {
            oneCounter++;
        }
        else {
            oneCounter = 0;
        }
        if (oneCounter == 6) {
            throw new FrameCorruptException("Frame corrupted, dropped!");
        }
        if (remove) {
            remove = false;
            continue;
        }
        if (oneCounter == 5) {
            remove = true;
        }
        unstuffedList.add(digit);
        bitCounter++;
        if (bitCounter == 8) {
            bitCounter = 0;
            bytenum++;
        }
    }
    final int[] newFrame = new int[unstuffedList.size() / 8];
    int[] bitArray = new int[8];
    int i = 0;
    int j = 0;
    for (Integer bit : unstuffedList) {
        i++;
        bitArray[i - 1] = bit;
        if (i == 8) {
            i = 0;
            final int token = ByteUtilities.binaryToByte(bitArray);
            ByteUtilities.print8BitHexAndBinaryOf(token);
            newFrame[j] = token;
            bitArray = new int[8];
            j++;
        }
    }
    return newFrame;
}
```

B.2.4 CRC Check

The provided CRC is checked against the calculated checksum from the rest of the packet. The following, custom CCITT implementation is required for proper AAU-SAT II checksum calculation:

```
protected int value;
protected final int crctab[] = new int[256];
public FCS16AAU() {
    super();
    reset();
    // CRC table creation
```

```
    final short P_CCITT = 0x1021;
    for (int i = 0; i < 256; i++) {
        int crc = 0;
        int c = i << 8;
        for (int j = 0; j < 8; j++) {
            if (((crc ^ c) & 0x8000) > 0) {
                crc = (crc << 1) ^ P_CCITT;
            }
            else {
                crc = crc << 1;
            }
            c = c << 1;
        }
        crctab[i] = crc;
    }
}
public void reset() {
    value = 0xFFFF;
    length = 0;
}
public void update(byte b) {
    int short_c = 0x00FF & b;
    int tmp = (value >> 8) ^ short_c;
    value = 0x0000FFFF & ((value << 8) ^ crctab[tmp]);
    length++;
}
public void update(int b) {
    update((byte) (b & 0xFF));
}
public long getValue() {
    return value;
}
public byte[] getByteArray() {
    long val = getValue();
    return new byte[] { (byte) (val & 0xff), (byte) ((val >> 8) & 0xff) };
}
```

The checksum algorithm was originally provided by Kresten Sorensen from AAU (Aalborg University) for the AAU-SAT II AX.25 stack in C. This implementation of the CRC-16 differs from the original FCS-16 (CCITT) as it automatically creates the CRCTAB (which differs from the original one) and includes a left shift of the CRC on XOR instead of a right shift. Furthermore it has a reversed CRC checksum byte order. The original CRC-16 is, amongst others, part of the Jacksum library available under GPL.

Appendix C

ICOM IC-910H Signal Strength Calibration Values

C.1 Measurement Equipment and Settings

Auto Gain Control (AGC): Off
Signal generator: Rohde & Schwarz SM300
Cable: 2.5 m Aircell 7
Connectors used at 145 MHz: 1 x Type N connector , 1 x Type PL connector
Connectors used at 435 MHz: 2 x Type N connector
Connectors used at 1268 MHz: 2 x Type N connector
Measured on: 21 November 2009
Measured by: PA1IVO (Ivo Klinkert) and PA0LEZ (Leo van Empel)
SN IC-910: TBD

C.2 S-Meter Measurements

C.2.1 Measurements at 145.900Mhz

	FM				USB	
145.900 MHz	wide		narrow			
Input	level	S	level	S	level	S
dBm	-	Bars	-	Bars	-	Bars
-127	0003	0	0007	0	0001	0
-123	0015	0	0021	0	0001	0
-117	0037	0	0045	1	0001	0
-111	0065	3	0071	3	0038	0
-105	0087	5	0092	6	0089	5

-99	0112	8	0120	9	0112	8
-93	0141	11	0150	12	0129	10
-83	0200	18	0211	19	0152	12
-73	0249	Over	0255	Over	0175	15
-63	0255	Over	0255	Over	0196	17
-53	0255	Over	0255	Over	0220	20
-39					0255	Over

Table C.1

C.2.2 Measurements at 435.000Mhz

	FM				USB	
435.000 MHz	wide		narrow			
Input	level	S	level	S	level	S
dBm	-	Bars	-	Bars	-	Bars
-127	0007	0	0010	0	0001	0
-123	0018	0	0028	0	0001	0
-117	0043	0	0054	2	0001	0
-111	0070	3	0078	4	0064	3
-105	0092	6	0099	6	0098	6
-99	0118	8	0128	10	0119	9
-93	0148	12	0159	13	0134	10
-83	0209	19	0220	20	0156	13
-73	0255	Over	0255	over	0178	15
-63	-		-		0201	18
-53	-		-		0225	20
-41	-		-		0255	over

Table C.2

C.2.3 Measurements at 1268.000Mhz

	FM				USB	
1268.000 MHz	wide		narrow			
Input	level	S	level	S	level	S
dBm	-	Bars	-	Bars	-	Bars
-127	0032	0			0001	0
-123	0037	0			0001	0
-117	0053	2			0042	1
-111	0078	4			0084	5

-105	0099	6			0112	8
-99	0128	10			0128	10
-93	0159	13			0143	11
-83	0218	20			0164	14
-73	0255	over			0187	16
-63					0208	18
-53					0232	21
-41					0255	over

Table C.3

Level: Value read from 'Read S-meter level', command15 02
Bars: Bars shown on display IC-910 (2 bars = S1, 4 bars = S3)

C.3 Observed Attenuator Influence

145.9 MHz – USB / FM
S9 no attenuator:-94 dBm / -96 dBm
S9 attenuator: -72 dBm / -74 dBm
Attenuation: -22 dB / -22 dB

435 MHz – USB / FM
S9 no attenuator:-96 dBm / -97 dBm
S9 attenuator: -74 dBm / -75 dBm
Attenuation: -22 dB / -22 dB

1268 MHz – USB / FM
S9 no attenuator:-98 dBm / -99 dBm
S9 attenuator: -82 dBm / -83 dBm
Attenuation: -16 dB / -16 dB

Appendix D

The Signal Strength Measurement Format

A series of measurements of more than 2500 satellite passes of the CubeSat AAU-SAT II over Aalborg University ground station has been analyzed and evaluated. Each measurement consists of several thousand samples (sample rate per second: 8) whereas each sample consists of the following information:

- Timestamp: The exact time of the measurement in milliseconds represented as UNIX timestamp.
- S-Meter: The current 8-bit digital signal strength measurement from the radio as integer value.
- RX Total: Total amount of received AX.25 packets.
- RX OK: The amount of received AX.25 packets without CRC error.
- Elevation: The current elevation of the antenna in degrees.
- Azimuth: The current azimuth of the antenna in degrees.
- Frequency: The frequency the radio is currently tuned to in Hertz.

The measurements have been performed by a custom ground station control application implemented by Kresten Sorenson. The measurements are delivered as Comma-Separated-Values. The following example illustrates the format of the measurements:

```
...
1213176256.335, 46, 157, 67, 0.180000, 16.309999, 437441224
1213176256.464, 48, 157, 67, 0.180000, 16.309999, 437441224
...
1213176754.796, 40, 170, 76, 34.340000, 181.470001, 437424552
```

```
1213176754.923, 39, 170, 76, 34.340000, 181.470001, 437424552
...
1213177034.788, 48, 176, 81, 0.090000, 192.009995, 437422804
1213177034.920, 45, 176, 81, 0.090000, 192.009995, 437422804
...
```

Bibliography

Ali, I., Al-Dhahir, N., and Hershey, J. (1998). Doppler Characterization for LEO Satellites. *IEEE Transactions on Communications*, 46(3):309–313.

Alminde, L., Bisgaard, M., Melville, N., and Schaefer, J. (2005). The SSETI-Express Mission: From Idea to Launch in One and a Half Year. In *Proceedings of the 2nd International Conference on Recent Advances in Space Technologies (RAST)*, pages 100–105. IEEE Press.

Arana, L. and Troncoso, S. (2003). Student Space Exploration And Technology Initiative (SSETI) and the European Student Earth Orbiter (ESEO) Micro-Satellite. In *IAF Abstracts of the 34th COSPAR Scientific Assembly*, page 629. International Astronautical Federation (IAF).

Arsinte, R. (2006). Effective Methods to Analyze Satellite Link Quality Using the Build-in Features of the DVB-S Card. *Acta Technica Napocensis - Electronics and Telecommunications*, 47(1):33–36.

Baker, K. and Jansson, D. (1994). Space Satellites from the World's Garage - The Story of AMSAT. In *Proceedings of the IEEE National Aerospace and Electronics Conference (NAECON)*, volume 2, pages 1174–1181. IEEE Press.

Barbulescu, L., Howe, A., Watson, J., and Whitley, L. (2002). Satellite Range Scheduling: A Comparison of Genetic, Heuristic and Local Search. *Lecture Notes in Computer Science*, 2439/2002:611–620.

Berenji, H. (1996). Computational Intelligence and Soft Computing for Space Applications. *IEEE Aerospace and Electronic Systems Magazine*, 11(8):8–10.

Bishop, C. M., Jordan, M., Schölkopf, B., and Kleinberg, J. (2006). *Pattern Recognition and Machine Learning*. Information Science and Statistics. Springer.

Brown, M., Gunn, S. R., and Lewis, H. G. (1999). Support Vector Machines as an Efficient Tool for High-Dimensional Data Processing: Application to Substorm Forecasting. *Ecological Modelling*, 120(2-3):167–179.

Buracchini, E. (2000). The Software Radio Concept. *Communications Magazine, IEEE*, 38(9):138–143.

Cakaj, S., Keim, W., and Malarić, K. (2007). Communications Duration with Low Earth Orbiting Satellites. In *Proceedings of the 4th IEEE/IASTED International Conference on Antennas, Radar and Wave Propagation*, pages 85–88. IEEE Press.

Chouraqui, S., Bekhti, M., and Underwood, C. (2003). Satellite Orbit Determination and Power Subsystem Design. In *Proceedings of 2003 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, volume 7, pages 4590–4592. IEEE Press.

Chu, V., Sun, W., and Sweeting, M. (1997). Optimising the LEO Satellite Communications Link Through Hybrid-ARQ Techniques. *Proceedings of International Conference on Information, Communications and Signal Processing (ICICS)*, 1:5–9.

Coletti, M., Grubisic, A., Collingwood, C., Wallace, N., Wells, N., and Gabriel, S. (2009). European Student Moon Orbiter Solar Electric Propulsion Subsystem Architecture: An All-Electric Spacecraft. *Acta Astronautica*, 65:354–364.

Cortes, C. and Vapnik, V. (1995). Support-Vector Networks. *Machine Learning*, 20(3):273–297.

Cuevas, E. and Rehwinkel, C. (1995). SPOCS: A System to Measure Satellite Link Performance. *10th International Conference on Digital Satellite Communications*, 2:674–681.

Cutler, J. and Kitts, C. (1999). Mercury: A Satellite Ground Station Control System. In *Proceedings of IEEE Aerospace Conference*, volume 2, pages 51–58. IEEE Press.

Dan, W., Xuemai, G., and Qing, G. (2005). Classification using a Novel Support Vector Machine Fuzzy Network for Digital Modulations in Satellite Communication. In *International Conference on Wireless Communications, Networking and Mobile Computing*, volume 1, pages 508–512.

Dinger, H. and Paine, H. (1947). Factors Affecting the Accuracy of Radio Noise Meters. *Proceedings of the IRE*, 35(1):75–81.

Drucker, H., Wu, D., and Vapnik, V. (1999). Support Vector Machines for Spam Categorization. *IEEE Transactions on Neural Networks*, 10(5):1048–1054.

Durkin, J. (1982). Citizens-Band Radio. *IEE Proceedings on Physical Science, Measurement and Instrumentation, Management and Education, Reviews*, 129(7):535–544.

Elbert, B. R. (1999a). *Introduction to Satellite Communication*. Artech House, Boston, London, 2nd edition.

Elbert, B. R. (1999b). *Introduction to Satellite Communication*, chapter 4, page 159pp. Artech House, Boston, London, 2nd edition.

Elbert, B. R. (2001). *Ground Segment and Earth Station Handbook*. Number 1-58053-046-X in Artech House Space Technology and Appliations Library: The Satellite Communications. Artech House, Boston, London.

Fujii, H., Kruijff, M., van der Heide, E., Watanabe, T., and Ockels, W. (2007). The Second Young Engineers' Satellite: Innovative Technology through Education. In *Electronical Proceedings of the 58th International Astronautical Congress (IAC)*.

Gavrishchaka, V. V. and Ganguli, S. B. (2001). Support Vector Machines as an Efficient Tool for High-Dimensional Data Processing: Application to Substorm Forecasting. *Journal of Geophysical Research*, 106(A12):29,911–29,914.

Globus, A., Crawford, J., Lohn, J., and Pryor, A. (2003). Scheduling Earth Observing Satellites with Evolutionary Algorithms. In *Electronical Proceedings of the International Conference on Space Mission Challenges for Information Technology (SMC-IT)*.

Horne, R., Thorne, R., Shprits, Y., Meredith, N., Glauert, S., Smith, A., Kanekal, S., Baker, D., Engebretson, M., Posch, J., et al. (2005). Wave Acceleration of Electrons in the Van Allen Radiation Belts. *Nature*, 437(7056):227–230.

Hutputtanasin, A. and Toorian, A. (2005). CubeSat Design Specification. http://cubesat.atl.calpoly.edu/media/Documents/Developers/CDS R9.pdf.

Joachims, T. (1998). Text Categorization with Support Vector Machines: Learning with many Relevant Features. *Lecture Notes in Computer Science*, 1398/1998:137–142.

Klofas, B., Anderson, J., and Leveque, K. (2008). A Survey of CubeSat Communication Systems. Technical report, California Polytechnic State University and SRI International.

Krinnigner, S., Preindl, B., Mehnen, L., Rattay, F., and Nielsen, J. D. (2010). Link Quality Prediction for LEO Satellite Communication in UHF. Submitted for IEEE Transactions on Wireless Communication.

Larsen, J. A., Amini, R., and Izadi-Zamanabadi, R. (2005). Advanced Attitude Control of Pico Sized Satellites. In *Electronical Proceedings of the 56th International Astronautical Congress (IAC)*.

Lee, J., Lee, S., Yoon, J., and Choi, K. (2003). Real-Time Orbit Determination of Low Earth Orbit Satellites Using Radar System and SGP4 Model. *Journal of Astronomy and Space Sciences*, 20:21–28.

Lee, Y., Wahba, G., and Ackerman, S. A. (2004). Cloud Classification of Satellite Radiance Data by Multicategory Support Vector Machines. *Journal of Atmospheric and Oceanic Technology*, 21(2):159–169.

Li, Y., Xu, M., and Wang, R. (2007). Scheduling Observations of Agile Satellites with Combined Genetic Algorithm. In *Proceedings of the 3rd International Conference on Natural Computation (ICNC)*, volume 3, pages 29–33.

Lorek, C. (2001). The ICOM IC-910 Transceiver. *Radio Communication*, 77(7):17.

Mahalanobis, P. (1936). On the Generalized Distance in Statistics. In *Proceedings of the National Institute of Science, Calcutta*, volume 12, pages 49–55.

Mierswa, I., Wurst, M., Klinkenberg, R., Scholz, M., and Euler, T. (2006). YALE: Rapid Prototyping for Complex Data Mining Tasks. In *Proceedings of the 12th ACM International Conference on Knowledge Discovery and Data Mining (SIGKDD)*, pages 935–940. ACM Press.

Nakasuka, S., Sako, N., Sahara, H., Nakamura, Y., Eishima, T., and Komatsu, M. (2009). Evolution from Education to Practical use in University of Tokyo's Nano-Satellite Activities. *Acta Astronautica*.

Newport, J. (2005). Amateur Satellites: A Neglected Vehicle for Satellite Communication Education. *Elsevier Space Policy*, 21(2):101–104.

Nugent, R., Munakata, R., Chin, A., Coelho, R., and Puig-Suari, J. (2008). The CubeSat: The Picosatellite Standard for Research and Education. *Aerospace Engineering*, 805:756–767.

Osuna, E., Freund, R., and Girosit, F. (1997). Training Support Vector Machines: An Application to Face Detection. In *Proceedings of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition*, pages 130–136. IEEE Press.

Panagopoulos, A. D., Arapoglou, P.-D. M., and Cottis, P. G. (2004). Satellite Communications at KU, KA, and V Bands: Propagation Impairments and Mitigation Techniques. *IEEE Communications Surveys & Tutorials*, 6(3):2–14.

Paolino, L., Sebillo, M., Tortora, G., and Vitiello, G. (2001). Monitoring Electromagnetic Pollution: A GIS-Based Visual Approach. *Lecture Notes in Computer Science*, pages 90–104.

Parry, R. (1997). AX.25 [Data Link Layer Protocol For Packet Radio Networks]. *IEEE Potentials*, 16(3):14–16.

Pasupathy, S. (1979). Minimum Shift Keying: A Spectrally Efficient Modulation. *IEEE Communications Magazine*, 17(4):14–22.

Plaunt, C., Frank, J., and Jonsson, K. (1999). Satellite Tele-Communications Scheduling as Dynamic Constraint Satisfaction. *Artificial Intelligence, Robotics and Automation in Space*, 440:277.

Pratt, T., Bostian, C., and Allnutt, J. (2003a). *Satellite Communications*, chapter 5.4, pages 187–201. John Wiley & Sons, 2nd edition.

Pratt, T., Bostian, C., and Allnutt, J. (2003b). *Satellite Communications*, chapter 7.6, pages 284–287. John Wiley & Sons, 2nd edition.

Preindl, B., Mehnen, L., Rattay, F., and Nielsen, J. D. (2009a). A Ground Station Link Quality Measurement Satellite. In *Electronical Proceedings of the 2nd European CubeSat Workshop*.

Preindl, B., Mehnen, L., Rattay, F., and Nielsen, J. D. (2009b). Applying Methods of Soft Computing to Space Link Quality Prediction. In *Applications of Soft Computing. From Theory to Praxis*, volume 58 of *Advances in Intelligent and Soft Computing*, pages 233–242. Berlin Heidelberg, Springer.

Preindl, B., Mehnen, L., Rattay, F., and Nielsen, J. D. (2009c). Design of a Small Satellite for Performing Measurements in a Ground Station Network. In *Proceedings of the IEEE International Workshop on Satellite and Space Communications (IWSSC)*, pages 186–190.

Preindl, B., Mehnen, L., Rattay, F., Nielsen, J. D., Krinnigner, S., Sørensen, K. K., and Klinkert, I. (2010a). Gaining Comparable Link Quality Information using COTS Satellite Ground Station Hardware. To be published.

Preindl, B., Mehnen, L., Rattay, F., Nielsen, J. D., Krinninger, S., and Sørensen, K. K. (2009d). A Global Satellite Link Sensor Network. In *Proceedings of IEEE Sensors*, pages 1400–1405.

Preindl, B., Page, H., and Nikolaidis, V. (2008). GENSO: The Global Educational Network for Satellite Operations. In *Electronical Proceedings of the 59th International Astronautical Conference (IAC)*.

Preindl, B., Seidl, M., Mehnen, L., and Rattay, F. (2010b). Towards an Advanced Satellite Range Scheduling Framework for Large Ground Station Networks. To be published.

Ratcliff, G. (1988). The Amateur Satellite Service – The Past, Present and Future. In *Proceedings of the 4th National Space Engineering Symposium*, page 146. Institution of Engineers, Australia.

Sakamoto, Y. (2000). Construction of Orbit Determination System Using Low-Cost Ground Station. In *Proceedings of the International Symposiom on Space Science and Technology*, volume 22, pages 2179–2184.

Schmidt, M. and Schilling, K. (2008). Satellite Scheduling for Educational Ground Station Networks. In *Electronical Proceedings of the 59th International Astronautical Conference (IAC)*.

Schmidt, M. S. (1997). Identifying Speakers with Support Vector Networks. *Computing Science and Statistics*, pages 305–316.

Sci, J. (2002). NORAD TLE Type Orbit Determination of LEO Satellites Using GPS Navigation Solutions. *Journal of Astronomical Space Sciences*, 19(3):197–206.

Shaffer, S., Barave, A., and Khan, Z. (2009). Communication Paradigm Switching Based on Link Quality Information. Technical report, Cisco Technology, Inc., US Patent App. 11/969,045.

Smola, A. (1996). Regression Estimation with Support Vector Learning Machines. Master's thesis, Physik Department Munich Technical University.

Stearns, S. (2008). Antenna Modeling for Radio Amateurs. In *Electronical Proceedings of the ARRL Pacificon Antenna Seminar*. Northrop Grumman, Electromagnetic Systems Laboratory.

Stolarski, M. (2006). The Use of Distributed Ground Station Systems for Very Low Power Communication. In *Proceedings of the 1st International Workshop on Ground Station Networks*, pages 18–19.

Swartwout, M. (2006). Twenty (plus) Years of University-Class Spacecraft: A Review of What Was, an Understanding of What Is, and a Look at What Should Be Next. In *Proceedings of the 20th Annual AIAA/USU Conference on Small Satellites*, pages 14–17.

Taylor, W. (1977). A Dynamic Satellite Scheduling Algorithm. Technical report, NASA STI/Recon.

Toorian, A., Diaz, K., and Lee, S. (2008). The CubeSat Approach to Space Access. In *Proceedings of the IEEE Aerospace Conference*, volume 1, pages 1–14.

Tuli, T. S., Orr, N. G., and Zee, R. E. (2006). Low Cost Ground Station Design for Nanosatellite Missions. In *Electronical Proceedings of the AMSAT Symposium*.

Vallado, D. and Crawford, P. (2008). SGP4 Orbit Determination. In *Electronical Proceedings of the AIAA/AAS Astrodynamics Specialist Conference*.

Viterbi, A. (1967). Error Bounds for Convolutional Codes and an Asymptotically Optimum Decoding Algorithm. *IEEE transactions on Information Theory*, 13(2):260–269.

Wang, Y., Martonosi, M., and Peh, L.-S. (2005). A New Scheme on Link Quality Prediction and its Applications to Metric-Based Routing. In *Proceedings of the 3rd International Conference on Embedded Networked Sensor Systems (SenSys)*, pages 288–289, New York, NY, USA. ACM.

Waydo, S., Henry, D., and Campbell, M. (2002). CubeSat Design for LEO-based Earth Science Missions. In *Proceedings of the IEEE Aerospace Conference*, volume 1, pages 435–445.

Wickramanyake, A. (2006). Design, Development and Operation of a Student Groundstation. Master's thesis, Luleâ University of Technology, Department of Science, Kiruna.

Wong, K. and Melliar-Smith, P. (1990). A Scheduling Algorithm for Communication Satellite Networks. In *Proceedings of the IEEE Global Telecommunications Conference and Exhibition (GLOBECOM)*, volume 2, pages 761–765.

Zhou, C., Nielsen, J., Kolmos, A., and Du, X. (2009). Group Creativity Development in Engineering Students in a Problem and Project Based Learning Environment. In *Electronical Proceedings of the 2nd International Research Symposium on Problem Based Learning (CD)*.

Zieliński, B. (2008). Efficiency Estimation of AX. 25 Protocol. *Theoretical and Applied Informatics*, 20(3):199–214.

Zieliński, B. (2009). A Comparison of Various Types of TNC Controllers. In *Preprints of IFAC Workshop on Programmable Devices and Embedded Systems (PDeS)*, pages 80–85.

Nomenclature

ACE .... Advanced Composition Explorer
AD/DA ...... Analog Digital / Digital Analog
ADCS .... Attenuation Determination and Control System
AFSK .... Audible Frequency Shift Keying
AMSAT ...... AMateur SATellite Radio
ARQ .... Automatic Repeat reQuest
AUS .... AUthentication Server
BER .... Bit Error Rate
bps .... bit per second
BPSK .... Binary Phase Shift Keying
BR .... Burst Rate
CB .... Citizens' Band
COTS .... Common Off The Shelf
CRC .... Cecksum Redundancy Check
EIRP .... Effective Isotropic Radiated Power
ESA .... European Space Agency
FEC .... Forward Error Correction
FM .... Frequency Modulation
FSK .... Frequency Shift Keying
GENSO ...... Global Educational Network for Satellite Operations
GEO .... Geostationary Earth Orbit
GMS .... Groundstation Management Service
GPS .... Global Positioning System
GSS .... Ground Station Server
HEO .... Highly Elliptical Orbit
HF .... High Frequency
IARU .... International Amateur Radio Union
ISEB .... International Apace Education Board
ISS .... International Space Station
JAXA .... Japanese Aerospace Exploratoin Agency
LEO .... Low Earth Orbit
LNA .... Low Noise Amplifier
MCC .... Mission Control Client

MEO .... Medium Earth Orbit
MSK .... Minimum Shift Keying
NASA .... National Aeronautics and Space Administration
NB .... Narrow Band
NCDC .... National Climatic Data Center
NORAD ..... NOrth american Aerospace Defencse command
P-POD ...... Poly Pico-Satellite Orbital Deployer
PLR .... Packet Loss Rate
PSK .... Phase Shift Keying
QPSK .... Quadruple Phase Shift Keying
RMSE .... Root Mean Square Error
RSSI .... Received Signal Strength Indication
RTSW .... Real-Time Solar Wind
Rx .... Receivement or receiving
SDR .... Software Defined Radio
SGP .... Simplified General Perturbations Satellite Orbit Model
SHF .... Super High Frequency
SNR .... Signal to Noise Ratio
SVM .... Support Vector Machine
TLE .... Two Line Elements
TNC .... Terminal Node Controller
Tx .... Transmission or transmitting
UHF .... Ultra High Frequency
USB .... Upper Side Band
VHF .... Very High Frequency
WB .... Wide Band

List of Figures

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