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Published in:

Proceedings of 2nd European CubeSat Workshop, ESA/ESTEC, Noordwijk, The Netherlands, 2009

Publication date:

2009

Document Version

Publisher's PDF, also known as Version of record

[Link to publication from Aalborg University](#)

Citation for published version (APA):

Nielsen, J. F. D., Preindl, B., Mehnen, L., & Rattay, F. (2009). A Ground Station Link Quality Measurement Satellite. In *Proceedings of 2nd European CubeSat Workshop, ESA/ESTEC, Noordwijk, The Netherlands, 2009*

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A Global Satellite Link Sensor Network

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Abstract—With the raising number of space missions performed with nano- and pico-sized satellites, significant increase of mission data return becomes more and more important. As a consequence of the low earth orbit the satellites are deployed in, the communication timeframe between spacecrafts and ground stations is limited to half an hour a day. Nowadays non-commercial ground stations join forces by establishing ground station networks to optimize resource utilization and data return. Although the primary goal of such networks is to increase the amount of data transferred between spacecrafts and ground controls, link quality measurements performed by the ground stations during each satellite pass provide impressive remote sensing potential. In this paper the interpretation of more than two thousand satellite pass recordings performed during the last year at the University of Aalborg in Denmark are presented. Furthermore the potential of remote sensing utilizing ground station networks is demonstrated by means of possible scenarios described in detail.

I. INTRODUCTION

Over the last decade educational and academic spaceflight became more and more popular. The introduction of the CubeSat standard [1] made the design, construction and launch of satellites affordable for academic institutions of all sizes. One requirement for the launch of one's own satellite is a local satellite ground station [2]. Most non-commercial space missions utilize the non-profit radio amateur frequency bands [3] for communication in both directions. As a consequence ground stations of the satellite radio amateurs (AMSAT) [4] are also able to communicate with spacecrafts sending and receiving data in these specific frequencies.

As nano-sized and smaller satellites like CubeSats operate on very lower power budgets (less than 1 W) and their hardware is not intended to resist very high radiations as present in the Van Allen Belt [5] they operate exclusively in the Low Earth Orbit [6]. As a consequence the average communication time frame between ground station and spacecraft is half an hour per day.

To counter those limiting factors, ground station networks are established which extend the maximum possible communication timeframe to a couple of hours a day. The most popular project is the Global Educational Network for Satellite Operations (GENSO) [7]. Besides the main purpose of the network, the increase of the overall data throughput between

ground stations and satellites by provision and orchestration of ground station hardware and communication tunneling over the Internet, the participating stations also collect signal strength data during satellite passes [8].

The collected signal strength measurements can be used for a manifold of scientific investigations. From April 2008 and 12 months ahead 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 chapters 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.

II. 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 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 [8] 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. 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 ground-tracks

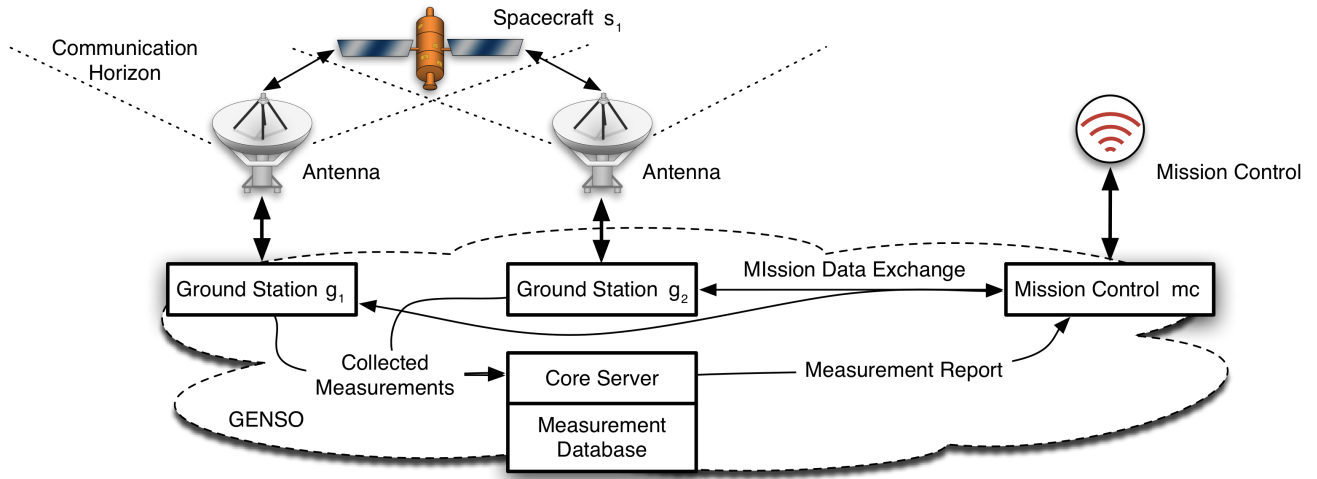


Fig. 1. Parallel to a direct data exchange between the mission control and the ground stations signal quality measurements are recorded by the ground stations and communicated to the core server. The core server stores all collected measurements for scientific investigations and to create reports for the mission controller.

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

A. Ground Station Hardware

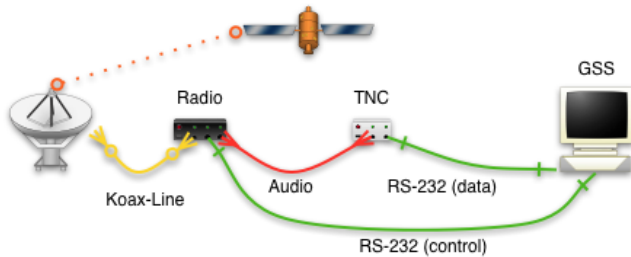


Fig. 2. Wiring diagram of a standard ground station.

The ground station hardware operating at Aalborg University (57°02'N, 9°54'E) consists of two typical YAGI antennas [9] 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 [10]. Figure 2

shows the wiring between the different components.

The signal strength reading has been performed by reading out the S-Meter indication value [11] via the RS-232 control connection of the radio. The sample rate was 8 samples per second.

B. Measured Satellite

The satellite which has been tracked and sensed was Aalborg Universities 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 [13] 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) [14] 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 [15]. 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 [12] can be up to 25KHz and requires continues frequency adjustments during the pass (see Figure 3-D).

The satellite is operating in Low Earth Orbit in a height of 615 to 634 kilometers and orbits earth almost 15 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. The

III. MEASUREMENT RESULTS

All recorded signal strength measurements have been filtered, normalized and analyzed using various scientific meth-

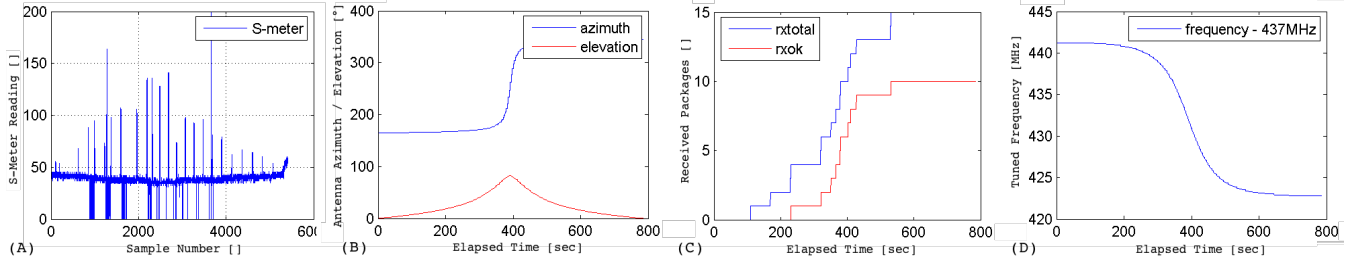


Fig. 3. Plot of the raw data recorded during a single satellite pass of 10 minutes: (A) shows the plot of the raw signal strength measurement per sample, (B) shows the antenna azimuth and elevation, (C) shows the amount of overall received packets and how many passed the CRC check, and (D) shows the change in carrier frequency as a consequence of the Doppler shift effect [12]

ods including methods from the field of machine learning [16] and used to create models of various kinds. The following sections describe the steps in detail.

A. Raw Measurements

Each recording sample indicates the currently measured signal strength as measured by the radio. During silent periods (between two communication beacons) the recorded samples reflect the background noise in the direction the antenna points at the specific moment. Figure 3 shows a plot of a raw, unprocessed pass measurement using 5500 samples of noise meter readings.

The primary attenuation factor for the signal strength is the distance between the ground station and the satellite. Hence the signal strength of the beacons is directly connected to the elevation angle of the antenna. Divergencies between the elevation angle and the beacon strengths can be ascribed to the satellite rotation. The raised signal strength on higher elevations is directly reflected in the amount of properly received and decoded beacon packets.

B. Preprocessing

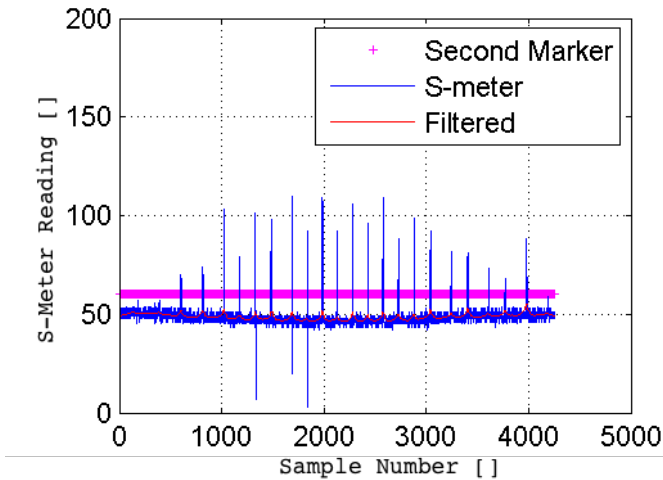


Fig. 4. A normalized pass measurement including the margin for noise floor separation

Every single measurement is automatically inspected in order to sort out passes showing strong variations compared to other passes to avoid corruption of the models. Sometimes passes are invalid due to antenna control failures, outdated orbital elements [17] or other hard- or software problems.

The raw measurements are normalized and an individual margin value is introduced to separate the noise floor and valid signals from the satellite. Figure 4 visualizes the margin value separating noise and signals.

C. Data Analysis and Normalization

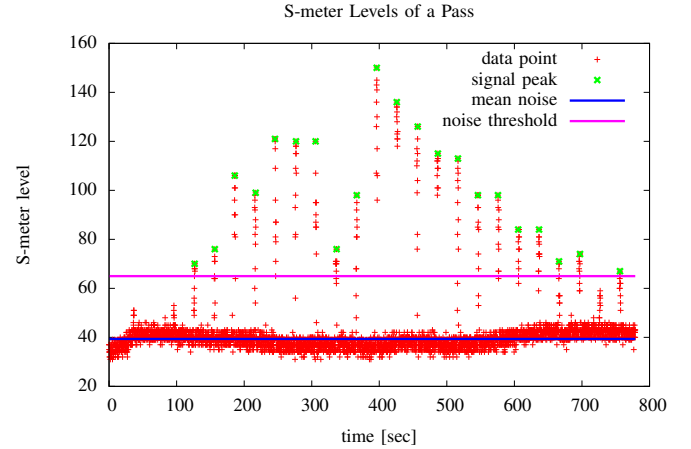


Fig. 5. This diagram shows the course of the S-meter levels of a typical satellite pass. The noise floor can be separated from the actual signal. Also, the peaks of the signal can be determined.

When all invalid passes have been filtered, we separate the noise from the signal and also determine the peaking values of the signal (see Figure 5). The signal-to-noise ratio (SNR) is then computed as the ratio between the mean of the best peak values and the mean noise value (in contrast to common understandings the signal to noise ratio is not measured in dB).

In total, we extracted the signal-to-noise ratio from over 1800 passes and calculated the distance between ground station and space craft for each pass. The relation between these two values is illustrated in Figure 7 using linear regression. It can be seen that there is a dependency between the minimal

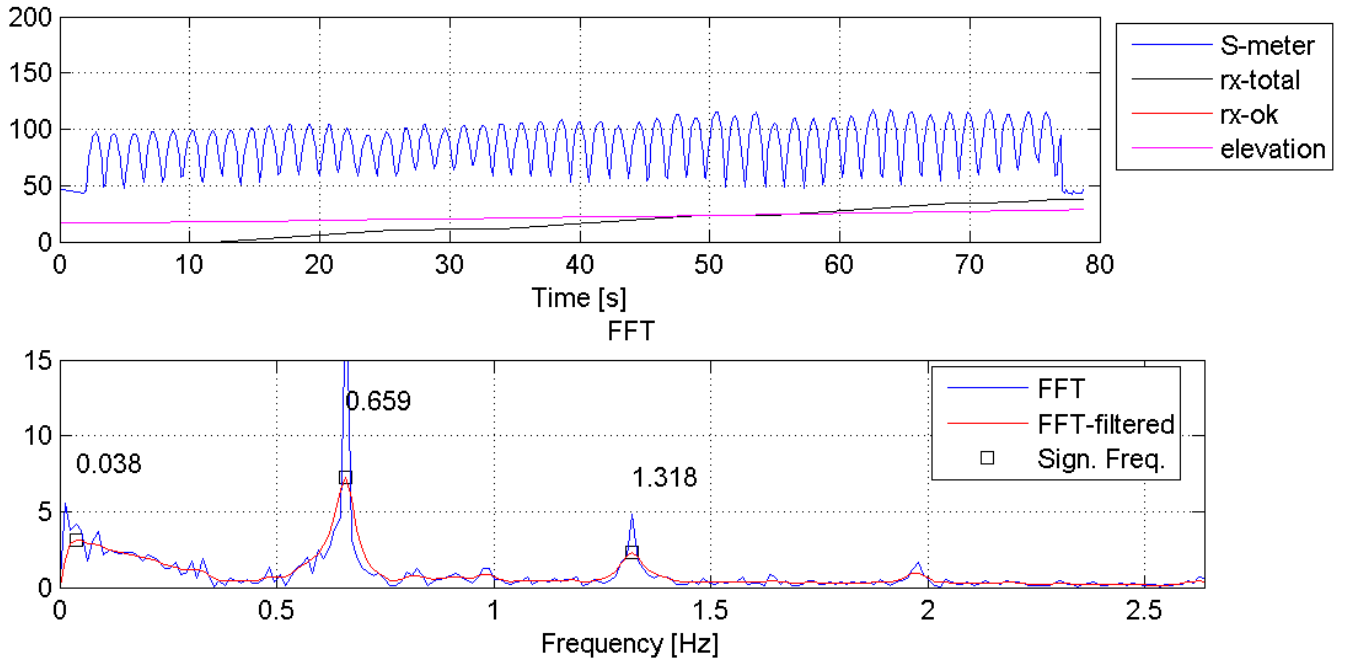


Fig. 6. The analysis of the signal strength measurement during permanent data transmission shows the tumbling interval of AAUSAT II (here: 0.66Hz).

distance and the signal-to-noise ratio: the lesser the distance, the better the link quality. This result coincides with the usual experience of radio amateurs. However, it would be desirable to have a more precise prediction besides this rough linear approximation. Our ongoing research indicates that other factors, like e.g. the surface weather, have an impact on the link quality. Machine learning techniques might help to predict the link quality given an appropriate feature vector.

Furthermore, we aim at predicting the quality of the link between the satellite and the ground station prior to a pass. This information about the expected quality could be used for example by the GENSO pass scheduler [18] to prefer ground stations that provide a good connection to the satellite which would in turn increase the mission return.

D. 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 8 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 floors 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

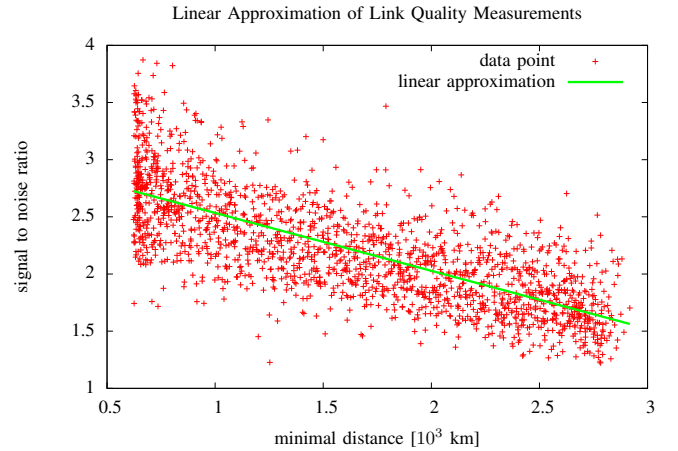


Fig. 7. This diagram shows the relation between the minimal distance of a satellite pass and the corresponding signal-to-noise ratio. A rough linear approximation of the link quality is possible.

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.

E. 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 6).

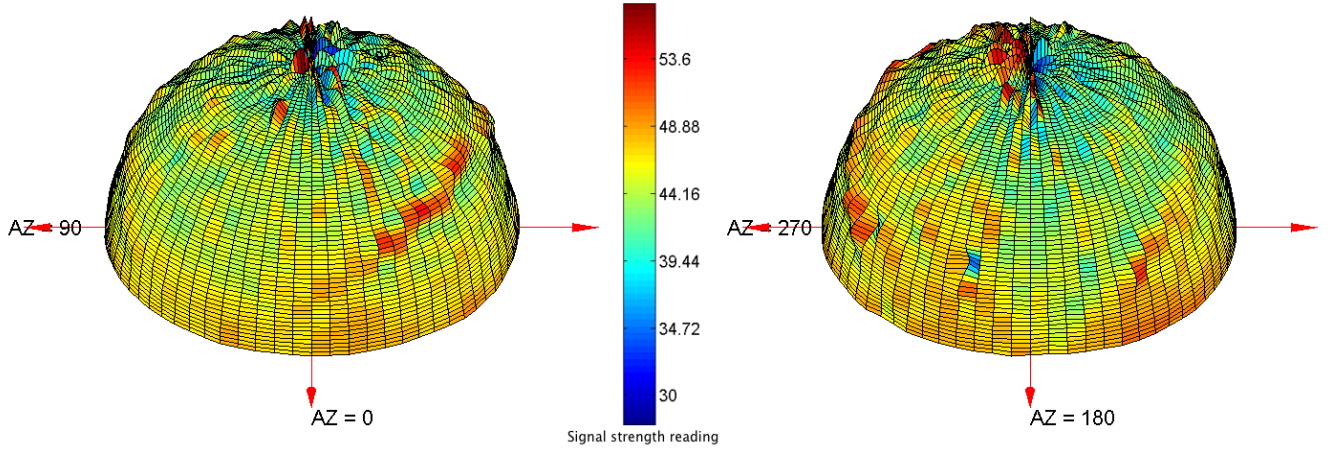


Fig. 8. Two 3D background noise plots (noise maps) calculated from 2500 passes covering the full 360° hemisphere around the Aalborg ground station. Azimuth resolution: 5° Elevation resolution: 1°

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.

IV. 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 [7] 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.

A. 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 [19]. 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 baud/second. As a consequence the precision will be a multiple of the current and the sample rate will grow a thousand times. Figure 9 shows a possible measurement setup for measuring the uplink performance of a ground station.

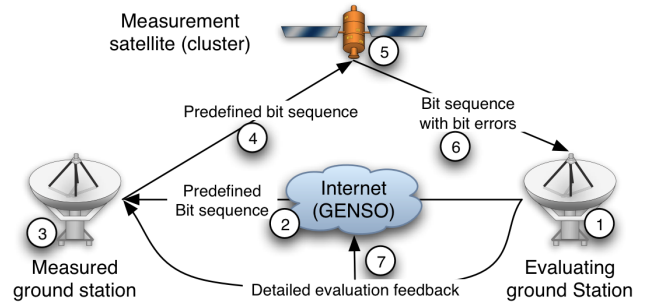


Fig. 9. The schematic sequence of an uplink quality determination: The satellite controlling ground station (1) transfers a sequence of bits (2) to the ground station over the Internet using the GENSO system to the ground station to be measured (3). When the measurement satellite passes the ground station, 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). [19]

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 10).

The measurement satellite is planned to be set into operation by beginning of 2011.

B. Full-Coverage Noise Maps

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

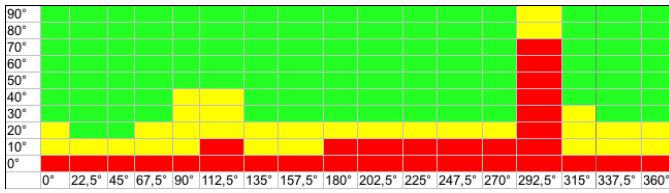


Fig. 10. The graphical evaluation of a hypothesized coverage window matrix with a very rough degree resolution (Green = high SNR, Yellow = low SNR, Red = no signal). [19]

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 [20].

C. 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 [21]. 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 [22] 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).

V. CONCLUSION

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 over the past year 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 enormous 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. Together with the projected remote sensing satellite a reverse engineering of the derived prediction models could lead to novel insights into radio propagation theory.

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