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Develoment of calibration and limit checking modules for a satellite's ground control software

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Department of Radio Science and Engineering

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All our dreams can come true, if we have the courage to pursue them.

Walt Disney

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Note: blablabla

Preface

Acknowledgements

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David.

Contents

Acronyms

ACL Access Control List. 114

API Application Programming Interface. 14, 15, 47, 48

APRS Automatic Position Reporting System. 11, 29–31, 35

ASCII American Standard Code for Information Interchange. 4, 25, 35, 40, 101, 103, 106, 109

ASOS Automated Surface Observing System. 17

AWOS Automated Weather Observing System. 17

AWS Automatic Weather Station. 17–31, 33, 35–40, 42–45, 48–51, 53, 55–57, 59, 63, 65, 71, 78–81, 85, 88–95, 98–100, 104, 108, 110–114

AX.25 Link Access Protocol for Amateur Packet Radio. 29, 30

BSON Binary-JSON. 101

CPU Central processing unit. 20, 31, 42, 65

CSV Comma-Separated Values. 5, 36, 113

CWOP Citizen Weather Observer Program. 11, 13, 14, 29, 35, 59, 60, 71, 113

DDoS Distributed denial-of-service. 114

DNS Dynamic Name Server. 73

DoS Denial-of-service. 114

ECMWF European Centre for Medium-Range Weather Forecasts. 12

FMI Finnish Meteorological Institute. 12, 15

FTP File Transfer Protocol. 34, 35, 39, 40, 43–45, 89, 113

GDPFS Global Data-processing and Forecasting System. 35, 44, 113

GOS Global Observing System. 35, 41, 44, 48, 49, 53, 113

GPRS General Packet Radio Service. 24, 26, 27

GSM Global System for Mobile Communications. 24, 26, 27

GTS Global Telecommunication System and WMO Information System. 35

GUI Graphical User Interface. 42, 95, 99, 117, 118

HTTP Hyper Transfer Text Protocol. 40, 48, 57, 76, 89, 91

ICAO International Civil Aviation Organization. 36, 113

IETF Internet Engineering Task Force. 34, 114

IO in / out. 20, 40

IP Internet Protocol. 45, 58, 69, 73, 87, 102, 103, 106, 109

ISO International Standard Organization. 56, 59, 75

JSON JavaScript Object Notation. 46, 48, 50, 53, 65, 67, 69, 77, 79, 86, 89–91, 96, 97, 99–101

kB Kilobyte. 20, 22, 23, 110

kbit kilobits. 22, 71, 93, 95

MB Megabyte. 21, 22

Mbits Megabits. 22, 71

METAR Meteorological Service For International Air Navigation. 36, 37

MHz Megahertz. 20

NAT Network address translation. 51, 73

NMEA-0183 National Marine Electronics Association 0183. 4, 25, 35

NOAA National Oceanic and Atmospheric Administration. 12, 18, 71, 113

NTP Network Time Protocol. 75, 101

OS Operating System. 49, 55, 57, 94

P2P Peer to peer. 47–51, 54, 55, 57, 58, 69, 70, 74, 86, 89, 91, 95, 98, 110, 113, 114

PROM Programmable Read-Only Memory. 25

PTH Pressure, Temperature, Humidity. 43

PTU Pressure, Temperature and Humidity. 78, 79, 82, 86, 110

RAM Random-access memory. 20

RFC Request for Comments. 34, 50, 51, 55, 59, 65, 75, 98

RS-232 Recommended Standard 232. 4, 22, 23, 33, 93

RS-422 Recommended Standard 422. 4, 22, 23

RS-485 Recommended Standard 485. 4, 22

RTT Round-trip time. 95

SDI-12 Serial Data Interface at 1200 Baud. 4, 25

SHA Secure Hash Algorithm. 59, 60

SI Système international d'unités - International System of Units. 9

SMB Server Message Block. 39, 40, 45

SOA Service-oriented architecture. 46, 47, 51, 52, 57, 62

TCP Transmission Control Protocol. 45, 61, 73, 96, 98, 102–111, 114

TLS Transport Layer Security. 114

TSV Tab-separated values. 5, 36

UML Unified Modeling Language. 97, 100

UMTS Universal Mobile Telecommunications System. 24, 26, 27

URI Uniform Resource Identifier. 59

URL Uniform Resource Locator. 59, 60

USB Universal Serial Bus. 4, 22, 26, 33

UTC Coordinated Universal Time. 75

UTF Universal Character Set - Transformation Format. 65

UTM Universal Transverse Mercator. 72, 93

WMO World Meteorological Organization. 11, 12, 15, 17, 18, 20, 21, 31, 33, 35, 36, 41, 48, 60, 77, 113, 114

XML eXtensible Markup Language. 67

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Chapter 1

Introduction

The relationship between human beings and space has existed since the beginning of time. It has always been a source of mystery, something we want to understand. More than 4000 years ago, the Egyptians and the Babylonians were influenced by the movements of the sun and the planets and, based on those movements, developed calendars for their crops. Later, the ancient Greeks developed the concept of *astronomy*, the science of the heavens. Subsequently, we can find philosophers such as Nicolaus Copernicus, Johannes Kepler, who explained the motion of the planets, and Galileo Galilei. In the 17th century, Sir Isaac Newton invented calculus, developed his law of gravitaion and performed important experiments in optics.

The technological advancements of the 20th century, specially accelerated by the World War II, made physical exploration of space become possible. This thesis is oriented towards one of those advancements, artificial satellites.

A *satellite* is a natural or artificial object moving around a bigger body. This motion is defined as an orbit, enabled by the dominant force of gravity from the bigger body. In early 1945, the United States started the Vanguard Rocket development to launch a satellite. However, after several failed launches, it was de Soviet Union who took the advantage by launching the Sputnik-1 (Figure 1.1) on October 4, 1957. During the Cold War, the space race between the Sovient Union and the United States was a hard fight which made space technology advance quite rapidly.

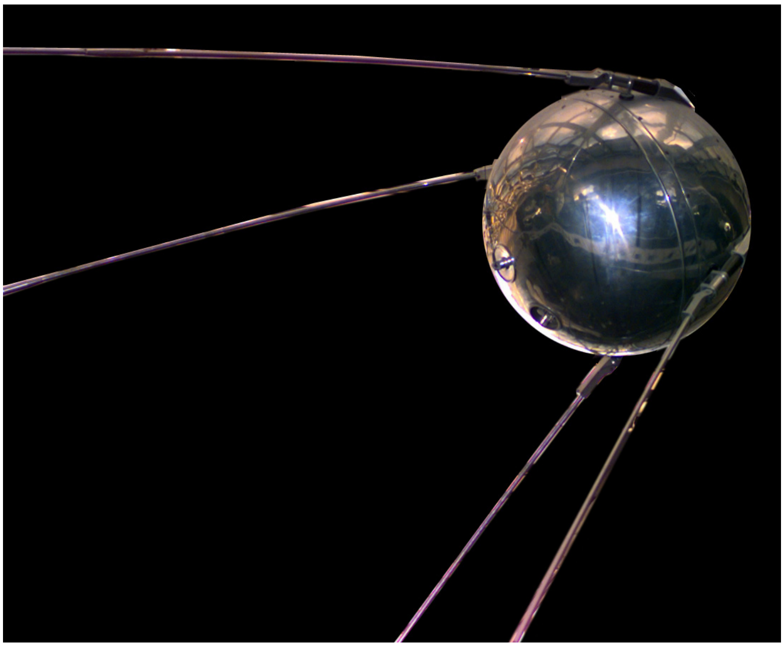


Figure 1.1: Sputnik 1 (NASA Public Domain)

Finally, on January 31, 1958 the United States managed to launch their first artificial satellite, the Explorer-1 (Figure 1.2).

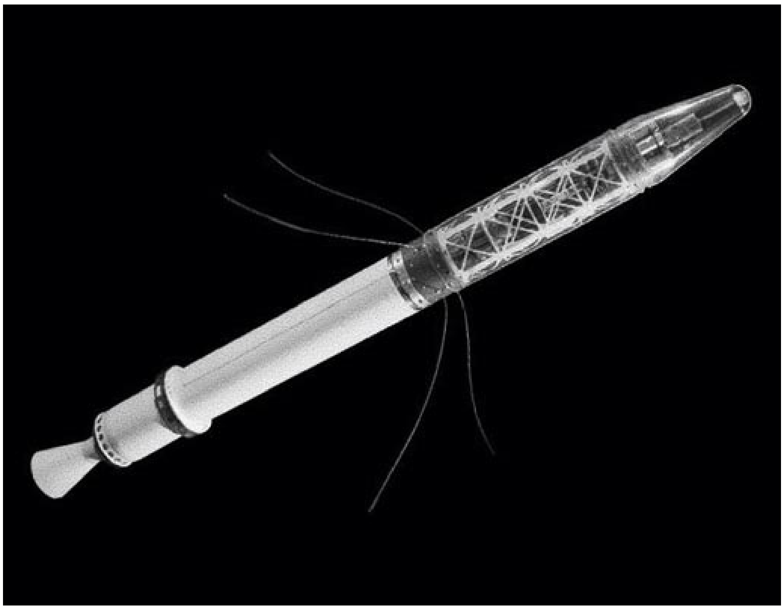


Figure 1.2: Explorer 1 (NASA Public Domain)

As of October 1, 2011 there were 966 operating satellites in orbit. About two-thirds of these were owned by the United States, Russia and China[1]. Their major types are:

- Communications: used for television, radio, Internet and telephone services.
- Navigation: using radio time signals, this satellites allow mobile receivers on the ground to determine their exact position. They are also used to determine the location of satellites situated in lower orbits.
- Exploration: used to observe distant planets, galaxies and other outer space objects by using telescopes and other sensors.
- Remote sensing: Remote sensing satellites are used to gather information about the nature and condition of Earth. The sensors in this kind of satellites receive electromagnetic emissions in several spectral bands and can detect the object's composition and temperature. Also, environmental conditions and so on. These satellites have also been widely used as military "spy satellites".

The constant evolution of technology and the growth of human needs have me the mission requirements rise throughout the last decades, thus, satellite mass has grown from Sputnik's 84 kg. and Explorer-1's 14k kg. to over 6,000 kg in 2007[2]. The main consequence of this, amongst others, has been an increment in mission costs.

To counter this trend, the small satellite movement was created by the academic community and it has shown how mission costs can be cut dramatically to a point in which a university can build a launch their own satellite. (Figure 1.3). Due to its success, it has become vigorous industry. Aalto-1 and ESTCube-1, projects with which this thesis is related, are nanosatellites, and the perfect example of this new concept.

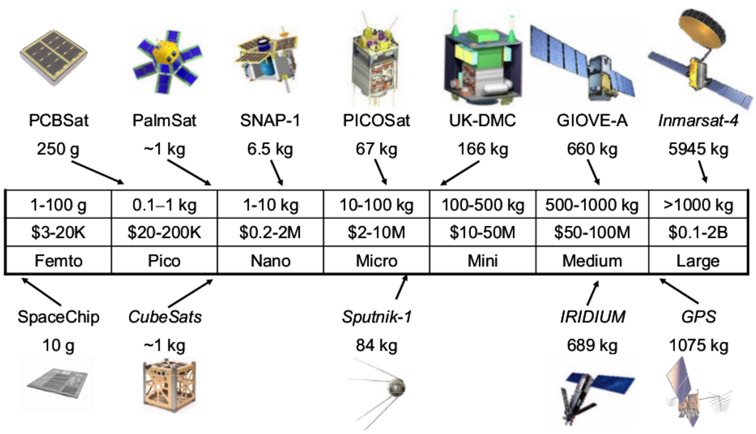


Figure 1.3: Satellite Mass and Cost Classification [2]

1.1 Background

As it was stated before, this thesis is closely related to two different projects. Aalto-1 and ESTCube. These two projects are based on the most common standard use by universities, CubeSat[3]. An open standard developed by the California Polytechnic State University and Stanford University.

1.1.1 Aalto-1

Led by Aalto University, Aalto-1 project aims to build a multi-payload remote sensing nanosatellite (Figure 1.4). The size of the satellite is approximately 34 cm x 10 cm x 10 cm with a mass of less than 4 kg[4].

Figure 1.4: Aalto-1

There are different institutions cooperating to make this possible. The main payload, the imaging spectrometer, has been designed and built by VTT Technical Research Centre of Finland. The Radiation Monitor (RADMON) has been designed by the Universities of Helsinki and Turku in cooperation with the Finnish Meteorological Institute (FMI). The Plasma Brake has been designed by a consortium including the FMI, the Department of Physics of the University of Helsinki, the Departments of Physics and Astronomy and Information Technology of the University of Turku, the Accelerator laboratory of the University of Jyväskylä, Aboa Space Resarch Oy, Oxford Instruments Oy and other Finnish companies. Meanwhile, Aalto University is responsible for designing and building the satellite platform and the day-to-day operation of the project.[5]

Aalto-1's mission is to validate the technologies used by the payloads in space environment and measure their performance. In addition, it is also an educational project. Students are the main workforce towards its success. Being the the first Finnish student satellite mission, it is a good tool to improve Finnish space teaching and also allow students to be in touch with prominent partners, both domestic and international, in the space technology field.

1.1.2 ESTCube-1

1.2 Problem statement

1.3 Research objectives and scope

1.4 Motivations

1.5 Outline of the thesis

Chapter 2

Orbits

One crucial topic that anyone working with satellites needs to understand is orbits and their characteristics. An orbit is the **gravitationally curved path of an object around a center of mass**. Examples of orbits can be the Earth around the Sun or artificial satellites around the Earth.

This section will cover the elements that describe and define an orbit, how it is represented on a map and in which way the elements that define a particular orbit can be delivered so they can be used by a computer.

2.1 Kepler's Laws

Planetary movements were first mathematically defined by the German mathematician, astronomer and astrologer Johannes Kepler in the 17th century. He concentrated his observations into three simple laws[6]:

- The orbit of each planet is an ellipse with the Sun occupying one focus.
- The line joining the Sun to a planet sweeps out equal areas in equal intervals of time.
- A planet's orbital period is proportional to the mean distance between the Sun and the planet, raised to the power of 3/2.

These laws apply to every celestial body. When analysing to bodies, if one is much bigger than the other, it conforms the "two-body problem". It assumes that both bodies are spherical and they are modelled as if they were point particles. This means that influences from any third body are discarded. The analysis of hits problem has resulted in six elements that completely define an orbit, which will be explained in the next section.

2.2 Classical Orbital Elements

The Classical Orbital Elements are six and uniquely identify an orbit. They also can be used to predict future positions.[7]

The first two elements, the orbit's size and shape are defined based on a 2D representation on an ellipse (Figure 2.1).

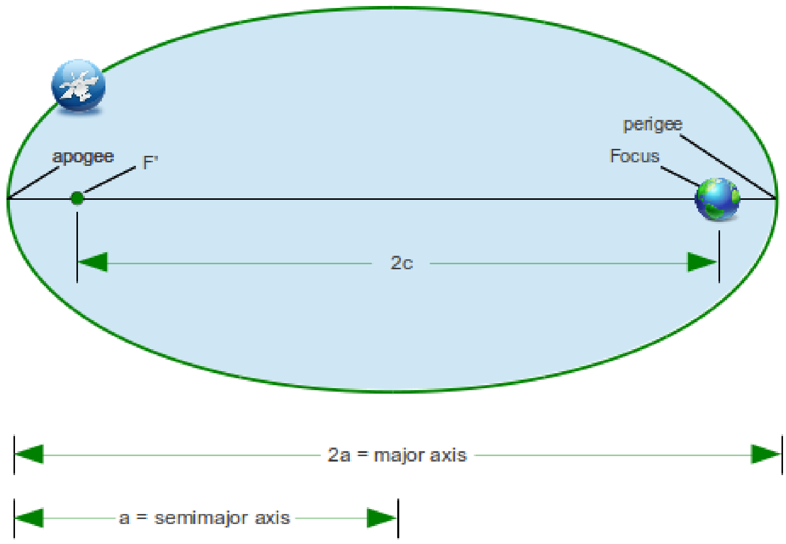


Figure 2.1: Semimajor Axis

- The *semimajor axis* (a) is one half the distance across the long axis of the orbit, and it represents the orbit's size.
- The *eccentricity* represents the shape of the orbit. It describes how much the ellipse is elongated compared to a circle. Based on the latter, the orbit can have the following shapes, as shown in Figure 2.2

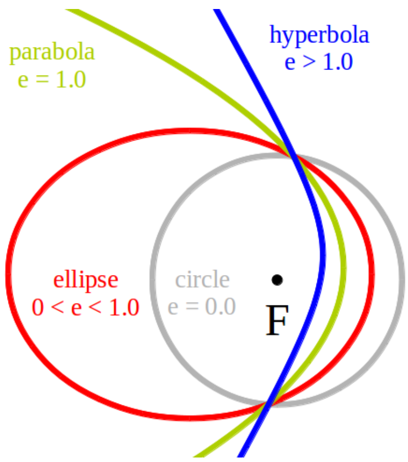


Figure 2.2: Eccentricity

Before jumping onto the next Orbital Elements it is necessary to point out that the Geocentric-equatorial Coordinate System will be used. It is now a 3D representation, where the fundamental plane is Earth's equatorial plane and the principal direction is in the vernal equinox direction.

The following orbital elements define the orientation of the orbital plane:

- The inclination (i) describes the tilt of the orbital plane with respect to the reference plane. It is measured at the ascending node. This is, where the orbit crosses with the reference plain when moving upwards.
- The right ascension of the ascending node (Ω) represents the angle between the principal direction and the point where the orbital plane crosses the reference plane from south to north measured eastward.

Based on this two elements, the orbits can be classified as shown in Table 2.1

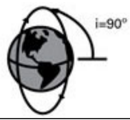
Inclination (i)	**Orbital Type**	**Diagram**
$0°$ or $180°$	Equatorial	
$90°$	Polar	
$0° \leq i < 90°$	Direct or Prograde (moves in the direction of Earth's rotation)	
$90° < i \leq 180°$	Indirect or Retrograde (moves against the direction of Earth's rotation)	

Table 2.1: Types of Orbits and Their Inclination [7].

Although it is not part of the COEs, orbits can also be sorted by their altitude. NASA's classification divides orbits in three groups (Table 2.2).

Orbit	**Altitude (a)**	**Uses**
Low Earth Orbit (LEO)	$a < 2000Km$	Scientific and weather satellites
Medium Earth Orbit (MEO)	$2000Km \leq a < 36000Km$	GPS
High Earth Orbit (HEO) or Geosynchronous (GSO)	$36000Km$	Communications (phones, television, radio)

Table 2.2: NASA's classification of orbits. [8]

It is now time to go through the last two COEs:

- The argument of perigee (ω) is the angle between the ascending node and the perigee, measured in the direction of the satellite's motion.
- The true anomaly (υ) specifies the location of the satellite within the orbit. Amongst all the CEOs, this is te only one which changes over time. It is the angle between the perigee and the satellite's position vector measured in the direction of its motion.

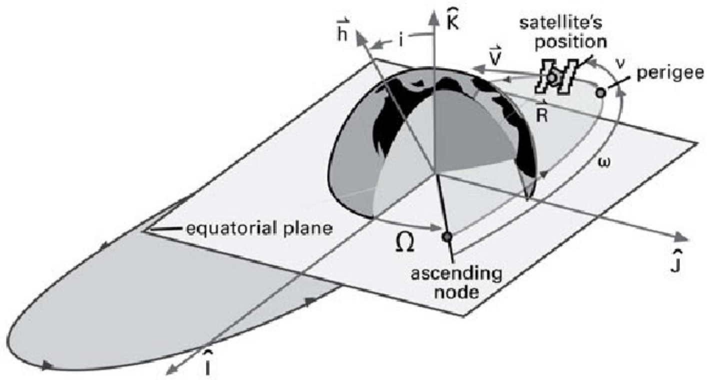


Figure 2.3: Classical Orbital Elements [7]

2.3 Ground Tracks

The satellite ground tracks are the projection of its orbit onto Earth. An example of this can be Figure 2.4.

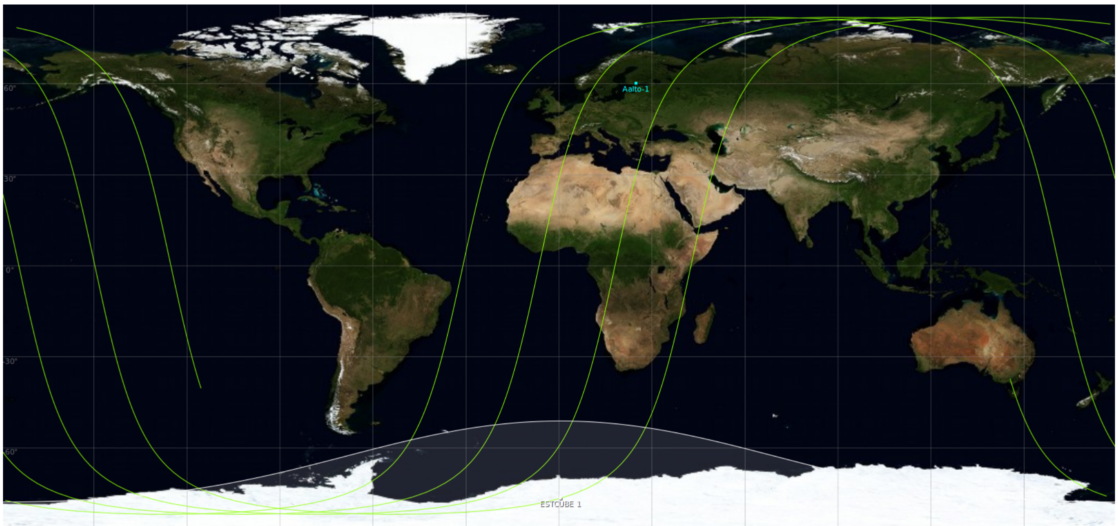


Figure 2.4: Ground Tracks of ESTCube-1

Since the orbital plane does not move in inertial space, the satellite's orbit will always be the same. If Earth did not move the representation of the orbit would be a single line, as the ground track would continuously repeat. However, Earth rotates at 1600 km/hr. Thus, even if the orbit does not change, from the Earth-based observer's point of view it appears to shift to the west.

2.4 Two Line Elements

A two line element set (TLE) is a data format created by the North American Aerospace Defense Command (NORAD) and NASA to transport sets of orbital elements describing satellite orbits around Earth. These TLEs can be later processed by a computer to calculate the position of a satellite at a particular time.

The following snippet shows an example of a TLE for the International Space Station.

```
ISS (ZARYA)
1 25544U 98067A 13166.62319444 .00005748 00000-0 10556-3 0 120
2 25544 51.6483 116.0964 0010829 73.3727 265.7013 15.50799671834453
```

Field	Columns	Content	Example
1	01	Line number	1
2	03-07	Satellite number	25544
3	08	Classification (U=Unclassified)	U
4	10-11	International Designator (Last two digits of launch year)	98
5	12-14	International Designator (Launch number of the year)	067
6	15-17	International Designator (Piece of the launch)	A
7	19-20	Epoch Year (Last two digits of year)	08
8	21-32	Epoch (Day of the year and fractional portion of the day)	264.51782528
9	34-43	First Time Derivative of the Mean Motion	-0.00002182
10	45-52	Second Time Derivative of Mean Motion (decimal point assumed)	00000-0
11	54-61	BSTAR drag term (decimal point assumed)	-11606-4
12	63	Ephemeris type	0
13	65-68	Element number	292
14	69	Checksum (Modulo 10) (Letters, blanks, periods, plus signs = 0; minus signs = 1)	7

Table 2.3: Two-Line Element Set Format Definition, Line 1

Field	**Columns**	**Content**	**Example**
1	01	Line number	1
2	03-07	Satellite number	25544
3	09-16	Inclination [Degrees]	51.6416
4	18-25	Right Ascension of the Ascending Node [Degrees]	247.4627
5	27-33	Eccentricity (decimal point assumed) (Launch number of the year)	0006703
6	35-42	Argument of Perigee [Degrees]	130.5360
7	44-51	Mean Anomaly [Degrees]	325.0288
8	53-63	Mean Motion [Revs per day]	15.72125391
9	64-68	Revolution number at epoch [Revs]	56353
10	69	Checksum (Modulo 10)	00000-0

Table 2.4: Two-Line Element Set Format Definition, Line 2

Chapter 3

Telecommunications

TODO: Introduction

3.1 Data

The data exchanged between a satellite and the ground stations on Earth can be divided into three different categories: the beacon, the telemetry and the telecommands.

3.1.1 Beacon

A *beacon* is a radio signal transmitted continuously or periodically over a specified radio frequency. It provides a small amount of information such as identification or location, but it can have more applications. Examples of these are: adjust the power of the ground station signal based on the beacon's strength or tune the ground station to compensate the doppler shift.

3.1.2 Telemetry

Telemetry data is sent from the satellite to the ground station and can also be divided in three sub-categories.

The *housekeeping data* provides information abouth the health and operating status of the satellite. Examples of this data can be pressure, voltages and currents, or also bits representing the operational status of all the components as it is shown in Figure 3.1. The size of this data is usually quite small, so a bit rate on only a few hundres of bits per second is enough to complete the transmission successfully.

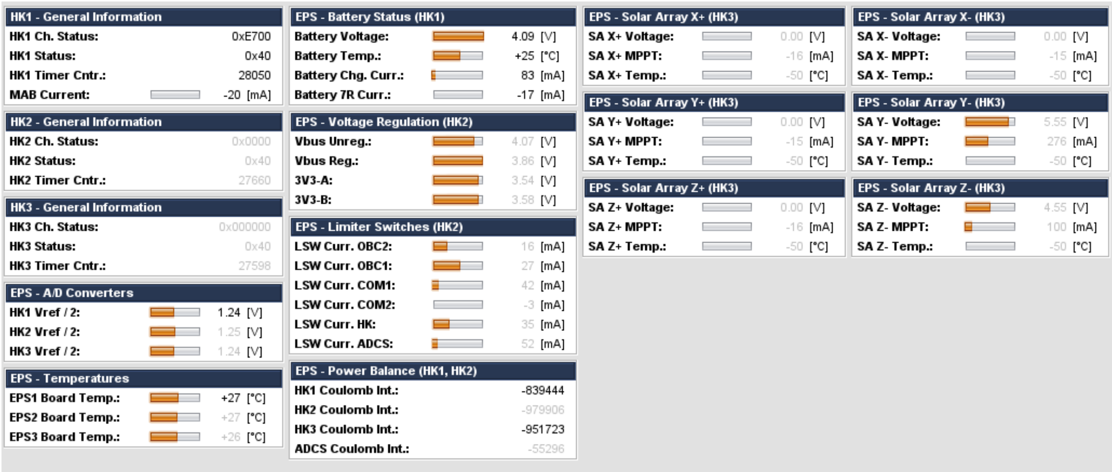


Figure 3.1: Housekeeping data of the satellite Masat-1

Attitude data is generated by different sensors, such as magnetometers, gyroscopes, accelerometers and Sun, Earth and star sensors.

Payload data changes with every mission and needs to be considered individually. Scientific or Earth-observing mission normally generate very large data volumes, specially in the form of images. An example of this can be Figure 3.2, the first picture taken by the Hungarian nanosatellite Masat-1[11].

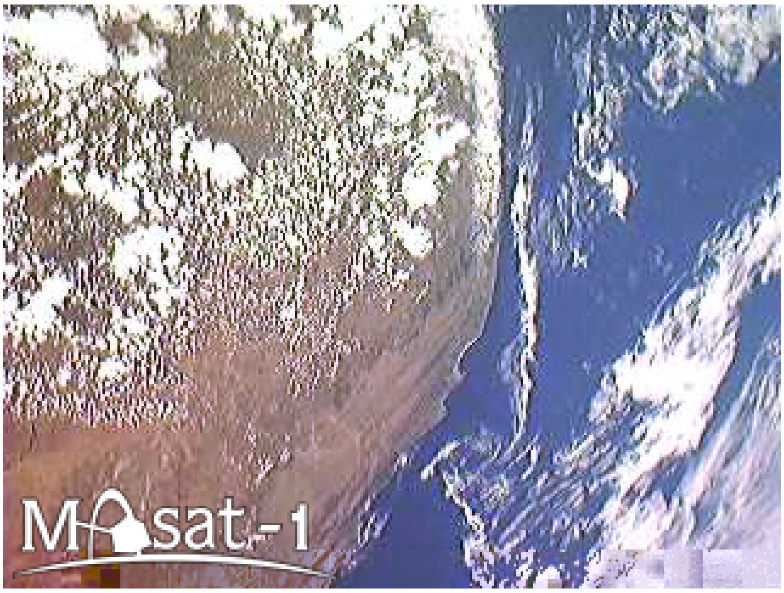


Figure 3.2: Picture of South Africa taken from the nanosatellite Masat-1

3.1.3 Telecomands

The telecommands are sent from the ground station to the satellite. They are used to remotely control its functions and are divided in three basic types [6]:

- *Low-level on-off commands.* These are logic-level pulses used to set or reset log flip-flops.
- *High-level on-off commands.* Higher-powered pulses, capable of operating a latching relay or RF waveguide switch direcly.
- *Proportional commands.* Digital words. Used for purposes such as reprogramming memory locations on the on-board computer or setting up registers in the attitude control subsystem.

3.2 Ground Station

One integral part of every satellite mission is the ground station. It works as the first and final piece of the communication link. Its main functions are the following:

- Tracking the satellite to determine its position in orbit.
- Gather data to keep track of the satellite's data and status.
- Command operations to control the different functions of the satellite.
- Process the received engineering and scientific data to present it in the required formats.

It is important to remember that university satellites are usually classified as amateur satellites. This means that they use amateur radio frequencies and the usage of the ground station is bound to each country's amateur radio regulations.

3.2.1 Hardware

The main components of a ground station are the antenna, the transceiver, the data recorders and the computers and their peripherals.

Antennas

The main hardware component of a ground station is the antenna. Its functions may include tracking, receiving telemetry, sending telecommands, etc.

The frequencies most commonly used for amateur satellites are shown in Table 3.1.

Table 3.1: TODO: Table with Frequencies.

Transceiver

A transceiver is a hardware unit containing both a transmitter and a receiver. It acts as an intermediary between the antenna and a computer, changing the radio frequency into bytes and viceversa.

3.2.2 Software

The activity in the ground station does not start when the satellite is passing over it and does not end once it is gone. There are certain tasks that need to be done before, during and after the pass.

Before the satellite arrives it is necessary to determine and predict its orbit. Based on this prediction the software will schedule future passes and generate the command list which will be sent during the pass.

The real-time software comes into operation when the satellite is visible from the ground station. It is in charge of controlling the antenna rotor to follow it across the sky; it will also send telecommands to the satellite and verify their correct reception. In addition, it will receive the data being transmitted from the satellite, which will be processed later.

Once the satellite is not visible any more the post-pass software comes into play. The data received during the pass is now processed and stored so the specialists can analyse it.

3.2.3 Protocols

A protocol is an agreement between the communicating parties on how communication is to proceed[12]. This section will be focused on the OSI Reference model as well as on some of the most popular protocols for amateur radio communications.

The OSI Reference Model

The Open Systems Interconnection (OSI) Reference Model was developed in 1983 and revised in 1995. This model deals with connecting systems that are open for communication with other systems. It consists on seven layers which are explained in Table 3.2.

<table>
<tr><th colspan="4">OSI Model</th></tr>
<tr><th></th><th>Data Unit</th><th>Layer</th><th>Function</th></tr>
<tr><td rowspan="4">Host Layers</td><td rowspan="3">Data</td><td>7. Application</td><td>Network process to application.</td></tr>
<tr><td>6. Presentation</td><td>Data representation, encryption and decryption, convert machine dependent data to machine independent data</td></tr>
<tr><td>5. Session</td><td>Interhost communication, managing sessions between applications</td></tr>
<tr><td>Segments</td><td>4. Transport</td><td>End-to-end connection, reliability and flow control</td></tr>
<tr><td rowspan="3">Media Layers</td><td>Packet/Datagram</td><td>3. Network</td><td>Path determination and logical adressing</td></tr>
<tr><td>Frame</td><td>2. Data link</td><td>Physical addressing</td></tr>
<tr><td>Bit</td><td>1.Physical</td><td>Media, signal and binary transmission</td></tr>
</table>

Table 3.2: OSI Model[12].

AX.25

AX.25 is a data link layer protocol designed for use by amateur radio operators. It occupies the first, second and third layers of the OSI model. However, AX.25 was developed before the model came into action, so its specification was no written to separate into OSI layers.

The link-layer packet radio transmission takes place in small blocks of data called frames. Those frames are represented in the Figures 3.3 and 3.4.

Flag	Address	Control	Info	FCS	Flag
01111110	112/224 Bits	8/16 Bits	N*8 Bits	16 Bits	01111110

Figure 3.3: Supervisory and Unnumbered frames [13]

Flag	Address	Control	PID	Info	FCS	Flag
01111110	112/224 Bits	8/16 Bits	8 Bits	N*8 Bits	16 Bits	01111110

Figure 3.4: AX.25 Information frame [13]

FX.25

FX.25 is an extension to the AX.25 protocol. It has been created to complement the AX.25 protocol, providing an encapsulation mechanism that does not alter the AX.25 data or functionalities. AX.25 packets are easily damaged, and this extension intends to remedy the situation by providing a Forward Error Correction (FEC) capability at the bottom of Layer 2.

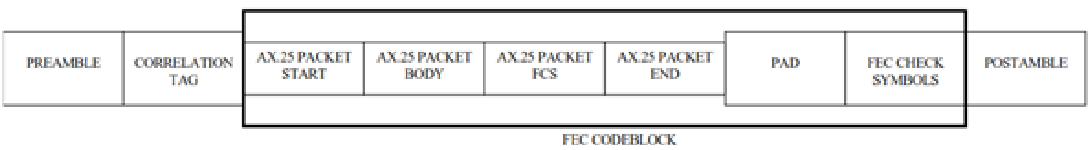


Figure 3.5: AX.25 Information frame [14]

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