İSTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

PRELIMINARY DESIGN OF THE COMMUNICATION SUBSYSTEM FOR THE PROPOSED SUDANESE EARTH OBSERVATION SATELLITE

M.Sc. THESIS

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TEKLİF EDİLMİŞ SUDAN YER GÖZLEM UYDUSU İÇİN HABERLEŞME SİSTEMİ ÖN TASARIMI

YÜKSEK LİSANS TEZİ

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MAYIS 2015

Mustafa Alhassan, a **M.Sc.** student of ITU **Institute of / Graduate School of Science Engineering and Technology** student ID **511121213**, successfully defended the **thesis** entitled "**PRELIMINARY DESIGN OF THE COMMUNICATION SUBSYSTEM FOR THE PROPOSED SUDANESE EARTH OBSERVATION SATELLITE**", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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FOREWORD

I would like to express my deep appreciation and thanks for my advisor Prof.Dr. Alim Rustem Aslan, this work could not been done without his great help and support during writing of this thesis and during my whole M.Sc. program. I really learned a lot from his great proficiency and experience.

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May 2015 Mustafa ALHASSAN

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ABBREVIATIONS

AA	: Atmospheric Absorption
ADCS	: Attitude Determination and Control Subsystem
AML	: Antenna Misalignment Loss
APM	: Antenna Pointing Method
ASK	: Amplitude-shift keying
BPSK	: Binary Phase Shift Keying
BER	: Bit Error Rate
C/N	: Carrier to Noise Ratio
CCSDS	: Consultative Committee for Space Data Systems
EIRP	: Effective Isotropic Radiated Power
FEC	: Forward Error Correction
FSK	: Frequency Shift Keying
FSL	: Free Space Loss
GS	: Ground Station
HPA	: High Power Amplifier
HRC	: High Resolution Geometric
HRS	: High Resolution Stereoscopic
IFOV	: Instantaneous Field of View
ITU	: International Telecommunication Union
Kbps	: Kilobits per second
LEO	: Low Earth Orbit
LNA	: Low Noise Amplifier
LTAN	: Local time of ascending node
Mbps	: Megabits per second
MPSK	: Multiple Phase Shift Keying
MS	: Multi-spectral
OOK	: On-off Keying
PCM	: Pulse Code Modulation
PL	: Polarization Mismatch loss
PM	: Phase Modulation
PSK	: Phase Shift Keying
R-S	: Reed-Solomon code
RAAN	: Right Ascension of the Ascending Node
RFL	: Receiver Feeder Loss
S/C	: Spacecraft
SEL	: Single Event Latchup
SEU	: Single Event Upset
SSPA	: Solid State Power Amplifier
SSTL	: Surrey Satellite Technology Ltd
TT&C	: Telemetry Tracking and Command
TID	: Total Ionizing Doze
TWTA	: Traveling Wave Tube Amplifier
QPSK	: Quadrature Phase Shift Keying

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PRELIMINARY DESIGN REVIEW OF THE COMMUNICATION SUBSYSTEM OF THE PROPOSED SUDANESE EARTH OBSERVATION SATELLITE

SUMMARY

Sudan is one of the richest countries in the world in terms of natural resources, agricultural fields in particular. The cost of monitoring these resources from space is very high. Establishing a national satellite mission has large initial cost, but it has a large significance in the long run.

SudaSat-1 is a proposed earth observation satellite mission funded by the government of Sudan to obtain high resolution images of various areas of the country and other countries as per request.

Establishing reliable communication is an essential function for any spacecraft; the failure of communication means loss of mission, the goal of this thesis is to provide a preliminary design for the communication subsystem for SudaSat-1 satellite.

The thesis provides a review of similar satellite missions to gain insight of the main considerations involved in the design. The review focused on the satellites with the same spatial resolution.

The main characteristics of remote sensing satellites is reviewed, image acquisition modes are also explained.

Satellite baseline mission design is introduced, a satellite platform is selected to satisfy overall mission requirements, imaging sensors specifications together with satellite orbit characteristics are also determined to provide the required ground sampling distance. Satellite orbit is designed and simulated using STK, orbit period and average communication time is determined. The thesis highlights mission design elements that influence the design and implementation of the communication subsystem.

Communication subsystem-level requirements, functions and design components are overviewed. Components selection is based on requirements satisfaction and space heritage. Redundancy of critical components is put into consideration to increase the reliability of the subsystem. Separate downlink channels are set for imagery data (X-band) and engineering data (S-band).

Satellite link power budget is calculated for both downlink channels and for uplink channel. An acceptable value of power margin is obtained.

Communication subsystem architecture is presented showing the interconnection between main subsystem components.

Satellite data transfer plan is determined illustrating the steps followed to transfer imagery and engineering data downlink and commands uplink.

TEKLİF EDİLMİŞ SUDAN YER GÖZLEM UYDUSU İÇİN HABERLEŞME SİSTEMİ ÖN TASARIMI

ÖZET

Astronomi 19. ve özellikle 20. yüzyılda baş döndürücü bir hızla ilerlemiştir. Teleskopların geliştirilmiş olması, spektroskopinin getirdiği imkanlar, evrenin genişleme içinde olduğunun farkına varılması, büyük patlama kuramı yoluyla kozmolojide meydana gelen gelişmeler ve diğer bilim dallarındaki gelişmelerin astronomiye katkıları bu bilimin ilerlemesine büyük katkılar sağlamıştır.

Bu gelişmelerin ardından devam eden süreçte, I. ve II. Dünya savaşını geride bırakıp 20. yy'ın üçüncü çeyreğinde soğuk savaş dönemine giren dünya aynı zamanda "uzay yarışı" diyebileceğimiz bir mücadeleye başlamıştır. Amerika Birleşik Devletleri ve Sovyet Sosyalist Cumhuriyetler Birliği arasında geçen bu mücadelenin astronomiye olan katkıları büyüktür. Uzaya uydu ve sonda yollayarak uzayı keşfetmek, insan göndermek, Ay'a insan indirmek gibi önemli olaylar bu dönemde gerçekleşmiştir.

Bu mücadeleden sonra uzayı keşfetme yarışı biraz olsun hızını kaybetsede, günümüzde insanoğlunu heyecanlandıran çalışmalar devam etmektedir. Avrupa Uzay Ajansı'nın en geç 2030 yılına kadar Mars'a insan göndermeyi amaçlayan Aurora programı bunlardan biri ve yarışı tekrar ateşleyebilir.

Sudan, doğal kaynaklar ve tarım alanları açısından Dünya üzerindeki en zengin ülkelerden biridir. Bu bölgelerin gözlenmesi oldukça maliyetlidir. Ancak bu amaçla oluşturulacak ulusal bir uydu ilk aşamalardaki yüksek maliyetine rağmen uzun vadede önemli bir projedir.

SudaSat-1, Sudan topraklarının ve talepleri doğrultusunda diğer ülkelerin yüksek çözünürlüklü görüntülerini almayı amaçlayan ve Sudan hükümeti tarafından finanse edilen uzaktan algılama uydusu projesidir.

Uzaktan algılama, yeryüzünün ve yer kaynaklarının incelenmesinde onlarla fiziksel bağlantı kurmadan kaydetme ve inceleme tekniğidir. Yer ile herhangi bir temas olmaksızın yerin çeşitli özelliklerinin tespiti işidir. Uzaktan algılama kısa bir tanım yapılacak olursa, fiziksel temas olmadan cisimler hakkında bilgi almaktır

Güvenilir bir haberleşmenin kurulması her uzay aracı için elzemdir; haberleşmede oluşabilecek bir hata görevin kaybedilmesi anlamına gelir. Bu tez de SudaSat-1 için haberleşme altsisteminin ön tasarımının yapılmasını amaçlar.

Bu tez benzer uydu projelerini inceleyerek tasarım için gerekli temel fikirlerin edinilmesini sağlar. İncelemeler, benzer uzaysal çözünürlüklü uydu projelerine odaklanmıştır.

Uzaktan algılama uydularının temel karakteristikleri incelenmiş ve görüntü elde etme modları açıklanmıştır.

Modlar 2 çözünürlük değerleri için belirlenmiştir. Yüksek çözünürlüklü şerit modu ve geniş alan modu. Yüksek çözünürlüklü şerit modu, 8 km'lik alan genişliğine, PAN kanalında 1x1'lik alansal çözünürlüğüne sahiptir. Geniş alan modu ise 300 km alan genişliği ve 10x10'luk alansal çözünürlüğüne sahiptir.

Uydu yörüngesinde ortalama 7.53 km hızla ilerlerken 1m yer örnekleme yüksekliği (YÖY) çözünürlüğünü sağlayan görüntülerin alınabilmesi için 1 CCD algılayıcısı yeterli olmayacaktır. Bir transfer gecikmesi ve entegrasyon (TDI), senkronize olmayan görüntülme modu, aşamalı CCD doğruları ya da bunların bir kombinasyonu gerekmektedir. Bu gereksinimmler göz önüne alınarak algılayıcı sistem seçilmiştir. Sonuç olarak 1m YÖY için pankromatik ve 4m YÖY için ise çoklu sprektral sistemler kullanılmıştır.

Pankromatik algılayıcılar, tek kanallı geniş spektrumlu ışınım duyargasına sahiptir. Eğer dalgaboyu aralığı görülebilir alan ile çakışırsa elde edilen görüntü uzaydan çekilen siyah-beyaz fotoğraf şeklinde olacaktır. Renk bilgisi vermeyecektir.

Çoklu-spektral sistemler ise, birkaç spektral bantlı çok-kanallı duyargadan meydana gelir. Her bir kanal, kısa dalgaboyu bant araklıklarına sahiptir. Bu algılayıcılardan elde edilen görüntüler çok katmanlıdır. Bu katmanlar gözlemlenen hedefin parlaklık ve spektral (renk) bilgilerini içerir.

Algılayıcıların seçimiyle SudaSat-1 uydu görevinin gereklilikleri tam olarak ortaya çıkmıştır. Uydu pankromatik görüntüler 1 metre çözünürlükle alınacaktır, çoklu-spektral görüntüler ise 4 metre çözünürlükte olacaktır. Uydudan beklenen görev süresi ise 10 yıldır.

Uydu görevinin temel hattı çizilerek, görev isterlerini karşılayacak bir uydu platformu seçilmiştir. Görüntüleme algılayıcıları özellikleri ve uydunun yörünge karakteristikleri kararlaştırılarak gerekli yer örnekleme uzaklığı belirlenmiştir. Uydu yörüngesi STK (System Tool Kit) programı aracılığıyla tasarlanmış ve simule edilmiştir, yörünge periyodu ve ortalama haberleşme süresi kararlaştırılmıştır. Sonuç olarak elde edilen değerler her geçiş başına yaklaşık 10 dakika olmuştur.

Bu tezde, haberleşme altsisteminin tasarımını ve entegresini etkileyen görev tasarım elemanları öne çıkarılmıştır.

Haberleşme altsistemi-seviye gereksinimleri, fonksiyonları ve tasarım bileşenleri gözden geçirilmiştir. Bileşen seçimleri, gereklilikleri karşılanması ve uzay geçmişi üzerine temellendirilmiştir. Sistemin güvenilirliğini arttırabilmek için kritik bileşenlerin yedekleri de göz önüne alınmıştır. Ayrı uydu-yer bağı kanalları görüntü verileri (X-bandı) ve mühendislik verileri (S-bandı) olacak şekilde düzenlenmiştir.

Uydu iletişim güç bütçesi hem uydu-yer hem de yer-uydu bağ kanalları için hesaplanmıştır. Güç için kabul edilebilir düzeyde bir marjin elde edilmiştir.

Ana sistem bileşenleri ile bağlantıyı tanımlayan haberleşme altsistem mimarisi sunulmuştur.

Görüntü ve mühendislik verilerinin uydu-yer bağlantısı ile transferi ve yer-uydu komuta, adımlarını izleyecek şekilde resmeden uydu veri transfer planı belirlenmiştir.

Özetle, bu tezde SudaSat-1 uydusunun haberleşme altsistemi tasarlanmıştır. Yukarıdan-aşağıya doğru bir tasarım yöntemi izlenerek, tüm görevin gereklilikleri belirlenmiş ve bunların haberleşme altsistem gereksinimleri üzerindeki etkileri incelenmiştir. Yörünge ve uzay ortam koşulları göz önüne alınarak bunların uydu-yer istasyonu arasındaki iletişime olan etkileri hesap edilmiştir. Bu doğrultuda uydu tasarımı tamamlanarak elde edilen sonuçlar sunulmuştur.

1. INTRODUCTION

One of the most important functions of spacecraft is establishing reliable communication with ground stations or other spacecraft for telemetry, tracking, command and payload data transfer. In fact communication is a vital requirement for all spacecraft regardless of their specific mission and the failure of communication results in a failure for the whole mission.

Remote sensing satellites in particular require high data rate downlink channel to transmit acquired data.

Spacecraft communication system is responsible for handling of data and telemetry from both payload and bus of the spacecraft to ground station and commands from ground station, it represents the only way of communication for the spacecraft. From these functions derived the term (TT&C) which stands for telemetry, tracking and command.

Communication subsystem design mainly concerns frequency selection, antenna and transmitting power selection and transmitted data characteristics.

1.1 Purpose of the Thesis

The main objective of this thesis is to provide preliminary design for the communication subsystem for the proposed Sudanese remote sensing satellite SudaSat-1.

1.2 Methodology

Preliminary design of the communication subsystem will be done by reviewing previous missions with similar specifications in terms of imaging resolution to gain insight about design aspects.

Main mission design characteristics are also highlighted to obtain mission-derived subsystem requirements. Systems Tool Kit (STK) is used to model satellite orbit.

General subsystem architecture is designed, after that main design components are selected based on the requirements satisfaction and space heritage.

Link budget is calculated to insure that there is enough power margin for worst case weather conditions.

1.3 Literature Review

1.3.1 Spot Satellites

(Systeme Pour l'Observation de la Terre) in French or earth observation satellite is a group of high resolution optical imaging satellites developed by French space agency CNES. Spot group of satellites consists of 7 commercial satellites which provide images to many users around the world, the most recent satellites will be considered here. Spot-5 launched in 2002 contains optical imagers, namely HRG (High Resolution Geometric) and HRS (High Resolution Stereoscopic) to provide a ground resolution of 5m. CNES has developed a new image acquisition scheme to achieve a resolution of about 3 m from two 5 m imagers.

Spot-6 and Spot-7 were launched in 2012 and 2014 respectively, they have typical specifications, and they have improved panchromatic and multispectral resolutions compared to Spot-5, the communication system of Spot-6 and Spot-7 contains two X-band payload downlink channels with 300 Mbps and QPSK modulation and a single antenna. There is an option of encrypting data prior to transmission. The TT&C data are transmitted in S-band (Url-1). Spot-6 and Spot-7 specifications are shown on Table 1.1.

Table 1.1: Specifications of Spot-6 and Spot-7 satellites

Orbit	Sun-synchronous, Altitude 694 km, period 97.73 minutes
Launch mass	714 kg
S/C Dimensions	1.55 m x 1.75 m x 2.7 m
On-board Storage	1 Tbits end of life (Solid State Memory)
Swath	60 km at nadir
Instrument telemetry link rate	X-band channel - 300 Mbps
Dynamic range at acquisition	12 bits per pixel

1.3.2 Ikonos-2

Ikonos-2 is a commercial high resolution imaging satellite designed by DigitalGlobe, USA, it provides high resolution civilian earth observation imagery. Ikonos-2 is capable of acquiring images with spatial resolution of 1 m. it has been launched in 2009.

Payload data downlink is in X-band at a rate of 320 Mbps, the TT&C date downlink is in S-band at 32 kbps (Url-2). Figure 1.1 below shows a schematic of Ikonos-2 satellite.

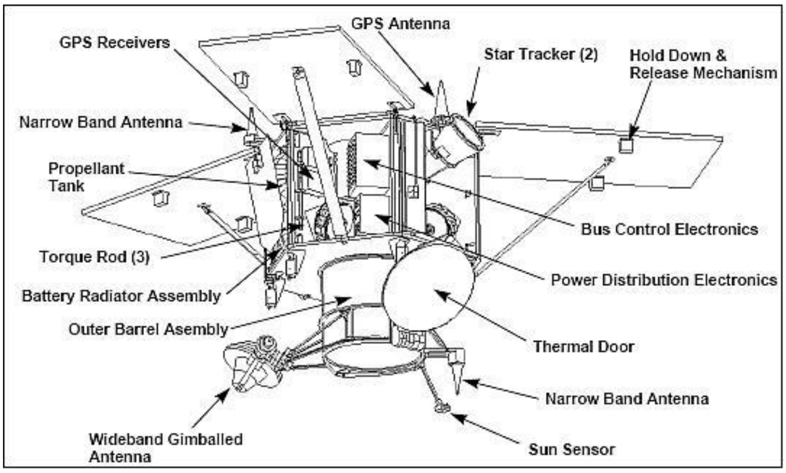

Figure 1.1 : Ikonos-2 satellite (Space Imaging Inc.)

1.3.3 Deimos-2

Deimos-2 is a high resolution earth observation satellite. The satellite was design and developed by SI (Satrec Initiative) of Korea for Deimos Imaging Inc. Spain. The satellite was launched in 2014 from Russia. Table 1.2 below illustrates the specifications of Deimos-2 satellite.

Table 1.2 : Specifications of Deimos-2 satellite

Spatial resolution	1 m PAN, 4 m MS
Launch Mass	310 kg
Dimensions	1.50 x 1.94 m (hexagonal configuration)
Power	450 W EOL
Swath width	> 12 km
Data quantization	10 bit
On-board Storage	256 Gbit
Telemetry Data rate	X-band channel - 160 Mbps
Orbit	Sun-synchronous near-circular, Altitude = 630 km, Inclination = 98 degrees

Deimos-2 engineering data is transmitted in S-band and imagery data is transmitted in X-band at a data rate of 160 Mbps with QPSK modulation (Url-8).

1.3.4 OrbView-3

OrbViww-3 is a high-resolution imaging satellite owned and operated by Orbital Imaging Corporation (ORBIMAGE) was launched 2003. The specifications of OrbView-3is presented in Table 1.3 below

Table 1.3 : Specifications of OrbView-3 satellite

Spatial resolution	1 m PAN, 4 m MS
Launch Mass	360 kg
Dimensions	1.2 m diameter and 1.9 m height(cylinder)
Swath width	8 km
Data quantization	11 bit
On-board Storage	32 Gbit
Telemetry Data rate	X-band channel - 150 Mbps
Orbit	Sun-synchronous circular, Altitude = 470 km, Inclination = 97.25 degrees

OrbView-3 downlink engineering data in UHF band and imagery data downlink is in X-band with data rate of 150 Mbps (Url-9).

1.3.5 KOMPSAT-2

KOMPSAT-2 was developed by KARI (Korea Aerospace Research Institute). The main mission objective of the KOMPSAT-2 is to provide a surveillance capability for large-scale disasters by acquiring high-resolution imagery. KOMPSAT-2 was launched in 2006. Table 1.4 below presents the specifications of KOMPSAT-2 satellite

Table 1.4 : Specifications of KOMPSAT-2 satellite

Spatial resolution	1 m PAN, 4 m MS
Launch Mass	800 kg
Power	955 W
Dimensions	1.85 m diameter x 2.6 m height (hexagonal:)
Swath width	15 km
Data quantization	10 bit
On-board Storage	96 Gbit
Telemetry Data rate	X-band channel - 320 Mbps
Orbit	Sun-synchronous circular, Altitude = 685 km, Inclination = 98.13 degrees

KOMPSAT-2 engineering data is transmitted in S-band and imagery data is transmitted in X-band at a data rate of 320 Mbps with QPSK modulation (Url-10).

1.3.6 QuickBird-2

QuickBird-2 is an imaging satellite developed by DigitalGlobe Inc, providing commercial imagery of 0.61 m (PAN) and 2.4 m (MS) resolution.

The downlink of imaging data is provided in X-band at data rate of up to 320 Mbps. it has real-time data channel (PCM/PSK/PM) modulated and playback data channel (PCM/PM) modulated. The TT&C data are provided in S-band at 4-16 Kbps data rate downlink (Url-3). Figure 1.2 below presents a schematic drawing of QuickBird-2 satellite.

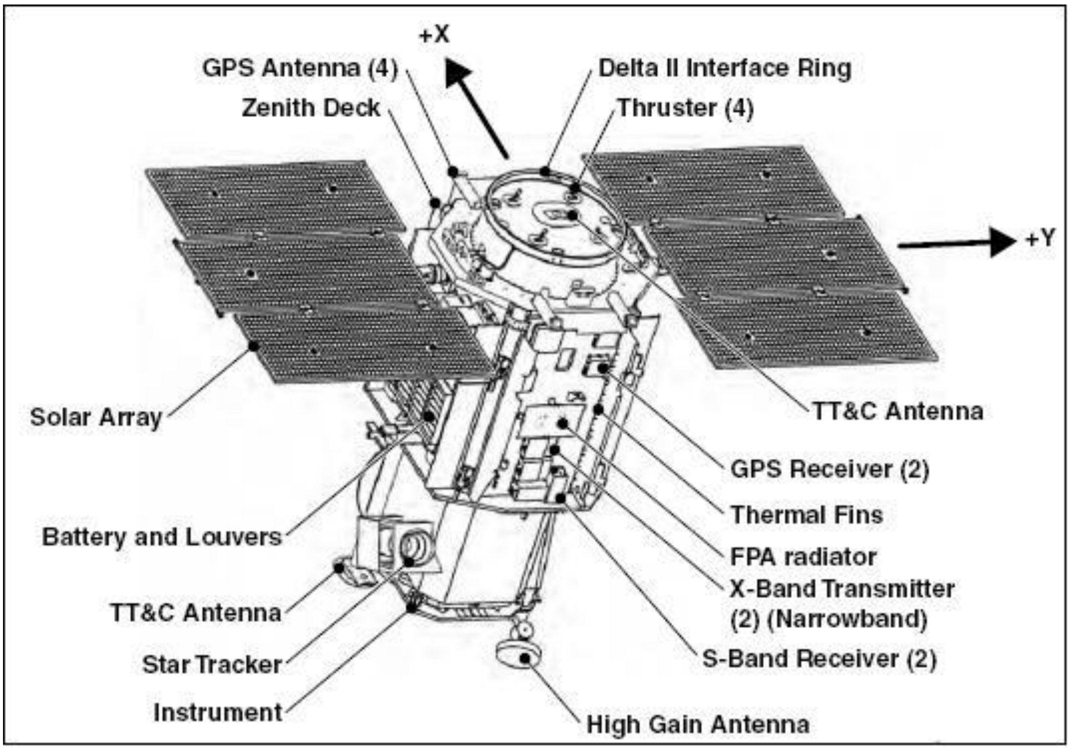

Figure 1.2 : QuickBird-2 spacecraft (DigitalGlobe)

Table 1.5 below illustrates the specifications of QuickBird-2 satellite

Table 1.5 : Specifications of QuickBird-2 satellite

Spatial resolution	0.61 m PAN, 2.4 m MS
Swath width	16.5 km
Pixel quantization	11 bit
On-board Storage	128 Gbits (SS memory)
Telemetry Data rate	X-band channel - 320 Mbps
Orbit	Sun-synchronous circular orbit, altitude :450 km, inclination = 97.3º,

1.4 Thesis Structure

In Chapter 2, a review of remote sensing satellites is presented, their general characteristics are discussed.

In Chapter 3 a baseline mission design is discussed, stating mission requirements, satellite orbit design and ground station.

In Chapter 4 the concept of communication subsystem design is discussed, stating the considerations and the impact of space environment which influence the design.

In Chapter 5 the design of the PDR design of the communication system is discussed staring with subsystem level requirements. The main design components which satisfy stated requirements are presented.

In Chapter 6 conclusion is presented.

2. REMOTE SENSING SATELLITES

This Chapter reviews the main characteristics of remote sensing satellites.

2.1 Sensors

Space borne sensors can be divided into two broad categories which are passive sensors and active sensors. Passive sensors can only detect naturally produced energy, such as sun light (only in day time) and thermal infrared radiation.

Active sensors use their own energy source, they emit radiation to the target being investigated and measure the reflected radiation. Active sensors can be used for examining wavelengths that are not sufficiently provided by the sun, such as microwaves, or to better control the way a target is illuminated.

Space borne sensors can be divided as well by their concept of operation to imaging and non-imaging sensors. Imaging missions measure the intensity of radiation reaching it as a function of position on the Earth's surface so that a 2-D picture of the intensity can be constructed, like a flash camera but at radio wavelengths.

A non-imaging system either does not measure the intensity of radiation or does not do so as a function of position. These systems are used to measure wind speed, clouds characteristics. Moisture, roughness and texture of soils, monitor vegetation and measure ice-sheet topography. If the target is the atmosphere, not the Earth's surface then, this type could be called sounding systems.

2.2 Optical Remote Sensing

Optical remote sensing makes use of visible, near infrared and short-wave infrared sensors to form images of the earth's surface by detecting the solar radiation reflected from targets on the ground. Different materials reflect and absorb differently at different wavelengths. Thus, the targets can be differentiated by their spectral reflectance signatures in the remotely sensed images. Optical remote sensing systems are classified into the following types, depending on the number of spectral bands used in the imaging process.

2.3 Panchromatic Imaging System

The sensor is a single channel detector sensitive to radiation within a broad wavelength range. If the wavelength range coincide with the visible range, then the resulting image resembles a "black-and-white" photograph taken from space. The physical quantity being measured is the apparent brightness of the targets. The spectral information or "colour" of the targets is lost (Rajendran 2009).

2.4 Multispectral Imaging System

The sensor is a multichannel detector with a few spectral bands. Each channel is sensitive to radiation within a narrow wavelength band. The resulting image is a multilayer image which contains both the brightness and spectral (colour) information of the targets being observed (Rajendran 2009).

2.5 Resolution

2.5.1 Spatial resolution

Spatial resolution of a digital image is an indication of the extent to which the viewing system can capture the details of the scene observed, It is related to the size of the smallest distinguishable object i.e. pixel size (Fourest 2012). Spatial resolution of a satellite depends on the instantaneous field of view of the satellite (IFOV) which is defined as the area on the ground that can be viewed by an instrument from a given altitude at a given instant of time.

2.5.2 Spectral resolution

Spectral resolution refers to the number of spectral bands in which the sensor can collect reflected radiance and spectral width of the bands. The sensors with more spectral bands and narrower spectral widths have higher spectral resolution.

2.5.3 Temporal resolution

Temporal resolution, often referred to Revisit Period, is the time between opportunities to obtain imagery over a given position on the earth's surface (Wulder 2012).

2.6 Swath Width

It is the strip of the Earth's surface from which a moving vehicle such as a satellite collects geographic data, in the course of swath mapping. It is affected by the altitude and instruments properties.

2.7 Image Acquisition

In order to acquire an image, there must be a type of energy reflecting from an area of interest, an optical system focuses the energy and finally a sensor which measures the amount of energy received. There are mainly two ways for digital image acquisition, either acquiring the image in analogue format then digitalize it or obtain the remote sensed image directly in digital format.

3. BASELINE MISSION DESIGN

This Chapter discusses main mission requirements and characteristics which are the primary input to the communication system design.

3.1 Mission Requirements

SudaSat-1 satellite mission is to acquire high resolution images of Sudan, below are the mission requirements.

- The satellite shall take panchromatic images of Sudan with 1-meter resolution.
- The satellite shall take multi-spectral images with 4-meter resolution.
- The Satellite shall have a lifetime of 10 years.

3.2 Orbit Design

The satellite will have a circular sun-synchronous orbit with an inclination of 98 degrees. The inclination is selected according to the designed altitude of 650 km. according to (Boain 2004), for a satellite circular orbit (eccentricity $\approx$ 0) and an altitude of 650 km, the inclination should be about 98 degrees. This is illustrated in Figure 3.1 below.

Figure 3.2 below shows one day ground track of SudaSat-1 created by STK, the green part of ground track shows the part of the pass where the ground station is in the field of view of the satellite.

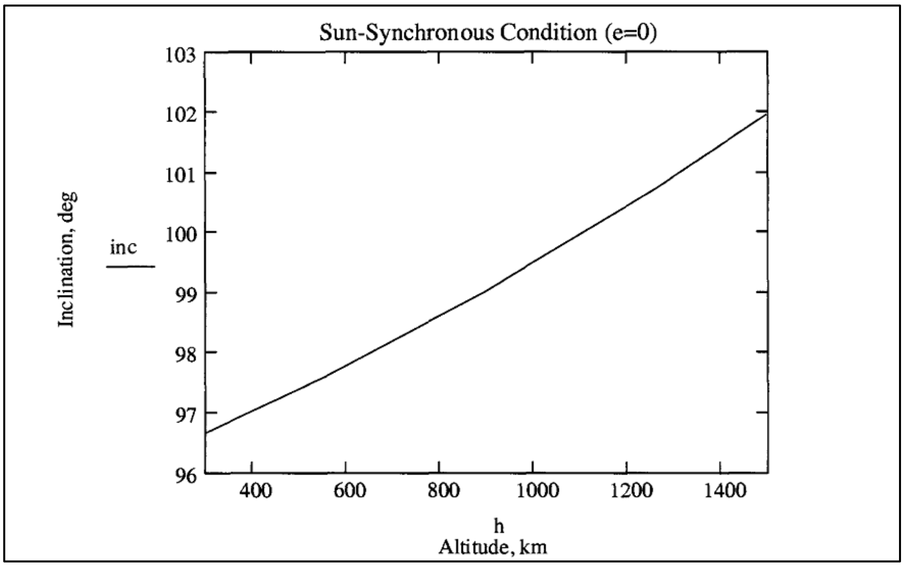

Figure 3.1 : Inclination vs. altitude for sun-synchronous circular earth orbit (Boain 2004)

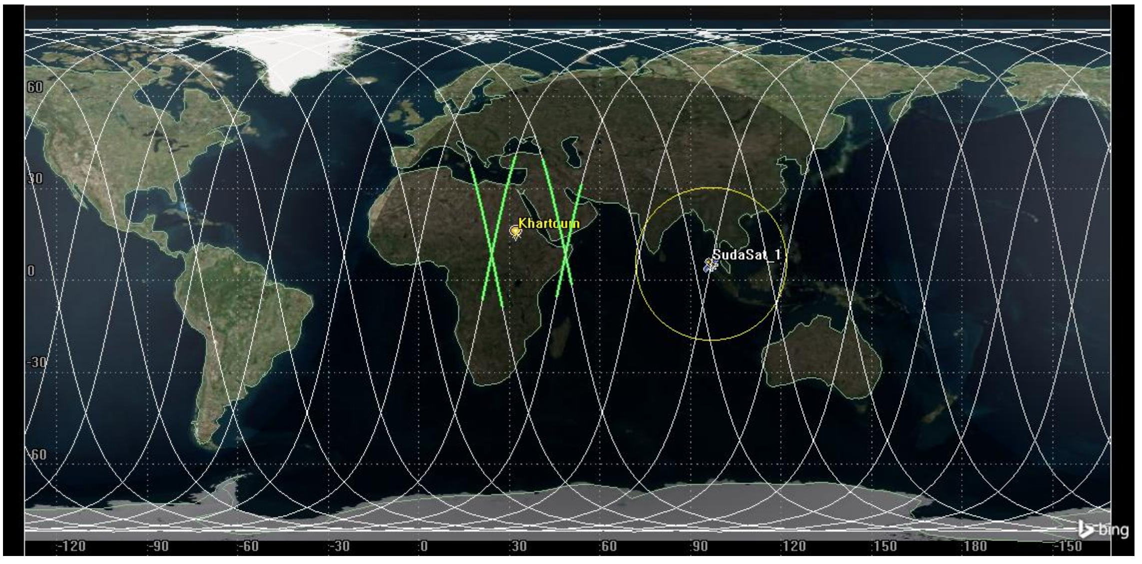

Figure 3.2 : SudaSat-1 24 hours ground track (STK)

Table 3.1 : SudaSat-1 orbit parameters

Orbit Epoch	26 Jun 2020 09:00:00.000 UTCG
Semimajor Axis	7028.14 km
Inclination	98.0687 degrees
Eccentricity	0
RAAN	124.465 degrees

Table 3.2 below contains a report generated by STK showing communication window time and duration for 3 consecutive days.

Table 3.2 : Access time and durations for 3 days

No.	Start Time (UTCG)	Stop Time (UTCG)	Duration (sec)	Duration (min)
1	26 Jun 2020 10:37:24.512	26 Jun 2020 10:48:41.454	676.942	11.28236667
2	26 Jun 2020 12:13:18.396	26 Jun 2020 12:25:44.921	746.525	12.44208333
3	26 Jun 2020 22:43:08.804	26 Jun 2020 22:53:14.124	605.320	10.08866667
4	27 Jun 2020 00:18:25.184	27 Jun 2020 00:31:19.773	774.590	12.90983333
5	27 Jun 2020 11:03:54.367	27 Jun 2020 11:16:43.738	769.371	12.82285
6	27 Jun 2020 12:41:48.115	27 Jun 2020 12:52:10.149	622.034	10.36723333
7	27 Jun 2020 23:09:29.789	27 Jun 2020 23:21:48.492	738.703	12.31171667
8	28 Jun 2020 00:46:24.734	28 Jun 2020 00:57:53.180	688.445	11.47408333
9	28 Jun 2020 09:59:05.109	28 Jun 2020 10:04:01.364	296.255	4.937583333
10	28 Jun 2020 11:30:58.404	28 Jun 2020 11:44:20.027	801.623	13.36038333
11	28 Jun 2020 13:11:40.547	28 Jun 2020 13:17:16.759	336.212	5.603533333
12	28 Jun 2020 23:36:26.813	28 Jun 2020 23:49:41.957	795.144	13.2524
13	29 Jun 2020 01:15:04.109	29 Jun 2020 01:23:36.804	512.695	8.544916667
14	29 Jun 2020 10:23:43.701	29 Jun 2020 10:33:38.399	594.698	9.911633333
15	29 Jun 2020 11:58:32.315	29 Jun 2020 12:11:33.099	780.784	13.01306667
16	29 Jun 2020 22:29:40.430	29 Jun 2020 22:37:40.780	480.350	8.005833333
17	30 Jun 2020 00:03:48.870	30 Jun 2020 00:17:04.500	795.630	13.2605
Minimum duration			296.255	4.94
Maximum duration			801.623	13.36
Average duration			647.960	10.8

3.3 Ground Station

The SudaSat-1 mission control ground station will be located in Khartoum, capital city of Sudan. The received images will for the benefit of the government of Sudan and can be utilized for monitoring different resources including forests, agricultural fields, wild animals, etc. Image can be available commercially for the benefit of private sector institutions. Table 3.3 below shows ground station antennas specifications.

Table 3.3 : Ground station X-band and S-band antennas specifications

Antenna type	Parabolic dish
Antenna Diameter	7.2 m (X-band), 3.7 m (S-band)
Antenna Efficiency	60 %
Antenna Azimuth Range	360 degrees
Antenna Elevation Range	180 degrees

Ground station antennas track the satellite from rise of signal (ROS) to loss of signal (LOS) during each ground station covering pass. This is done by determining satellite position accurately using two line elements (TLE) and calculating azimuth and elevation angles internally from GS to satellite's position. Doppler shift correction will be done automatically using receiver control software.

3.4 Imaging Sensors

The satellite speed in orbit is about 7.53 km/sec. in order to take 1 m GSD image with this configuration a single CCD sensor is not sufficient, a transfer delay and integration system (TDI), an asynchronous imaging mode or staggered CCD lines, or a combination of them are required. These consideration will be taken into account when selecting an imager for the mission.

3.5 Resolution

As in requirement the designed resolution is 1 m GSD for Panchromatic and 4 m for multi-spectral.

Also the satellite can provide lower resolution in wide swath images modes.

3.6 Swath Width

Swath width is area that the satellite imager covers as the satellite revolves around earth, Figure 3.3 below demonstrates imager swath width. The imager swath width will be 8 km for the strip map mode, and 300 km for the wide swath mode.

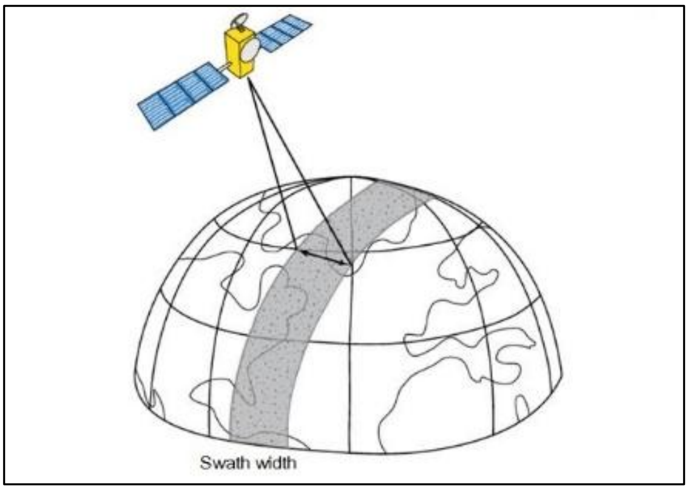

Figure 3.3 : Imager swath width (Url-7)

3.7 Image Acquisition Modes

SudaSat-1 has two modes for image acquisition for both PAN and MS namely:

- High resolution strip map mode

8 km swath width, 1x1 m spatial resolution in PAN channel.

- Wide swath Mode

300 km swath width, 10x10 m spatial resolution in PAN channel.

4. COMMUNICATION SUBSYSTEM DESIGN CONCEPTS

This Chapter discusses the main factors and parameters taken into account in the communication subsystem design.

4.1 Transmitter and Receiver

The selection of transmitters and receivers type, size and gain depends on the type of mission and the orbital characteristic of the spacecraft, LEO satellites require less power transmitters than higher range satellites. The main aspects that affect the selection of transmitters and receivers are filters, amplifiers and modulation

4.2 Filters

Filters have the mission of selecting the required signal frequency band and remove unwanted bands. Band-pass filters are mainly used in satellite receivers.

4.3 Amplifiers

The signal is passed through low noise amplifier (LNA) after being received by antenna to minimize the added noise and to enhance the original signal. Typical power amplifiers used in satellites are solid state power amplifiers (SSPA). If higher power is required traveling wave tube amplifiers (TWTA) are used.

4.4 Noise

Electrical noise can be defined as all unwanted electrical energy within the passband of a signal that is not part of the originally transmitted signal.

Presence of noise affects the quality of the signal. Receivers' sensitivity has improved significantly over time that allows todays receivers to detect a signal with quite small power. The problem is that, there is an amount of electrical noise added up to received signal.

Signal amplification will not solve the problem unless the received signal power is significantly greater than noise because it will amplify noise as well. Noise can be divided into correlated and uncorrelated.

4.4.1 Correlated noise

Correlated noise occurs internally in the device in the presence of a signal. It is generally created by imperfect components which generate nonlinear distortion such as harmonic distortion and intermodulation distortion.

4.4.2 Uncorrelated noise

Uncorrelated noise is the type of noise that is present in a communication system regardless of whether a signal is transmitted or not. This type of noise may be generated by both external and internal sources.

External noise sources can be divided to three categories:

- Atmospheric noise: the electrical disturbances that occur naturally in the space.
- Extra-terrestrial noise: includes the unwanted energy generated by the sun and the cosmic rays.
- Man-made noise: includes the unwanted energy generated by electrical equipment, e.g. interference from other communication systems, engine ignition systems.

Internal noise has four main types

- Shot noise: arising from the current generated randomly by the flow of mobile charge carriers due to the discreteness of electron charge.
- Thermal noise: Thermal noise is caused by random thermal motion of electrons in different resistive and active devices in the receiver, Thermal noise is also generated in the lossy components of antennas, and thermal-like noise is picked up by the antennas as radiation (Roody 2006).
- Low frequency noise (Flicker noise): arises due to charge carriers fluctuations caused by the impurity of semiconductor materials.

- Transit-time noise: produced in semiconductors when the transit time of the carriers crossing a junction is close to the signal's period.

4.5 Modulation

Modulation is the process by which a baseband signal varies the characteristics of an RF carrier signal; these characteristics are amplitude, phase, frequency and polarization. The RF signal is modulated before transmitting to achieve the required data rate, the required signal to noise ratio and to fit the signal into the available channel bandwidth.

Amplitude-shift keying (ASK): or on-off keying (OOK)is a form of modulation where baseband signal switches carrier signal on and off as illustrated in Figure 1. ASK is common in terrestrial applications but is rarely used for satellite communications due to its low bandwidth efficiency.

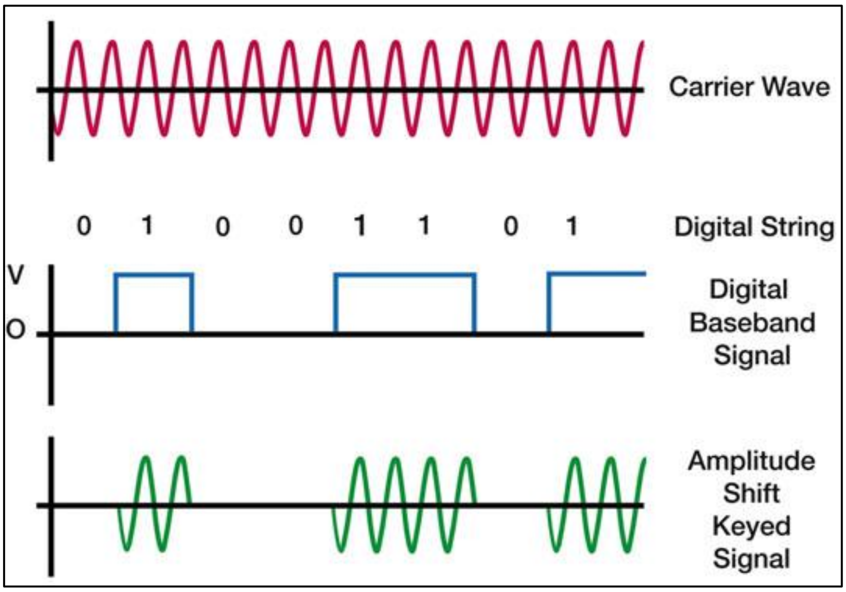

Figure 4.1 : Amplitude Shift Keying (ASK) (Pelton 2013)

Frequency-shift keying (FSK): the binary signal modulates the carrier signals' frequency, one frequency being used for binary 1 and another for binary 0.

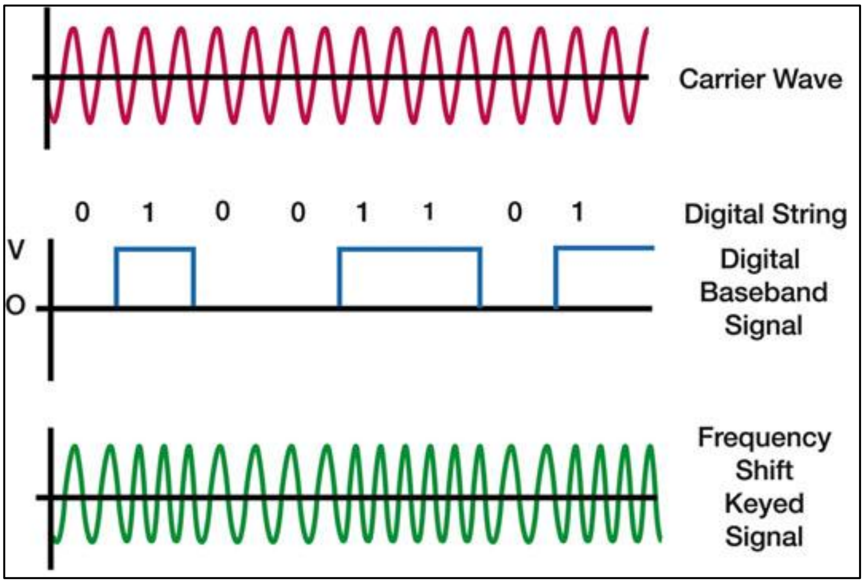

Figure 4.2 : Frequency Shift Keying (FSK) (Pelton 2013)

Phase-shift keying (PSK): is the process of altering the phase of the carrier signal according to binary signal, when the signal is binary 0, the carrier phase is changed by 180 degrees and when the signal is binary 1 the carrier signal remains as it is.

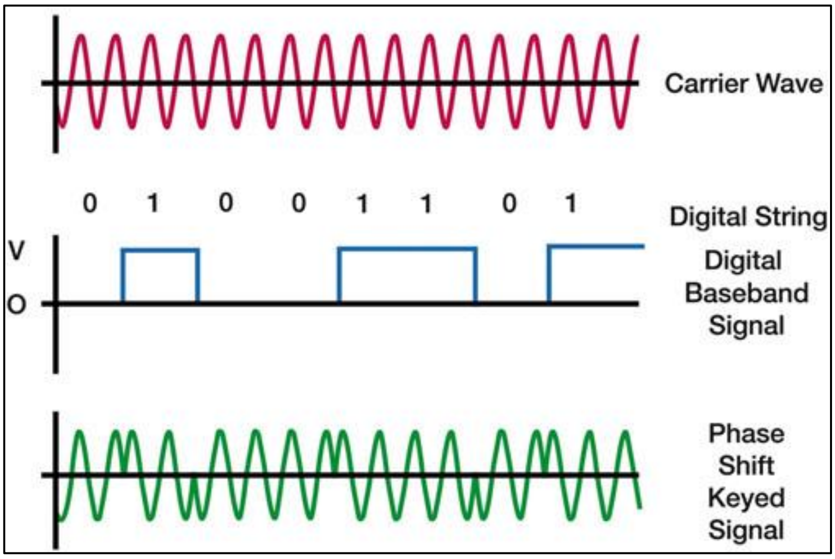

Figure 4.3: Phase Shift Keying (PSK) (Pelton 2013)

Quadrature phase-shift keying (QPSK): takes two bits at a time and changes the phase of the carrier signal between four possible phase values. The concept of taking more than 1 binary bit at a time can be extended to 8-PSK which takes 3 bits at a time or generally to multiple phase-shift keying (MPSK).

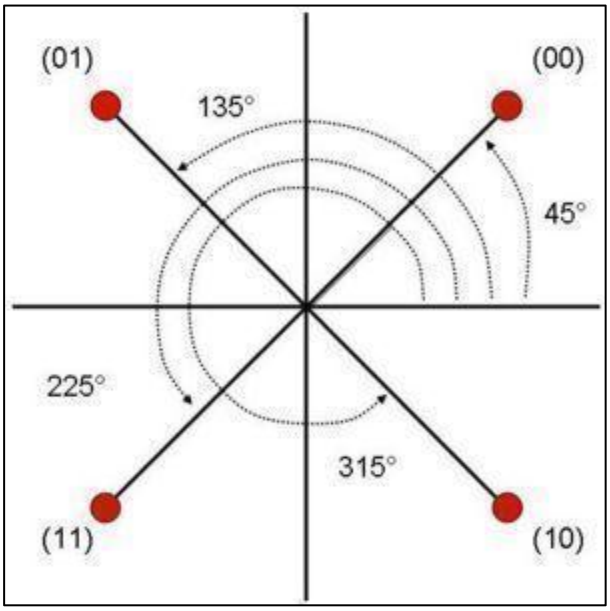

Figure 4.4 : Quadrature Phase Shift Keying (QPSK) (Url-6)

Phase-shift keying modulation techniques are widely used in satellite communications due to their efficient utilization of available bandwidth. The larger the number of bits in a modulation scheme the more efficient use of bandwidth and the more complex the implementation, therefore there is a trade-off in selecting the optimum modulation scheme regarding bandwidth efficiency and complexity. Table 4.1 below shows QPSK states.

Table 4.1 : Quadrature Phase Shift Keying States

Phase	Data
45 degrees	Binary 00
135 degrees	Binary 01
225 degrees	Binary 11
315 degrees	Binary 10

4.6 Bit Error Rate (BER)

Bit Error Rate (BER) is a very important figure of merit for digital data communication, it is the ratio between the number of bits received in error to the number of bits transmitted. A typical acceptable value for satellite data transfer is

10^{-6}. BER depends on a number of factors, mainly

- The carrier to noise ratio (C/N): C/N is a measure of the performance of the link between the satellite and ground station, particularly it is the ratio of the received carrier signal power to the power of the received signal noise.

$$\frac{C}{N} = \frac{P_C}{P_N} \quad \textbf{(4.1)}$$

The expression in decibels can be as follows

$$C/N = P_C - P_N \quad \textbf{(4.2)}$$

- The modulation and error correction scheme used.

Shannon’s theorem states that in order to achieve an error-free communication a certain minimum energy per bit E_b is required. E_b is the ratio of the average carrier power at receiver P_R to bit rate R_b

$$E_b = P_R/R_b \quad \textbf{(4.3)}$$

A very important parameter in digital communication is the ratio of energy per bit to noise spectral power density E_b/N_0

$$\frac{E_b}{N_0} = \frac{P_R}{R_b N_0} \quad \textbf{(4.4)}$$

P_R/N_0 is the carrier to noise density ratio, always denoted as C/N_0, therefore

$$\frac{E_b}{N_0} = \frac{C/N_0}{R_b} \quad \textbf{(4.5)}$$

4.7 Coding

Encoding is important for error detection and correction. Generally most codes are capable of detecting more errors than it can correct, if a code is only capable of detecting errors, a request of retransmission must be sent to the satellite, this well decrease channel efficiency, the other option is to correct the errors in the receiver side, this procedure is called forward error correction (FEC).

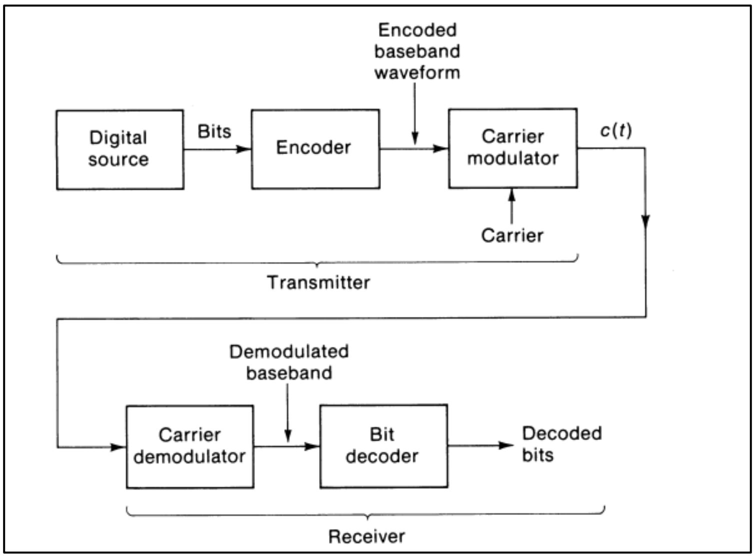

Figure 4.5 : Encoding Block Diagram (Roddy 2006)

Coding is the process of adding redundant bits (coding head) to transmitted bit stream to allow a decoder in the receiver to detect the errors occurred in the transmission. There are two types of errors that need to be detected:

Random errors: which are caused by random noise and can occur anywhere in the transmitted bit stream sequence.

Error bursts: this type of errors occur due to a certain disturbing factor, e.g. clouds, obstacles that intervene the path of a signal or any locally varying atmosphere conditions.

There are four common types of coding will be discussed below.

4.7.1 Block codes

Block codes is a linear coding technique in which digital data streams are partitioned to equal blocks of bits. Let each block contain k bits, where a block defines a single dataword. The total number of datawords is 2k. A dataword is encoded in codeword of n bits, hence there are n-k bits that added to the block that are not part of the original message. These redundant n-k bits are called parity check bits.

If an error occurred in the codeword during transmission, there is a high probability that the decoder will detect it, unless a rare condition occur in which the errors transformed the codeword into another legitimate codeword, in this case the decoder will not be able to detect the error.

4.7.2 Convolution codes

Convolution codes are also linear codes. A convolution encoder consists of a shift register and exclusive-OR logic circuits. The shift register temporarily stores the input pits and perform shift operations before passing them through the exclusive-OR logic circuits.

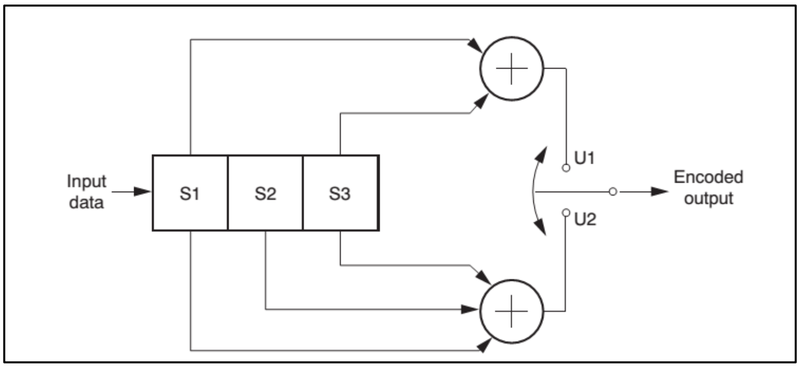

Figure 4.6 : An example of (1,2) convolutional encoder (Roody 2006)

We can denote the number of bits shifted in the register k and the number of codewords generated n. the number of the stages of the shift register represents the memory (m) of the encoder, a convolution encoder is characterized by (k,n,m).

4.7.3 Reed-Solomon codes

Reed-Solomon (R-S) codes unlike block and convolutional codes correct errors occur in bursts rather than random errors, burst errors may occur as a result of impulse type noise or impulse type interference.

R-S codes encode in symbol-level rather than bit-level, the number of bits per symbol can be denoted k; then the number of possible symbols is q = 2k. let K be the number of symbols in a dataword and N be the number of symbols in a codeword, the datawords of K symbol are mapped into codewords of N symbols and an R-S code is denoted by (N,K). Therefore there are additional N – K symbols that are not part of the original datawords, these additional symbols are called redundant symbols. If the decoder detects one of the redundant symbols in the transmitted codewords it will recognize that this codeword is received in error. Below is design roles for R-S codes

$$q = 2^k \quad \textbf{(4.6)}$$

$$N = q - 1 \quad \textbf{(4.7)}$$

$$2t = N - K \quad \textbf{(4.8)}$$

Where t is the number of symbol errors that can be corrected.

Often a symbol is selected as a byte (k = 8) therefore q = 256 and N = 255, also it is common to select the number of symbols to be corrected as 16 then K = 223. Therefore the standard R-S code is (255,223).

4.8 Antenna

Antenna design involves determining the proper antenna type and size which are required to achieve stable communication. Antenna is a crucial part of the communication link, it has the role of transducing the electrical signal to electromagnetic waves and vice versa. There are several parameters has to be optimized in the design of an antenna, e.g. gain, radiation pattern, polarization and bandwidth.

4.8.1 Antenna diplexer

Antenna diplexer allows the same antenna to be used for transmission and reception. The commands uplink and engineering data downlink are sent in the same band (S-band), the use of diplexer eliminates the need for different antennas for transmission and reception to save mass and volume on-board the satellite.

4.9 Link Budget

As the transmitted radio wave travels from satellite to ground station it spreads out into large cross-sectional area and loses much of its energy, this loss of energy is so-called free space loss (FSL), the received power flux density decreases inversely proportional to the square of the distance between transmitting and receiving antennas.

4.9.1 Feeder losses

Receiver feeder losses (RFL) occur in the components between receiving antenna and receiving device such as filters, couplers and waveguides. Similar losses occur in the satellite between HPA output and transmitting antenna.

4.9.2 Antenna misalignment losses (AML)

To achieve maximum gain the satellite and ground station antennas must be aligned. Misalignment loss can occur from satellite or from ground station antennas, satellite antenna pointing is considered in the design of satellite ADCS, ground station antenna misalignment is quite small, typically in terms of tenth of decibels.

4.9.3 Atmospheric losses

This kind of losses caused by absorption of energy by atmospheric gases. Atmospheric losses can be divided to atmospheric attenuation and atmospheric absorption. The difference is that attenuation is weather related, while absorption is independent of weather.

The ionosphere which is the highest layer of the atmosphere contains ionized particles which can alter the direction of the electron vectors of the signals passing through it, hence shifts the electrons from their original polarization direction.

Atmospheric layers also has different refraction index, this difference may cause scattering and multipath effect, due to the different directions the signals may follow.

Troposphere is composed of molecules of different compounds; radio waves that pass through it may be attenuated in different ways like scattering, depolarization, and absorption.

Rain attenuation is also a source of loss to a satellite signal, the effect of rain attenuation is serious only in the case of heavy rainfall, therefore the effect of rain in SudaSat-1 link budget is minor because ground station location (Khartoum) is rarely encounter heavy rainfall.

4.9.4 Noise temperature

Noise temperature is one way of expressing the level of available noise power introduced by a component or source. The contributions of all noise sources can be lumped together and regarded as a level of thermal noise.

$$N_o = kT_s \tag{4.9}$$

Where T: is the temperature of a passive system (e.g. resistor) which would generate the same amount of noise as the considered source of noise

k: Boltzman constant = $1{,}379.10^{-23}$ W/K.Hz

The noise power produced by noise sources P_N is given by

$$P_N = kT_sB_N \tag{4.10}$$

Where B_N is the equivalent noise bandwidth.

5. COMMUNICATION SUBSYSTEM DESIGN

This Chapter presents communication subsystem requirements, design characteristics, selected components, link budget, subsystem structure and data transfer plan.

5.1 Requirements

Below are the requirements of SudaSat-1 communication system

5.1.1 Payload data transmission

- Receive payload imagery data packets from C&DH subsystem
- Encode and encrypt packets prior to transmission
- Perform lossless data compression in case of real-time imagery transmission
- Transmit payload data according to mission operation sequence software

5.1.2 Carrier tracking

- Two way coherent communication must be established; downlink transmitter phase-locks to the received uplink carrier and the downlink frequency is a specific ratio of the uplink carrier frequency. This allows satellite frequency to be acquired more quickly.
- Doppler shift value can be used to calculate range rate.

5.1.3 Command reception and detection

- Commands must be received and decoded
- Commands must be decrypted
- Unverified commands must be rejected
- Verified commands must be passed to OBDH subsystem.

5.1.4 Telemetry modulation, encoding and transmission

- Acquire subsystems health data from OBDH subsystem.
- Encode telemetry data.
- Transmit telemetry data to GS.

5.1.5 Determine S/C range

- An uplink code is detected and retransmitted on the downlink; the turnaround time is used to calculate the range.

5.1.6 Data rate

- Payload data must be transmitted with 300 Mbps.
- Status and health data telemetry must be transmitted with 512 Kbps.

5.2 Frequency band

Payload imagery data is transmitted in X-band (8.025 - 8.400) GHz which is allocated by international Telecommunication Union for earth exploration satellites. The other advantage of X-band is the availability of bandwidth to accommodate the required bandwidth.

The health and status telemetry data is transmitted in S-band (2.200 - 2.290) GHz. The commands uplink is sent in the same band as well.

5.3 Microcontroller

The microcontroller is the core of the TT&C electronic board. It manages the overall activities of the communication subsystem. The STM32F107 family of the ARM Cortex microcontroller was selected. The trade-off between performance and power consumption was taken into account.

This microcontroller is considered a powerful device for a TT&C board, but for the number of operations required and the number of connected peripherals, the use of such a powerful microcontroller is necessary.

The microcontroller manages the interfaces with other electronic equipment, encode/decode digital data transmitted and received and controls RF transmitters and receivers. Table 5.1 below shows the specifications of STM32F107 ARM Cortex Microcontroller.

Table 5.1 : Specifications of STM32F107 ARM Cortex Microcontroller

CPU	32 bit
Frequency	72 MHz
Memory	64 to 256 Kbytes of Flash memory 64 Kbytes of general-purpose SRAM
Modes	Sleep, Stop and Standby
Interfaces	I^2C, USART, SPI, CAN
Power Supply	2 – 3.6 V

5.4 Transmitters

Two X-band transmitters will be available on-board, on will be operational and the other one will be standby for redundancy. The transmitter will be acquired from Surry Satellite Technology Ltd (SSTL). Table 5.2 below shows the specifications of SSTL X-band transmitter.

Table 5.2 : Specifications of SSTL X-band transmitter

Operating frequency	8025 to 8400 GHz
Data rate	300 Mbps
Output RF power	5 – 12 W
Modulation	BPSK/QPSK/8PSK
Interface	LVDS, CAN-SU or RS422
Mass	4 Kg

The S-band transmitter will also be acquired from SSTL. It has space heritage of more than twenty missions. Redundant S-band transmitter will be also available in the case of the failure of the main transmitter. Table 5.3 below shows the specifications of SSTL S-band transmitter.

Table 5.3 : Specifications of SSTL S-band transmitter

Operating frequency	2.2 to 2.29 GHz
Data rate	9.6 Kbps – 10.0 Mbps

Output RF power	0.25 - 4 W
Modulation	BPSK/QPSK
Interface	LVDS, CAN-SU or RS422
Mass	1.8 Kg

5.5 Antennas

Two X-band antennas are selected, one of them is steerable to achieve maximum gain and one redundant iso-flex antenna that covers the whole footprint of the satellite. The redundant antenna will be operational only in the case of the failure of the main antenna.

The main antenna from (SSTL) uses two-axis pointing mechanism (APM).to achieve high gain, the antenna pointing device is integrated with a high gain horn antenna. SSTL APM and horn antenna is shown in Figure 5.1 below.

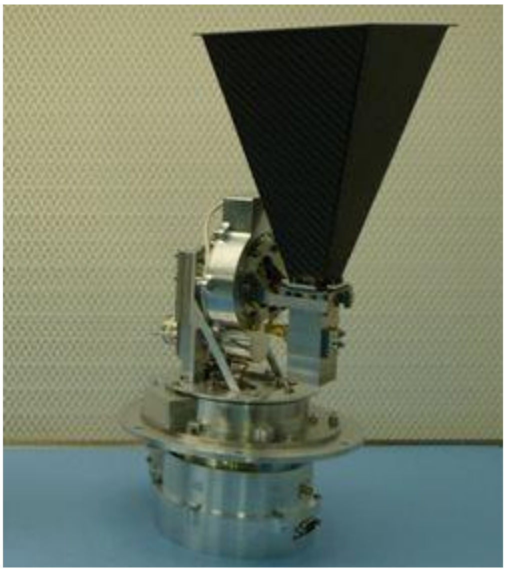

Figure 5.1 : APM and horn antenna (SSTL)

Table 5.4 below shows the characteristics of SSTL APM antenna

Table 5.4 : Characteristics of X-band antenna

Gain	18 dBiC
Mass	3.3 kg

Frequency	8.0 to 8.5 GHz
Pointing accuracy	< 0.25 degrees
Step size	≤ 0.24 degrees
Azimuth range	± 270 degrees
Elevation range	± 80 degrees

The standby X-band antenna is a helix antenna acquired from RUAG Space and is shown in Figure 5.2 below.

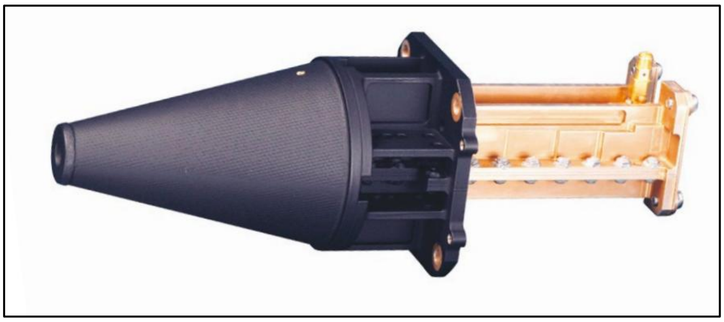

Figure 5.2 : Standby X-band antenna (RAUG Space)

Two identical S-band helix antennas are designed to work simultaneously, one pointing at nadir and the other pointing at zenith, the radiation pattern of the each antenna is cardioid as shown in Figure 5.3 below. This will eliminate the need for antenna steering.

Table 5.5 : S-band helix antenna specifications

Power	Up to 10 W
Mass	500 g
Frequency	2.200 - 2.290 GHz
Polarization	Right or Left Hand Circular Polarization
Dimensions	100 x 100 x 389 mm
Beam Width	120 degrees

The shape of the radiation pattern has a null at nadir direction to allow for constant power flux density at the earth’s surface. S-band helix antenna is shown in Figure 5.3 below.

Figure 5.3 : S-band antenna

5.6 Encoding

Convolutional encoding (explained in section 4.7.2) concatenated with an outer Reed-Solomon coding (explained in section 4.7.3) schemes will be used to encode downlink and uplink channels, this coding architecture is recommended by CCSDS. Convolutional coding is used for random error detection and correction and outer Reed-Solomon (R-S) coding is used for burst errors detection and correction if the correction capabilities of the convolutional coder is exceeded. The block diagram of a punctured encoder is shown in Figure 5.4 below.

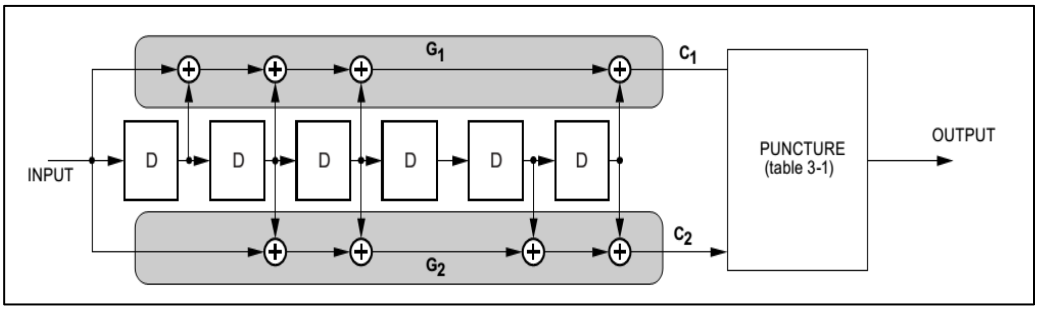

Figure 5.4 : Punctured Encoder Block Diagram (CCSDS 2011)

The R-S encoder is (255,223) which is capable of detecting 16 symbols received in error within a single codeword.

5.7 Bandwidth requirements

The required bandwidth should be calculated to know upper and lower frequency limits of the transmitted signal in order to avoid interference. The required bandwidth depends on the simple rate, transmission frequency and roll-off factor. Simple rate depends on the scheme of modulation used. Required bandwidth is given by the following equation (Roddy 2006):

$$B = (1 + \rho)R_{sym} \tag{5.1}$$

Where B = required bandwidth, ρ = roll-off factor, R_{sym} = symbol rate.

For QPSK modulation R_{sym} = R/2, where R is the data rate, because QPSK takes 2 bits at a time. If we set ρ = 0.65 and R 300 Mbps, then the required band will be:

$$B = 1 + 0.65 \quad \frac{300}{2} = 247 \text{ MHz}$$

5.8 Link Budget

Link budget has been calculated using Microsoft Excel for clear sky, worst case (rain) conditions and an elevation angle of 5 degrees.

The maximum power flux density at distance r from transmitting antenna of gain G is

$$\psi_M = \frac{GP_S}{4\pi r^2} \tag{5.2}$$

If we supplied an isotropic radiator with an input power equal to GPS it would produce the same flux density, hence the former term is conventionally referred to as equivalent isotropic radiated power EIRP

$$EIRP = GP_S \tag{5.3}$$

Substituting the value of EIRP in eq. 5.2 yields

$$\psi_M = \frac{EIRP}{4\pi r^2} \tag{5.4}$$

The power received could be obtained by multiplying power flux density by the effective aperture of the receiving antenna

$$P_R = \psi_M A_{eff} \quad \textbf{(5.5)}$$

The relationship between the power gain of an antenna and its effective aperture is

$$\frac{A_{eff}}{G} = \frac{\lambda^2}{4\pi} \quad \textbf{(5.6)}$$

Substituting the value of A_{eff} for receiving antenna in eq. 5.5

$$P_R = \frac{EIRP}{4\pi r^2}\frac{\lambda^2 G_R}{4\pi} \quad \textbf{(5.7)}$$

Rearranging previous eq.

$$P_R = (EIRP)(G_R)\left(\frac{\lambda}{4\pi r}\right)^2 \quad \textbf{(5.8)}$$

Transforming previous equation to decibel notation

$$P_R = EIRP + G_R - 10\log\left(\frac{4\pi r}{\lambda}\right)^2 \quad \textbf{(5.9)}$$

Combining all losses in one term gives:

$$LOSSES = FSL + RFL + AML + AA + PL \quad \textbf{(5.10)}$$

Therefore the power margin in decibel is given by:

$$P_R = EIRP + G_R - [LOSSES] \quad \textbf{(5.11)}$$

From previous equations we can calculate the over-all carrier to noise ratio as follows

$$\frac{C}{N_0} = EIRP + G_R - LOSSES - k - T_s - [B_N] \quad \textbf{(5.12)}$$

Antenna gain and antenna noise temperature can be combined in one ratio denoted by G/T which is a key parameter to specify receiver system performance.

$$G \quad T = G_R - [T_S] \tag{5.13}$$

Therefore link equation (5.11) becomes

$$\frac{C}{N_0} = EIRP + \frac{G}{T} - LOSSES - k - [B_N] \tag{5.14}$$

5.8.1 Link budget for X-band downlink

X-band downlink has a data rate of 300 Mbps and QPSK modulated. The link budget is calculated for an elevation of 5 degrees. X-band downlink power budget is shown in Table 5.6 below.

Table 5.6 : X-band downlink link budget

Parameter	value	result	unit
Satellite altitude	650	-	km
Satellite Elevation angle	5	-	degrees
Data rate	300		Mbps
modulation	QPSK		-
Roll-off factor	0.65		-
Channel coding	R-S(223,255)+CC(7,7/8)		-
Required bandwidth		247.5	MHz
Net data rate	229		Mbps
Satellite			
Transmitter output power	7		W
Antenna gain	15		dBi
Antenna depointing loss	0.5		dB
Antenna polarization loss	0.3		dB
Cable loss	1.5		dB
EIRP	-	20.55	dB
Free-Space Loss	-	178.44	dB
Ground Station			
Ground station antenna diameter	7.2		m
Antenna efficiency	0.60		-
Antenna depointing loss	0.5		dB
Antenna polarization loss	0.3		dB
Antenna feeder loss	1		
Antenna gain	-	53.55	dBi
LNA noise temperature	50		K
Antenna feeder noise temperature	290.00		K
Antenna noise temperature		80.00	K

System noise temperature		207.50	K
System equivalent noise density		2.86E-21	W/Hz
Receiver G/T		27.58	dB/K
Receiver C/N_0		101.11	dBHz

Table 5.6 (continued): X-band downlink link budget

Receiver E_b/N_0		16.33	dB
Required BER	10^{-6}	-	-
Required E_b/N_0		2.4	
Link margin (Rain)	-	**8.27**	dB
Link margin (clear sky)	-	**10.62**	dB

5.8.2 Link budget for S-band downlink

S-band downlink has a data rate of 2 Mbps and BPSK modulated carrier. The link budget is calculated for an elevation of 5 degrees. S-band downlink power budget is shown in Table 5.7 below.

Table 5.7 : S-band downlink link budget

Parameter	value	result	unit
Satellite altitude	650	-	km
Satellite Elevation angle	5	-	degrees
Data rate	2		Mbps
modulation	BPSK		-
Roll-off factor	0.65		-
Channel coding	R-S(223,255)+CC(7,1/2)		-
Required bandwidth		3.3	MHz
Net data rate		0.875	Mbps
Satellite			
Transmitter output power	2		W
Antenna gain	1		dBi
Antenna depointing loss	0.3		dB
Antenna polarization loss	0.3		dB
Transmitter imperfections	0.6		dB
Cable loss	1		dB
EIRP	-	1.81	dB
Free-Space Loss	-	167.45	dB
Ground Station			
Ground station antenna diameter	3.7		m
Antenna efficiency	0.60		-
Antenna depointing loss	0.3		dB
Antenna polarization loss	0.3		dB

Antenna feeder loss	1		
Antenna gain	-	34.18	dBi
LNA noise temperature	50		K
Antenna feeder noise temperature	290.00		K

Table 5.7 (continued): S-band downlink link budget

Antenna noise temperature		72.42	K
System noise temperature		202.72	K
System equivalent noise density		2.8×10^{-21}	W/Hz
Receiver G/T		11.11	dB/K
Receiver C/N_0		73.53	dBHz
Receiver E_b/N_0		10.52	dB
Required BER	10^{-6}	-	-
Link margin (Rain)		**10.52**	dB
Link margin (clear sky)	-	**10.60**	dB

5.8.3 Link budget for S-band uplink

S-band uplink carrier is BPSK modulated and has a data rate of 512 Kbps, the link budget is calculated for an elevation of 5 degrees. S-band uplink power budget is shown in Table 5. below.

Table 5.8 : S-band uplink link budget

Parameter	value	result	unit
Satellite altitude	650	-	km
Satellite Elevation angle	5	-	degrees
Data rate	0.5		Mbps
modulation	BPSK		-
Roll-off factor	0.65		-
Channel coding	R-S(223,255)+CC(7,1/2)	1.65	-
Required bandwidth			MHz
Net data rate		0.437	Mbps
Ground Station			
Transmitter output power	30		W
Transmitter carrier frequency	2100		MHz
GS antenna diameter	3.7		m

Antenna efficiency	0.6		
Antenna depointing loss	0.3		dB
Antenna polarization loss	0.6		dB

Table 5.8 (continued): S-band uplink link budget

Cable loss	1		dB
Antenna gain		36	dBi
Transmitter EIRP		46.86	dBW
Free-Space Loss	-	166	dB
Satellite			
Antenna depointing loss	0.3	-	dB
Antenna polarization loss	0.5	-	dB
Antenna feeder loss	1	-	
Antenna gain	3	-	dBi
LNA noise temperature	75	-	K
Antenna feeder noise temperature	290.00	-	K
Antenna noise temperature	290		K
System noise temperature		365	K
Receiver G/T		-24.42	dB/K
Receiver C/N_0		83.83	dBHz
Receiver E_b/N_0		23.84	dB
Required BER	10^{-6}	-	-
Link margin (Rain)		**13.34**	dB
Link margin (clear sky)	-	**13.38**	dB

From above tables we can find that the worst case link margin is very acceptable.

5.9 System Architecture

The architecture of the communication subsystem is shown in Figure 5.5 below.

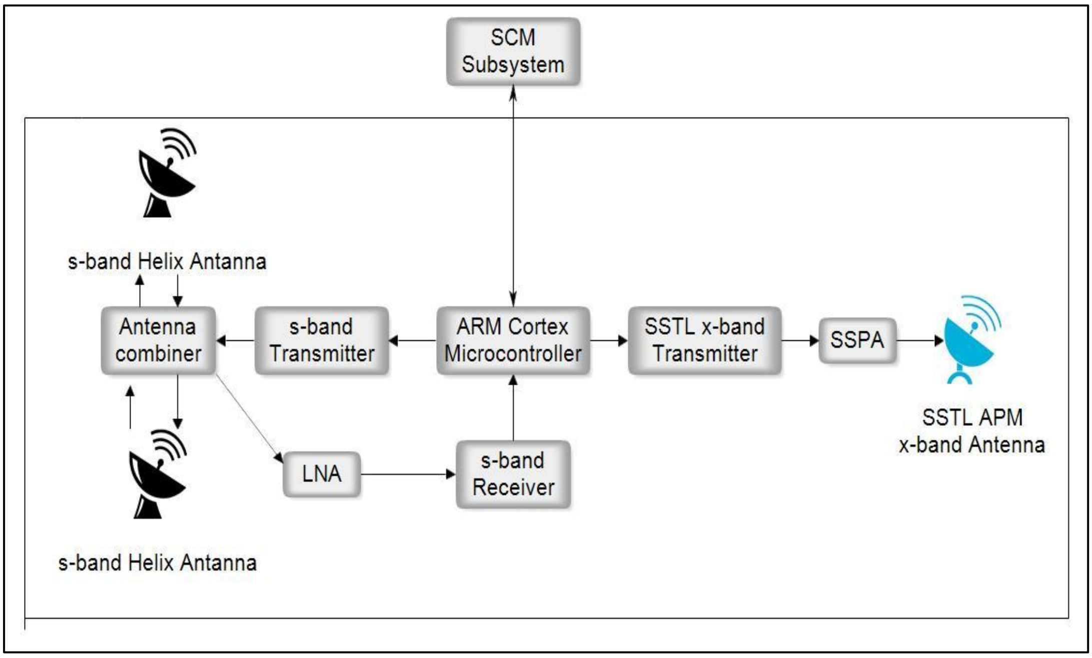

Figure 5.5 : Subsystem architecture

5.10 Data Transfer Plan

The satellite communication subsystem listens to data bus and waits for data to be transferred, once a data stream arrives it check headers of data frames to distinguish whether the arrived data is housekeeping telemetry or payload data, then it transfer it to respective downlink channel. Figure 5.6 below shows data transfer plan.

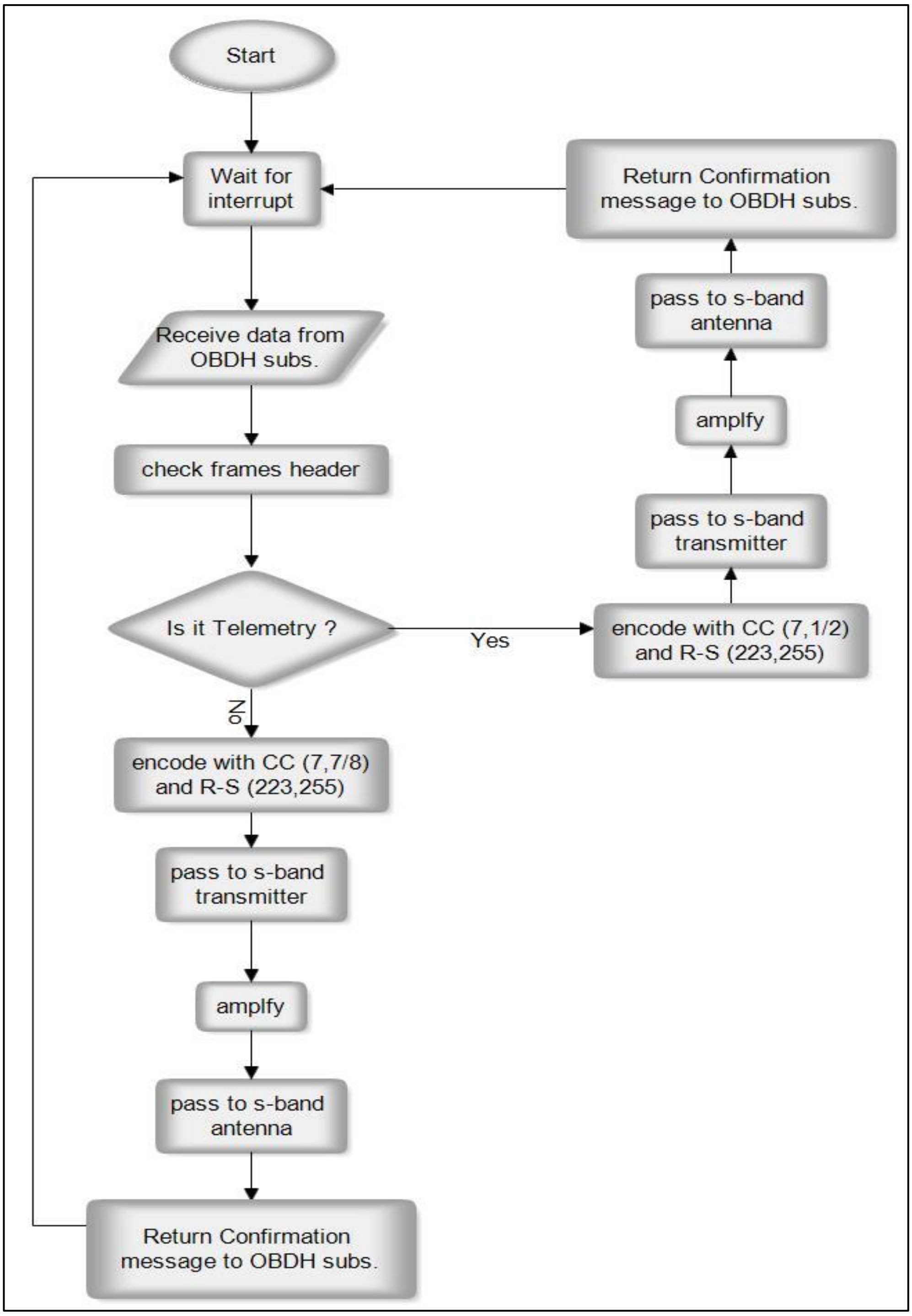

Figure 5.6 : Data transfer plan

On the receiving side the TT&C subsystem the commands are received, demodulated, decoded and check for consistency internally, then transferred to OBDH subsystem for execution. The steps of receiving command data are illustrated in Figure 5.7 below.

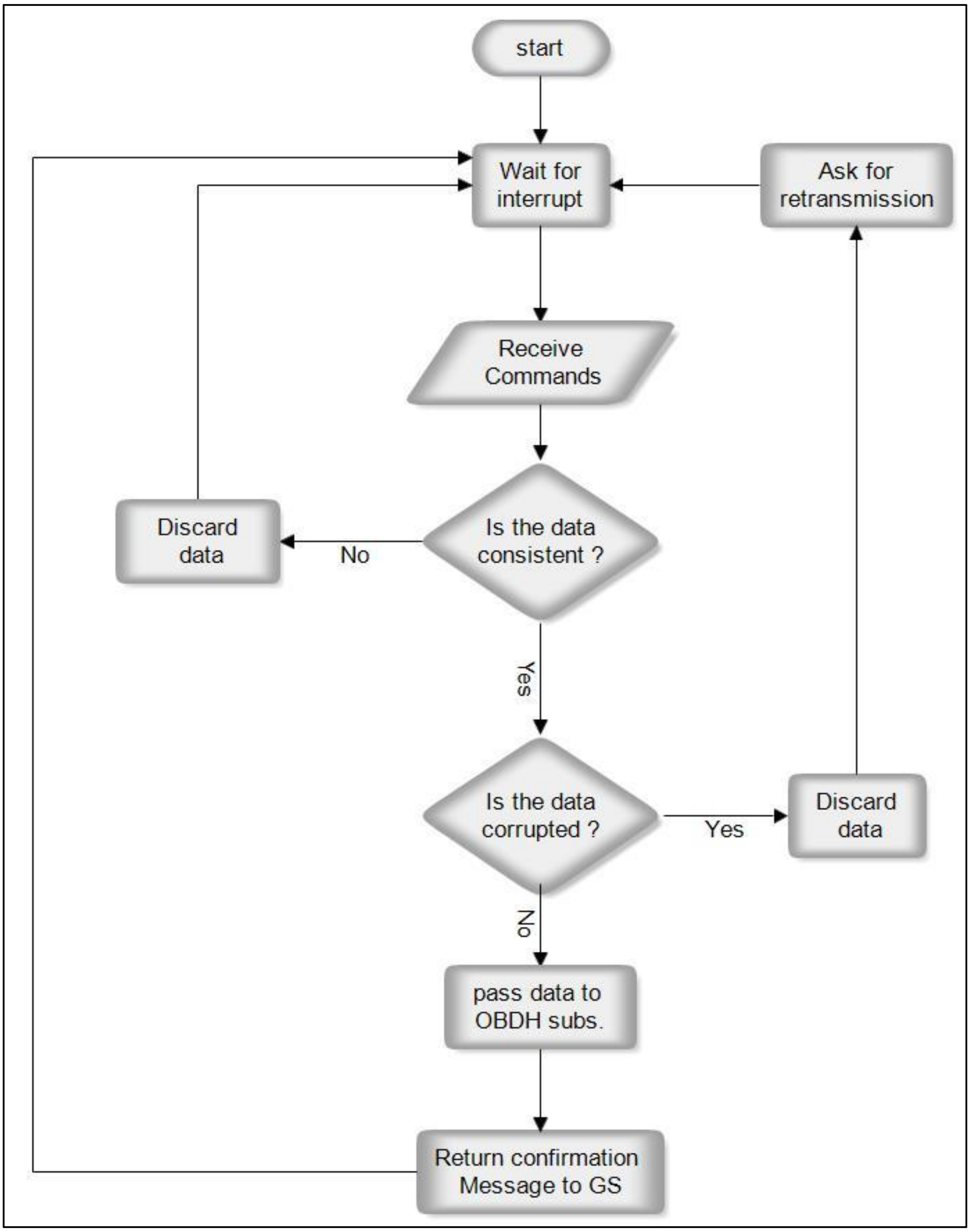

Figure 5.7 : Command reception procedure

6. CONCLUSION

This thesis discussed the design of communication subsystem for SudaSat-1 satellite mission. A top-down design approach has been conducted; stating the overall mission requirements and the impact of these requirements in the design of the communication subsystem.

Orbit and space environment effects on satellite communications systems were discussed. The orbit of the satellite was modelled using STK, average visibility time per pass is about 10 minutes was obtained.

Major design components were selected considering requirements satisfaction and space heritage. Redundant components were designed to work in the case of the failure of one of the devices.

Communications link budget of X-band downlink channel and S-band downlink/uplink channels was calculated for worst case conditions; acceptable power margins were obtained.

REFERENCES

Balanis, C.A P., 2005: Antenna Theory Analysis and Design. Third edition, published by John Wiley & Sons, Inc., ISBN: 0-471-66782-X.

Boain, R.J., 2004, A-B-Cs of Sun-Synchronous Orbit Mission Design, 14th AAS/AIAA Space Flight Mechanics Conference, Maui, Hawaii, February 8-12.

Brown, C. D., 2002: Elements of Spacecraft Design, published by American Institute of Aeronautics and Astronautics, Inc., ISBN: 1-56347-524-3.

CCSDS, 2011 *TM Synchronization and Channel Coding*. Recommendation for Space Data System Standards, CCSDS 131.0-B-2. Blue Book. Issue 2. Washington, D.C.: CCSDS, August 2011.

Davide C., Tortora P., 2012 *TT&C System for the ALMASat-EO microsatellite Platform*. AESS European Conference on SatelliteTelecommunications (ESTEL), Rome, 2-5 Oct. 2012, E-ISBN: 978-1-4673-4686-3, IEEE.

Fourest, S., Briottet, X., Lier, P. and Valorge, C., 2012. Satellite Imagery, From acquisition principles to processing of optical images for observing the Earth, authorized translation from the French language edition, entitled Imagerie Spatiale : Des principes d'acquisition au traitement des images optiques pour l'observation de la Terre, ISBN: 978.2.36493.036.0

Larson, W.J. and Wertz, J.R., 1999. Space mission analysis and design, Third edition, published by Microcosm Press and Kluwer Academic Publishers. ISBN: 1-881883-10-8.

Pelton, J.N., Madry, S., and Camacho-Lara, S., 2013. Handbook of Satellite Applications, published by Springer. ISBN: 978-1-4419-7670-3.

Rajendran, S., 2009, Hyperspectral Remote Sensing and Spectral Signature Applications, published by New India Publishing.

Roddy, R., 2006: Satellite Communications. Fourth edition. published by McGraw-Hill. ISBN: 0-07-146298-8.

Tresvig, T.L., 2010**:** Design of a Prototype Communication System for the CubeSTAR Nano-satellite, M.Sc. thesis.

Wulder, M., Franklin S. E., 2012. Remote Sensing of Forest Environments: Concepts and Case Studies,

Url-1<https://directory.eoportal.org/web/eoportal/satellite-missions/content/-/article/spot-6-7>, accessed at 19.04.2015.

Url-2<https://directory.eoportal.org/web/eoportal/satellite-missions/i/ikonos-2>, accessed at 19.04.2015.

Url-3<https://directory.eoportal.org/web/eoportal/satellite-missions/q/quickbird-2>, accessed at 19.04.2015.

Url-4<https://directory.eoportal.org/web/eoportal/satellite-missions/v-w-x-y-z/worldview-1>, accessed at 19.04.2015.

Url-5<http://www.crisp.nus.edu.sg/~research/tutorial/optical.htm>, accessed at 2.05.2015.

Url-6< http://www.tech-faq.com/qpsk.html >, accessed at 2.04.2015.

Url-7< http://littlebits.cc/browse-lessons/space-lesson-satellite-orbit >, accessed at 26.05.2015.

Url-8<https://directory.eoportal.org/web/eoportal/satellite-missions/pag-filter/-/article/deimos-2 >, accessed at 27.05.2015.

Url-9<https://directory.eoportal.org/web/eoportal/satellite-missions/o/orbview-3>, accessed at 27.05.2015.

Url-10<https://directory.eoportal.org/web/eoportal/satellite-missions/k/kompsat-2>, accessed at 27.05.2015.

APPENDICES

APPENDIX A: SATELLITE ORBITAL PARAMETERS

A.1 Kepler's Laws

Kepler's laws are applicable to any two bodies in space, they have derived by German astronomer Johannes Kepler in the 17th century. They are three laws, described below, the more massive body is referred to as primary and the other, the secondary or satellite.

- The path followed by the secondary around the primary is an ellipse with the canter of mass of the primary at one of the foci.
- In equal time intervals the secondary object sweeps equal areas in its orbital plane.

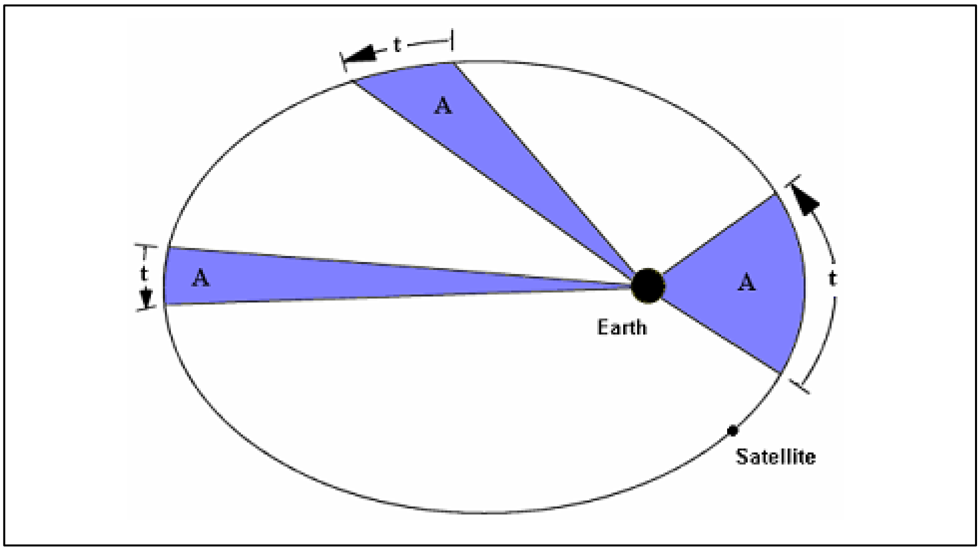

Figure A.1 : Kepler's second law

- The square of the periodic time of the satellite is proportional to the cube of the mean distance between the two bodies. This can be expressed as follows:

$$T^2 = \frac{a^3}{\mu} \qquad \textbf{(A.1)}$$

Where T = orbital period in s, $\boldsymbol{a}$ = semi-major axis of satellite elliptic orbit in km, $\boldsymbol{\mu}$ = earth geocentric constant. $\boldsymbol{\mu = 3.986005 \times 10^{14}\ m^{3}\ s^{2}}$

A.2 Orbital Parameters

Orbital elements or Keplerian elements are six quantities that sufficiently defines the position of a satellite around earth in a given time.

A.2.1 Semi-major axis

A line that divides the ellipse in a half and passes through the widest part of the ellipse is called major axis. Half the length of major axis is called semi-major axis.

A.2.2 Eccentricity

The eccentricity (e) defines the shape of the elliptic orbit, it is the relation between the semi-major and semi-minor axes of the ellipse, the value of e lies between $0 < e < 1$, if e = 0, the orbit is circular.

$$e = \frac{\overline{a^2 - b^2}}{a} \tag{A.2}$$

Where “a” is the semi-major axis of the ellipse and “b” is the semi-minor axis.

A.2.3 Right ascension of the ascending node (RAAN)

The ascending node is point where the satellite crosses the equator going from south to north. Right ascension is an angle measured in the equatorial plane from reference point in the sky called vernal equinox. Now RAAN is the angle measured east-ward, in the equatorial plane, from vernal equinox to the ascending node. RAAN is often denoted as Ω (omega).

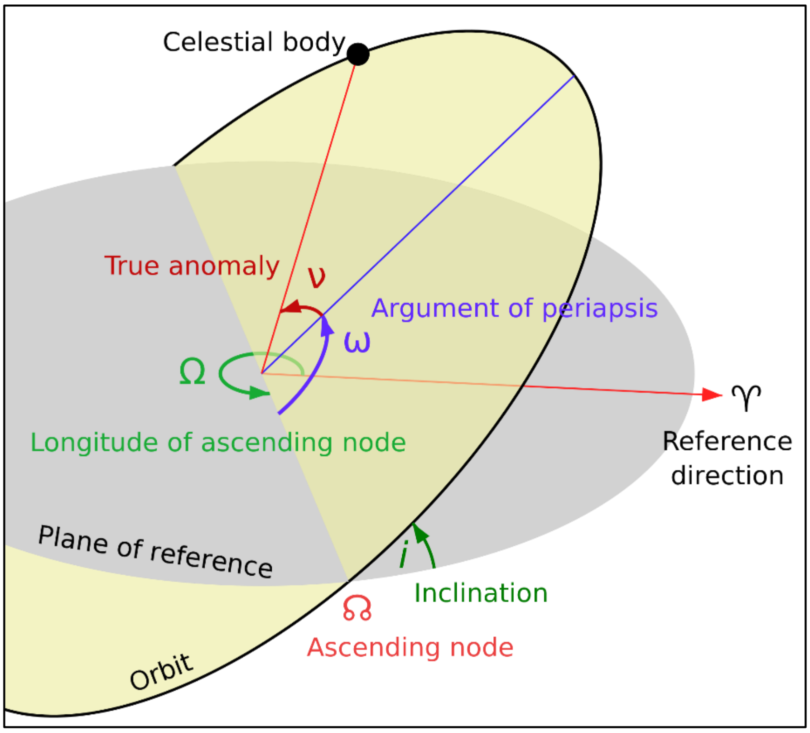

Figure A.2 : Orbital elements (Wikipedia)

A.2.4 Inclination

Inclination (i) is the angle between the equatorial plane and orbital plane in the ascending node.

A.2.5 Argument of perigee

Perigee is the point in the elliptical orbit where the satellite is closest to earth. Argument of perigee is an angle measured in the orbital plane between the ascending node and the perigee.

A.2.6 True anomaly

Now the previous five elements described the orbit of the satellite. The true anomaly (v) describes the current positon of the satellite in its orbit. It is measured from the perigee to the position of the satellite.

APPENDIX B: ANTENNA PARAMETERS

B.1 Gain

The gain of the antenna is the ratio of total power radiated (or received) per unit solid angle by the antenna in a given direction to the power radiated (or received) per unit solid angle by an isotropic antenna fed with the same power. Isotropic antenna is a hypothetical radiator that is assumed to be radiating equal power in all directions.

$$G = \frac{\psi_M}{\psi_i} \quad \textbf{(B.1)}$$

Antenna again determines the ability of an antenna to direct radio frequency energy in a particular direction. The gain can be expressed also in terms of the effective aperture of the antenna.

$$G = (4\pi/\lambda^2)A_{eff} \quad \textbf{(B.2)}$$

Where A_{eff} is the effective aperture of the antenna. And λ is the wavelength of radio frequency wave.

B.2 Radiation Pattern

Radiation pattern of an antenna describes how the gain varies with direction. In a radiation pattern graph the gain of the antenna is normalized to its maximum value. Antenna radiation patterns are taken at one frequency, one polarization, and one plane cut.

Antenna beam width shows angular characteristics of the radiation pattern of the antenna. Beam width can be defined as the angular separation between the half power points on its power density radiation pattern.

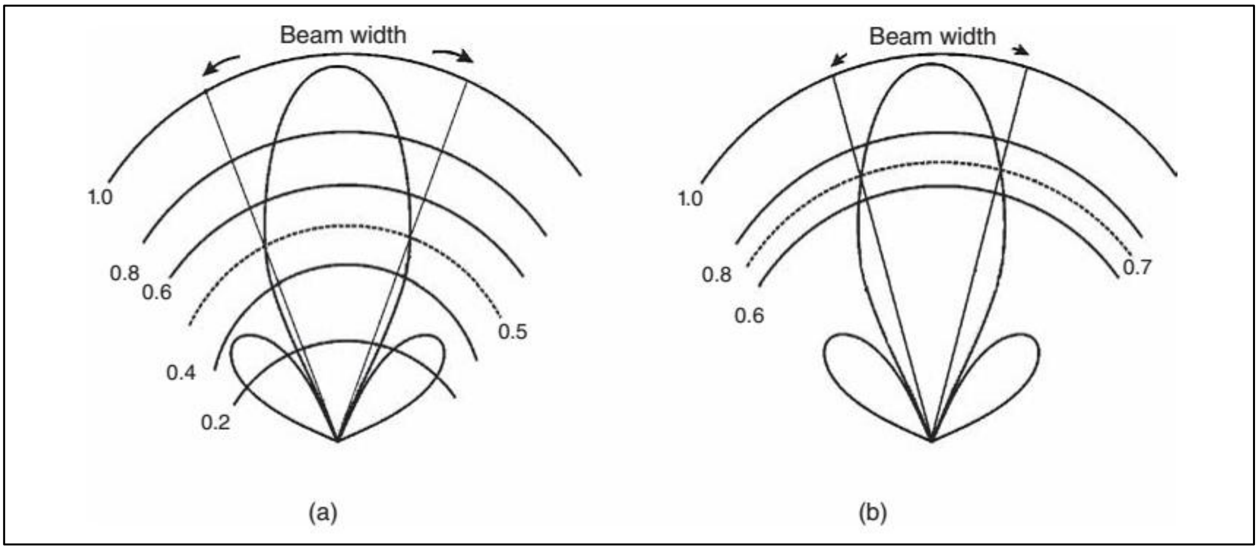

Figure B.1 : Antenna radiation pattern (Balanis 2005)

B.3 Antenna Bandwidth

Antenna bandwidth refers to the range of frequency over which the antenna gives a certain specific performance. It is always defined with reference to a certain parameter, e.g. gain, in which case it is taken as the frequency range around the center frequency over which the power gain falls to half of its maximum value.

B.4 Antenna Polarization

Polarization is a property of an electromagnetic wave describing the variation of direction and relative magnitude of electric field vector with time and the orientation of the electric field vector as observed in the direction of propagation.

The polarization of an antenna can be classified into two main types, linear polarization and elliptical polarization.

In the case of linear polarization, the electric field vector direction is constant with respect to time and the two perpendicular field components are in phase. Linear polarization can be horizontal or vertical depending on the plane on which electric field vector lies.

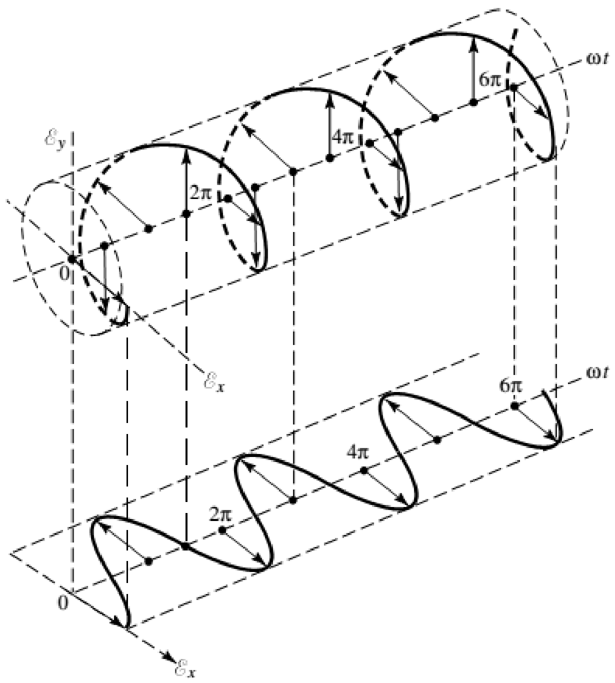

Figure B.2 : Rotation of the wave (Balanis 2005)

In elliptical polarization the electric field components are not in phase, the orientation of the electric field vector traverses an ellipse. An elliptical polarized wave has two orthogonal linearly polarized components, a special case when the magnitudes of the two orthogonal components are equal, the resultant polarization is called circular polarization.

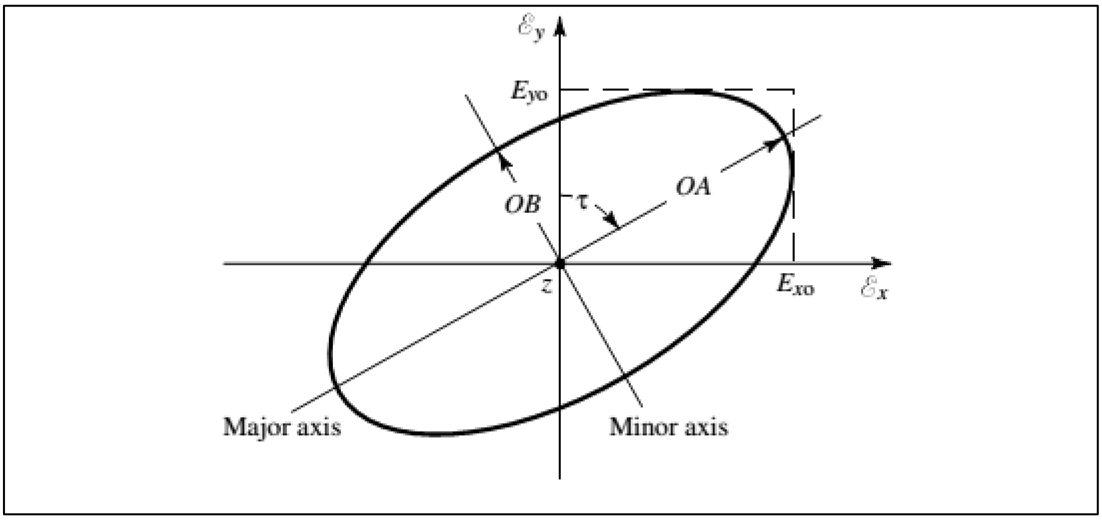

Figure B.3 : Polarization ellipse (Balamis 2004)

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Education & academic Qualifications

- Istanbul Technical University, Istanbul, Turkey: February 2013 – Present.
  - M.Sc. student in Aeronautics and Astronautics Faculty – Department of Aeronautics and Astronautics Engineering.
- University of Khartoum, Khartoum, Sudan: October 2005 – July 2010.
  - B.Sc. (Honors) in *Electrical and Electronic Engineering* (Sub specialization: *Communication Engineering*).
  - Courses of Specialization:

    1- Digital Systems Design
    2- Electronics and Microelectronics
    3- Electromagnetic Theory and Applications
    4- Computer Organization and Design
    5- Database systems
    6- Microprocessor and Assembly language

7- Signal Analysis and Systems
8- Digital Signal Processing
9- Communication Systems
10- Satellite Communication Systems
11- Performance Evaluation Engineering
12- Digital Communication Systems
13- Data Communication and Computer Networks
14- Operating Systems Engineering
15- Optical Fibers Communication Systems
16- Antennas and Waves propagation
17- Switching and Traffic Theory

- Al-Mogama Al-yamani Model Secondary School for Boys, Khartoum, Sudan: 2002 – 2005..

- Al-Ryadh Modern Private Elementary School, Khartoum, Sudan: 1994 – 2002.

Academic achievements

- Obtained **275 marks out of 280** in the State's Basic School Certificate Examinations.
- Recorded an **average of 95.4%** in the Sudan School Certificate (SSC) examinations.
- Ranked **the ninth** among the republic of Sudan – more than 300,000 candidates - in Sudanese School Certificate Examinations.

TECHNICAL EXPERIENCE

- **Programming Languages** C
  x86 assembly language
  MATLAB
  PASCAL

- **Database Management Systems** MySQL

- **CAD Programs** ISIS Proteus Professional
  ANSYS HFSS
  Eagle layout Editor (PCB Design)
  Electronics Workbench
  AutoCAD

- **Software** Satellite tracking software(Nova & Orbitron)
  Satellite telemetry decoders

- **Satellite** Nano satellites' system Engineering & Design
  Nano satellites' Communication system Design

- **Ground station operations** Ground Station Design
  Signal reception, decoding, analysis.

- **Office Suites** MS Office

Professional training

- Advanced Training in the designing and Testing of nano satellites at Istanbul Technical University (ITU), Turkey, 2010
- A special training program organized by the Advanced Engineering & Innovation Center (AEIC), Kulliyyah of Engineering, International Islamic University Malaysia, Kuala Lumpur, Malaysia 2009, including courses on CDMA Networks and satellite, PLC and Scada Systems, PIC Microcontroller, Robotics, and Power Distribution.
- GSM and GPRS Advanced Course at Jelecom Company coordinated with University of Khartoum, Khartoum, Sudan, 2010.
- Advanced Course in Mobile Communications (GSM & GPRS, UMTS & CDMA, LTE) at Jelecom Company coordinated with University of Khartoum, Khartoum, Sudan, 2013.

ADDITIONAL SKILLS

- **Languages**
  Arabic: Native language
  English: Fully operational command (writing, speaking, listening and reading.
  Turkish: Intermediate.

Projects & other contributions

- Worked in a team of 2 in a project of Digitally Programmable Hearing Aid, that provides solutions for people of hearing loss problems.
- Participated in University of Khartoum Annual Post-Graduate Studies conference Exhibition as cube satellite team member.

Activities & awards

- General Sudanese Students Union Award for the ninth best performance in Sudanese School Certificate Examination among participants from all over the Sudan, 2005.
- Jelecom Company award for best performance in GSM and GPRS Advanced Course.

WORK EXPERIENCE

- **Collaborative Teaching Assistant,** Department of Electrical and Electronic Engineering, Faculty of Engineering, University of Khartoum, October 2011 – 2012.
- Working in a team of 10 in University of Khartoum cube satellite research project (KN-SAT1), which aims to launch the first Sudanese satellite, October, 2010 – 2013.

Publications

- Co-author of "*Cube Satellite Project (KN-SAT1)* ", Proceedings Vol. 1 pp. 212-213 of Annual Conference of Postgraduate Studies and Scientific Research 2012.
- Co-author of" *Design, Implementation and Impact of Educational Satellite Ground Station, Case Study: University of Khartoum, Sudan*", 2nd IAA Conference on University Satellites Missions 2013.