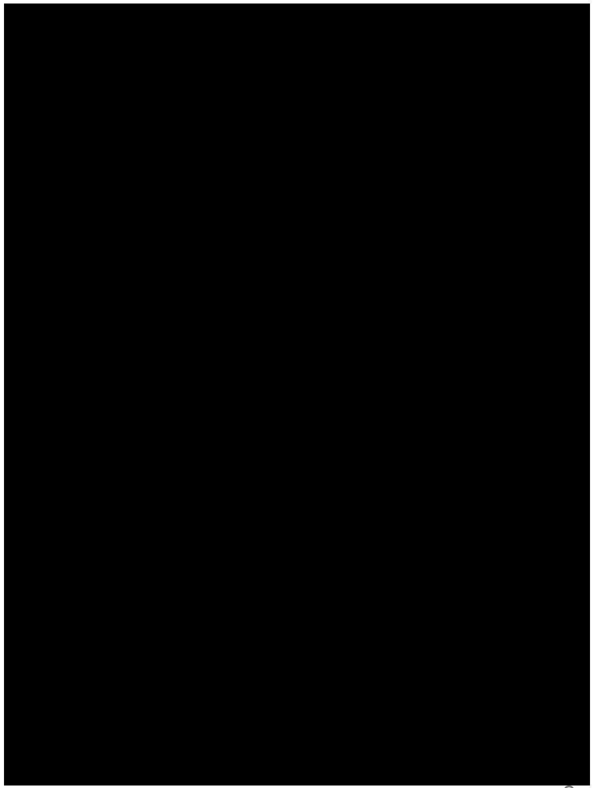
Communication Systems

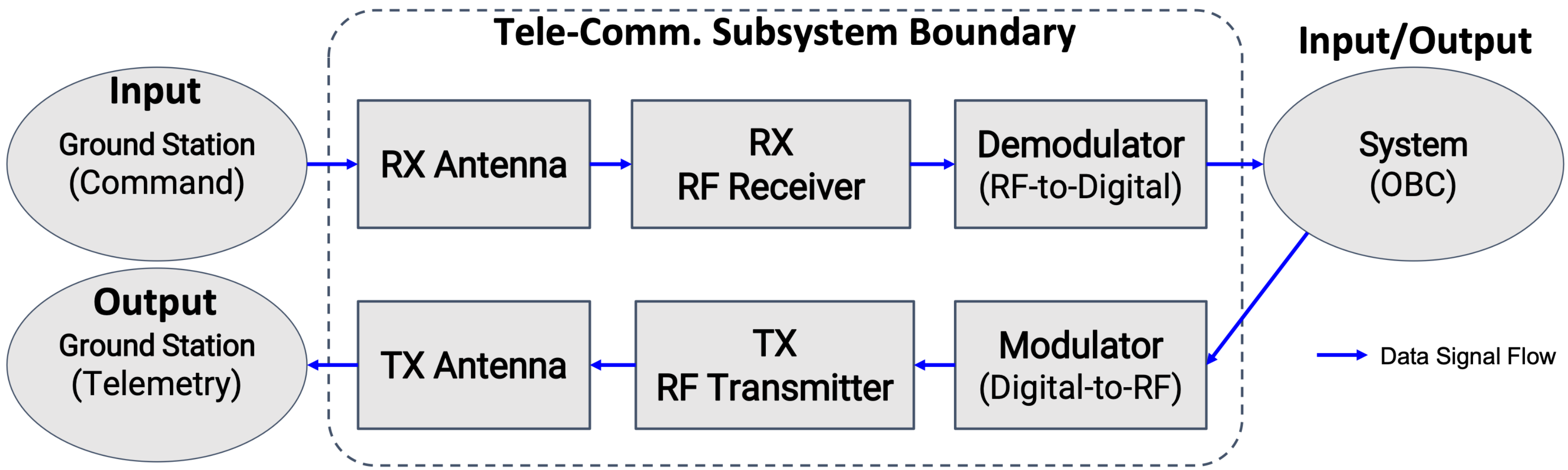
Small Satellite Workshop 2025

RF Communication For CubeSat

- RF communication subsystem is the most powerful and mature option to get information or send command from/to long distance
- Communication subsystem's responsibility = very long-term activity
  (Start with comm, finish with comm)
  - Satellite project start from frequency coordination, and radio station license coordination
  - Satellite project finish with sending RF transmit termination command
- In the case of entry/research project, amateur station (UHF/VHF) is commonly considered
- Higher bands (S-band/X-band) are considered for matured project (like Earth Observation, Science Mission)



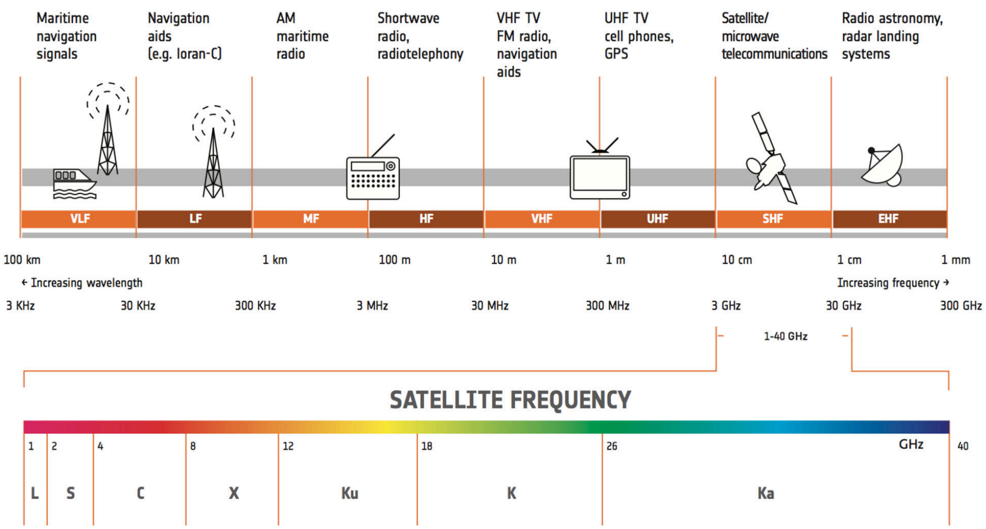
Communication Subsystem Architecture



Key Functions for Communication

- Tele-Communication Objectives
  - To confirm of the satellite survival (Beacon or CW Morse)
  - To get telemetry (digital packet data of housekeeping of the satellite (like temperature, voltage, current, status, and attitude parameters),
  - CCSDS in professional/commercial mission, AX.25 in amateur mission
- To control the satellite (change operational mode, start mission camera shooting, registering the mission schedule)
- To get the distance information between the satellite to ground (ranging, especially for deep space mission)
  - LEO case: GPS/GNSS-based positioning is common

Satellite RF Frequency Band



Band	Frequency	Wavelength	Typical Application
Ka	27 – 40 GHz	1.1 – 0.8 cm	Rarely used for SAR (airport surveillance)
K	18 – 27 GHz	1.7 – 1.1 cm	rarely used (H_2O absorption)
Ku	12 – 18 GHz	2.4 – 1.7 cm	rarely used for SAR (satellite altimetry)
X	8 – 12 GHz	3.8 – 2.4 cm	High resolution SAR (urban monitoring,; ice and snow, little penetration into vegetation cover; fast coherence decay in vegetated areas)
C	4 – 8 GHz	7.5 – 3.8 cm	SAR Workhorse (global mapping; change detection; monitoring of areas with low to moderate penetration; higher coherence); ice, ocean maritime navigation
S	2 – 4 GHz	15 – 7.5 cm	Little but increasing use for SAR-based Earth observation; agriculture monitoring (NISAR will carry an S-band channel; expends C-band applications to higher vegetation density)
L	1 – 2 GHz	30 – 15 cm	Medium resolution SAR (geophysical monitoring; biomass and vegetation mapping; high penetration, InSAR)
P	0.3 – 1 GHz	100 – 30 cm	Biomass. First p-band spaceborne SAR will be launched ~2020; vegetation mapping and assessment. Experimental SAR.

UNITED STATES FREQUENCY ALLOCATIONS

THE RADIO SPECTRUM

RADIO SERVICES COLOR LEGEND

- AERONAUTICAL MOBILE
- AERONAUTICAL MOBILE SATELLITE
- AERONAUTICAL RADIONAVIGATION
- AMATEUR
- AMATEUR SATELLITE
- BROADCASTING
- BROADCASTING SATELLITE
- EARTH EXPLORATION SATELLITE
- FIXED
- FIXED SATELLITE
- INTER-SATELLITE
- LAND MOBILE
- LAND MOBILE SATELLITE
- MARITIME MOBILE
- MARITIME MOBILE SATELLITE
- MARITIME RADIONAVIGATION
- METEOROLOGICAL
- METEOROLOGICAL SATELLITE
- MOBILE
- MOBILE SATELLITE
- RADIO ASTRONOMY
- RADIODETERMINATION SATELLITE
- RADIOLOCATION
- RADIOLOCATION SATELLITE
- RADIONAVIGATION
- RADIONAVIGATION SATELLITE
- SPACE OPERATION
- SPACE RESEARCH
- STANDARD FREQUENCY AND TIME SIGNAL
- STANDARD FREQUENCY AND TIME SIGNAL SATELLITE

ACTIVITY CODE

- FEDERAL EXCLUSIVE
- FEDERAL/NON-FEDERAL SHARED
- NON-FEDERAL EXCLUSIVE

ALLOCATION USAGE DESIGNATION

SERVICE	EXAMPLE	DESCRIPTION
Primary	FIXED	Capital Letters
Secondary	Mobile	1st Capital with lower case letters

This chart is a graphic single-point-in-time portrayal of the Table of Frequency Allocations used by the FCC and NTIA. As such, it may not completely reflect all aspects, i.e. footnotes and recent changes made to the Table of Frequency Allocations. Therefore, for complete information, users should consult the Table to determine the current status of U.S. allocations.

U.S. DEPARTMENT OF COMMERCE
National Telecommunications and Information Administration
Office of Spectrum Management

JANUARY 2016

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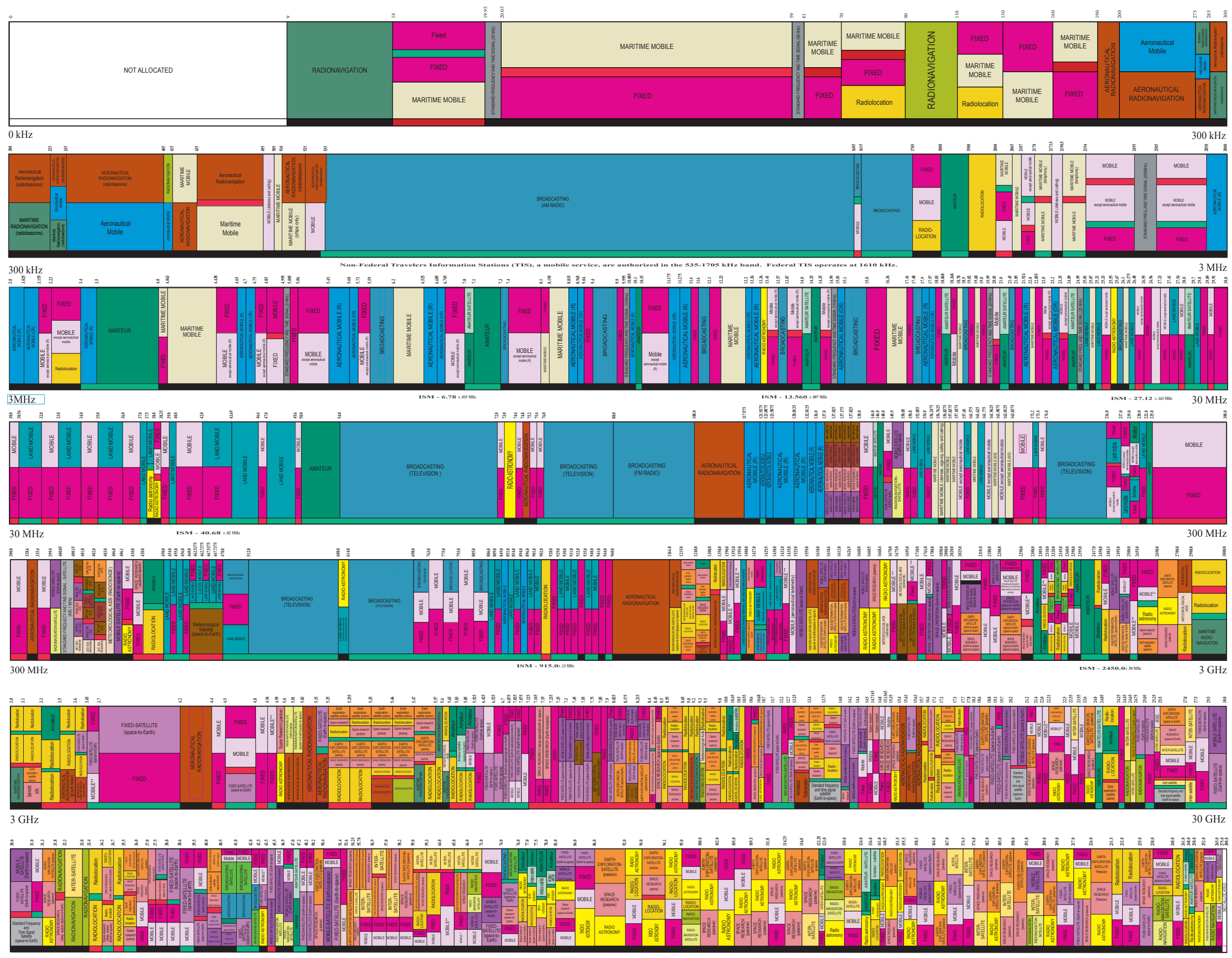


* EXCEPT AERONAUTICAL MOBILE (R)

** EXCEPT AERONAUTICAL MOBILE

PLEASE NOTE: THE SPACING ALLOTTED THE SERVICES IN THE SPECTRUM SEGMENTS SHOWN IS NOT PROPORTIONAL TO THE ACTUAL AMOUNT OF SPECTRUM OCCUPIED.

RF Band Considerations

- All key design features and constraints depend on which frequency is used
  - RF band allocation is the most important and the first action to kickoff satellite projects

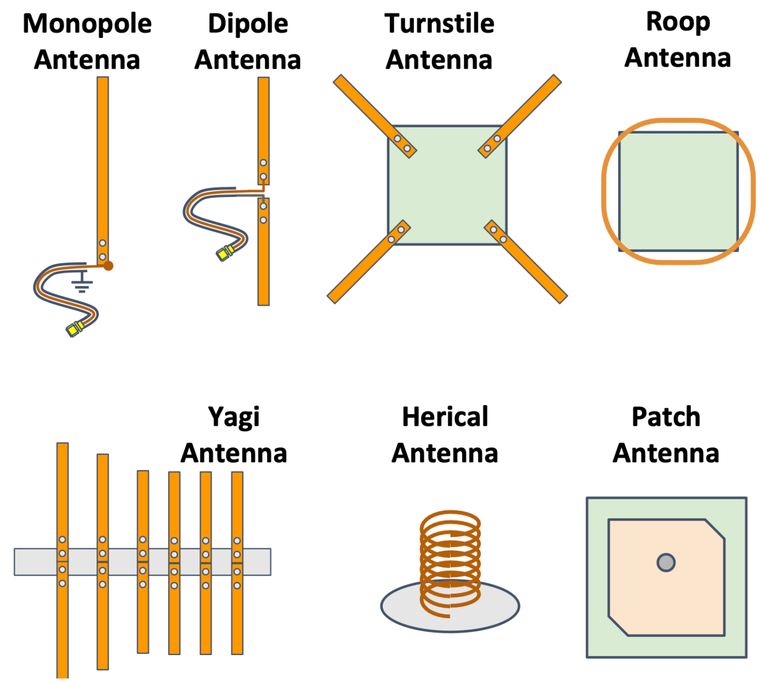
- Lower frequency (VHF/UHF) is well-demonstrated
- Higher frequency (5 ~ 20 GHz) is difficult to use (especially for first time developer like university mission)

- New possible option is Specified Low Power Radio Station
  - Such as LoRa (**Lo**ng **Ra**nge): a kind of LPWA (Low Power Wide Area) protocol → several CubeSats have already demonstrated the feasibility of the technology

CubeSat Antenna

How to emit RF to space / correct RF from space

- Antenna is a key component for satellite operation
  (No antenna, no mission data from space)
- Antenna design is based on studying the electromagnetic field, there are many kinds of antenna design
  - All current-flowing conductors can emit RF potentially = micro-dipole model
  - Even, tiny copper line on PCB is always emitting RF!
- Antenna performance is affected by…
  - **Length** (corresponding to target frequency)
  - **Material** (permissiveness)
  - **Shape** (rod, plate, circle, ring, cubic, corn …)
  - **Combination** of multiple antennas (arraying)
  - Relationship to GND plane (distance and angle)

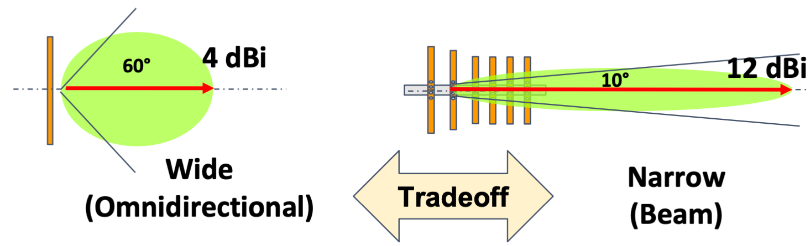


Antenna Characteristics

- Antenna Gain : ***dBi*** [dB is logarithmic scale] (i stands for Isotropic antenna)
  - **Antenna Pattern**: Wide (broad) or narrow (beam) HPBW (Half Power Beam Width) [deg]
  - **EIRP** (Effective Isotropic Radiated Power)
  - **G/T** (Antenna gain-to-noise-temperature)
  - **VSWR** (Voltage Standing Wave Ratio)
  - **Polarization**: Linear or circular (RHCP, LHCP)

- Deployable or non-deployable :

  Most Critical Decision for CubeSat Mission Success
  - Major reason of “Dead on Arrival” status might be antenna deployment failure
  - In the non-deployed state of the antenna, the performance of RF transmitting is few expected to nominal condition



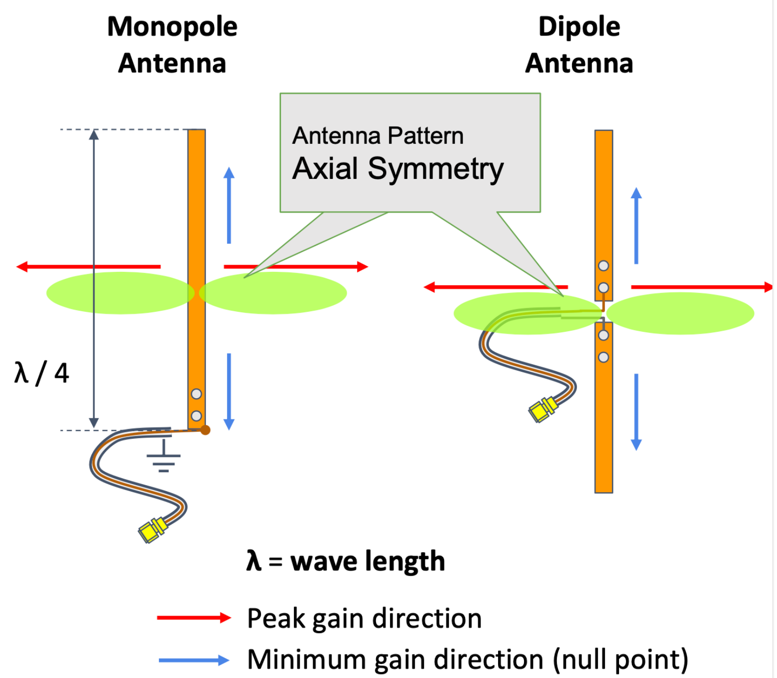
Deployable Antenna VS **Non-Deployable Antenna**

	Deployable Antenna	Non-Deployable Antenna
Pros	Ideal antenna gain wide coverage	Independ from deployment risk
Cons	Risk of deployment failure	Limited performance (gain) Depend on satellite attitude

Antenna Design and Testing

Example : Typical monopole and dipole for CubeSat

- Material: Thin ribbon steel tend to be selected for antenna element (to store inside envelope of CubeSat by bending)
- Adjustable parameters are its length, width, thickness (length is most important factor for performance)
- One side is free end, the power feed point and mechanical interfaces are located on the other side
- The center wire of the coaxial cable is attached to this power feed point of the antenna element by soldering or spot welding
  - Monopole: the outer shield of coaxial cable is attached to GND
  - Dipole: the outer shield of coaxial cable is attached to the other paired antenna element
- Linear polarization: Electric field oscillating direction is kept in the same plane



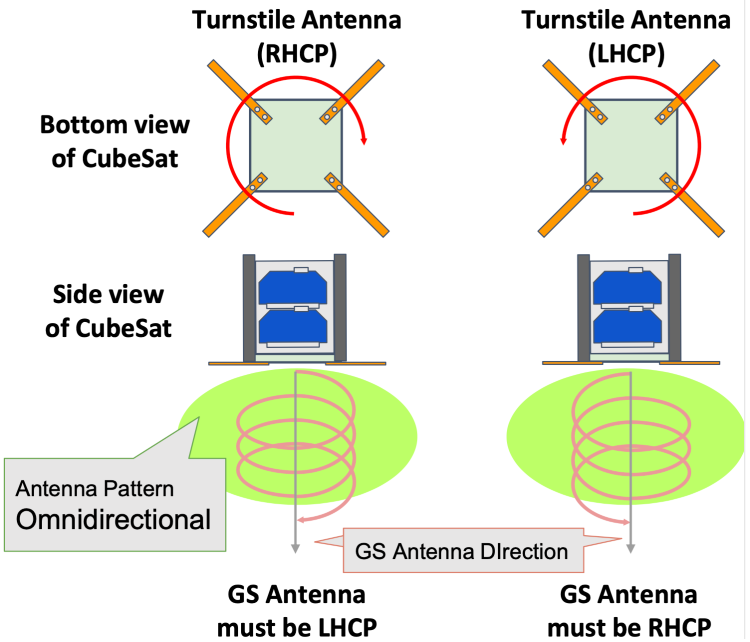
Antenna Design and Testing

Example : Turnstile Antenna for CubeSat

- Combination of 4 antenna elements
  (= a set of 2 dipole antennas = cross-dipole)
- Single element's properties are same as dipole case
- Input RF power is fed to 4 antenna elements by changing the phase every 90 degrees
  (0, +90, +180, +270)
- Omnidirectional radiation pattern
  Circular polarization: Electric field rotates in the direction of propagation
  - RHCP: Right Hand Circular Polarization
  - LHCP: Left Hand Circular Polarization

Circular polarization is much more robust for space telecommunication than linear polarization

GS antenna's RHCP or LHCP must be match the satellite's condition

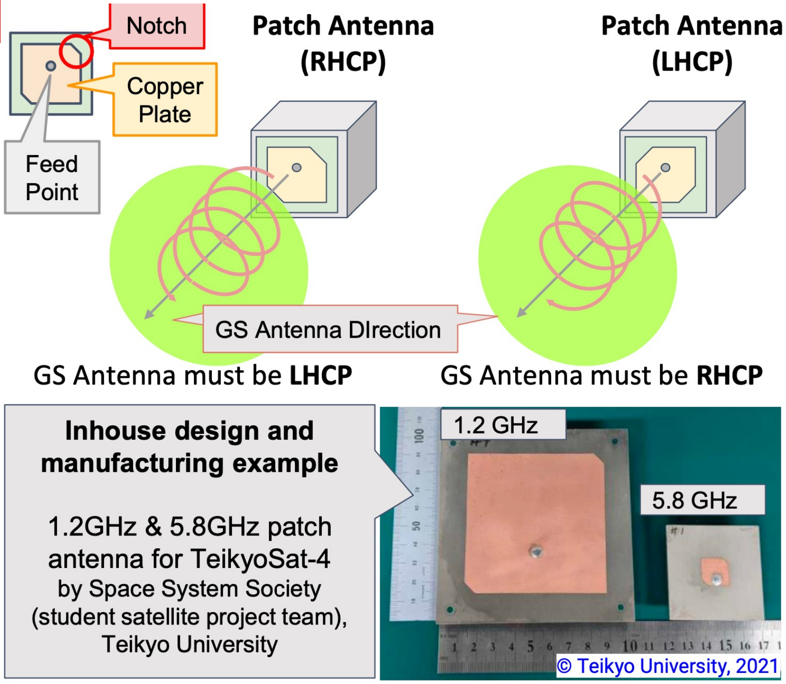


Antenna Design and Testing

Example : Patch Antenna for CubeSat

- Plate style
  (good for keeping within the envelope requirement)
- PCB and copper plate sizes depends on frequency
  - In the case of over 1.2GHz-band, the entire antenna size is suitable for typical 1U CubeSat Surface [10x10cm]
- Omnidirectional radiation pattern
  - Circular polarization: Electric field rotates in the direction of propagation depending on the position of a **feed point** and a **paired notch**
    - RHCP: Right Hand Circular Polarization
    - LHCP: Left Hand Circular Polarization

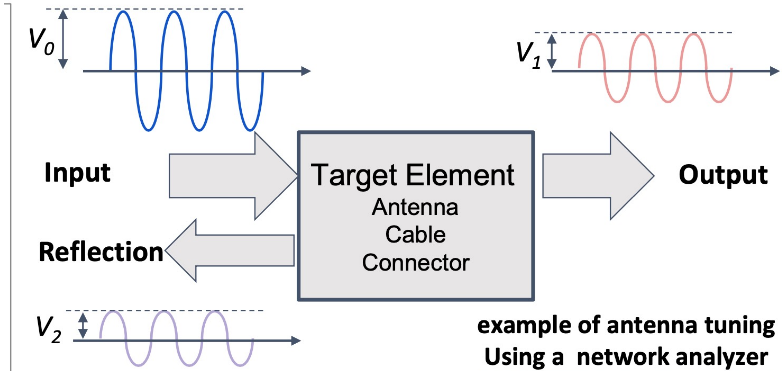
- Circular polarization is much more robust for space telecommunication than linear polarization
- GS Antenna's RHCP or LHCP must be match the satellite's condition



Antenna Design and Testing

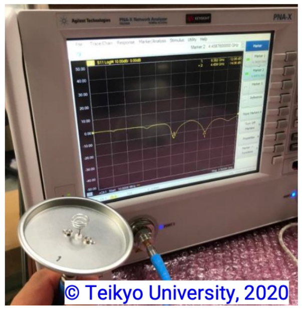
Impedance Matching & Antenna Tuning

- Impedance: the degree of signal flow (alternative current) easy or not
  - ex) 50[Ω] or 75 [Ω] : standard RF component
- Signal reflection happens at different impedance points
- For effective signal transmission, this reflection should be as small as possible
- VSWR (Voltage Standing Wave Ratio)
  - At no reflection case → VSRW = 1.0
  - At realistic case : VSWR < 2.0 (especially for transmit antenna)
- VSWR tuning can be made by cutting the antenna element or by adjusting circuit constant (discreet parts: R or C or L) with measuring by a network analyzer



$$VSWR = \frac{1 + \frac{V_2}{V_1}}{1 - \frac{V_2}{V_1}}$$

example of antenna tuning Using a network analyzer



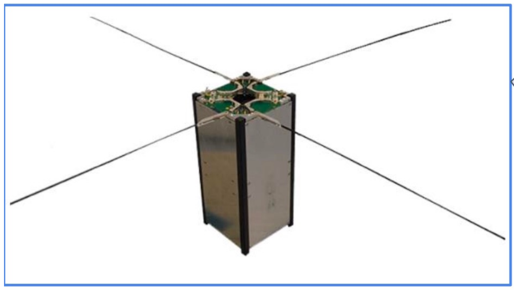
Example Antennas

CubeSat Kit Example

- Deployable antenna integrated structure
- Frequency and data rate are standardized for typical amateur (VHF/UHF) CubeSat missions
- Users do not need to consider detailed design in the case of the combination of recommended TX/RX and Antenna
- Example (right Images)
  - ISISPASE: CubeSat Antenna System for 1U/3U
  - GomSpace: NanoCom ANT430
- If TX/RX or antenna were to be newly developed, users should verify the combined performance of antennas and TX/RX hardware

Structure + Solar Panel + Antenna = Standard Kit

(If user’s interest is NOT focused on these developments, this kind of standard CubeSat Kit is very useful to reduce the project workload)



ISIS CubeSat antenna system for 1U/3U

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GomSpace NanoCom ANT430

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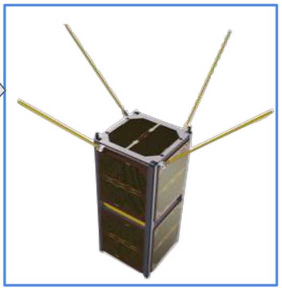
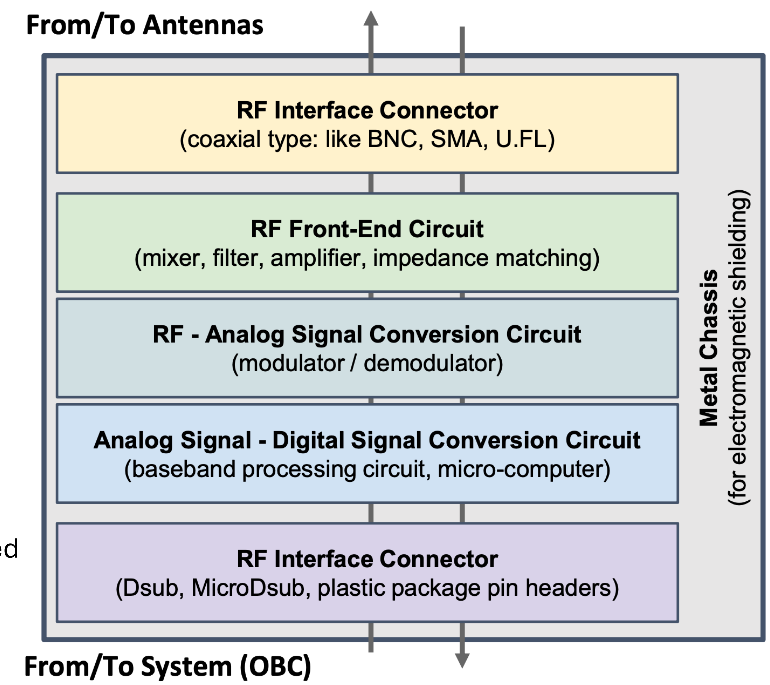


Radio Hardware (TX/RX)

Radio Hardware

- Fundamental configuration (major functions)
  - RF power amplify
  - Frequency conversion (upconvert/down-convert)
  - Modulation / demodulation: (D/A conversion or A/D conversion)
- Baseband signal processing
- Make or Buy
  - Make: for mature projects, require experiences on digital, analog and RF)
  - Challenging for first project
  - Higher frequency, higher difficulty
  - Amateur radio operators (HAM)'s support
  - Alternative option: SDR (Software Defined Radio) supported by FPGA
- Buy: CubeSat kit often includes packaged TX/RX



Radio Hardware (TX/RX)

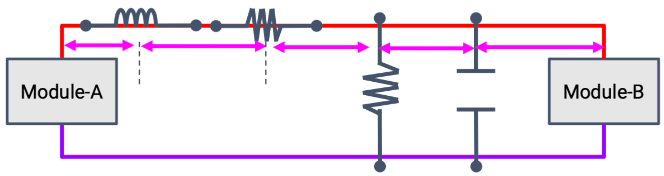
- TX (Transmitter)
  - **Transmit power** [W]
  - **Frequency stability** [Hz/degC] or [ppm]
  - **Bitrate** (bps)
  - Modulation
  - **Power efficiency** (%)
    (= transmit power / power consumption of module)
- RX (Receiver)
  - **Sensitivity** (dBuV) or (dBm)
  - **RSSI** (received signal strength intensity) [dBm/V]
  - Modulation
- Common
  - Operational temperature range (degC)
  - Operational voltage [V] ex) +5.0V or +3.3V
  - Power consumption [W]
  - Dimensions [mm]
  - Mass [g]

	Items	**Example Product Values**
TX	Frequency Range	435 ～ 438 [MHz]
TX	Transmit Power	CW: 0.1 [W], FM: 0.8[W]
TX	Frequency Stability	± 2.5 [ppm] (-30 ~ 60 [degC])
TX	Modulation	AFSK, GMSK
	….	….
RX	Frequency Range	145 ～ 146 [MHz]
RX	Sensitivity	-13 [dBu/V] (-120 [dBm])
	….	….
	Power Consumption	0.2 ~ 0.5 [W] (@Standby/CW) 2.5 [W] (@FM Transmitting)
	Dimensions	80 x 50 x 12 [mm]
	Mass	50 [g]

Radio Hardware (TX/RX)

Key Design Points of RF Components

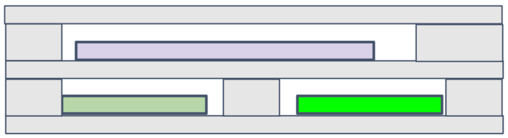
- Circuit **impedance** consideration:
  - Dimensions and shape of signal line pattern on PCB should be designed with consideration for properties corresponding to wavelength of RF Signal
- **Shielding** to improve S/N (signal-to-noise Ratio)
- **Connector selection** corresponding to the frequency
- Signal line **filtering** and power line decoupling to reduce noise effect from/to system



Each parts' **distance, position**, and **pattern shape** are important to realize suitable RF circuit performance

Testing Key Points of RF Components

- TX frequency stability (corresponding to operational temp)
- TX power stability (corresponding to operational temp)
- RX frequency stability (corresponding to operational temp)
- RX sensitivity stability (corresponding to operational temp)
- TX/RX combined operation (TX's effect to RX: EMC/EMI)



TX/RX Hardware Cross-section View
Compartment of each function (digital, analog, rf front-end) to minimize electromagnetic interference each other

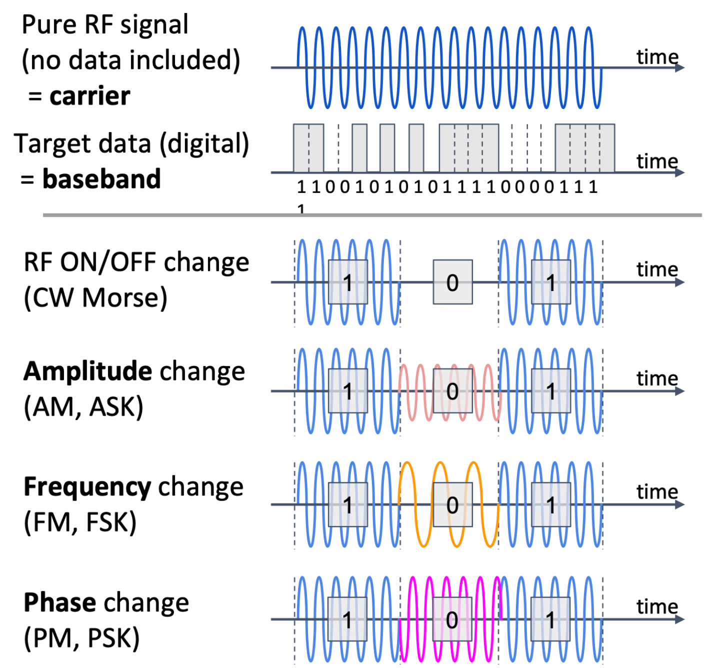
Signal Processing and Software Functions

How to add information (0 / 1 bit pattern) on RF Signal

- ❑ **Baseband**
  (0/1 pattern converted from original digital data)

- ❑ **ON/OFF: CW (Morse)**
  Ex) ON = 1, OFF = 0,
  Morse code case:
  the length of bar(—) = 3 times of the length of dot(・)

- ❑ **Amplitude change: AM, ASK**
  Ex) large amplitude = 1, small amplitude = 0
- ❑ **Frequency change: FM, FSK**
  Ex) high frequency = 1, low frequency = 0
- ❑ **Phase change: PM, PSK**
  Ex) 0deg-start = 1, 180deg-start = 0



Major Characteristics of Signal Processing and Software Functions

Modulation Methods

- **Modulation**: Data conversion of digital to analog signals
  Demodulation: Data conversion analog to digital signals
- **CW**: Continuous wave = no modulation
  (just ON/OFF carrier RF) → **simple, legacy,** but **robust**
- **FM** + **FSK** or **AFSK** (Audio Frequency Shift Keying)
  is popular for university missions to communicate digital data based on the protocol (**AX.25** in amateur)
  1200bps is nominal usage
- **GMSK** 9600bps or more high speed
- To achieve higher bitrate communication,
  advanced modulation methods must be considered

Term	Description
AM	Amplitude Modulation
FM	Frequency Modulation
PM	Phase Modulation
PQM	Phase Quadrature Modulation
PCM	Pulsed-Code Modulation
PPM	Pulse Position Modulation
ASK	Amplitude Shift Keying
FSK	Frequency Shift Keying
PSK	Phase Shift Keying
BPSK	Bi-Phase Shift Keying
QPSK	Quadrature Phase Shift Keying
GMSK	Gaussian Filtered Minimum Shift Keying

Design and Testing of Signal Processing

Digital Signal Packet Design

Open Systems Interconnection model (OSI model)

- ❑ Developed by the International Organization for Standardization (ISO) to classify and clarify the roles of the many protocols used in computer networks
- ❑ Defines communication functions (communication protocols) in seven layers
- ❑ A conceptual model for understanding the overall architecture of internet communications

Digital packet design of TeleCom. for CubeSats is also based on this OSI model concept

Layer Name	Description
7. Application	Specific services (Ex. E-mail, HTTP, FTP)
6. Presentation	Data presentation style (Ex. ASCII Code)
5. Session	Starting and terminating management, Reconnection management
4. Transport	End-to-end communication management (error correction, retransmission control)
3. Network	Decides which physical path the data will take (rooting)
2. Data link	Defines the format of data on the network
1.Physical	Physical (electromagnetic) signal connection (Ex. wired: RS-232, 10BASE-T, wireless: wifi)

Design and Testing of Signal Processing

Data Packet Protocol Example: Amateur AX.25
- A protocol originally derived from layer 2 of the X.25 protocol suite and designed for use by amateur radio operators in 1984
- AX.25 v2.0 and later occupies the **data link layer**, the second layer of the OSI model
  (Reference: AX.25 Version 2.0, By WB4JFI)

Data Packet Protocol Example: CSP
- **CSP:** CubeSat Space Protocol
- Developed by a group of students from Aalborg University in 2008, and further developed for the AAUSAT3 CubeSat mission (2013 Launch)
  (Reference: GitHub, GomSpace/Space Inventor)

Data Packet Protocol Example: CCSDS
- **CCSDS**: Consultative Committee for Space Data Systems, Space Packet Protocol
- **Error correction** by RS(Reed-Solomon) Code
- Most popular for commercial space mission
  (Reference: Space Packet Protocol (CCSDS 133.0-B-2))

For detailed descriptions, refer to official documents

If you want many ground stations to receive your CubeSat's telemetry, you need to consider these protocols

AX.25 (V.2.0)

※FCS (Frame Check Sequence) = Error Detection Method

Flag (0x7E)	Address (CallSign)	Control	Info (User Data)	FCS	Flag (0x7E)
1 Byte	**14 or 28 Bytes**	**1 or 2 Bytes**	**Max. 256 Bytes**	**2 Bytes**	**1 Byte**

CSP (V.2.0)

※CRC (Cyclic Redundancy Checksum) = Error Detection Method

Header **6 Byte**		User Data
• Priority (2 bits) • Destination (14 bits) • Source (14 bits) • Destination Port (6 bits) • Source Port (6 bits)	• Reserved (2 bits) • HMAC (1 bit) • XTEA (1 bit) • RDP (1 bit) • CRC (1 bit)	**Max. 65,535 Bytes**

CCSDS Space Packet