Telemetry, Tracking, Communications, Command and Data Handling

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Abbreviations

AA	Atmospheric Absorbtion
ADC	Analog to Digital Converter
ADCS	Attitude Determination and Control System
AFRL	Air Force Research Laboratories
AI	Artificial Intelligence
AML	Antenna Misalignment Loss
AM	Amplitude Modulation
ATX	Advanced Technology X
C-band	Compromise Band
CC&DH	Communications, Command and Data Handling
C/N	Carrier to Noise Ratio
C&DH	Command and Data Handling
CLC	Command Logic Controller
COTS	Commercial, Off-the-Shelf
dB	Decibel
DOS	Disk Operating System
ECC	Error Correction Code
EIRP	Equivalent Isotropic Radiated Power
EEPROM	Electrically Erasable Programmable Read-Only Memory
EHF	Extremely High Frequency
FCC	Federal Communications Commission
FM	Frequency Modulation
FSL	Free-Space Spreading Loss
GEO	Geo-Stationary Earth Orbit
GPS	Global Positioning Satellite
HPA	High Power Amplifier
IC	Integrated Circuit
ICS	Interface and Control Systems
IEEE	Institute of Electrical and Electronics Engineers
ITU	International Telecommunications Union
ITOS	Integrate Test and Operations System
ISA	Industry Standard Architecture
ISS	International Space Station

JPL	Jet Propulsion Laboratory
K-band	Kurz-band
Ka-band	Kurz-above Band
Ku-band	Kurz-under Band
L-band	Long Band
LEO	Low Earth Orbit
LNA	Low Noise Amplifiers
mA	MilliAmps
MB	Megabyte(s)
miniATX	Mini Advanced Technology X
MIPS	Millions of instructions Per Second
MMS	Manufacturing Message Specification
ms	MilliSeconds
MEO	Medium Earth Orbit
MOST	Microvariability and Oscillations of STars
NASA	National Aeronautics and Space Administration
NRZ	Non-Return to Zero
OBC	On Board Computer
OS	Operating System
PC	Personal Computer
PCI	Peripheral Component Interconnect
PCM	Pulse Code Modulation
PL	Polarization Mismatch Loss
PM	Phase Modulation
RAM	Random Access Memory
ROM	Read Only Memory
RF	Radio Frequency
S-band	Short Band
SBC	Single Board Computer
SCL	Spacecraft Command Language
SEU	Single Event Upset
SDRAM	Synchronous Dynamic Random Access Memory
SHF	Super High Frequency
SOI	Silicon on Insulator
SOTA	State of the Art
SGLS	Space Ground Link Subsystem
SNR	Signal to Noise Ratio
SPRG	Space Physics Research Group
SSPA	Solid State Amplifier
STDN	Space Tracking and Data Network
STOL	Spacecraft Test and Operations Language
SuperMOCA	Space Project Mission Operations Control Architecture

TWTA	Traveling Wave Tube Amplifier
UHF	Ultra High Frequency
USAP	United States Antarctic Program
VHF	Very High Frequency
WARC	World Administrative Radio Conference
X-Band	Spot Band

Symbols

η_A	Aperture Efficiency
λ	Operating Wavelength
ψ_M	Saturation Flux Density
π	Pi
A	Total Attenuation
A_{cs}	Atmospheric Attenuation in Clear Sky
A_{rain}	Atmospheric Attenuation due to Rain
A_0	Effective Area for an Isotropic Antenna
A_{ant}	Area of the Antenna Aperture
B	Bandwidth Signal
$B0$	Specified Backoff
B_N	Noise Bandwidth
c	Speed of Light
D	Downlink
D_{sg}	Distant From Satellite to Ground Station
F	Noise Factor
f	Operating Frequency
G	Available Power Gain
G_R	Receiver Antenna Gain
G_t	Satellite Antenna Gain
K	Boltzmann's Constant
L_a	Clean Air Atmospheric Loss
L_{ant}	Edge of Beam Loss for Satellite Antennas
L_{FRX}	Feeder Loss between Receiver and Antenna
L_{FTX}	Feeder Loss
L_m	Other Random Losses
L_p	Free Space Path Loss
m	Size of Data Frame in Bits
n	Length of the Synch Word in Bits
N_0	Noise Power Spectral Density
$N_{0,out}$	Output Noise
$N_{0,in}$	Input Noise

P_{fs}	Probability of False Synchronization
ΔP_{nrain}	Increase in Noise Temperature due to Rain
P_{nrain}	Receiver Noise Power in Rain
P_N	Noise Power
P_R	Received Power
P_{rain}	Received Power at Earth Station in Rain
P_{RX}	Signal Power at Input of Receiver
P_T	Antenna Power
P_{TX}	Power Output
R	Rain Rate
r	Radius
T_0	Room Temperature
T_a	Apparent Absorbed Temperature
T_{ant}	Antenna Temperature
T_{CS}	Clear Sky Temperature
T_e	Equivalent Noise Temperature
T_N	Equivalent Noise Bandwidth
T_{rain}	Effective Noise Temperature of Rain
T_s	System Noise Temperature
T_{sky}	Total Sky Noise Temperature
U	Uplink

Chapter 1

Introduction

The basic function of all but the simplest spacecraft requires extensive contact with ground stations for control, command, communication, and data return, and sufficient computer processing power to run all spacecraft subsystems with, in many cases, a high degree of autonomy.

A spacecraft communication system handles all data sent and received by the spacecraft, including spacecraft bus commands, and payload operations. The system incorporates a transmitter and a receiver that are the sole point of passage for data entering or leaving the spacecraft. Thus payload and bus operations data are both handled by this system.

The driving concerns in the design and implementation of spacecraft communications systems are access, radio frequency selection, and data characteristics. In considering communication access, the selection of ground station location, visibility windows for those candidate locations for a given spacecraft orbit, and antenna and transmitter power selection are key concerns. In selecting the radio frequency, issues such as the transmitter power and receiver sensitivity requirements for given frequencies and the power required to overcome atmospheric conditions must be considered. Additionally, permission to use a particular frequency must be applied for and granted by the appropriate regulatory agency. Finally, antenna and transmitter power required to attain the bandwidth and maximum error level allowed by the characteristics of the data to be communicated are determined.

The command and data handling system (C&DH) receives all commands and data for both bus and payload operations from the communications system. The integration of payload data with bus data into the data stream bound for the communications system and the disintegration of the incoming data stream into individual data streams bound for the bus and payload are the primary roles of the C&DH system. The final major function is the handling of bus commands by directing them to the appropriate subsystem or executing them directly. The handling of payload commands would generally not be done by the C&DH system, but would instead be passed, fully encapsulated, directly to the payload.

In selecting, or more usually, designing a command and data handling system, concerns vary somewhat based on the spacecraft payload. Science payloads may make extensive use of C&DH subsystems in terms of high bandwidth data streams and even data storage and computation. Payloads often require continuous communication with ground stations, precise attitude control, and other services which together necessitate a close interoperation of C&DH systems with the payload. Selection is a predominately linear process, requiring the advance preparation of commands to be executed by the bus and payload, telemetry to be sent and received by all spacecraft subsystems, determination of time criticality of subsystem functions, and finally determining the parameters of a system that will address all of these issues satisfactorily.

In CC&DH, there are two major functional divisions. The communication subsystem controls the data transfer between the spacecraft and a station on Earth. The C&DH subsystem covers the control of data flow internally as well as the disassembly of commands to individual sections of the spacecraft. The C&DH subsystem directs the rest of the spacecraft in how to accomplish the mission. Both of these combined encompass the whole of the CC&DH system.

1.1 Communications

The communications subsystem is an important aspect to consider in the design of satellites. The communications subsystem deals with the data transfer from the satellite to a ground station on Earth. This transfer can be made either by linking through radio waves to a ground station directly or by linking to other satellites and then finally to a ground station on Earth. The main types of data that are transferred between the satellite and the ground station are the updated command controls for the spacecraft, the collected mission data from the spacecraft and the operational health status of the spacecraft. The main components in the communications subsystem are the receivers, transmitters, and antennas. The systems in place in the communications systems are set up to be redundant. Redundancy is needed on satellites because system failure makes the satellite ineffective.

1.1.1 Receiver and Transmitter Selection

The size, type and gain of the receiver, transmitters and antennas used depend mainly on the type of mission the spacecraft is designed to accomplish. There are two main types of missions dealing with communications: near Earth communication and long-range data relay. The receivers and transmitters consist of several parts. The key components in receivers and transmitters are amplifiers, filters and demodulators. The amplifiers and filters are combined into a single unit.

Transponder

A transponder consists of several parts. These parts include a band-pass filter, a down converter, and an output amplifier. The band-pass filter is used to select the particular channel's band of frequencies. The down converter is used to change the frequency from 6 GHz at the input to 4 GHz at the output. Most communication systems have multiple transponders, usually 12 to 44 for a high-capacity satellite. The main bandwidths for the transponders are 36, 54, and 72 MHz. These narrow bandwidths are used in order to avoid intermodulation.

Amplifier

The signal that is received by the satellite's antenna is passed through two low noise amplifiers (LNA) and is recombined at the output. The use of two LNA is needed to provide redundancy. The low noise amplifiers are used in order to minimize the addition of noise to the incoming signal.

The signals that are sent from a satellite require amplification in order to produce a signal that can be received from Earth. Typically, the output power amplifier that is used is a solid state amplifier (SSPA). If the satellite requires a high power output, a traveling wave tube amplifier (TWTA) is used. Redundancy in the high power amplifiers (HPA) is provided by including a backup TWTA or SSPA that will be activated in case of the primary's failure. The least reliable part of any transponder is the HPA. This reliability issue is resolved by providing a spare HPA in each transponder.

Modulation

The signal that is received is modulated in order to obtain several goals. These goals include obtaining the required data rate, fitting the signal into the available radio frequency (RF) bandwidth, and obtaining the required signal to noise ratio (SNR). There are several types of modulation that may be used. These types of modulations include amplitude modulation (AM), phase modulation (PM), and frequency modulation (FM).

The type of modulation that is performed on the signal is determined by the desired output. Amplitude modulation requires a higher SNR to attain a high performance but the performance degrades slowly as the SNR is reduced. The FM and PM degrade quickly as the SNR is decreased but can operate at lower RF SNR than AM.

The modulation is performed on the amplified signals in order to attain the desired output. The modulated signal is then transmitted to the command decoder and processor.

Noise

The noise of the system is an important aspect of the system to determine. In the communications subsystem, the need for a maximized carrier to noise ratio (C/N) is desired. In order to achieve this goal, the amount of noise present in the system needs to be minimized. This minimization is needed because of the weak carrier signals involved. A method of dealing with noise minimization is to allow only the desired bandwidth to pass through the filter. This process of filtering all the bandwidths blocks excess signals that may be a source of noise.

The performance of the receiving system is determined by comparing the total thermal noise power against the signal demodulation. Thermal noise is produced by every active and passive device involved in the communications system. The goal is to minimize the addition of noise from the satellite's components. An additional source of noise to the signal is the atmospheric conditions that the carrier signal has to travel through. The noises encountered throughout the system are simplified to a single term, the system noise temperature (Ts). Losses occur in the connection between the antenna and receiver. These losses are part of the feeder loss. They occur in the connecting waveguides, filters, and couplers. Similar losses will occur between the antenna and amplifier in the filters, waveguides, and couplers.

1.1.2 Antenna Selection

The main goal in antenna selection is determining the proper type and size of antenna needed. In general, a larger antenna has a better gain and SNR than a smaller antenna. The main constraint on antenna sizing is the weight and power requirements. The main types of antenna are wire, horn, reflector and helical antennas.

Wire Antenna

Wire antennas provide omni-directional coverage that are used primarily during launch and orbit insertion. They are primarily used when the main antenna have not been deployed or properly positioned. The main frequencies for wire antennas are UHF and VHF.

Horn Antenna

Horn antennas are used when a wide beam has to be produced for global coverage. The main frequencies that are used with horn antennas are microwave frequencies. The gains that can be obtained from horn antenna are usually less then 23 dB and the beamwidths are usually larger then 10 degrees.

Reflector Antenna

Reflective antennas usually contain at least one horn and provide a larger usable area then a horn antenna alone. The basic shape of the reflector antenna is a paraboloid. The reflecting shape is based on a three-dimensional parabolic shape. It has a unique property of directing all incoming wave fronts perpendicular to its axis, in phase, to a point focus. Reflective antennas are generally made of steel, aluminum, or fiberglass with an embedded reflective foil.

Antenna Arrays

An antenna array is defined as being more than one antenna brought together to accomplish a task. The antennas in the array will be brought together and driven from a source of power at the same frequency. The resulting antenna pattern is more complex. The complexity is due to the interference between the signals transmitted separately from each of the individual antennas. This interference can be constructive causing the transmitted signal to increase.

Coverage Selection

The type of coverage is also an important aspect of antenna selection and the communication system. The main types of coverage are a global beam, spot beams, multiple spot beams and scanning beams, and orthogonally polarized beams. The global beam is used to allow access to as much of the Earth as possible at any given time. The spot beams are used to search a specific area of the Earth's surface. The spot beam is useful when communicating with only one ground station since the satellite antenna can be properly aligned to produce the best gain. Multiple spot beams and scanning beams are used to communicate with several ground stations at the same time. The orthogonally polarized beams are used to allow a greater number of channels to be used by the satellite.

1.1.3 Frequency Selection

Frequency selection is a key issue in the design of communication subsystems. Specific, limited bands of frequencies are available for use by spacecraft. The list of available frequency ranges are shown in Table 1.1. The limitations on the available frequency ranges are imposed by the ITU, International Telecommunications Union, and the WARC, World Administrative Radio Conference and, in the United States, by the FCC, Federal Communications Commission. To facilitate frequency planning, the world is divided into three regions: region 1 includes Europe, Africa, Russia and its satellites, and Mongolia, region 2 includes North and South America with Greenland, and region 3 includes Asia, Australia, and the southwest Pacific. As more spacecraft are placed in space, the number of satellites using these frequency ranges is increasing.

This crowding of the frequency bands could lead to possible problems, like signal interference. In all there is eight frequency bands: L, S, C, X, Ku, Ka, Q, and V.

Table 1.1: Limitations of Frequency Band[7]

Frequency Band	Frequency Range (GHz)		Service	Downlink Power Flux Density Limit (dbW/m2)
	Uplink	Downlink		
UHF	0.2 - 0.45	0.2 - 0.45	Military	-
L	1.635 - 1.66	1.535 - 1.58	Maritime/Navy	-144/4 kHz
S	2.65 - 2.69	2.5 - 2.54	Broadcast	-137/4 kHz
C	5.9 - 8.4	3.7 - 4.2	Domestic Comsat	-142/ 4 kHz
X	7.9 - 8.4	7.25 - 7.75	Military Comsat	-142/ 4 kHz
Ku	14.0 - 14.5	12.5 - 12.75	Domestic Comsat	-138 4 kHz
Ka	27.5 - 31.0	17.7 - 19.7	Domestic Comsat	-105/ 1 kHz
SHF/EHF	43.5 - 45.5	19.7 - 20.7	Military Comsat	-
V	60	60	Satellite Crosslinks	-

The long-band (L-band) is frequencies between 1 and 2 GHz, and was not applied to commercial satellite communications until the late 1970's. The most convenient L-band ground antennas are small and do not require pointing toward the satellite. Long-band does not have rain attenuation; however the ionosphere introduces a source of significant link degradation. This occurs in the form of rapid fading called ionospheric scintillation, which is the result of the RF signal being split into two parts. The direct path and the refracted (bent) path at the receiving stations the signals combine with random phase then may cancel, producing a deep fade. Ionosphere scintillation is the more common in the equatorial regions and around the equinoxes.

A short-band (S-band) frequency has a low background noise and suffers less from ionosphere scintillation effects than L-band does. Having a higher frequency band than L-band it will suffer more atmospheric loss and have less ability to adopt to local terrain. Low Earth Orbits (LEO) and Medium Earth Orbits (MEO) satellites are good matches to S-band frequencies since the path loss is inherently less than for GEO.

The compromise-band (C-band) is the most used and developed frequency band in the satellite spectrum. Having a bandwidth from 568 GHz to 1.44 THz, that compares well to ground based fiber optic systems. The bandwidth can be delivered across an entire country or ocean region.

The radar spot-band (X-band) frequency is mostly used by government and military satellite communications. It is generally only used for fixed satellite applications. Spot-band can provide service quality on par with C-band frequency.

Kurz-band (K-band) frequencies are split into two distinct bands, Kurz-under (Ku) and Kurz-above (Ka). Kurz is German for short. Kurz-under is more plentiful than C-band frequency. The downside to Ku-band is that it has more rain attenuation then C-band. It has regional shaped spot beams with geographic separation allowing up to approximately ten times the frequency reuse. Kurz-under is used for radar and communications satellites.

Kurz-above is abundant and therefore attractive for services that cannot find room at lower frequencies. Ground antenna beamwidths are between one-half and one-quarter the values that correspond at Ku- and C-bands, allowing more satellites to be accommodated. Kurz-above has many challenges corresponding with it. It has a much greater attenuation for a given amount of rain fall. This can be overcome by increasing the transmitted power or receiver sensitivity to gain link margin, or reducing the data rate during rain fall.

The Q- and V-bands are frequencies above 30 GHz. These bands are still considered to be experimental in nature and not many organizations have seen fit to exploit this region. Intense rain attenuation and more atmospheric absorption can be experienced on space-ground paths.

1.1.4 Link Budget

The link budget is the method of determining the received power and noise power in a link. The link budget depends on several key factors in the calculation. These factors include the type of transponder available on the satellite, the alignment of the antenna, the gain of the antenna, the atmospheric losses and the weather effects on the signal. The alignment of the antenna is important in the calculations because the power and quality of the signal decreases as the antenna moves further out of alignment. The alignment for the antenna includes both the alignment of the antenna on the satellite and also the alignment of the antenna for the ground station. For most calculations, the alignment of the antenna for the ground station is assumed to be aligned perfectly at the satellite. The atmosphere also plays an important part in the calculation of the link budget since the atmosphere is a source for noise as well as power reduction in the signal. Atmospheric losses are calculated for clear sky or clear air. The addition of weather into the atmosphere produces more loss in terms of power received and a greater amount of signal noise temperature.

Link budgets are calculated at the worst conditions possible. The conditions, which contribute to a worst-case link budget, include having the ground station on the edge of the satellite visibility, having a low angle of elevation of the satellite, and having poor weather conditions like rain. The effect of having the ground station on the edge of the satellite visibility is that the received signal is usually 3 dB lower then if the ground station was located at the center of the satellite coverage area. Another effect that is also associated with the ground station being located at the edge of satellite visibility is that the path length between satellite and ground station is at its maximum. The path length is important to take into consideration because the signal quality decreases as the path length increases. The effect of having a low elevation angle of the satellite is that the signal transmission will have the highest atmospheric attenuation in clear air. The presence of rain or other poor weather conditions would increase rain attenuation.

1.2 Telemetry, Computer, Command and Data Handling

The computer, C&DH, and telemetry systems make up the functional nervous system of any spacecraft bus. Without these systems, a spacecraft cannot fulfill its intended mission. Should any one of these systems fail permanently without a redundant backup, the spacecraft is lost. We now address some of the key concerns of the design of these systems, and discuss fundamental concepts involved in the basic structure of that design.

1.2.1 Computer States and State Diagrams

A state diagram provides a convenient method to begin determining computer requirements. The most basic states included in a state diagram are usually ON and OFF. We generally incorporate the OFF mode into system states even if we design the system operate continuously in the event of an unexpected shutdown. Other computer states exist depending on specific mission requirements. A state diagram shows all the states in a system and the requirements to achieve different states. Figure 1.1 shows a typical state diagram for an onboard computer system.

1.2.2 Interface Design and Architecture Selection

Once the basic states for a system are defined, an architecture to govern the interaction between the processor and subsystems must be created. In developing an architecture for any system, several factors must be considered: the data architecture, the hardware architecture, and the software architecture. Some examples of common architectures for computer systems are centralized, ring, federated bus, and distributed bus architectures.

In a centralized architecture, all of the other systems, such as sensors and thrusters are directly connected to the central processor. This is convenient because it allows everything to interface directly with the central processor. It also stops failures with one subsystem from affecting other subsystems. However, because all the systems are connected directly to the central processor, this architecture requires more space and complicates the addition of other subsystems into the design.

In a ring architecture, all of the subsystems connected to the central processor are connected in series, allowing data from one subsystem to pass to the processor by way of the other subsystems. Although this architecture is less reliable due to the

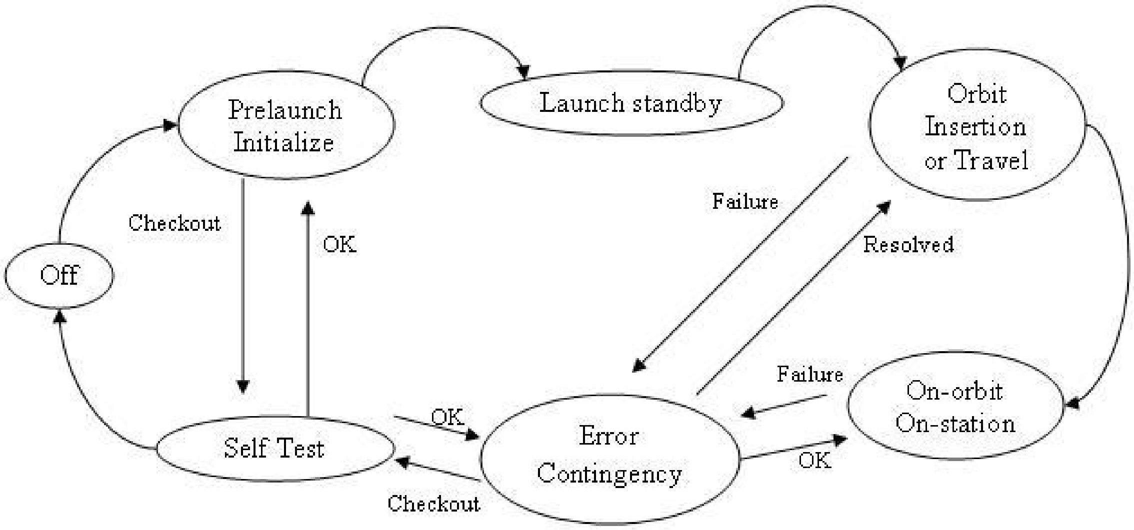


Figure 1.1: Typical State Diagram for Onboard Computer System[7]

fact that errors in one subsystem can affect multiple other subsystems, connecting the subsystems in series saves space and simplifies the addition of other subsystems.

Federated and distributed bus architectures are similar. Federated bus architectures use a common bus between the processor and all of the systems connected to the processor. This method is useful because troubleshooting of the system is facilitated by the existence of a single main data path, but it also requires that the subsystems in this architecture have specific interfaces in order to communicate via a common bus. A distributed bus architecture uses the common bus, but utilizes multiple central processors. This architecture is advantageous because it can execute multiple software commands as they are needed. Because of the multiple processors, though, this system is more complex to test. These are some of the common architectures that are used alone or in combination to meet the mission requirements.

While the architecture may remain constant between multiple designs, it is possible if not likely that the logical arrangement of systems, their function and interaction, and the flow and handling of data may change substantially. The use of multiple devices presents another option, as devices often have multiple operating modes and sometimes even multiple interfaces, such as measuring devices that include their own analog to digital converters (ADCs) but also provide direct access to the analog signal. Additionally, multiple outlet paths for data provide a degree of redundancy, whereas performance issues may make alternative operational modes desirable under certain circumstances, such as a reduced power mode of some device while the spacecraft is in eclipse.

Software development and implementation provides several more alternatives.

While software cannot provide performance beyond the physical limits of the onboard instrumentation, it can affect how efficiently that instrumentation operates. Because the addition of new software functionality carries a very small cost in terms of mass, fuel, and similar cost factors compared to the addition of hardware functionality, a broad range of additional software functionality can be made available.

1.2.3 Software

Onboard software may be classified in one of two categories: individual elements of software to run different processes; and the complete operating system (OS). The operating system itself does not directly provide any spacecraft function or directly service any onboard system. Rather, it facilitates the operation of the computer system in much the same way that the spacecraft bus facilitates the operation of the spacecraft. It provides the housekeeping and background administration without which the computer could provide no useful function, and controls the execution of the individual software programs that do provide service for and administer the operation of the spacecraft systems.

The OS is generally based on what is known as a kernel, which is essentially an individual program. As far as the processor and hardware know, the computer is running this kernel. But that program divides time into small intervals, and thus affects the multitasking necessary to allow multiple programs to share the system processor.

The kernel is typically a custom written, proprietary piece of code written specifically for the spacecraft, although it is not unheard of to use some type of Unix or Windows kernel. Typically when using a commercial kernel, the kernel itself has many modifications made to it before it is installed into the spacecraft. These kernel can be as small as required by the mission specifications, although after a certain point they can lose functionality. Determining the size of the OS and system run overtop of it is important in determining the type of computer used in the spacecraft. Depending on the mission requirements, the computer may run nothing more than a modified, commercial, off-the-shelf (COTS) OS or a more specialized one.

Required application-specific software varies with varying mission requirements and onboard hardware, including payload hardware. Two classes of approaches to system architecture prevail. With a lower performance computer system, data collected from bus and payload subsystems may be passed unprocessed and uncompressed directly to the ground station. With a higher performance system, data may be processed and/or compressed before anything is relayed to the ground. Thus, the interaction between the selection of computing power and communication system bandwidth is clear and substantial.

The partitioning of computational services necessary to the overall space system into ground and space portions becomes a consideration in computer system design when this division of computation effort is considered. This is a relatively new consideration made possible by the swift increase in computer power in recent years, coupled with a decrease in required electrical power. Traditionally, few options existed. Because of mass and power limitations, and because computers were massive and power hungry, the only choice was to keep the onboard systems as simple as possible, and to do as little processing as absolutely necessary onboard. This resulted in a large data stream being fed down to the ground station. But with modern computing power, it is not only possible, but highly desirable to do as much processing and compression onboard as possible, so as to conserve downlink bandwidth, and only provide raw data when the mission specifically requires it.

This division of computational function is extended into the spacecraft subsystems as well. The onboard data bus is another bandwidth-limited choke point, not unlike the downlink between spacecraft and ground station. Thus, the same issues arise in determining whether the computer, or the individual hardware devices should do more or less of the processing of raw data.

1.2.4 Flow Diagrams

One of the better ways to describe subsystem functions is with a functional flow diagram. This diagram breaks up a system function into smaller subsections in the order that they are performed. Once the basic subsections are identified, it can also be broken down further into more subsections for analysis. Functional flow diagrams can also be used to describe data-flow.

Data-flow diagrams are used primarily to make sure that collected data from a mission is utilized efficiently. They allow the designer to plan out what they intend to do before they begin looking into details about how to go about doing it. A complete data-flow diagram is considered the starting point for designing the hardware for the system. These diagrams also help make up the requirements for networking the system.

1.2.5 Operating Budget Considerations

Since computers are constantly becoming smaller and more power-efficient in recent years, one may be tempted to presume that the mass and electrical draw of a computer would be insignificant on any spacecraft. While it must be admitted that this presumption would hold true for a great many spacecraft, it most certainly cannot be accepted as universal.

There are nanosatellites with a total mass of just a few pounds. Since even the smallest moderately-powered computers with power comparable to modern desktop personal computers (PCs) weigh two to three pounds, the mass of the computer can be significant. Similarly, while the power draw of a computer may be as little as 5 - 10 W, that may account for the majority of the power budget on some lower power spacecraft.

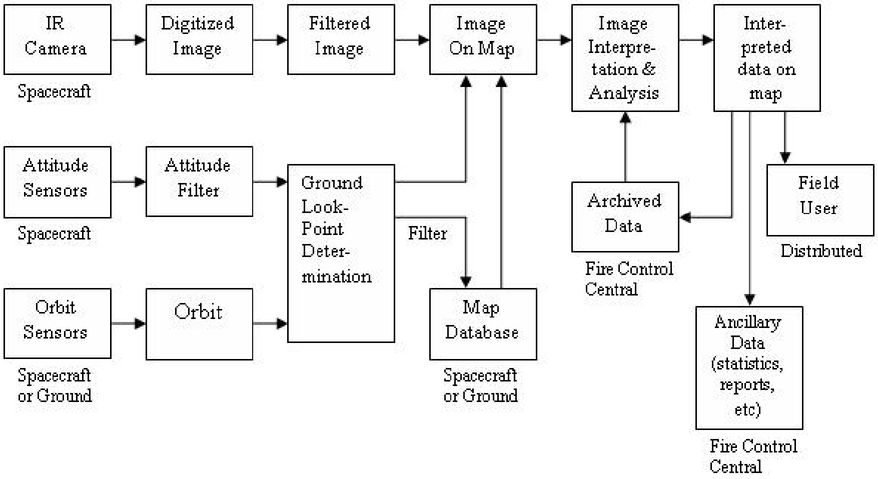


Figure 1.2: Data-Flow Diagram[7]

The need for redundancy can also add to these power and mass requirements substantially. Thus, the mass and power requirements of computer systems can be a significant concern in the design and/or selection of a suitable system. Cost can also be a factor. COTS systems rated for space flight can be purchased for \$500 to \$1,000, while custom designed systems can run over \$1,000,000 once the cost of engineering is taken into account.

1.2.6 Modeling and Analysis

Proficiency with modeling and analysis is a key part of designing computer systems for space applications because one or the other is needed at virtually all stages of the development process. Some form of structured methodology of analysis or modeling is required from defining top-level requirements to final selection and integration. Analysis may be as simple as comparing benefits and drawbacks of a solution to the use of benchmark programs (e.g. Linpack, MIPS or Whetstone) to compare computers to some kind of performance standard. Other methods include the use of blueprints, flowcharts, and matrices. Modeling can be applied, for example, to predicting the impact of thermal and heat radiation on crucial components and their performance during the selection phase. Still another application is the creation of data logging software to test and record what happens to machine in a simulated test of launch and standard orbit and any important orbital procedures.

Most of the tools for modeling and analysis are available as COTS products, including spreadsheets, math, and data logging software, as well as more sophisticated modeling and simulation software. However, one of the biggest drawbacks of using COTS software is that it may not meet the needs of the project exactly. Oftentimes, large organizations with sufficient resources use custom modeling software. The best option for smaller companies, however, is to use COTS software and tailor it as necessary.

As previously stated, knowing how to use the right modeling and analysis tools is of great importance to integration and testing. Testing at every stage of development, building up incrementally from the lowest (unit) level to the highest (system) level, ensures that the final product (or space system) will meet the mission objectives. It also serves to reduce the complexity and the risk involved. Because this kind of rigorous testing directs the subsystems toward a configuration that meets top-level, system requirements, there will at least be an increase of confidence (or assurance) in the overall performance of the integrated whole system.

Maintaining communication with members of other functional groups during the C&DH system design is essential to the success of the mission. Because the C&DH system handles all data for the spacecraft, and because payload data needs can vary so greatly, most aspects of computer design are affected by other functional groups. For this reason, the C&DH system is often one of the last to be designed and/or selected for a given spacecraft, once all operating parameters of the other systems have been established. For example, various computers will control or monitor the different subsystems on board the spacecraft. These may include directing the Sun and Earth sensors, controlling gyros and thrusters, error determination, power management, and thermal control, all of which operate under specific parameters that are decided by the other functional groups to accomplish the overall mission. These parameters must be taken into consideration when designing computer and data handling software or hardware, as well as how successfully the total system interfaces. Appropriate software capable of handing the data from the sensors, compensating for tracking error and determining the spacecraft attitude would be needed. The right type of hardware would be needed to communicate this information to whatever subsystem is responsible for the onboard thrusters or other attitude control systems to make any necessary attitude correction.

Computer Operation

Developing a working model of computer operation is a valuable tool in the selection and/or design of a flight computer system. This can be done with custom software that calculates processing time, power requirements, and other resource usage, or even runs simulated computations in an elaborate simulation environment. It may also be done largely by rough estimation using simpler analysis tools such as spreadsheets and basic algorithm analysis of the software routines to be employed.

Using the more elaborate methods also allows for all the additional benefits of simulation, in that software can be written and tested in the simulation, results can be compared to those expected, and performance may be evaluated before the system is ever built.

1.3 Conclusion

Inside of the CC&DH functional division, there are two major subsystems. The communications subsystem describes how the spacecraft interacts with ground stations and other spacecraft. It covers in detail how the spacecraft will receive data, at what speed it will receive it, and how it will send data back to the source in a useful form. The C&DH subsystem covers how data and commands are handled internally by the spacecraft. In the next section these subsystems are looked at in greater detail, describing how they are modeled as well as giving an in depth look at the interactions between various subsystems.

Chapter 2

Modeling and Analysis

Modeling and analysis is an in-depth look at how different subsystems interact within CC&DH. The complete CC&DH system for most spacecraft begins with ground support. When the operator on the ground sends instructions to the satellite, these instructions are encoded and modulated and the resulting signal is sent to the satellite via the radio frequency link. The spacecraft CC&DH system then receives the signal and processes the instructions. A diagram of this process is shown in Figure 2.1.

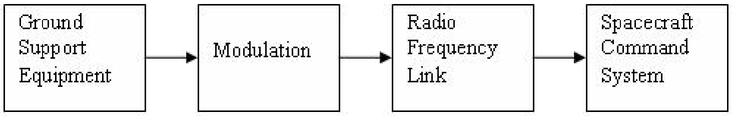


Figure 2.1: Complete Command System

2.1 Communications

Communications is affected by all subsystems involved with a satellite. Attitude determination and control, command and data handling, power, thermal, environment, and structures all effect communications. Each subsystem interacts to create a working spacecraft that can complete missions successfully. To communicate effectively with the spacecraft, communications technicians need to ensure that the signal quality is at an acceptable level. The primary way of accomplishing this is to calculate the carrier to noise ratio, antenna gain, and amplifier noise. This process begins with the interaction of the communications subsystem with all other subsystems.

2.1.1 Effect of Other Subsystems on Communications

The communications systems on satellites are affected by several other satellite subsystems. The other subsystems that affect the communications subsystem include the attitude determination and control system (ADCS), the command and data handling system (C&DH), the power, thermal, and environment system (PT&E), and the structures and launch vehicle system (S&LV). All of these systems affect the communications subsystem.

The ADCS affects the communications subsystem by ensuring that the antenna is aligned in the desired direction, particularly in GEO. Since the earth station antennas used are normally fixed, movement of the satellite away from its appointed position in the sky will cause a loss of signal. When a satellite link is established, the ideal situation is to have the earth station and the satellite antennas aligned for maximum gain. This need for continuous communications is a problem for the ADCS technicians.

The C&DH system relies on the communications subsystem in order to receive and send data from the ground station. The C&DH system determines the amount of data that is required to be sent through the link with the ground station. The command system is used to make changes in attitude and corrections to the orbit. The communications system is controlled by the command system.

The PT&E systems are relied upon to provide electrical power and insulation. Due to continuous computing, over heating is a factor for computer and communications components. The overheating of components produces an increase of noise, and a reduction in the SNR. Communications systems require adequate power to perform within the given mission parameters.

The S&LV subsystem is important in the design of communications subsystem. The type of antenna array that can be deployed is dependant on the launch vehicle selected. The placement of antennas and transponders are important in the effectiveness of the communications systems. The distance between the antennas and transponders is proportional to the amount of feeder loss in the system. In order to attain the best SNR, the feeder loss in the system should be minimized.

2.1.2 Communication System Modeling

The communications subsystem can be modeled by several equations. These equations deal with the calculation of the carrier-to-noise ratio (C/N), the amplifier noise, the feeder loss, the rain effects, and the antenna gain.

Carrier to Noise Ratio

The main measure of effectiveness of a communications link is the carrier to noise ratio. The C/N depends on several important factors. The C/N can be modeled by the equation:

$$\frac{C}{N} = \frac{P_R}{P_N} \tag{2.1}$$

where P_R is the received power and P_N is the noise power. The C/N can also be modeled in terms of decibels by the equation:

$$\left[\frac{C}{N}\right] = [P_R] - [P_N] \tag{2.2}$$

where $[C/N]$ is the decibel equivalent of C/N, $[P_R]$ is the received power and $[P_N]$ is the noise power both in terms of decibels. In order to convert between a ratio and the decibel equivalent, a log_{10} conversion is needed. The log_{10} conversion is modeled by the equation:

$$[x(dB)] = 10\log_{10}(x) \tag{2.3}$$

where x is the variable being used in the conversion. Several factors are involved in the determination of the received power and the noise power.

The received power can be modeled by the following equation:

$$[P_R] = [EIRP] + [G_R] - ([FSL] + [RFL] + [AML] + [AA] + [PL]) \tag{2.4}$$

where $EIRP$ is the equivalent isotropic radiated power, G_R is receiver antenna gain, FSL is free-space spreading loss, RFL is receiver feeder loss, AML is antenna misalignment loss, AA is the atmospheric absorption, and PL is polarization mismatch loss. Free-space spreading loss, receiver feeder loss, antenna misalignment loss, atmospheric absorption, and polarization mismatch can all be grouped into one variable, Losses. The Losses can be written as:

$$[Losses] = [FSL] + [RFL] + [AML] + [AA] + [PL] \tag{2.5}$$

The free space spreading loss can be determined in decibels by the equation:

$$[FSL] = 20\log_{10}(\frac{4\pi D_{sg}}{\lambda}) \tag{2.6}$$

where D_{sg} is the distance from the satellite to the ground station. These equations can be combined into the simplified power received equation:

$$[P_R] = [EIRP] + [G_R] - [Losses] \tag{2.7}$$

The power received by the satellite is one of the main components in the carrier to noise ratio.

The noise power from a thermal noise source can be modeled by:

$$P_N = kT_N B_N \tag{2.8}$$

where P_N is the available noise power, k is Boltzmann's constant, T_N is the equivalent noise temperature, and B_N is the equivalent noise bandwidth. The noise power can also be expressed in terms of decibels by the equation:

$$[P_N] = [k] + [T_N] + [B_N] \tag{2.9}$$

The noise power from thermal noise directly relates to the noise per unit bandwidth, termed the noise power spectral density, equated by:

$$N_0 = \frac{P_N}{B_N} \tag{2.10}$$

The saturation flux density is needed to calculate the uplink carrier to noise ratio. It is also needed to calculate the $EIRP$ at the earth station. The saturation flux density is modeled by:

$$\psi_M = \frac{EIRP}{4\pi r^2} \tag{2.11}$$

where r is the radius of the antenna. The $EIRP$, which the earth station must provide, is modeled by:

$$[EIRP] = [\psi_M] + [A_0] + [Losses] - [RFL] \tag{2.12}$$

where A_0 is the effective area for an isotropic antenna. The $EIRP$ is the minimum value the earth station must provide, in clear sky conditions.

The uplink carrier to noise ratio is modeled by:

$$\left[\frac{C}{N}\right]_U = [\psi_S] + [A_0] - [BO]_i + \left[\frac{G}{T}\right]_U - [k] - [RFL] \tag{2.13}$$

where BO is the specified backoff. The downlink carrier to noise ratio is modeled by:

$$\left[\frac{C}{N}\right]_D = [EIRP]_D + \left[\frac{G}{T}\right]_D - [Losses]_D - [k] - [B] \tag{2.14}$$

where B is the bandwidth signal. Both the uplink and downlink equations are for clear sky conditions.

Amplifier Noise

The amplifier noise can be split up into two different sources the input and output noise. The output noise can be modeled by:

$$N_{0,out} = Gk(T_{ant} + T_e) \tag{2.15}$$

where $N_{0,out}$ is the output noise, G is the available power gain of the amplifier, T_{ant} is the antenna temperature, and T_e is the equivalent input noise temperature for the amplifier. The input noise is modeled by:

$$N_{0,in} = k(T_{ant} + T_e) \tag{2.16}$$

with $N_{0,in}$ is the input noise.

The alternative way of representing amplifier noise is by means of its noise factor. In defining the noise factor of an amplifier, it is taken to be at room temperature. The output noise is modeled by:

$$N_{0,out} = GKFT_0 \tag{2.17}$$

where F is the noise factor, and To is room temperature. Room temperature is generally taken to be 290 K.

Feeder Loss

Feeder loss is the loss that occurs in the connection between the antenna and receiver. Similar losses occur between the transmitter and antenna as well. The power output from the amplifier due to feeder loss is modeled by:

$$P_{TX} = P_T L_{FTX} \tag{2.18}$$

where P_T is the antenna power, P_{TX} is the power output, and L_{FTX} is the feeder loss. The signal power input to the receiver from the antenna can be modeled by:

$$P_{RX} = \frac{P_R}{L_{FRX}} \tag{2.19}$$

Table 2.1: Rain Attenuation Models [10]

Variable		Function	Frequency Range
a	=	$4.21x10^{-5}f^{2.42}$	$2.9 \leq f \leq 54$ GHz
	=	$4.09x10^{-2}f^{0.669}$	$54 \leq f \leq 180$ GHz
b	=	$1.41f^{-0.0779}$	$8.5 \leq f \leq 25$ GHz
	=	$2.63f^{-0.272}$	$25 \leq f \leq 164$ GHz

P_{RX} is the signal power at input of receiver, P_R is the receiver power, and L_{FRX} is the feeder loss between receiver and antenna. The feeder loss occurs in the connecting waveguides, filters, and couplers.

The Effects of Rain

Rain results in attenuation of the signal and an increase in noise temperature. Rain attenuation caused the carrier to noise ratio to be decreased. The increase in noise, however does not usually affect the uplink. This is because the satellite antenna is pointing towards a hot earth, adding this to the satellite receiver noise temperature tends to hide any additional noise induced by rain attenuation. The rain attenuation can be modeled by the equation:

$$A_{rain} = aR^b \tag{2.20}$$

where a and b are constants determined over several years of analysis of slant rain attenuation**??** and R is the rain rate. The equations for determining a and b are shown in table 2.1 and f is the frequency of operation.

The effective noise temperature of rain is modeled by:

$$T_{rain} = T_a \left(1 - \frac{1}{A}\right) \tag{2.21}$$

where T_a is the apparent absorbed temperature and A is the total attenuation. The total attenuation in decibels is determined by the equation:

$$A = A_{cs} + A_{rain} \tag{2.22}$$

where A_{cs} is the atmospheric attenuation and A_{rain} is the additional attenuation due to rain. The rain noise temperature is needed to calculate the total sky-noise temperature. The total sky noise is modeled by:

$$T_{sky} = T_{CS} + T_{rain} \tag{2.23}$$

where T_{CS} is the clear sky temperature and T_{sky} is the total sky noise temperature.

In order to determine the resulting C/N from rain attenuation, the inverse of the C/N has to be found. The equation to determine the inverse is:

$$\left[\frac{N_0}{C}\right] = 10^{\left(\frac{-1}{10}\right)} \left[\frac{C}{N_0}\right] \tag{2.24}$$

The inverse of the C/N had to be determined because the inverses have additive properties. The method for taking the resulting overall inverse of the C/N is:

$$\left[\frac{C}{N_0}\right] = -10 \log \left(\frac{N_0}{C}\right) \tag{2.25}$$

The overall C/N is the measure of effectiveness of the communications system.

The inverse of the C/N for rain is determined by the equation:

$$\left(\frac{N}{C}\right)_{rain} = \left(\frac{N}{C}\right)_{CS} \left(A + (A-1)\frac{T_a}{T_{S,CS}}\right) \tag{2.26}$$

where $T_{S,CS}$ is the clear sky temperature.

Antenna Gain

An important factor in determining the C/N is the antenna gain. The antenna gain is based on the geometry of the antenna and the operating wavelength of the signal. The equation for the antenna gain is:

$$G_R = \frac{\eta_A 4\pi A_{ant}}{\lambda^2} \tag{2.27}$$

where A_{ant} is the area of the antenna aperture, λ is the operating wave length, and η_A is the aperture efficiency. The area of the antenna aperture can be modeled by he area of a circle and follows the equation:

$$A_{ant} = 4\pi r^2 \tag{2.28}$$

Another needed equation is the relationship between frequency and wavelength. The frequency and the wavelength are related through the equation:

$$f\lambda = c \tag{2.29}$$

where f is the operating frequency and c is the speed of light. These equations are needed in the modeling of the communications system.

2.1.3 Sizing of Communications System

The reason that the communications system was modeled by equations was to determine the size needed for the communications system. The sizing of the communications system is important in the design of every spacecraft. A communications system needs to be designed so that the requirements of the mission are met while not imposing too great of a cost on the mission. The costs that can be imposed on the mission by the communications system are the additional mass and power requirements.

The sizing of the antenna system is dependent on the desired gain and the desired C/N ratio. The link budget is used to determine the sizing of the communications systems. The link budget output is compared with the threshold C/N ratio. The threshold C/N ratio is the C/N that yields a still favorable signal. The main variables that the link budget deals with is the size of the antennas, the power of the transponder and the frequency of operation. The ground station antenna is mainly fixed but the designer can alter the diameter of the antenna on the spacecraft. If the link budget C/N ratio is greater then the threshold C/N, the antenna diameter on the spacecraft can be decreased until the desired C/N ratio is found.

2.1.4 Interactions of Subsystems

The communications subsystem mainly interacts with one other subsystem. The subsystem that the communications subsystem interacts with is the command and data handling subsystem. The communications subsystem provides the link between the ground station and the satellite. The data is received from the ground station through the antenna. The data is then sent through the receiver. The receiver filters and amplifies the received signal. The signal is then passed through a modulator. The modulator alters the signal in order for the computer system to utilize the incoming data. The modulator is the main connection between the communications subsystem and the computer subsystem.

The data that is needed to be sent to the ground station is passed through a similar system. The data is modulated to attain the proper frequency. The signal is then amplified in order to attain the desired SNR and is sent to the ground station by means of the antenna.

The main objective of communications is sending and receiving signals to and from earth ground stations. In this process computer and data handling are used to alter the input signal so it is ready to be outputted. To even start this process the signal to noise ratio needs to be calculated to ensure the signal will be received. There are many factors that come into play when calculating the signal to noise ration. Clear sky conditions tend to alter the signal less allowing for a better quality signal, while rainfall causes attenuation potentially altering the signal and jeopardizing its quality. After this step the spacecraft command system will take the recognizable signal and start a process to ensure the information is outputted correctly.

2.2 Spacecraft Command System

Once the communications process has finished and the spacecraft has received a recognizable signal, it has another process to begin. The signal is first sent to a receiver for demodulation and amplification, resulting in a command. This command is decoded and its validity is determined. If the command system decides that the command comes from a valid source, the now-decoded command is passed through the command logic. Inside the command logic subsystem the type of the command is determined and what actions are required from it accordingly. Lastly, the final instructions are passed to the appropriate subsystems via the interface circuitry. This process is detailed in Figure 2.2.

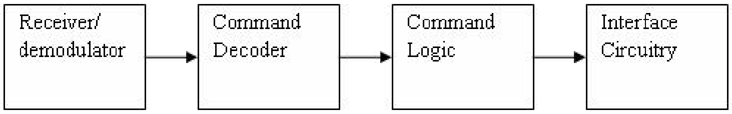


Figure 2.2: Spacecraft Command System

2.2.1 Receiver/Demodulator

The command receiver amplifies and demodulates the signal from the communications subsystem. Amplification of the signal is necessary because the signal strength is low by the time the RF carrier reaches the satellite. The receiver takes the RF energy and reproduces the original signal. The demodulation process is different for the AM, FM, and PM modulations. AM is the simplest form, but FM usually has a lower SNR and therefore usually outperforms AM.

There are two primary types of command receivers: crystal filter and superheterodyne. A crystal filter receiver uses a special crystal that resonates only to a specific RF frequency[9]. Amplification and demodulation are then performed directly on the received RF signal. Figure 2.3 shows a diagram of a superheterodyne receiver. This type of receiver uses an on-board oscillator to generate a second signal and form sum and difference signals from the original RF signal. The lower frequency then gets filtered and used as an intermediate frequency. Amplification and demodulation are performed on this intermediate frequency instead of the original RF signal.

There are several other considerations involving the command receiver. The center frequency of the receiver must be the same as the RF frequency. Care must also be taken to make sure that the frequency is internationally registered and approved. The bandwidth of the receiver is also a major consideration. If the bandwidth is too narrow, parts of the signal will be lost in transmission. If the bandwidth is too wide, there will be too much noise. The major deciding factor in bandwidth is the bit rate of the command message. A higher bit rate requires a higher bandwidth.

2.2.2 Command Decoder

Figure 2.4 shows a simple block diagram of a typical command decoder. The purpose of the command decoder is to detect the encoding of a subcarrier signal, which is usually sent from a receiver/demodulator subsystem, and reconstruct the original

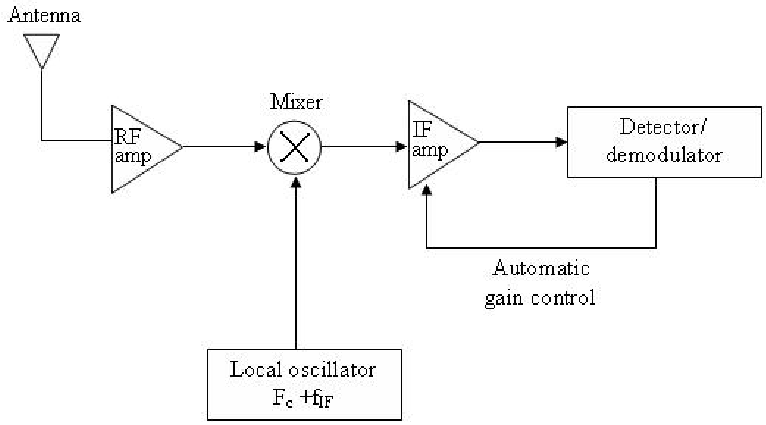


Figure 2.3: Superheterodyne Receiver Diagram

command message. The command message is nothing more than a set of instructions for performing a specific task, such as changing the orbit of the spacecraft or deploying the payload. Command messages can come from a variety of sources as illustrated by Figure 2.4. For instance, commands could come from a ground station via an uplink. It should be noted that the term uplink encompasses all of the intermediate hardware, such as antennas, detectors, and demodulators, necessary to communicate with the ground station. Commands can also come from the on-board computer (OBC) and the hardline test interface. In many cases, the input signal will be *Pulse Code Modulation*, or PCM, encoded[6]. As previously stated, the decoder detects and interprets this encoding. It then produces an output in the form of simple binary bit streams, called non-return-to-zero (NRZ) data[9]. In addition to NRZ data, the decoder also sends out a lock signal. The function of the lock signal is to inform the command logic that it is about to receive output from the command decoder.

A command system will typically have two redundant decoders and two receivers, either one of which is capable of decoding commands. This is failsafe measure that allows one decoder to take over in the event that the other malfunctions or fails completely. The two receivers and the two decoders are cross-strapped so that all four subsystems are active simultaneously[9]. Figure 2.5 illustrates this kind of configuration. Sometimes the command message will specify the decoder to be used by including a decoder address in the spacecraft address field. The spacecraft address is simply a group of bits that identifies the particular spacecraft to which the command is directed.

Arbitration Schemes and Command Output Types

With so many possible sources from which the decoder can receive commands, there has to be an arbitration scheme to prevent the command system from being bogged

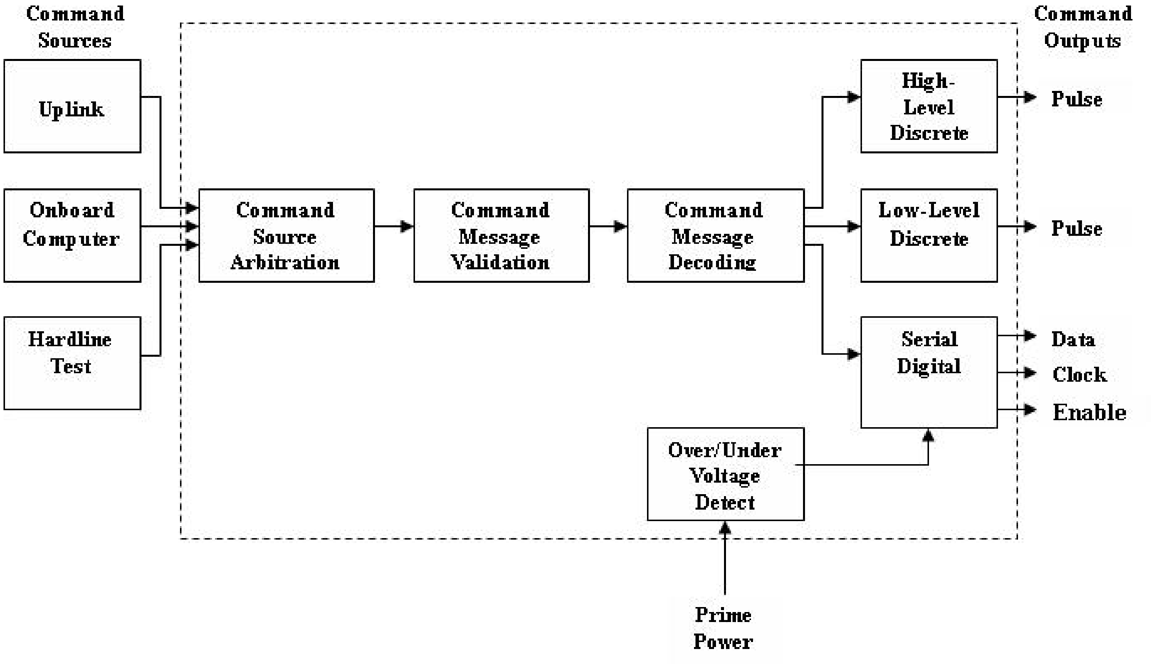


Figure 2.4: Command Decoder Block Diagram

down. Typically uplink commands, or commands that come from ground stations, have priority over the other sources. Computer commands are delayed until a time slot is available[7]. However, if a space vehicle that is not expected to receive frequent input commands from a ground station, or if it intended to perform mostly preprogrammed tasks, then the OBC may be given first priority. The hardline test interface is not active during flight and when in use overrides the other command sources[7].

There are typically two kinds of output: discrete and serial. They are given in the following table, using information obtained from Reference [7].

Command Messages

As stated in the previous section, the command decoder outputs the reconstructed command message to the command logic in the form of a digital stream of bit-it is the job of the command logic to interpret the command message. A typical command message contains some, if not all, of the following components:

1. Input checkerboard bits
2. Synchronization (Barker word) bits
3. Command bits
4. Error detection bits[9]

Only the first two components, input checkerboard bits and synchronization bits are

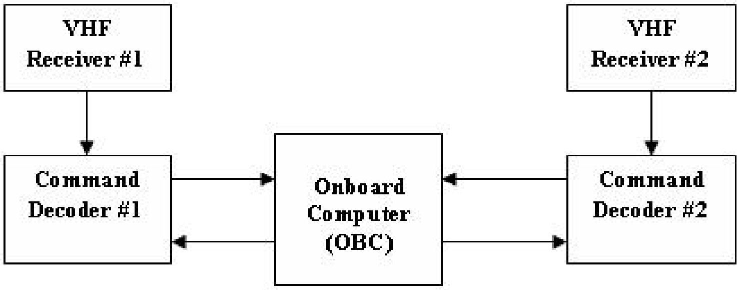


Figure 2.5: Redundant Decoders and Receivers

Table 2.2: Command Output Types

Type	Sub-Type	Defining Characteristics
Discrete	High-Level	Fixed amplitude and pulse duration
	Discrete Command	Typically +28 V, 10 to 100 ms pulse
	Low-Level	Fixed amplitude and pulse duration
	Discrete Command	Typically 5 V pulse interfacing with digital logic
Serial		A 3-signal interface consisting of:
		○Shift clock
		○Serial command data
		○Data enable used to indicate the interface is active.
		8-16 bits of the command message sent to subsystem

needed by the command decoder. The input checkerboard is a sequence of alternating 1's and 0's, whose purpose is to provide the bit detector and command decoder time to acquire, or lock on to, the modulated subcarrier signal[9]. The input checkerboard does not contain any data, therefore, nothing important is lost if some of the bits are missed or improperly decoded. Once the decoder locks on to the subcarrier, it sends out a lock signal. Recall that the lock signal informs the command logic that a new command message is imminent[9]. For command systems that do not use input checkerboard, a synchronization word will be at the beginning of the command message. This synchronization word, or Barker word, is a pseudorandom bit-or frame-pattern that performs the exact same function as the input checkerboard-it acquires and verifies that the command decoder has properly locked on to the transmitted command signal[9]. If both an input checkerboard and a synchronization word are present, the decoder will only use the input checkerboard to acquire a lock on the signal. The synchronization word also performs its secondary function: preventing false commands from being executed by the command logic.

When a Barker word is used to synchronize fixed-length data frames, the probability of false synchronization P_{fs} can be given an upper bound[9]:

$$P_{fs} < 1 - (1 - 2^{-n})^{m-1} \tag{2.30}$$

where P_{fs} is the probability of false synchronization, n is the length of the Barker word in bits, and m is the size of the data frame in bits. The table below gives some typical values of P_{fs} for a fixed 32-bit synchronization word. As an example, 32-bit Barker word will be assumed to look like the following:

1111 1110 0110 1011 1000 0100 0010 0000

Table 2.2 clearly shows that as the frame size increases, the probability of false synchronization decreases.

Table 2.3: Typical P_{fs} values for a 32-bit Barker word

Frame Size (m)	P_{fs}
1,024	$3x10^{-7}$
2,048	$5x10^{-7}$
4,096	$9x10^{-7}$
8,192	$2x10^{-6}$
16,384	$3x10^{-6}$
32,768	$5x10^{-6}$
65,536	$1x10^{-5}$

2.2.3 Command Logic and Handling

The Earth-to-space command link provides all ground control for the satellite and requires the highest security and reliability. Clearly, the execution of incorrect or unauthorized commands can be catastrophic. To guard against this, command handling system passes all commands received over the link through a robust validation process to ensure their authenticity and error-free reception.

Command Receipt and Verification

The implementation of secure and robust command logic is vital to the operation of any satellite. The command logic interprets the decoded command word, verifies its authenticity and correctness, and executes verified commands. The system safeguards the satellite from unauthorized commands and unintended operation of a control due to errors in received commands. Once the system receives and verifies commands, it may execute them immediately, or in the case of delayed commands, queue them along with a timestamp for later execution.

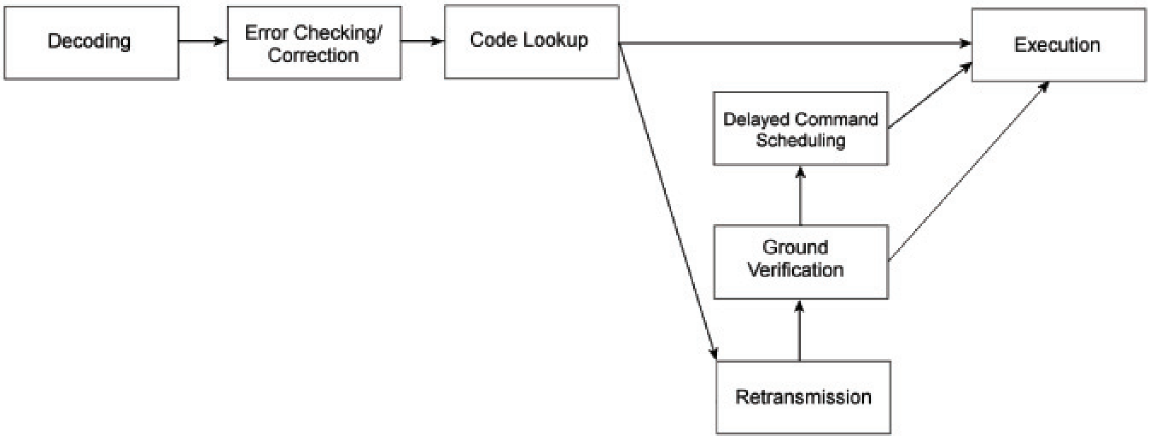


Figure 2.6: Command logic diagram for command receipt and execution

When the system receives a command from the command decoder, it begins a validation process to ensure the command is properly interpreted. First, the system checks for the proper spacecraft address code, and bitwise error detection and correction are applied, enabling to receive commands over error prone links. The time of transmission is evaluated to ensure that the command was received in a reasonable amount of time for the given data rate. If the command took too long or too short a period to receive completely, then it cannot be a valid command and is rejected.

Next, a command received and verified thus far is matched against the internal command operation code table. This table is a one-to-one index of command words and operation codes that is generally not numbered contiguously. Rather, the commands are numbered throughout the numerable range of values for the allocated command word size, so that no single bit error may result in one transmitted command being received and interpreted as another, which would be possible if command operation code were contiguously numbered. This check also helps prevent false commanding resulting from errors in command encoding on the ground.

Then an authenticity check is performed. Commands sent over encrypted links are generally considered self-authenticating and no further confirmation is performed, because only an authorized source will know how to encrypt the message properly. Many methods of modern digital encryption allow messages to be signed and authenticated with a private key that need not be transmitted with the message. The public key which matches that private key may be shared openly and can only be used to decrypt messages encrypted with the private key. The public key will only encrypt message encrypted with the private key, so any message properly decrypted with that public key can only be from a holder of the private key.

Encryption is the process of embedding a message in a stream of data that is difficult to decipher and/or forge without corresponding cryptographic keys. It is used both to protect sensitive data transmitted from the satellite from eavesdropping and to protect the satellite command system from unauthorized commands. This is distinct from encoding, which is merely the conversion of a message into a format suitable for transmission over a particular medium, in this case a low bandwidth (2,000 - 8,000 bps) high frequency digital link. Any message must be encoded for transmission, but if it is not encrypted it may be easily forged.

For this reason, commands sent over unencrypted links are verified by retransmission to the ground station over the telemetry link. If the ground station verifies that the correct command was received by the satellite, an execute command is sent. Because of the limited communication data rate available to the command and telemetry links, this process may take several seconds, but is necessary to ensure only authorized commands are executed.

This process ensures that the probability of accepting and executing a false command is minimized, generally around 1 in 10^{-18} to 1 in 10^{-22}. Critical commands may require even lower probabilities which are generally achieved by using longer operation codes, or splitting the command across multiple operation codes.

Command Handling and Execution

Nearly all modern command systems are microprocessor based. The processor receives commands from the decoder, interprets them according to some internal program, and outputs the results to the interface circuitry. The inputs are the decoded commands which may or may not be partially validated. The processor may then complete the validation, and will interpret and control execution of the command.

The most critical property of any microprocessor based command system is reliability. The system must be fault tolerant and highly resistant to the hazards of the space environment. Errors in the command system can jeopardize the mission, and complete failure of the entire system will almost always result in loss of the spacecraft. This applies to both the hardware and software comprising the command system. While complex software can never be guaranteed to be error-free, its design must provide a high degree of redundancy so that errors in the command handling program do not result in unintended command execution.

Local Commands

Whereas the ground station is the primary source of command data for the spacecraft, the onboard systems may generate their own commands. A finite amount of time is required for the ground station to observe a condition and command a response. Often, the response is required in less time than the generation, transmission, and validation of that command may take. Situations also occur where the spacecraft would be required to generate a response autonomously. Generally, these situations occur during the launch and transfer orbit phase of a mission, when the communication system is not operating in its normal.

Loss of communication may occur at any time however, and the spacecraft must respond to these loss of signal events without ground commands to restore the command ground link or put itself in a position where the ground station may restore the link.

In these scenarios, spacecraft subsystems may generate commands for spacecraft attitude changes, subsystem activation and deactivation, and enabling a *safe mode* to protect the spacecraft from damage or power reserve depletion.

These commands bypass the normal validation process, allowing the spacecraft to respond quickly to locally observed conditions, but still pass through the same command logic path as commands transmitted from the ground.

2.2.4 Interface Circuitry

Interface circuitry is the final link in the spacecraft command system. Once a valid command is detected, the command logic drives the command to the appropriate interface circuitry, which in turn executes the command. The type of interface circuitry that is driven varies with the type of command sent to the command logic. The four major commands, relay, pulse, level and data, each possess their own type of interface circuitry.

Relay Commands

Every spacecraft command system has relay commands. A relay command is ostensibly an on-off command, turning a specific system or device on or off, or switching a component of a device from one state to another. Relay commands work by activating an electromagnetic relay in the central power switching unit. There are typically two electromagnets, one that switches the contact into the on position, one which pulls it into the off position. To activate one coil or the other, the command logic sends a pulse to that coil, typically in the range or 50 to 300 mA. Primarily, relay commands switch power to the different subsystems on the spacecraft. While it would be beneficial if the system could directly drive the relay coil currents, integrated circuits (ICs) are incapable of driving more than a few milliamperes. This adds another requirement of power-driving interface hardware to run the relays. Typically, this hardware is set up in an array of source drivers and sink drivers. This has the added benefit of protecting against accidental relay activation. One single source/sink combination could not activate a relay on its own, so multiple drivers must be activated at once to ensure the relay goes active. This protection can be furthered by requiring additional enable signals before the coil can be activated.

Pulse Commands

A pulse command is a short set of pulses sent to a subsystem with durations lasting from 1 to 100 milliseconds (ms). The pulses drive small relays or logic latches in the subsystem. Depending on what the pulse drives, it is referred to differently. If the pulses drive a small relay, then it is called a *remote relay command.* If used to drive a logic latch or logic gate system, then the pulses are called *logic pulse commands.*

Level Commands

Level commands are the same as pulse commands, except that instead of varying the time duration of the pulse the power level is varied. Level commands act as toggle switches for logic, changing the gate from a 1 to a 0 or vice versa. The other way to handle level commands is to have two discrete commands, one forcing a 1 on the logic, the other a 0. This is currently the preferred method, as the previous state of the logic need not be known.

Data Commands

Data commands require the most bandwidth of all the types of commands. Data commands send whole words, in the binary sense, to subsystems. These commands may range in size from a word (8 bits) to 64 kilobits and more. This transfer of data is accomplished in one of two major forms, via serial or parallel bus. In a serial bus the system can either send or receive data, but not both at the same time. In a parallel bus the system can both send and receive data at the same time. Data commands are used to modify the memory, either the RAM or the ROM. These commands are ultimately used to load new programs or patch systems which are malfunctioning, among other things.

2.3 Conclusion

When modeling a complete CC&DH system for a spacecraft, it is important to realize that almost every single subsystem onboard interacts in some way with the CC&DH system. Whether attempting to send or receive commands from a ground station or attempting to communicate with another spacecraft, communications is vital to the working of any spacecraft. The C&DH subsystem interacts directly with each separate subsection, sending and receiving commands and interpreting data before sending it to an outside source. The next step in modeling and analyzing these interactions involves looking in-depth at specific examples of subsystems currently used in Communications, Command and Data Handling.

Chapter 3

Examples

The CC&DH systems on all spacecraft perform essentially the same function, regardless of the mission of the individual spacecraft. Every spacecraft needs a channel of secure communication with its control authority, which provides an uplink for command data and a downlink for command verification and telemetry data, and a spacecraft control system capable of interpreting commands and controlling spacecraft subsystems to execute the commands.

While the fundamental CC&DH needs have essentially remained the same throughout the history of space travel, the capabilities and the specific technologies available to provide them change constantly. This chapter provides a brief survey of the components available to build modern CC&DH systems, examining the various hardware requirements and availability to build the actual systems and the software environments currently in use on current and under development for future missions.

3.1 Communications

The communications sub-system is important for any spacecraft operation. There is a need to model the communications subsystem effectively. A method for modelling and sizing the communications subsystem is to perform a link budget calculation. The main components used for the link budget calculations are antennas and transponders. The selection of communications components is limited by the currently available technology.

3.1.1 Communications Components

The main components in the communications system are the antennas, receivers, and transmitters. The components chosen for a spacecraft must be able to meet the needs of the mission and must be compatible with the other communications components.

Antennas

Antenna selection is based on the frequency, flight path, and needs of the spacecraft. Once an antenna has been selected, a manufacturer can be contacted to build the antenna. The antenna size, mass, gain, power consumption, price, and building/shipping time are all factors in the decision process.

Table 3.1 shows model antennas from ERA Technology and integrated systems. There are four model types: 1m, 1.2m, and 1.5m. Model selections is by the diameter of the antenna. The models listed have segmented options. The ∗ in the table denotes a special design for 2 degree satellite spacing. The frequency band at which the antenna operates is also listed. More models are available at C-band frequencies since it is the most commonly used frequency band.

Table 3.1: ERA Technology and Integrated Systems Antennas[13]

Frequency	Receive Band (GHz)	Transmit Band (GHz)	Model 1 m	Model 1.2 m	Model 1.5 m
C-Band	3.4-4.2	5.85-6.65	Enquire For More Details	Enquire For More Details	15CLP 15CCP 15CLP∗ 15CCP∗
Ku-band	10.7-12.75	13.75-14.5	10Ku	12Ku	15Ku
Ka-band	18.5-21.2	27.5-30	10KaCP	12KaCP	15KaCP
	20.2-21.2	30-31	10KaCPM	12KaCPM	15KaCPM

Saab Ericsson Space makes reflector antennas for four different frequency bands: Ku, S, X, and Ka. There are five main categories of antennas: Front-fed symmetrical, Front-fed offset, Cassegrain symmetrical, Cassegrain offset, and Gregorian offset, as seen in Table 3.2. Also included in the table are previous application of their antennas. Their most common band is the Kruz-band.

The Physical Science Laboratories have designed and built a series of MicroStrip antennas. The most notable ones are for S, C, and X frequency bands. The S-band MicroStrip is capable of operating on the JPL Deep Space network, USAP, SGLS, and NASA STDN networks; The C-band MicroStrip operates at an approximate frequency of 7175.03 MHz.

Wide band horn antennas in double ride wave guide bands covering frequencies from 1 to 18 GHz are available from R.A. Mayes Company, Inc. In Table 3.3 a series of antennas is listed along with their frequencies, Gain, beamwidth, and Wave-guide. Horn antennas are good for large viewing areas when a need for longer periods of transmission is needed. A wide band horn antenna is also capable of receiving a signal that is not in its direct path due to its large viewing area.

Table 3.2: Saab Ericsson Space Reflector Antennas[11]

Topology	Application	Frequency
Front-fed Symmetrical	Ulysses Deep-Space Probe	S/X-band
	SOHO Deep-Space Probe	S-band
	Astra 1K/Hotbird 6	Ku-Band
	RF Sensing Antenna	
Front-fed Offset	Giotto Deep-Space Probe	S/X-band
	SAR Lupe SAR Mission	X-band
	TV-dat / TDF-1	Ku-Band
Cassegrain Symmetrical	Columbus KBS Data Relay	Ka-band
	Siral / Cryosat	Ku-band
Cassegrain Offset	Tele-XDBS and Data	Ku-band
	Odin Telescope	Up to 575 GHz
Gregorian Offset	Sirius 2	Ku-band
	Eutelsat W4	Ku-band
	AMC-9	Ku-band

Table 3.3: R. A. Mayes Company Wave-Guide Antennas[8]

Model	Frequency (GHz)	Wave-Guide	Gain dB	Beamwidth
HOD-085-17	0.85-2.0	WRD-085	17	15x15
HOD-200-17	2.0-4.8	WRD-200	17	15x15
HOD-200-20	2.0-4.8	WRD-200	20	20x10
HOD-350-20	3.5-8.2	WRD-350	20	20x10
HOD-475-20	4.75-11	WRD-475	20	20x10
HOD-750-20	7.50-18	WRD-750	20	20x10

Receivers

When deciding on a receiver it is important to determine if it will work with the antenna and transmitter. The company supplying the receiver needs to be given sufficient time to build and deliver the receiver. Receivers need to be light weight and have a good data rate.

CMC Electronics based out of Cincinnati, Ohio already has working receivers. Some examples of these receivers are the: CR-309, CR-311, and S-band digital receiver [4]. The CR-309 model is a single conversion super heterodyne receiver demodulator, which can operate at frequencies between 150 and 450 MHz. The CR-311 receiver demodulator uses a Space-to-Ground link System, SGLS, for command services. The receiver was designed for spacecraft with constrained power, volume, and mass requirements. The S-band digital receiver is based on an existing S-band and

UHF receiver products. The demodulator is implemented digitally utilizing modern sampling techniques. The digital receiver is designed to for extended duration missions.

The AeroAstro S-band receiver has a frequency range from 2025 to 2120 MHz and a mass of 165 grams [1]. A phase lock loop receiver is used for locking onto the S-band carrier, and a demodulator produces a base-band output. The receiver is designed to be compatible with any spacecraft bus and consumes less than 800 mW of power.

Transmitters

Lower frequencies attenuate less in the atmosphere than high frequencies, with a lower frequencies a transmitter requires less power to maintain a nominal signal quality at the receiver. Signal quality and power supply are the two most important qualities when selecting a transmitter. If a poor signal is obtained more power will be needed to keep the transmitter running.

CMC Electronics makes transmitters to pair with their receivers. The C/TT-505 UHF transmitter for wireless links between two orbiting spacecraft is used for command telemetry. The CMC X-band modulator is a high data array phase shift keyed transmitter designed for use on spacecraft and satellites where large amounts of data are transmitted. The unit employs a solid state power amplifier capable of delivering a 25 W output.

The T-704 and T-708 are X-band transmitters for satellite data downlinks and vehicle downlinks. The T-704 is designed to transmit large volumes of payload data. The T-708 model was designed for long duration missions.

AeroAstro Corporation has S-band transmitter that was successfully launched on June 30, 2003 aboard the Canadian Space agencies MOST mission. It provides a high power amplifier that reaches 5 W, and is compatible with any spacecraft bus. This particular model has data rates from 2 kbps to 1 kbps, with a power output from 10 to 500 mW. The operating frequency is from 2200 to 2300 MHz with a mass of 180 grams.

3.1.2 Link Budget Examples

Link budgets are important tools in determining the sizing of the communications subsystem. The link budget allows the designer or analyst to alter the sizing of individual communications components and view the resulting carrier-to-noise ratio. The C/N needs to be above a desired threshold decibel level in order for the signal to be usable. The main alterables in the link budget equation are the size of the antenna on the spacecraft, the frequency used and the power output of the transponder used. The link budgets are performed for two cases: the clear air case and the bad weather or rain case. The following are two examples each of link budgets in clear air and in rain.

Link Budget Example for Geostationary C-Band Satellite

The first link budget example uses a geostationary satellite that utilizes the C-band frequency for downlink. The satellite uses multiple transponders with bandwidth of 36 MHz. The main satellite components used in this example are a satellite antenna diameter of 1 m, a transponder power output of 20 W, and a frequency of 4 GHz. The link budget table for the clear air case is shown in Table A.3. The main sections of the link budget table are the downlink power budget and the downlink noise power budget in clean air.

The C-band satellite parameters section is used for the definition of the satellite components. The satellite communications components listed are the components that are able to be varied. In this case, the efficiency associated with the chosen antenna is 55%. The frequencies are given as the range of values associated with the C-band. These parameters are used to perform basic calculations in the second section of the table.

The basic calculations section determines several important variables. The conversion of the frequency into the wavelength is a basic calculation needed in the determination of the C/N ratio. The 4 GHz and the speed of light are used in Equation 2.29 to determine the wavelength of 0.075 m. The total area of the antenna is determined using Equation 2.28. The total area is determined to be 0.785 m^2 which is used in Equation 2.27 to determine the effective antenna area. The effective area is used in the determination of the antenna gain.

The satellite interacts with a ground station on Earth. The next section of the link budget table includes the parameters of the Earth ground station. This spacecraft is at a distance of about 40,000 km from the ground station, which has a 5 m diameter antenna. The antenna diameter is used in Equation 2.27 to determine the antenna gain from the ground station. The antenna gain from the ground station is important in the determination of the C/N ratio of the communications link.

The downlink power budget section of the link budget is important in the determination of the C/N ratio. The C/N ratio is expressed in decibels by the equation:

$$\left[\frac{C}{N}\right] = [P_R] - [P_N] \tag{3.1}$$

The power received, $[P_R]$, is determined by Equation 2.4. This equation requires the summation of the components listed in the link budget table in the downlink power budget section. The transponder output backoff is set at 2 dB but is transponder specific. The edge of beam loss for the antenna is set at 3 dB because the signal fades at the edge of coverage. The clean air atmospheric loss is set at 0.2 dB. Other random losses are included in the calculation of the power received and for this case is set to 0.5 dB. The power received is determined to be -112.958 dB.

The second part of the C/N ratio is the receiver noise power. The receiver noise power is determined by Equation 2.9. The equation requires the summation of the equivalent system noise temperature, the equivalent noise bandwidth and the Boltzmann constant. In this case, the receiver power noise, $[P_N]$, is determined to be -135.536 dB.

The C/N ratio for the satellite in this example is calculated to be 22.578 dB. This calculated C/N ratio is for the clear air case. The C/N ratio of 22.578 dB is only a rough estimate since the effects of weather need to be taken into account. The weather effects are calculated and introduced into the C/N ratio in Table A.1.

The main contributions the rain add to the link budget analysis are the addition of the rain attenuation and the increase of noise temperature. The rain attenuation can be determined from Equation 2.20. In this case, the rain rate is unknown so an estimated value of 1 dB was used. The ΔP_{nrain} is calculated by using Equations 2.22, 2.21, 2.23, and 2.26. Using the equation listed above, the C/N ratio in decibels for rain is calculated to be 16.542 dB.

This value is noticeably less than the clear air case. The difference between the clear air case and the rain case is 6 dB. The calculated rain C/N ratio allows the designer some options in resizing of the communications system.

Link Budget Example for Moon Bound Satellite using X-Band

Another link budget example uses a satellite travelling to the moon. The satellite transmits data to the ground station by means of the X-band. The ground station will have a 10 m diameter antenna. The communications subsystem includes a 1 m antenna and a 40 W transponder. The link budget table for this satellite is shown in Table A.4.

The calculations for this example link budget table follow the same equations as the link budget table for the geostationary C-band satellite. The C/N ratio for the clear sky case is 17.411 dB. The link budget table for the rain case is shown in Table A.2.

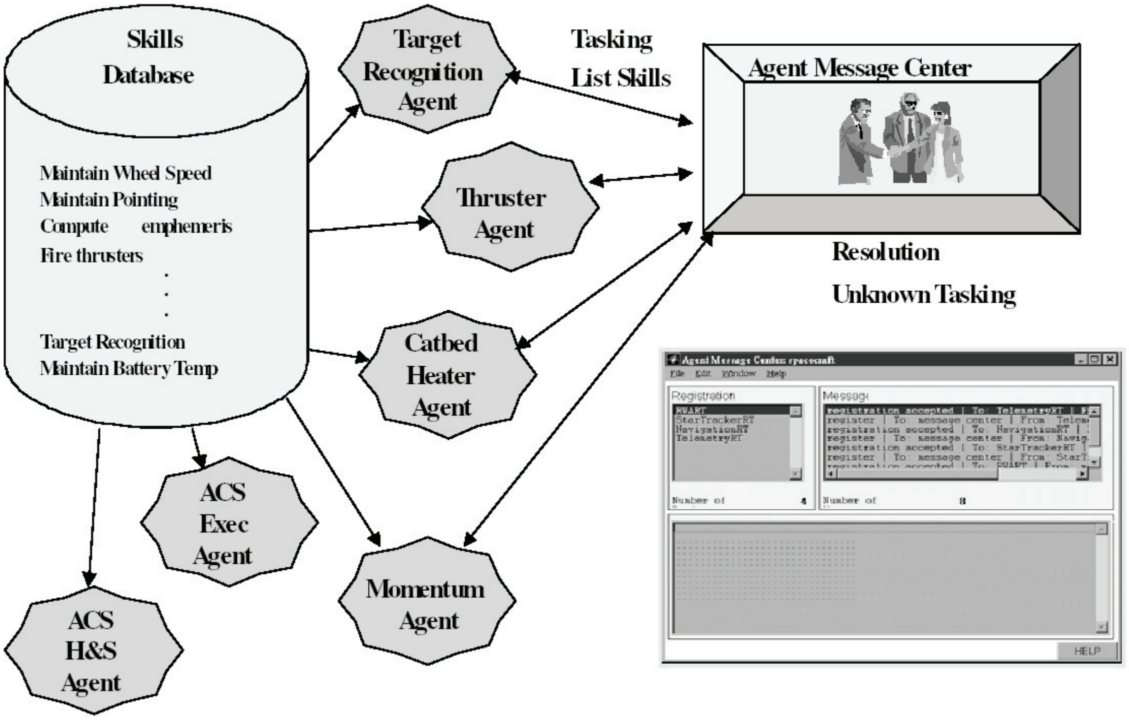
The link budget table for the rain case is calculated the same way as for the pervious case. In this case, the C/N ratio in rain has decreased by 8.7 dB to a value of 8.77 dB. This value for the C/N ratio allows some options in resizing of the communications system depending on the required C/N threshold.

3.2 Command Handling and Execution

The command logic controller is the heart of the control system for most spacecraft. It receives commands from the communication subsystem, verifies their authenticity either through a scheme of retransmission and confirmation or, in more modern systems, encryption or digital signatures which are difficult to forge. Thus, the command logic controller generally has either access its own downlink to the ground station, or access to the telemetry downlink. The system then executes the commands by activating the appropriate interface circuitry, which varies greatly depending on the hardware onboard.

Command Logic Controller

Nearly all modern spacecraft are controlled by one or more onboard computers. The command logic controller (CLC) is the interface between these computer systems and the command source, which is usually the ground station. It must receive, verify, interpret, and execute commands. The CLC must perform with a high degree of reliability owing to its interaction with nearly every other subsystem onboard. It is often a single point of failure system. Thus, simplicity is desirable, but the complexity of many spacecraft functions often necessitates a sophisticated CLC.



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registration accepted | To: TelemetryRT | F
register | To: message center | From: Telem
registration accepted | To: NavigationRT |
register | To: message center | From: Navig
registration accepted | To: StarTrackerRT |
register | To: message center | From: StarT
registration accepted | To: RWART | From:
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Figure 3.1: The ObjectAgent agent communication model[14]

One such system is the ObjectAgent[14] architecture under development by the Air Force Research Laboratories (AFRL). In this model, each controllable object, which may be a ground asset, spacecraft, or spacecraft subsystem, is designated as an agent, capable of decision-making and collaboration with other agents to complete a commanded task (Fig. 3.1). This architecture decentralizes the control authority while also giving each individual agent a degree of autonomy (Fig. 3.2).

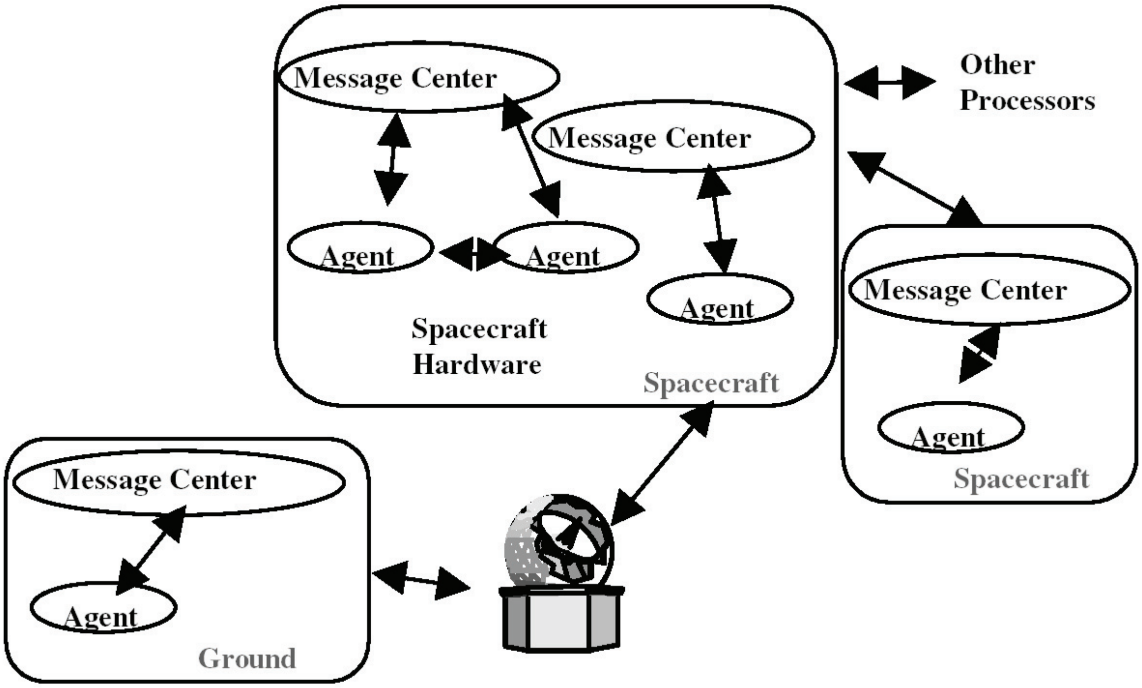

Figure 3.2: The ObjectAgent architecture model[14]

The system will use the Spacecraft Command Language[2] (SCL), a command environment developed by Interface and Control Systems (ICS) in 1988 and widely used on many military, scientific, and commercial spacecraft. The Spacecraft Command Language is designed to provide artificial intelligence (AI) algorithms in a processor poor environment. The SCL makes the autonomy required by the ObjectAgent architecture possible. At the time SCL was developed, 20 MHz processors were still being designed, and radiation hardened versions did not appear for another decade[2]. Since the advent of personal computers (PC), widely available PCs have been more powerful than the onboard computers of the spacecraft launched at that time. Spacecraft Command Language is used on many spacecraft, including TechSAT 21, the Near Earth Map Observer, and the X-33 Reusable Launch Vehicle Technology Program.

The problem with SCL is that it is a closed, commercial architecture, limiting interoperability with alternative systems. In response to this problem and other factors, NASA has developed an open standard in control architectures, the Space Project Mission Operations Control Architecture (SuperMOCA), which produced an open command language, the Space Messaging Service (SMS).

The language was born out of commercial manufacturing control languages, specifically the Manufacturing Message Specification (MMS), which was closely scrutinized in the early planning stages of the ISS[5]. Having been extensively used in industry, MMS was already a well-developed, robust language. The "faster, better, cheaper" initiative at NASA led the organization to adopt a part of the mass production men-

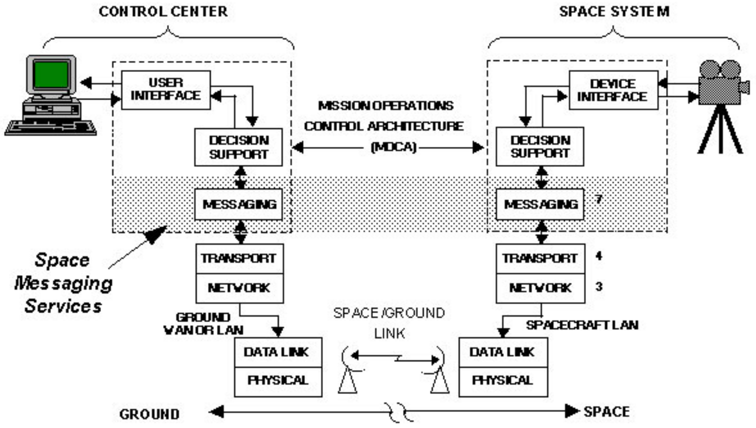

Figure 3.3: The SuperMOCA control system operates over a communications stack of which SMS is an integral part.[5]

tality. Interchangeability of parts, in this case, the command and control architecture, brings down the costs of individual spacecraft. Rather than creating a new language, NASA built on the industrially proven capabilities of MMS to produce SMS.

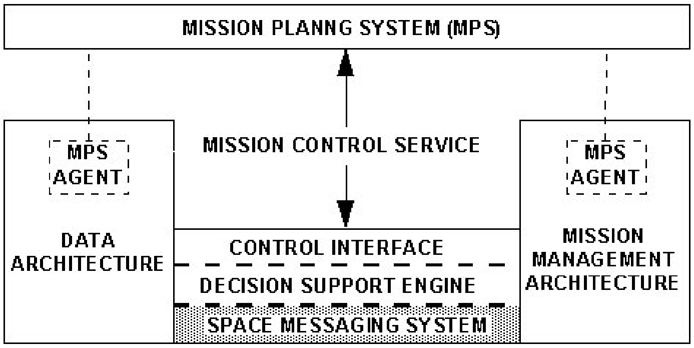

Figure 3.4: The five basic elements of SuperMOCA.[5]

Another system is the Spacecraft Test and Operations Language (STOL) from the Integrated Test and Operations System (ITOS) under development at the Space Physics Research Group at the University of California at Berkeley. This language is the primary user interface to the ITOS, which was developed for space system integration testing, but is increasingly being used for spacecraft mission control. Capable of interpreting the full set of command and telemetry mnemonics from the ITOS Telemetry and Command database, STOL may provide interactive control of the spacecraft, or run prewritten scripts.

The user interface of STOL is similar to a command line shell utility similar to Unix^{TM} shells or the personal computer Disk Operating System (DOS) command shell. Within the ITOS environment, STOL is capable of providing direct, end-user access to all spacecraft subsystems in real time, where applicable. The environment provided by ITOS is analogous to the environmnent an operating system provides to the shell, functioning as the “back-end” interface to hardware on the ground and onboard the spacecraft.

One unique capability of ITOS is the ability to provide telemetry data to a World Wide Web server for access via that medium. The system is sufficiently well devloped that it address scenarios where the webserver is the same machine as the ITOS server, a different machine on a local network, and a different machine on a distant network outside the local firewall.

3.3 System Hardware

While software controls every single aspect of a computer system, it requires hardware to run. Different situations require different hardware systems. Two largely different but common situations in which hardware is an important decision are when designing a simulator on the ground and when designing a calculation intensive spacecraft.

3.3.1 PC104

The PC104 is a computer system design standard that focuses on small, lightweight computer systems. It functions as a counterpoint to form factors like ATX and miniATX, both of which are used on current home computer systems. The PC104 bus uses the PCXT and PCAT card specifications (IEEE P996) but instead creates a smaller form factor to decrease size and weight as well as heat emission. In addition, the PC104 form factor is stackable, as shown in Figure 3.5. The individual system cards, instead of being attached as in a normal computer, are instead stacked on to one another with up to 6 boards in a single standard PC104 system. This stacking of the boards decreases the imprint of the system immensely, creating a denser compaction of the system where total volume is an issue. System cost is also a major benefit of utilizing a PC104 system. From standard breakdowns available on vendors sites, a complete PC104 system can cost $600 US or less, much less expensive than many COTS ATX computer systems currently available. In addition, the number of vendors available ensures a fast shipping time.

The PC104 has many drawbacks when used for space applications like many other computer systems. The PC104 standard uses the ISA bus, which is years behind the standard PCI bus or the even newer PCI-X system bus. An ISA bus is a 16-bit standard running at 33 Mhz, while PCI and PCI-X are 32-bit buses running at 66 and 133 Mhz, respectively. This bus speed more than quadruples data rate transfer. Manufacturers have introduced the PC104-Plus and PCI104 standards in order to keep up with the competition. The PC104-Plus is the logical next step, introducing

PCI support in addition to the ISA Legacy support, while PCI104 does away with ISA altogether, creating a faster on-board bus and reducing bottlenecks.

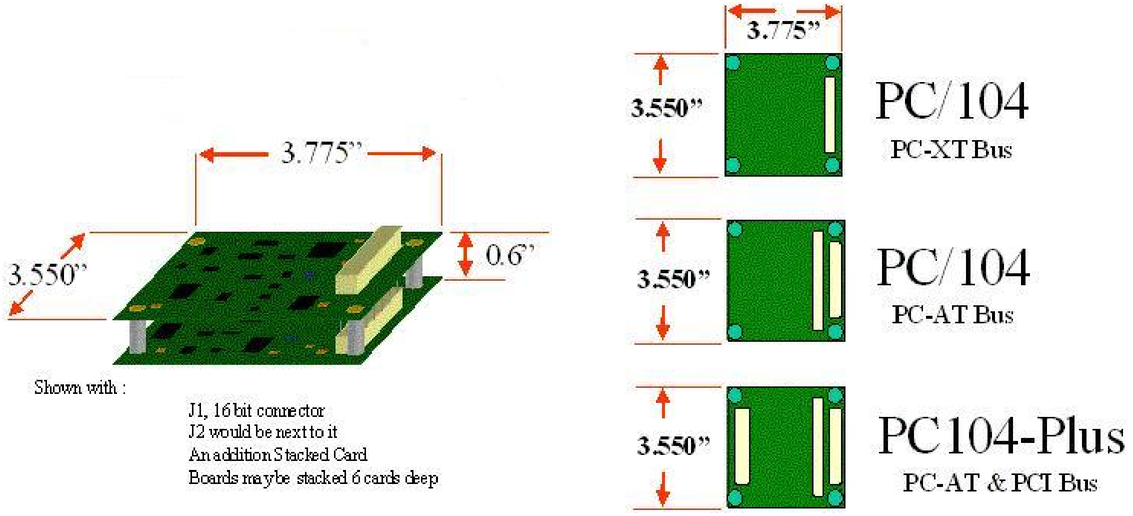

Figure 3.5: PC104 Form Factor Sizes[3]

In addition to the difficulties involved with keeping the PC104 standard current, there are major problems with using PC104 in any space-based mission. While small, lightweight and heat-efficient, PC104 is not radiation-hardened. Radiation-hardening is the standard constraint for usable space-worthy computer system. Using PC104 in ground-based control systems and simulators where size is an issue is a workable alternative to using the ATX or miniATX standards.

3.3.2 Radiation-Hardened Computer Systems

When looking at computer systems that are intended to be space worthy, a major consideration in choice is whether or not it is radiation-hardened. Computer systems, as complex machinery is wont to due, is susceptible to radiation. When in space, everything on board is subjected to much more radiation than on Earth. In addition, thermal changes and physical shock due to takeoff and maneuvers create the need for a system that is more resistant to the rigors of space.

Currently there are many available radiation-hardened single-chip and multi-chip systems. A commonly used single-chip Single Board Computer (SBC) is the Maxwell SCS750P as shown in Table 3.4. In addition to standard hardening techniques, Maxwell utilizes a 3 processor setup that automatically checks itself on each command, ensuring fewer errors in calculations. The power loss of the Maxwell SCS750P is also variable along with the clock speed of the processor, maintaining power system integrity and constant drain, as well as keeping losses to a minimum except during times of peak calculations.

Table 3.4: Maxwell SCS750P Specifications[12]

Radiation Tolerance	$>$ 300 Years without an uncorrected upset
	SEU rate $< 9\times10^{-6}$ upsets/day
	TID: $>$ 100 krad (Si) - Orbit dependent
	SEL (th): $> 80 MeV - cm^2/mg$
Processors	3 PowerPC 750FXTM on Silicon on Insulator (SOI), $0.13\mu m$
	2.32 Dhrystone MIPS/MHz
	$>$ 1800 Dhrystone MIPS at 800MHz
	400 to 800MHz - Software Selectable Core Clock Rate
	50MHz PowerPC Local Bus
Memory	256 MByte SDRAM - Reed-Solomon Protected
	8 MByte EEPROM - ECC Protected
Processor Cache	64 KByte L1 Cache
	512 Kbyte L2 Cache
Power	7 - 25 watts (typical) dependent on clock rate
	5V for 1553 interface, $3.3V$ for rest of board
Temperature	$-40°C$ to $+70°C$ (Rail)
Weight	1.5 kg (3.3 lbs.) Max

The Maxwell SCS750P uses the standard PowerPC 750FXTM processor, usually found in COTS Apple computers. It is commonly referred to as the G3 processor. While the latest processor available to the public manufactured by IBM is currently the G5. The best available radiation-hardened processor is a full two generations behind the current technology. This generation lag illustrates one of the major constraints when working with radiation-hardened systems. Factor in 10 year time scales for most projects as a minimum and the computer that eventually gets sent up in the spacecraft is a full 15 years behind the state of the art (SOTA).

3.3.3 Conclusion

Spacecraft hardware is an area of broadening choices. As computers become more advanced, the technology needed to make them smaller, cooler, faster and more resistant to the environment becomes better and less expensive. With non-critical ground applications, computer and simulator costs are already in the range of the enthusiast. In spacecraft, mission-critical computers required to withstand the rigors of space are quickly catching up to the SOTA. Cost of military specification computers is still in the range of \$200,000 to \$300,000 and more, but the prices are slowly decreasing. In the future of spacecraft computer systems, we can expect things to continue in the current fashion, becoming smaller, faster, hardier and less expensive.

3.4 Demodulation and Amplification

Demodulation and Amplification are performed by a Radio Frequency (RF) filter. There is a wide range of RF filters used, but are generally broken into two categories: electrical circuit filters and mechanical filters.

3.4.1 Low- and High- Pass Filters

The simplest form of electrical circuit filter is a high-pass or low-pass filter. A low-pass filter prohibits high frequencies but allows low frequencies to pass. Figure 3.6 shows a diagram of a typical low-pass filter. A high-pass filter does the opposite, allowing high frequencies but prohibiting the low frequencies from passing. Figure 3.7 shows a diagram of a typical high-pass filter. For a high or low pass filter, the cutoff frequency, ω_c, can be described by Equation 3.2.

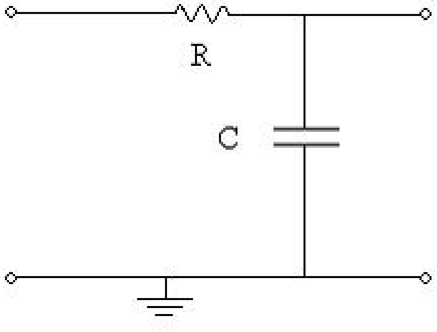

Figure 3.6: Typical Low-Pass Filter

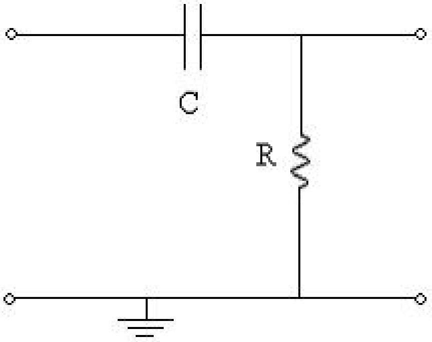

Figure 3.7: Typical High-Pass Filter

$$\omega_c = \frac{1}{RC} \tag{3.2}$$

3.4.2 Band-pass Filters

High-pass or low-pass filter are not commonly used individually. Typically, these two filters are combined so that both high and low frequencies can be filtered out, leaving a small range of frequencies that will pass through the filter. This multiple range filtering is known as a band-pass filter. A diagram of a band-pass filter is shown in Figure 3.8. A band-pass filter allows all frequencies within the range

$$\frac{1}{R_1C_1} \leq \omega_c \leq \frac{1}{R_2C_2} \tag{3.3}$$

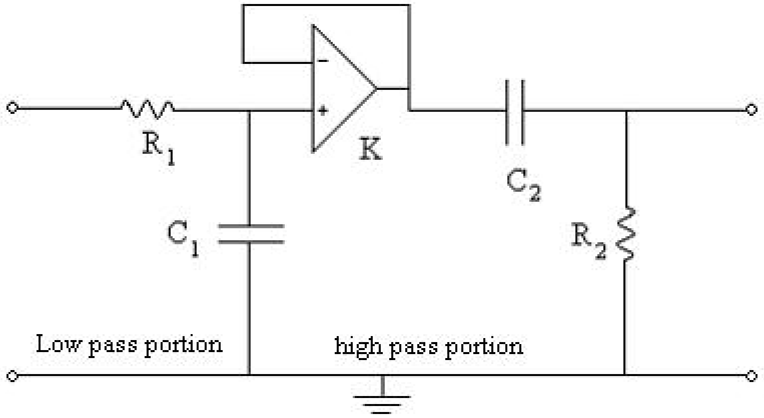

Figure 3.8: Typical Band-Pass Filter

One noticeable difference between the low- and high-pass filters shown in Figures 3.6 and 3.7 and the band-pass filter in Figure 3.8 is the presence of an operational amplifier, or op-amp. The circuit in Figure 3.8 is known as an active filter due to the presence of this op-amp, while the low- and high-pass filters shown in Figures 3.6 and 3.7 are known as passive filters. Passive filters have two major limitations: they cannot add energy to the circuit, and they perform poorly at low frequencies. In addition, active filters are often smaller and cheaper than passive filters. Active filters can also add energy to the circuit and amplify the signal. However, active filters are also often less reliable and less stable. Active filters are not used over a frequency of 100 kHz.

3.4.3 Band-reject Filters

An alternative to the band-pass filter is the band-reject filter. A band-reject (or Notch) filter can be created by combining a low-pass and high-pass filter in parallel. Notch filters provide a gain that is approximately double that of a band-pass filter.

3.4.4 Superheterodyne Filters

Although the band-pass filter is a simple and elegant method for filtering RF carriers, another method is used more commonly due to the necessity of amplifying the signal. Because the signal strength is so low when it gets to the satellite, amplification is always necessary and the Superheterodyne receiver discussed in Chapter 2 was designed to simplify this process. As described before, a local oscillator creates a secondary signal and from which sum and difference signals can be determined. The smaller of the two frequencies becomes the intermediate frequency (IF) on which demodulation and amplification are then conducted. The IF is used in this process because it is smaller than the RF, making amplifiers and detectors easier to build. Typically, RF values will vary from 100 kHz to 30 GHz but IF values will vary from 50 to 100 kHz.

3.4.5 Mechanical Filters

Mechanical RF filters differ from electrical circuit filters in that they utilize natural, mechanical properties of materials to demodulate the incoming signal. One example of a mechanical filter is the crystal filter that was mentioned in Chapter 2. A crystal filter resonates at a specified frequency and performs the low-pass and high-pass functions naturally through mechanical vibration rather than an electrical circuit. Some other common mechanical filters are ceramic, SAW, and cavity filters.

Table 3.5: Ranges for several types of RF filters

Type	Frequency Range(MHz)	Operating Temperature(°C)
Bandpass	300-6000	-20 - 60
Notch	400-2500	0 - 40
Crystal	.005-500	-30 - 75
Ceramic	300-2800	-20 - 60
SAW	100-2500	-20 - 60
Cavity	800-6000	15 - 40

3.4.6 Conclusion

Each of these types of filters has a range of frequencies for which it is typically used. Table 3.5 shows the ranges where each type can be used.

3.5 Conclusion

Though CC&DH systems are generally custom built for every space mission, clearly a great deal of COTS hardware is available for the individual components, and the construction of a CC&DH system has largely become an exercise in sizing, equipment selection, and assembly of existing hardware. These tasks are certainly substantial, but the engineering of custom major components for CC&DH systems is uncommon. At most, the engineer must figure out how to make a particular set of selected components interoperate, and perhaps design the interfaces. The next chapter will provide a brief overview of all the subjects perviously covered as well as provide recommendations into areas that require future research.

Chapter 4

Summary and Conclusions

The CC&DH system provides all spacecraft-to-ground communications and handles the execution of ground commands. The composition and function of the system may be broken up into a set of distinct categories.

4.1 Communications

The communications system is the link between the spacecraft and ground station. To complete the overall design of the communications subsystem, components such as antennas, receivers and transmitters need to be selected. These components interact with the command and data handling subsystem.

4.1.1 Summary

The important aspects of communications sub-systems are frequency selection, antenna selection, transmitter selection, receiver selection, and link budget. A limited number of frequency bands are available for spacecraft applications, thus frequency selection is important to the overall design of the communications systems. Regulation by WARC, FCC, and ITU is causing crowding of certain frequency bands. These organizations have divided the world into three regions for frequency allocation. This frequency crowding is leading to new experimental bands being used. The proper type and size of the antenna are two main components in antenna selection. With a larger diameter and viewing area, an antenna can have a larger gain and higher SNR. Power requirements and mass are the main constraints with antenna selection. A few basic antennas were discussed, including reflector antennas, horn antennas, wire antennas, and antenna arrays. Transmitter and receiver selections are chosen by size, type, and gain, with the key components being the amplifiers, filters, and demodulators. The link budget is a method used to determine the received power and noise power in the link. Link budget calculations are done to determine the signal quality. The link budget calculation depends on several key factors, such as;

transponder type, antenna alignment, antenna gain, atmospheric loses, and weather conditions between the spacecraft and ground station.

Modeling the communications system comes down to two calculations; the SNR and the antenna gain. The SNR is a ratio of the power received to the noise power. The received power takes into account losses that occur in between the ground station and spacecraft. Losses that occur are feeder loss, free-space spreading loss, losses due to antenna misalignment, atmospheric absorption, and polarization mismatch loss. Antenna gain is based on the geometry of the antenna and the operating wavelength. The antenna gain is taken into account in the received power equation.

Once the signal is received from the antenna, it is demodulated and amplified using an RF filter. Radio Frequency filters break down into two main categories: electrical and mechanical. Three main types of electrical RF filters are bandpass, bandreject, and superheterodyne filters. These filters are advantageous because they tend to be cheaper than mechanical filters. Four main types of mechanical filters are crystal, ceramic, SAW, and cavity filters. Mechanical filters are advantageous because they tend to be simpler than electrical filters.

Each of these filters are designed to operate at a range of frequencies and selection of particular filters will depend greatly on what frequency range is meant to be received. Another major concern when selecting the appropriate RF filter is the SNR. Some filters are capable of decreasing the SNR. This is especially important if the incoming signal needs to be amplified too much because amplification will increase the noise received as well as the signal.

4.1.2 Future Research

In the future, research and new technologies need to focus on new frequency bands. The compromise-band is the most commonly used frequency band even though there are multiple other frequency bands. Crowding is starting to occur in the C-band, creating a need for new frequency bands. Another important aspect in frequency band selection is determining why people choose specific bands.

Further research is also needed on antennas, transmitters, and receivers. The power required to keep the antenna, receiver, and transmitter running throughout the duration of the mission needs to be determined. Also the cost, production time, and shipping time need to be determined for specific components. More examples of manufacturers that supply spacecraft communications components should be included.

Further research is needed to determine the amount of data that can be sent from the satellite to the ground station. The amount of data that can be sent is dependent on the link budget and link margin. The amount of data that can be sent needs to be determined from the link margin.

4.1.3 Conclusion

The Communications subsystem is an integral part to the day to day operations of a space mission. Interaction between sub-systems is necessary for successful completion of the mission. Interaction is important since the antenna receives the signal then passes it along to other components before sending it back to a ground station.

4.2 Command and Data Handling

The command system is the heart of the spacecraft, and controls the operation of all other subsystems. Many issues must be considered in the design of a command system, including robustness, reliability, and security. Though the bulk of modern CC&DH systems are comprised mostly of COTS components, the command system, especially the software that processes commands, involves the most custom engineering.

4.2.1 Reliability and Robustness

The command system is the heart of the spacecraft and the importance of robustness in its design cannot be overstated. Whereas many bus subsystems are single points of failure, meaning failure jeopardizes the mission, steps can be taken to repair or bypass failures of these subsystems. However, the command subsystem is the only subsystem that cannot be bypassed or repaired in the event of complete failure. In the event of failures of the other subsystems, the task of repair or workaround falls on the command and logic system.

If an antenna fails, and the telemetry downlink and/or the command uplink are lost, the command system must act autonomously to restore communication. It must take actions to reset or otherwise attempt to repair the failed antenna, or possibly even reorient the spacecraft so that another antenna may be used.

If an electric motor in an attitude control device fails, the command subsystem will report the failure to the ground station and process the controllers' commands in an attempt to restart, repair, or bypass the motor. Every effort made by ground controllers to address the failure will ultimately be manifested as a command to the command system.

However, if the command system fails in such a way that it can no longer process commands, there is no controlling system capable of carrying out repairs analogous to those just described. Without a functioning command system, no commands can be processed. At best, the communications system may be made capable of power cycling the flight computer, but this is problematic. The communications system, even if designed to accept commands directly, lacks an authentication capability. So enabling the system to process commands poses a security risk and the ability to power cycle the command system is clearly a major capability from a security standpoint.

Reliability is therefore the single most important consideration in the design of a command system, as failure will almost certainly result in loss of the spacecraft and failure of the mission. Thus, multiple computer command systems are not uncommon, with ultra-high reliability systems generally taking the form of multiple independent computers which all process the same input and vote on the resulting action. In the past, these systems have generally run custom-written OS's. Tn recent years, as COTS and Open Source OS's have improved in robustness and computer hardware performance has increased, pre-existing OS's have been used. These OS's operate around a kernel, which is essentially a single program run by the computer hardware. The kernel then provides the platform and multitasking environment upon which the application software, in this case the command logic software, may operate.

Other application software may also operate on the same OS. For instance, software to preprocess and/or compress the data stream from the payload may operate concurrently. In earlier times, when computing power onboard spacecraft was at a premium due to the slow, power hungry systems available, data was often passed directly to the ground without processing. With more modern computer hardware, which can provide greater performance and consume a fraction of the power of older hardware, the data stream may be preprocessed and compressed prior to transmission, and inbound data can be encrypted because computing resources to decrypt it are available.

4.2.2 Security

Whereas older systems tended toward a model of retransmission to the ground station to verify the authenticity of commands, newer systems increasingly rely on encrypted data streams. In these cases, the authenticity of any command received through the encrypted data stream may be, and generally is, safely assumed.

However, the retransmission scheme is still used in some systems. Commands received over the uplink are retransmitted to the ground station either through a special downlink, or through the telemetry downlink. The ground station analyzes the command received and, if identical to the one transmitted, sends an execute command, which instructs the command system to operate on the command already received. The command is then matched against the command code table, which is generally not numbered consecutively so as to eliminate the possibility of single bit errors causing the system to interpret one command as another. The command is then either executed directly by the command system, or passed on to the appropriate subsystem, which in turn, may generate their own commands.

4.2.3 Other Issues

These internal commands are usually considered self-authenticating. An unauthentic external source cannot mimic an internally generated command, as the command is not transmitted over a radio link, except possibly through the telemetry link to inform the ground station that it is being executed. Thus, there is no need to authenticate these commands. The ObjectAgent architecture at AFRL is one such system which does not authenticate internal commands. In this multiple agent design, every component of every asset involved in a mission is a separate agent, but interactions between agents on a single spacecraft may be treated differently than those transmitted across radio links.

4.2.4 Existing Systems

The ObjectAgent architecture uses SCL for inter-agent communication with a minimum of computing overhead. This language was designed for the low computing power environments of the 1980's when 20MHz processors were still in the design phase, and is thus an efficient user of computational resources. But since SCL is a closed, proprietary language, NASA developed SuperMOCA, and the accompanying SMS language. Closely related to the industry proven MMS language used in industrial automation, SMS is performance oriented but also very robust, providing modularity to allow for new functionality rather than requiring modification to the language and control architecture.

A system designed originally for a testing environment, ITOS provides the STOL language, and is increasingly being used for spacecraft mission control operations. The language can accept commands using a mechanism similar to a DOS or UNIX^{TM} command shell, or run prewritten scripts.

4.2.5 Future Research

The fundamental aspects of command logic and handling are well-developed areas. Data encryption, in combination with increases in computing power, has simplified many issues. For instance, authentication schemes involving retransmission are being deprecated in favor of encrypted command links. Recent advances have been made in the form of new command and control architectures. The continued development of these architectures promises advanced functionality for the command and control system and, consequently, the entire space system.

4.3 System Hardware

While the command system is the heart of the spacecraft, the system hardware that runs the command system, or more precisely the onboard computer control system, is the brain of the spacecraft. Without the main computer, a spacecraft cannot accomplish anything. The system hardware, generally comprised of either solely COTS parts or a hybrid of COTS parts with expensive custom components, is one of the last subsystems to be designed. Finalizing the design of the computer system last allows for a better scaling of the computer to the needs of the entire spacecraft.

4.3.1 Architecture Selection

When designing the system hardware for a spacecraft, it is necessary to develop an architecture to control the interaction between the processor or processors and the individual subsystems. There are a few architecture types that are primarily used in system design, as listed below.

- Centralized Architecture
- Ring Architecture
- Federated Bus
- Distributed Bus

While there are similarities between the four main architectures, each represents a fundamental difference in how the system can operate. Within a Centralized Architecture, every subsection interfaces directly with the central processing computer. Having a direct interface with the central processing unit prevents a failure in one subsystem from affecting another subsystem, but because it requires that everything be connected to one central processor, the architecture requires more room and can create difficulties when attempting to add a new subsystem to an existing design. In a Ring Architecture, all subsystems are connected in a series. While connecting in a series can save space an allow for easy addition of new subsystems, if one subsystem fails then it creates the possibility that the entire spacecraft will fail. In a Federated Bus Architecture, all of the components are connected to one another and to the central processor through a common bus. Having a common bus allows for easy troubleshooting as well as a direct path between all individual subsystems, as well as eliminating some of the problems with the Centralized Architecture, including difficulties in adding new subsystems. Similar to the Federated Bus Architecture is the Distributed Bus Architecture. In the Distributed Bus Architecture, all of the subsystems are connected to a common bus, but the bus may have more than one processor. Possessing more than one processor on a common bus allows for multiple simultaneous command execution, but can create difficulties for testing and software design due to its complexity.

4.3.2 Interface Circuitry

Just as important as controlling and deciding which commands to execute is relaying those commands to the various subsystems. Without the proper interface circuitry, commands from the central processor will never execute correctly. There are four major command types that a spacecraft can utilize to relay its orders:

- Relay Commands
- Pulse Commands
- Level Commands
- Data Commands

Each type of command is used for different situations, and multiple command types are generally present onboard a given spacecraft. The Relay Command is the most common command, and is onboard practically every single spacecraft launched. It is ostensibly an on/off command, turning individual subsystems either on or off or activating some automated subsystem, such as a detachment sequence. A Pulse Command is similar. It uses a small series of pulses, instead of a single pulse, to activate either a remote relay or a logic gate. A Level Command is the same as a Pulse Command, but instead of varying time duration of the pulse it varies the power level. The Level Command is used mainly with logic gates, and is useful because it does not require a user to know the setting of the gate prior to activation. The last command is a Data Command. The Data Command command sends actual data from one system to another using whole words. This command also uses the most bandwidth. If one subsystem needed to send data to another subsystem or to the control processor, it would utilize a Data Command.

4.3.3 Commercial Off The Shelf Computers

Selecting COTS hardware for a spacecraft is generally dependent on the availability space-qualified computer equipment. While developing the architecture that a spacecraft will use to communicate between the central processor and all of the subsystems is relatively easy and can be inexpensive in terms of both time and money, it is almost impossible to design a custom computer processor or SBC. Instead a designer generally takes components that are readily available and assembles them in the desired fashion. Having to use COTS parts means that a hardware designer is limited in scope by what is currently available and tested for spacecraft. Generally it is cheapest and most effective to use a complete computer system sold COTS. Custom or hybrid systems generally have high non-recoverable costs associated with their development and fabrication.

4.3.4 Future Research and Recommendations

With advances in computer hardware happening at almost a daily rate, it is important to make sure that research is done on the newest technologies in computing at the start of any new project. Research into what typically makes a processor be considered “Radiation Hardened” and what goes into creating a processor that is would also be useful.

Further research should go into determining what is being used by current spacecraft projects and what was used in the past. In addition, research should go into what other aspects of a processor are important to look at when selecting for a specific mission. Computers sometimes have variable power requirements and clock speeds, allowing for changes on the fly. Having a variable voltage requirement is most important when trying to conserve power, such as in the shadow of a planet.

Another area of future research is how to scale systems. After a spacecraft has been designed, it is important to match a suitable computer to it. The individual subsystems and programs required to run on the computer dictate how much power, in the computing sense, a processor will need. Accurate scaling equations are vital to the design on the command system. Too few MIPS and a computer will be unable to run the spacecraft, while too many and the computer will be wasting power and money. A good guess is to predict the total MIPS that a given spacecraft will require and then assume that is 70% of the total. An effective model can save millions of dollars in a project.

4.3.5 Conclusion

When designing the hardware subsystem, there are a few key points. The system is one of the last things to be designed on the craft to allow for proper scaling. However, it is important to have a rough understanding of what is currently available in spacecraft computers while designing the subsystems in order to create a reasonable computer power demand, which helps to minimize cost.

The selection of an appropriate system architecture provides the best combination of simplicity, modeling, flexibility and versatility for a given mission. Combined with a properly scaled computer control system and appropriate interface circuitry for communication with individual subsystems, costs can be minimized while performance is maximized.

4.4 Conclusion

The first chapter established the need for the CC&DH system and defined its function and subsystems. The issues inherent in the design of the CC&DH were discussed, and typical methods of optimizing the various subsystems were discussed.

The second chapter introduces the methods employed in the modelling and analysis of the CC&DH systems. Detailed description of the specific calculations performed in the analysis of potential solutions are given, and ways to address the various obstacles presented in some missions are discussed.

The third chapter presented a series of example solutions to the various problems inherent in the design of CC&DH systems. Specifically, typical subsystem hardware components are presented, and existing software and system architectures are presented and discussed.

This chapter has provided a summary of the previous three chapters, restating the major points covered and suggested areas for further research.

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Appendix A

Tables

Table A.1: Link Budget Example for C-Band in Rain [10]

C/N Ratio in Receiver in Rain	in dB
P_R = Received Power at Earth Station in Clear Air	-112.958
A = Rain Attenuation	-1
P_{rain} = Received Power at Earth Station in Rain	-113.947
P_N = Receiver Noise Power	-135.536
ΔP_{nrain} = Increase in Noise Temperature due to Rain	5.046
P_{nrain} = Receiver Noise Power in Rain	-130.490
$[C/N]_{rain} = P_{rain} - P_{nrain}$	16.542

Table A.2: Link Budget Example for X-Band in Rain [10]

C/N Ratio in Receiver in Rain	in dB
P_R = Received Power at Earth Station in Clear Air	-118.124
A = Rain Attenuation	-2
P_{rain} = Received Power at Earth Station in Rain	-120.124
P_N = Receiver Noise Power	-135.536
ΔP_{nrain} = Increase in Noise Temperature due to Rain	6.641
P_{nrain} = Receiver Noise Power in Rain	-128.894
$[C/N]_{rain} = P_{rain} - P_{nrain}$	8.77

Table A.3: Link Budget Example for C-Band in Clear Air [10]

C-Band Satellite Parameters	
Transponder Satellite Output Power, W	20
Antenna Diameter, m	1
Antenna Efficiency	0.55
Transponder Bandwidth, MHz	36
Downlink Frequency, GHz	3.7 - 4.2
Basic Calculations	
Wavelength, m	0.075
Antenna Area, Total, m^2	0.785
Antenna Area, Effective, m^2	0.432
Receiving Earth Station	
Distance from Ground Station, km	40000
Antenna Diameter, Earth Station, m	5
Antenna Area, Total, Earth Station m^2	19.635
Downlink Frequency, GHz	4
Antenna Gain, on axis, dB	46.421
Receiver IF Bandwidth, MHz	27
Receiving System Noise Temperature, K	75
Downlink Power Budget	in dB
P_t = Satellite Transponder Output Power at 20W	13
B_o = Transponder Output Backoff	-2
G_t = Satellite Antenna Gain, on Axis	29.845
G_r = Earth Station Antenna Gain	46.42
L_p = Free Space Path Loss	-196.524
L_{ant} = Edge of Beam Loss for Satellite Antennas	-3
L_a = Clean Air Atmospheric Loss	-0.2
L_m = Other Losses	-0.5
P_R = Received Power at Earth Station	-112.958
Downlink Noise Power Budget in Clean Air	in dB
k = Boltzmann's Constant,dBW/K/Hz	-228.6
T_s = System Noise Temperature at 75 K	18.751
B_n = Noise Bandwidth	74.313
P_N = Receiver Noise Power	-135.536
C/N Ratio in Receiver in Clear Air	in dB
C/N = $P_R - P_N$	**22.578**

Table A.4: Link Budget Example for X-Band in Clear Air [10]

X-Band Satellite Parameters	
Transponder Satellite Output Power, W	40
Antenna Diameter, m	1
Antenna Efficiency	0.55
Transponder Bandwidth, MHz	36
Downlink Frequency, GHz	7.25 - 7.75
Basic Calculations	
Wavelength, m	0.04
Antenna Area, Total, m^2	0.785
Antenna Area, Effective, m^2	0.432
Receiving Earth Station	
Distance from Ground Station, km	385000
Antenna Diameter, Earth Station, m	10
Antenna Area, Total, Earth Station m^2	78.54
Downlink Frequency, GHz	7.5
Antenna Gain, on axis, dB	57.902
Receiver IF Bandwidth, MHz	27
Receiving System Noise Temperature, K	75
Downlink Power Budget	in dB
P_t = Satellite Transponder Output Power at 40W	16.021
B_o = Transponder Output Backoff	-2
G_t = Satellite Antenna Gain, on Axis	35.305
G_r = Earth Station Antenna Gain	57.902
L_p = Free Space Path Loss	-221.652
L_{ant} = Edge of Beam Loss for Satellite Antennas	-3
L_a = Clean Air Atmospheric Loss	-0.2
L_m = Other Losses	-0.5
P_R = Received Power at Earth Station	-118.124
Downlink Noise Power Budget in Clean Air	in dB
k = Boltzmann's Constant,dBW/K/Hz	-228.6
T_s = System Noise Temperature at 75 K	18.751
B_n = Noise Bandwidth	74.313
P_N = Receiver Noise Power	-135.536
C/N Ratio in Receiver in Clear Air	in dB
C/N = $P_R - P_N$	**17.411**