DESIGN OF AN INTERPLANETARY EXPLORATION TELEMETRY SUPPORT PACKAGE

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ABSTRACT

This student paper was produced as part of the team design competition in the University of Arizona course ECE 485, Radiowaves, and Telemetry. It describes the design of a telemetry support package for interplanetary exploration.

Control and processing of telemetric signals between an earth based control station, an exploratory orbiter and probe pods are the focus of this design. Using this design data retrieval is achieved at a highly reliable rate of 1 error in 10^{-10} bits. The exploratory orbiter, carrying a payload of probes, is launched and proceeds along its predetermined trajectory. Commands from the earth-based control station is used to send the orbiter to planetary destinations. The craft then establishes a stable non-geosynchronous orbit. Several probe pods are launched towards the planet at predetermined locations. These probe pods collect and send data, as well as system monitoring information to the orbiting craft. The orbiting craft then retrieves the signals generated by all pods and relays that information to an earth-based control station.

KEY WORDS

BER, Up/Down Link Telemetry, Transducers, Power Budget, Microstrip Antenna, QPSK Modulation, Packet Synchronization.

INTRODUCTION

Remotely sensed data from spectral reflectances help in identifying planet conditions, but do not provide the same accuracy as an observer on the planet itself. A more reliable method of obtaining highly accurate information is by utilizing probes on planetary surfaces to collect and transmit data back to earth. In order to achieve optimal accuracy in data retrieval, the lowest bit error rate (BER) is desired. Use of a solid state data recorder enabled a remarkable BER of 10^{-10} to be realized. This BER is the focal point of many satellite and probe designs.

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Probe pods will not be retrieved and are designed to be compact as well as cost effective. The probe is a sphere of radius 0. 15 m which is large enough to accommodate all detectors, sensors, and processing equipment. A maximum of five probes per planetary system is earmarked, however this number is subject to change depending on mission requirements. The orbiter has a maximum payload capacity of 30 probes.

An earth to orbiter telemetry link is required to monitor spacecraft functions as well as to send control instructions. This link requires a specific antenna design, as well as up/downlink budgets, which are addressed first. The next link is that between the probe and the orbiter. Detectors and sensors on the probe collect information, which is sent via packet telemetry to the orbiter. This requires another power budget and synchronization scheme. The types and methods of Minor system monitoring will be included in the probe circuitry in order to optimize retrieved data results. Both system and data signals will be transmitted to the orbiting craft at predetermined frequencies. Closure is achieved when the data collected by the probe is transmitted to the orbiter and relayed to earth successfully. Factors such as launching, propulsion and navigation systems are beyond the scope of this design and are not addressed.

Earth to Orbiter Telemetry Link

Communicating between the deep space orbiter and planet Earth is the focus of this part of the design. The areas of concern that will be addressed are antenna size, budget constraints, frequency allocation, and power utilization.

NASA’s Deep Space Network (DSN) will provide the necessary requirements for the uplink between the Earth and orbiter. The downlink setup was designed around the capabilities of the DSN. Using basic gain, EIRP, received power, and noise equations [1], the needed values for the orbiter parameters were calculated. A list of known quantities and assumptions were also needed [1].

Tables 1 and 2 provide a thorough look at what the current design has to offer at the maximum possible design distance. Basic elements of the DSN and orbiter are displayed in Table 1 to show what type of system, physically, is being considered. Table 2 shows what type of power and noise constraints are needed for such a system.

Table 1. DSN Ground Station and Orbiter Characteristics

Parameter	**Ground Station Value**	**Orbiter Value**
Transmitter Power	400 kW	20W
Antenna Temperature	25 K	40 K
Antenna Diameter	70 m	4 m
Antenna Gain	74.712 dB	53.373 dB
Antenna Half Power Beamwidth	$(4.197 * 10^{-5})°$	.000560°
Physical Antenna Area	15,393.804 m^2	50.265 m^2
Effective Antenna Area	8,466.592 m^2	27.646 m^2
Antenna Efficiency	55%	55%
Transmitter EIRP	130.733 dB	66.383dB
Data Rate	100 Kbits/sec	100 Kbits/sec
BER	-60.000 dB	- 100.00 dB
Line Loss	.05 dB	.1 dB
Receiver Temperature	7K	35 K
System Temperature	35 K	82 K
Amplification Type	Maser Amp	Cooled Paramp

Table 2. Uplink and Downlink Power Budgets

Parameter	Uplink	Downlink
Orbiter-Earth Distance (maximum)	$6.0 * 10^9$ Km	$6.0*10^9$ Km
Carrier Frequency	5.000 GHz	7.500 GHz
Transmitter Output Power	56.021 dBW	13.010 dBW
Multiple Carrier Loss	.200 dB	.500 dB
Transmitting Circuit Loss	.500 dB	1.000 dB
Transmitted Carrier Power	55.321 dBW	11.510 dBW
Transmitting Antenna Gain	74.712 dB	53.373 dB
Transmitted EIRP	130.033 dBW	64.883 dBW
Space Loss	301.990 dB	305.510 dB
Polarization Loss	.500 dB	.500 dB
Total Transmission Loss	302.490 dB	306.010 dB

Ground Terminal G/T	34.273 dB /K	39.712 dB/K
Required C/N	2.969 dB	.469 dB
Required E_b/N_o	12.000 dB	9.500 dB
C/N (calculated)	3.969 dB	1.469 dB
E_b/N_o (calculated)	13.000 dB	10.500 dB
Margin	1.000 dB	1.0000

Remote Sensing

a. Sensors on the probe

Since the probes are expandable and used only once, they must be relatively inexpensive, and so more sophisticated detector technology and apparatus must be resident on the orbiter. The probe carries sensors, listed in Table 3, with supporting circuitry to convert the data to digital form, route it to a microprocessor and transmit it to the orbiter using packet telemetry. Additional system detectors, such as an internal temperature sensor are resident within the probe to ensure it is functioning properly. The probes are preprogrammed for the target planet. This takes into account the flyby distance of the orbiter and the probe-to-orbiter interface.

The ranges of the transducers are determined by using catalogued planetary information and extrapolating available information. The functional range of the transducers and the desired resolution yield the number of bit required.

Table 3. Probe sensors and their associated sampling rates and bits

Sensor type	# sensors	Relative rate	#Bits/sample	#Bits/s
Temperature	1	1	12	1.2
Pressure	1	1	13	1.3
Humidity	1	1	14	1.4
Altimeter	1	1	17	1.7
Magnetic Field	1	0.1	10	0.01
Seismograph	1	1.5	10	1.5
Geiger-counter	1	0.1	10	0.01
CCD Array	1	1	22	2.2
Radiometer chl	1	0.1	17	0.017

Radiometer ch2	1	0.1	17	0.017
Radiometer ch3	1	0.1	17	0.017
Time (Microprocessor)	1	1	17	1.7
System controls		0.5	500	25

b. Orbiter imaging systems

The orbiter contains active imaging and remote sensing instruments which will be in use while it is orbiting the planet. These include the laser-induced-mass analysis at a distance (LIMA-D) and the Cassini II Radar, a modified version of the Cassini Radar to be used for the Cassini mission. The modifications include a movable antenna, which will be used for probe-to-orbiter and orbiter-to-earth communications.

Design of Orbiter/Probe Telemetry Link

Table 1 summarizes the specifications of the telemetry link between the orbiter and probe. As per Federal Communications Commission standards, a frequency range of 2.25 - 2.325 GHz is chosen for the down-link (probe-to-orbiter), giving rise to a 5 MHz gap between probes' center frequencies. 2.3 - 2.325 GHz is similarly chosen for the up-link.

Table 4 Specifications

Component	*SIC at Cold Stellar*	*S/C at Warm Stellar Body*
Data Rate	8 kbps down-link, 1 kbps up-link	
Receiver bandwidth	1 MHz	
Required Bit Error Rate (QPSK)	10^{-10} down-link, 10^{-6} up link	
Up-link frequency	2.3-2.325 GHz	
Down-link frequency	2.25 - 2.275 GHz	
Probe System Temperature	3.54K	130.6K
Orbiter System Temperature	55.46K	180.76K

A microstrip antenna array is incorporated on the probe. This provides an antenna with moderate gain and beamwidth, light weight, and small size. The orbiter antenna is chosen based on the requirement to meet specified E_b/N_o, G/T_{sys}, and C/N_o ratios. These requirements, along with link budgets, are shown in Tables 2 and 3.

System temperatures are calculated based on whether the spacecraft is at a cool stellar body or a warm stellar body. Atmosphere and distance to the sun are two characteristics of these types of bodies. System temperature was calculated and from the resulting G/T_{sys} ratio, available $C\backslash N_o$ and E_b/N_o ratios were found and are displayed in the Tables below.

Table 5 Orbiter-to-Probe UP-Link Power Budget

Component	*S/C at Cold Stellar Body*	*SIC at Warm Stellar Body*
EIRP	28.75 dBW	
Receiver G/T	-4.21dB/K	-9.9dB/k
C/N_o Available	52.98dB	47.3dB
E_b/N_oAvailable	22.98dB	17.3dB
E_b/N_oRequired	10.5dB	
Margin	12.48dB	6.8dB

Table 6 Probe-to-Orbiter Down-Link Power Budget

Component	*S/C at Cold Stellar Body*	*SIC at Warm Stellar Body*
EIRP	21.27 dBW	
Receiver G/T	17.5dB/K	12.4dB/K
C/N_o Available	67.4dB	62.3dB
E_b/N_oAvailable	28.4dB	23.24dB
E_b/N_oRequired	13 dB	
Margin	15.4dB	10.24dB

On-board Processing & Modulation

On-board Proessing

The orbiter and probes contain electronics which control data collection, data storage, telemetry up/downlink synchronization, and other system functions. Other system functions include spacecraft attitude (craft positioning), thruster controls, and all other non-telemetry related areas which are beyond the scope of this project. Implementation of the orbiter and probes require three main components; a central processing unit (CPU), memory, and input/output (I/O) evices [1].

Retrieved data is converted to a digital format and stored in RAM or on a hard dive. Onboard programming directs data manipulation and synchronization schemes. The probe and orbiter have similar formats. However, on-board orbiter processing is more intensive requiring faster processing speeds and more storage space.

Modulation

Accurate retrieval of probe and orbiter data was the most important factor for all design parameters. One step in achieving high accuracy of data retrieval is by converting all sensor and detector data to a digital format (as covered in the Detector and Sensor part). A significant reason for using digital modulation was due to its ability to completely regenerate a digital signal.

Quadrature Phased Shift Keying (QPSK) was chosen as the modulation scheme on account of several factors; low bit error rate (BER) with low carrier power (C), narrow bandwidth (B), and widely available components. QPSK modulation and demodulation is achieved through coherent quadrature methodology [1]. Integrate-and-dump bandpass filters are used to help recombine modulated signals.

Packaging and Synchronization

In considering the sensors for use on the probes, the sampling rates of the sensors, and the fact that data will not be transmitted continuously while the probe is in operation, the most reasonable style of packaging is packet telemetry. The individual packets can be made up of a predetermined style which the orbiter can recognize.

Each packet will consist of a primary header, secondary header, data, and a trailer. The primary header will be comprised of a 32 bit synchronization word, an eight bit identifier to tell which probe is sending the data, a sending packet count represented by one eight bit word, a sixteen bit word specifying the length of the secondary header and a an eight bit secondary header flag to signal the beginning of the secondary header. The information in the primary header will be contained in fixed fields and thus is a fixed length. The secondary header will give the number of data fields and the identification and format of the data fields. The data fields themselves will contain data from the sensors and the time at which each batch of data was sampled. Following the data fields will be a trailer which will consist of a 16 bit error check code.

There are three different sampling rates for the sensors. All of the sensors sampling at the same rate will be grouped together and sent in the same packet. The packet will also be using eight bit word lengths therefore, data from the sensors will be broken up in such a way that low-order bits from the sensors will be transmitted first followed by the high-order bits transmitted at the end.

Packet telemetry will also be used for transfer of information between the orbiter and the earth based stations. The orbiter will be transmitting data collected over many hours from five different probes; the amount of data being transmitted can't be predetermined thus packet packaging will work better than frame packaging considering the necessary frame design for such data. The packets themselves will be of the same composition for the orbiter to earth as it is for the probe to orbiter.

In order for synchronization to take place, the receiver will first look for the 32 bit synchronization pattern, and acquire it with perfect correlation. Given the extremely low BER, 10^{10} this will occur very quickly. With perfect correlation the probability of false lock is once every 4.29 Mbits or, with a data rate of 8 kbits/sec, a false lock every 149 hours.

The 32 bit synchronization word to be used is 77465450200_8. This is a predetermined optimal synchronization code. A 32 bit code is used for several reasons. First, since eight bit word lengths are being used, data that takes up increments of eight bits is desirable. Second, to reduce the synch code length to 24 bits would result in a false lock every 35 minutes. This is undesirable because there needs to be a large amount of assurance that the data received is the correct data.

Once the synchronization code has been found the orbiter must assume it has located a packet since no real checking of the synch code can be done, thus the need for the remaining information in the primary and secondary headers. The packet counter does act as a checker in a sense because it should increment by one for each consecutive packet from a single probe, thus if the sequence is disturbed the orbiter knows a packet has been lost.

Conclusion

This design of the telemetry system between an Earth-based station, orbiter, and numerous probes on the surface of a planet has set forth the requirements needed by NASA's Deep Space Network, the necessary operating frequencies, the characteristics of a number of desired sensors onboard the orbiter and probes, the desired link budgets from the planet to the orbiter and from the orbiter to Earth, and the preferred format, packaging, and synchronization of the data to be telemetered from the planet to Earth. The overall design has been created with safety margins, and flexibility in mind. Where applicable FCC regulations and IRIG suggestions have been utilized.

The orbiter is launched from Earth with a payload of probes. The probes can be delivered to virtually any celestial body within the bounds of the Solar System. NASA's Deep Space Network, already in place, is the primary link between the orbiter and Earth. The orbiter itself is capable of making numerous topographical profiles of a desired planet, while the probes are capable of retrieving data during the descent through the atmosphere and while at the surface of the planet. Data can be transmitted from the probes, to the orbiter, and from the orbiter to Earth with significant reliability.

There are many characteristics about the design which will allow for minor changes, thus the overall design is adaptable to numerous applications. This has the benefit of greater production numbers at lower costs than other more specialized systems of this type. Changes could include different sensors onboard the probes and the orbiter, or possibly a prolonged investigation by the probes on the surface before data is retrieved. The possibilities are certainly numerous.

As a possible improvement upon the design a relay station can be incorporated between the orbiter and Earth, allowing for less power usage onboard the orbiter, and/or increasing the range of the orbiter enabling the orbiter and it's payload of probes to exceed the bounds of the Solar System.

Overall, the design presented gives a good example utilizing various aspects of telemetering knowledge that have been woven together with the desire to turn an idea into a reality.

References

[1] Dean, A., Goisman, S., King, B., Ohnstad, M., Raby, S., "Interplanetary Exploration Telemetry Support Package," Tucson, AZ, 1996.