ISAT-1 COMMUNICATION SYSTEM

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Abstract

The communication system of the Iowa satellite ISAT-1 provides contact links between the satellite, the ground station, and a moderate number of remote ground data collection systems through the operation of two functional units. In this system, data is transferred over four VHF/UHF channels, each with a bandwidth of 16 KHz, at the rate of 9,600 bps per channel. The continuous phase binary frequency shift keying (CP-BFSK) is used for digital modulation/demodulation in the attempt to achieve a transmissin error bit rate of 10^{-6} or lower under the constraint of a very limited financial and power budget. Also, a command-driven time division multiple access (CD-TDMA) scheme is employed for data exchange between the remote data collection systems and the central ground station in order that the communication resources be utilized efficiently and effectively. In this paper, different aspects of the system, including the specifications and the preliminary designs of all operation blocks, are described in detail.

1. Introduction

The ISAT-1 communication system consists of the satellite, the ground station, and 100 remote data collection system (RDCS) transponders. It is divided into two functional units, called COMM-1 and COMM-2. COMM-1 is the main communication link between the satellite and the ground station. All commands and control data from the ground station to the satellite bus and payload systems as well as software updates for the flight computer system will be transferred through this link. Data for bus health status and most payload systems of the satellite will also be handled by this link. COMM-2 mainly serves as the data link for the RDCS network. It will collect data from the RDCS transponders and then pass the data to the ground station. In addition, it will also transfer some part of the satellite payload data through its downlink to the ground station. The design, building, and operation characteristics of COMM-1 and COMM-2 will be identical so that in the event of failure of COMM-1, COMM-2 will act as the main communication link.

In this paper, different aspects of the communication system are addressed. The specifications and preliminary designs of different operation blocks of the system as well as the justifications are also presented. The organization of the paper is as follows. First, brief descriptions of the structure and the operation of the communication system in terms of functional units and operation blocks are given in Section 2. Then, the general specifications of the system and calculations of the communication link budgets are presented in Section 3 and 4, respectively. In Section 5, several multiple access schemes potentially suitable for data exchange between the ground station and the RDCS transponders are described. A comparison of implementation requirements and complexities between the schemes and a preliminary design of multiple access protocol corresponding to the best suitable scheme are also presented. In the subsequent two sections, preliminary design of the antennas and that of the modems, transmitters, and receivers for the ISAT-1 communication system are described, respectively. It is expected that most parts of the system will be built by assembling off-the-shelf products available in the market. Therefore, these preliminary designs will serve as detailed specifications for the selection and purchase of the products. Finally, in Section 8, a brief summary is given. Several miscellaneous issues, such as those related to the ground station and flight computer systems, are also addressed in the same section.

2. Structure and Operation

The communication system of ISAT-1 is divided into two functional units: COMM-1 and COMM-2, as shown in Figure 1. COMM-1 is the primary communication link between the satellite and the ground station, whereas COMM-2 is mainly an experimental communication system providing a data link between the ground station and a group of remote data collecting and handling ground transponders via the satellite. The idea is to have 100 small, relatively inexpensive, and portable transponders spread all over the state of Iowa which could collect, process, and relay some kind of local data up to the satellite while the onboard COMM-2 passes the data over to the ground station.

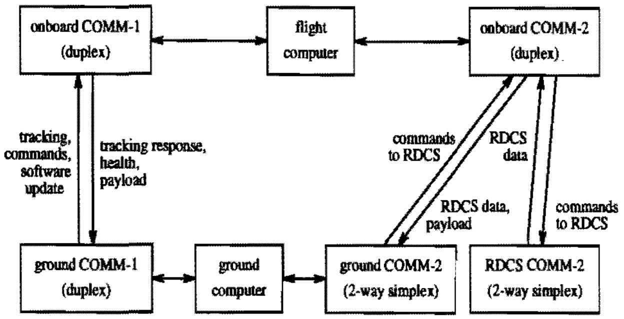


Figure 1: Functional units of ISAT-1 communication system.

The structures of the two functional units at the three types of terminals are described in the following and the operation block diagrams are shown in Figure 2.

1. *Satellite*: Each of the two onboard units consists of the flight computer, a modem, and a transmitter/receiver pair; both operate in full duplex mode. A combiner, a divider, and a duplexer are used so that the two units share one common antenna for both transmission and reception.
2. *Ground Station*: COMM-1 is composed of the ground computer, a modem, and a transmitter/receiver pair, and operates in full duplex mode; while COMM-2 is formed by the ground computer, a modem, and a transmitter/receiver pair, and operates in two-way simplex mode. Once again, a combiner, a divider, and a duplexer are used so that both units share one common antenna for transmission and reception. The antenna has tracking capability so as to be able to point to the satellite automatically once it appears in the sight of the ground station.
3. *RDCS Transponders*: Each of the 100 transponders forms a COMM-2 terminal, and consists of several sensors, a data acquirer/processor, a modem, and a transmitter/receiver pair. The antenna is physically fixed, *i.e.*, it does not have tracking capability, but should have a wide angle of sight instead. A duplexer is also used such that the antenna is used for both transmission and reception. All of the transponders operate in two-way simplex mode.

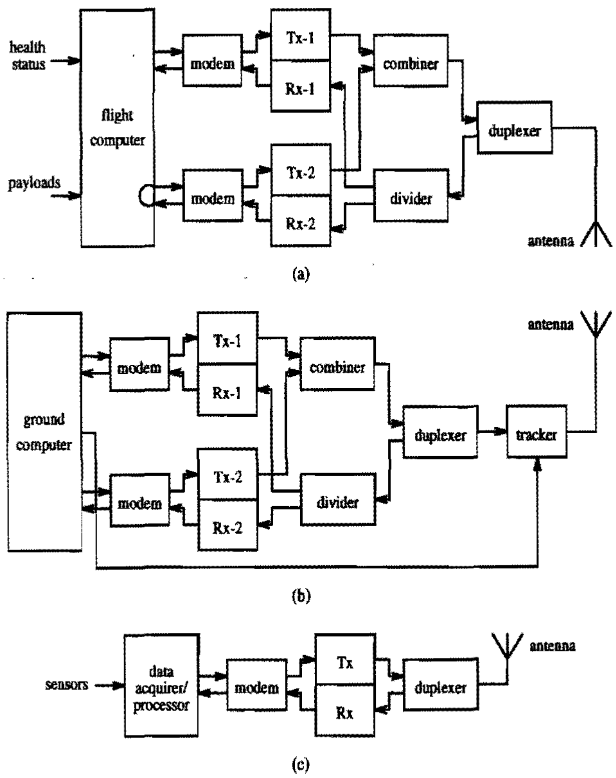


Figure 2: Operation block diagram of (a) the onboard terminal, (b) the ground station terminal, and (c) the RDCS transponder terminals.

Under the control of the ground computer, the ground station COMM-1 will be always operating in active mode: its transmitter will be sending tracking signals constantly while the receiver detecting responses from the satellite. The onboard COMM-1 receiver will be also operating in active mode all the time. As soon as the satellite flies into the sight of the ground station and the receiver detects the upcoming tracking signal, the onboard COMM-1 transmitter will start operation and send response back to the ground station, which then completes the establishment of communication link between the satellite and the ground station. After that, the ground station and the onboard COMM-2 units will enter and leave active operation mode upon commands from the ground computer. The receivers of the RDCS transponders, once again, will be always operating in active mode, whereas the transmitters will start and cease operation upon commands from the ground computer that were forwarded by the onboard COMM-2.

When the satellite leaves the sight of the ground station, the ground station COMM-1, the onboard receiver, and the transponder receivers will remain in

Table 1: Frequency bands allocated by the WARC for small satellite communication systems.

Primary Band	Secondary Band
137.000 - 137.025 MHz	137.025 - 137.175 MHz
137.175 - 137.825 MHz	137.825 - 138.000 MHz
148.000 - 149.900 MHz	
400.150 - 401.000 MHz	

Table 2: Selection of carrier frequencies f_0 and bandwidths B for use by ISAT-1 communication system.

Channel	f_0	B
COMM-1 uplink	137.1875 MHz	16 KHz
COMM-1 downlink	400.1625 MHz	16 KHz
COMM-2 uplink	137.8125 MHz	16 KHz
COMM-2 downlink	400.8875 MHz	16 KHz

active operation mode while all other blocks will go into standby mode.

3. General Specification

Carrier Frequency Selection

Recently, the World Administrative Radio Conference (WARC) in Spain allocated new frequencies (listed in Table 1) in both VHF and UHF bands for use by small satellite systems. In the following, the relative merits and demerits of different selections of carrier frequency are briefly discussed.

1. At a higher frequency, an antenna has smaller physical size, and hence is easier to manage and has better functioning characteristics. The effect of man-made noise on signal reception at ground terminals is also smaller. However, at such a frequency, the free-space loss will also be higher and the Doppler frequency shift effect will be more significant. In addition, the physical size of the satellite will be comparable with the wavelength, and therefore will complicate the design of the onboard antenna.
2. The use of higher frequencies by the onboard communication units for transmission and lower frequencies for reception will reduce the effect of man-made noise on signal reception at ground terminals, and also make impedance match of the onboard feed line easier.
3. Since the transmission and reception with only one antenna at all of the terminals are realized by using a duplexer and a few bandpass filters, to reduce the duplexer loss and the duplexer/antenna cost as well as to ensure match of impedances, it is preferred that the transmitting and receiving frequencies be separated by a 1:3 ratio [1].

Based on this justifications, selection of carrier frequencies and channel bandwidths has been made and is shown in Table 2 (selection of bandwidths will be addressed later in this section).

Communication Contact Time

Communication contact time is the time duration when the satellite passes the sight of a ground terminal. It is determined by the orbital altitude H and inclination angle θ_i of the satellite as well as the minimum contact elevation angle ϕ_e of the ground terminal. The latter (see Figure 3 for illustration), specifying the sight of the terminal, is in turn dependent of the beamwidth of the antenna at the terminal and whether the antenna has tracking capability. To meet other requirements, a sun synchronous orbit with an orbital altitude of 700 km have been chosen for ISAT-1. As a result, the orbital inclination θ_i is 98.19°. Based on these values of H and θ_i, quantities related to communication contact time for different values of ϕ_e as well as the maximum contact distances D between the satellite and a ground terminal can be calculated as listed in Table 3.

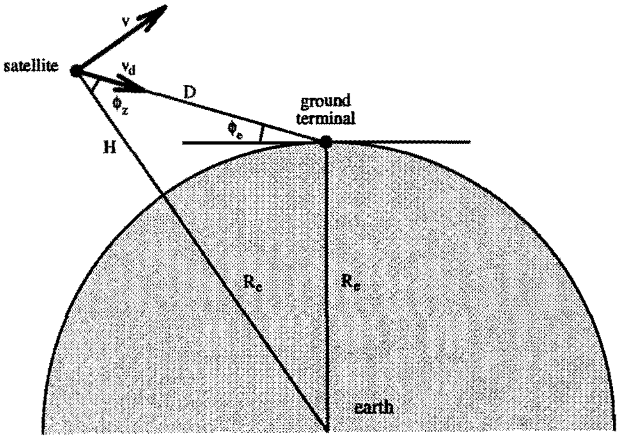


Figure 3: Relation between elevation angle ϕ_e, orbital altitude H, and distance D.

From Table 3, it can be seen that for a smaller value of ϕ_e, the contact time would be longer and, as a trade-off, the maximum contact distance D would also be larger, which implies a higher free-space loss. Considering this trade-off and the tracking capabilities of different antennas, a minimum contact elevation angle of 5° has been chosen for the ground station

Table 3: Communication contact times and maximum contact distances.

ϕ_e (deg)	Average Contact Time (min/day)	Shortest Contact Time (min/day)	Average Number of Passes	Max Contact Distance (km)
0	67.31	≈ 64.1	6.13	3069
5	45.17	≈ 42.7	5.03	2564
10	30.54	-	4.05	2156
15	21.00	≈ 19.1	3.35	1835
20	14.87	-	2.91	1584
25	10.48	-	2.42	1390
30	7.57	≈ 6.4	2.03	1237

antenna and 15° for the RDCS transponder antennas. Beamwidths and other specifications of antennas will be addressed later in this section.

Data Rates and Channel Bandwidths

COMM-1 data rate and channel bandwidth The types of data to be transferred using COMM-1 are listed as follows.

- *Uplink*: tracking signal, all commands and control data to the bus and payload systems, and flight computer software update data.
- *Downlink*: tracking response, bus health status data, earth imaging data, earth radio frequency experiment data, and other payload experiments data.

Since both the uplink and downlink data can only be transferred when the satellite passes in sight of the ground station, and the average contact time is only about 45 minutes per day, COMM-1 must have efficient and reliable data transmission capability. Considering the volume of the above mentioned data and some other constraints, it is expected that a channel data rate R_b of 9,600 bits per second (bps) for each of the link directions will be sufficient to handle the data traffic on a time shared basis. At this channel data rate, depending on whether channel coding (error control coding) is used, the source data rate will be about 6,400 or 9,600 bps, *i.e.*, about 17 or 26 Mb per day, by assuming the common channel coding efficiency of 2/3. Also, the channel bandwidth will be 16 KHz, which can be realized by using the CCIR 25 KHz channel space separation technology.

COMM-2 data rate and channel bandwidth The types of data to be transferred using this link are listed as follows.

- *Uplink*: commands to RDCS transponders from the ground station and RDCS transponder data.
- *Downlink*: commands to RDCS transponders passed by the satellite, RDCS transponder data passed by the satellite, and part of payload experiments data.

Since COMM-2 acts as the backup of COMM-1, the channel data rate of 9,600 bps is also chosen for both of its uplink and downlink directions. Therefore, like in COMM-1, the source data rate is again about 17 or 26 Mb per day depending on whether channel coding is used; and the channel bandwidth is 16 KHz.

It has been specified that each of the 100 RDCS transponders has 10 sensors with sampling period of 15 minutes and resolution of 8 bits per sample. As result, the total volume of the transponder data is $8 \times 10 \times 100 \times 1440/15 = 768$ Kb/day. At the transmission rate of 6,400 bps, the transfer of these data can be completed in about 2 minutes. Therefore, the remaining contact time can be utilized to transfer some part of the payload experiments data.

System Reliability Requirement

Because of the uniquely important role that the communication system plays in the entire ISAT-1 system, a high level of data transmission accuracy and system reliability is required. Typically, a transmission bit error of one in a million, *i.e.*, $P_e = 10^{-6}$, is considered reasonable. To achieve this high degree of reliability, issues such as the digital modulation/demodulation scheme, transmission power, feed line loss/antenna gain, and error control coding scheme must be carefully considered.

Digital Modulation/Demodulation Scheme

In general, the selection of digital modulation/ demodulation scheme should be based on the following specifications and considerations: 1) the data transmission rate $R_b = 9,600$ bps; 2) the channel bandwidth $B = 16$ KHz; 3) how much the ratio E_b/N_o of the energy per bit to the noise power spectral density (PSD) measured at the detector input of the receiver is required for the bit error rate $P_e = 10^{-6}$; 4) whether the energy spread into neighboring channels is low enough; and 5) whether the amplitude of the modulated signal is constant (which in turn determines whether efficient constant-amplitude amplification technologies, such as the class C power amplification [2], can be used). It is found that the Binary Phase Shift Keying (BPSK) and the Binary Frequency Shift Keying (BFSK) schemes are reasonable

Table 4: Performance comparison between BDPSK and CP-BFSK.

	BDPSK	CP-BFSK (h=0.715)
Modulated Signal Bandwidth at $R_b = 9,600$ bps (Containing 95% of Signal Power)	20 KHz	12 KHz
Required E_b/N_o for $P_e = 10^{-6}$	11 dB	12 dB
Power Level in Neighboring Channels	-20 dB	-30 dB
Amplitude of Modulated Signal	variable	constant
Implementation Complexity	complex	simple

candidates for our application. Their corresponding realization schemes are Binary Difference Phase Shift Keying (BDPSK) and Continuous Phase Binary Frequency Shift Keying (CP-BFSK) [2], respectively. A comparison between BDPSK and CP-BFSK (with a modulation index h of 0.715) in different aspects is shown in Table 4. The modulated signal power spectral density and the relations between P_e and the required E_b/N_o for these schemes are also shown in Figures 4a and 4b, respectively.

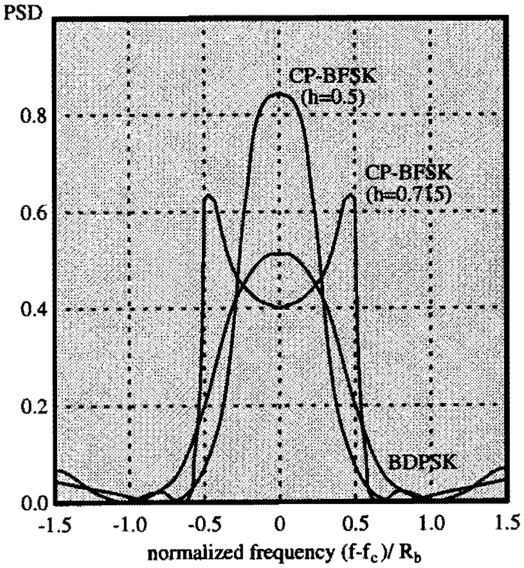
From Table 4, it can be easily seen that CP-BFSK (h=0.715) is better than BDPSK in most aspects with only one slight disadvantage, *i.e.*, CP-BFSK requires one more dB of signal-to-noise ratio to achieve the desired transmission error performance. Therefore, CP-BFSK is selected as the digital modulation/demodulation scheme for the ISAT-1 communication system.

Feed Lines and Antennas

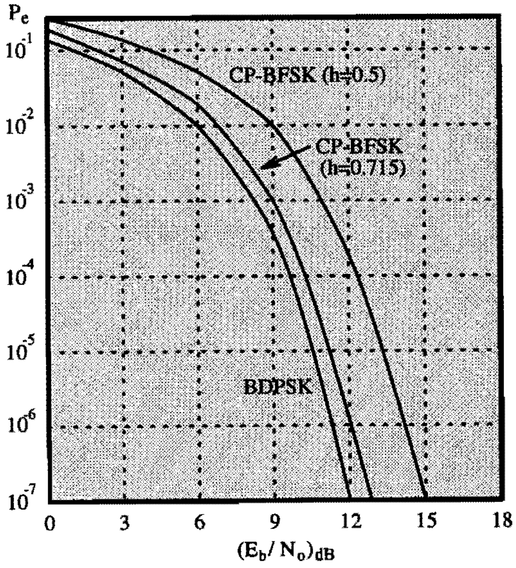
Feed lines Since both onboard COMM-1 and COMM-2 share one common antenna for both transmitting and receiving, the feed line consists of a duplexer, a 2-combiner, and a 2-divider. The transmitting end of the duplexer is connected to the 2-combiner that combines signals around 400 MHz from the two transmitters; whereas the receiving end is connected to the 2-divider that feeds signals around 137 MHz to the two receivers.

Similar to the onboard units, both COMM-1 and COMM-2 at the ground station share one common antenna for both transmitting and receiving, and thererfore the feed line is also composed of a duplexer, a 2-combiner, and a 2-divider. The only difference is that the frequency ration is different, *viz.*, the transmitted signal is around 137 MHz and the received signal around 400 MHz.

As far as the RDCS transponders are concerned, one antenna and one duplexer are used for each of the transponders. The transmitted and received signals are around 137 MHz and 400 MHz, respectively.



(a)



(b)

Figure 4: Comparison between BDPSK and CP-BFSK: (a) PSD of the modulated signals, and (b) relation between P_e and E_b/N_o.

Antennas The onboard antenna will be a cross Yagi antenna consisting of 8-16 quarter wavelength dipole elements, and form two symmetrical main beams in opposite directions, one facing the earth and the other opposite to the earth (Figure 5a). It is so specified that in the event when the satellite is not in its nadirpointing attitude it should still be able to maintain communication with the ground station. More details of the antenna are specified as follows.

- *Type of antenna*: cross Yagi [1];
- *Number of elements*: 8-16 quarter wavelength dipole elements;
- *Beam shape*: two opposite conical beams each with beamwidth $\leq 150°$; and
- *Antenna gain*: ≥ 4 dB.

The ground station antenna must meet the requirement that communication between the satellite and the ground station be established for an elevation of angle of 5°. Detailed specifications of the antenna are listed as follows.

- *Type of antenna*: cross Yagi;
- *Number of elements*: 24-28 quarter wavelength dipole elements;
- *Beam shape*: one conical beam with beamwidth 60° (Figure 5b); and
- *Antenna gain*: 12 dB.

This antenna is attached to the ground and can rotate fully 360° in azimuth and elevate from 5° to 90° above the horizon. Since the orbit of the satellite can be predicted, the antenna, under the control of the ground station computer, will be able to point to the satellite with some small error whenever the satellite appears in its sight, *i.e.*, 5° above the horizon in any azimuth direction. After the communication link between the satellite and the ground station is established, the ground station computer will constantly update its prediction of the satellite orbit based on the received tracking response, and also fine-tune the antenna's direction, thereby allowing the antenna to keep track of the satellite and to maintain high level of antenna gain while the satellite passes in its sight. Clearly, in this manner, the antenna will have a tracking capability of complete 360° in the horizontal plane and 170° in the vertical plane.

Antennas of the RDCS transponders should also meet the requirement that the communication between the satellite and a transponder be established once the satellite appears in the sight of the transponder. Their specifications are listed in the following.

- *Type of antenna*: cross Yagi;
- *Number of elements*: 12-16 quarter wavelength dipole elements;
- *Beam shape*: one zenith-pointing beam with beamwidth of 150° (Figure 5c); and
- *Antenna gain*: ≥ 7 dB.

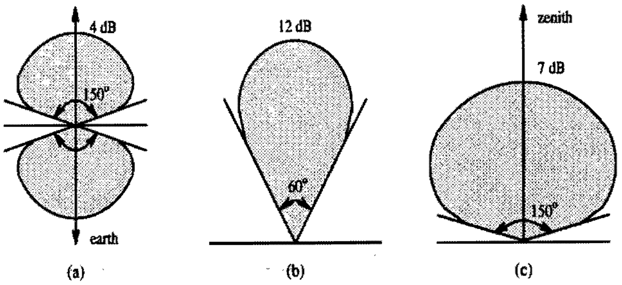


Figure 5: Beam shape of (a) the onboard antenna, (b) the ground station antenna, and (c) the RDCS transponder antennas.

Power Consumption

The peak total power consumption allocated to the onboard COMM-1 and COMM-2 units is 14 watts. It is expected that, when operating in active mode, each of the two transmitters will consume 5 watts while each of the two modem/receiver pairs will consume 2 watts in total. Using current technology, a transmission efficiency of 30%-50% can be realized. Therefore, the transmission power of each of the two downlinks will be about 2 watts. When the satellite leaves the sight of the ground station, only the modem and the receiver of COMM-1 will keep operating in active mode, consuming about 2 watts of power, and all other onboard blocks will go into standby mode.

It is expected that the transmission power of all the ground terminals will be also 2 watts.

Physical Size, Weight, and Cost

Each of the onboard COMM-1 and COMM-2 units should be of size smaller than 170mm×110mm ×85mm and should have a mass of less than 3 kg. The cost of the entire communication system has not been determined yet.

4. Link Budget Calculation

The link budget of a communication system is the formula that relates the system parameters, such as the transmission power, noise power, antenna gain/feed line loss, and free-space loss, to the ratio E_b/N_o of the energy per bit to the noise PSD at the detector input of the receiver. Its evalution provides a quantitative measure of the transmission error performance of the communication system. Specifically, the formula is expressed as

$$\begin{aligned}\left(\frac{E_b}{N_o}\right)_{dB} &= P_s - P_n + 10\lg\frac{B}{R_b} \\ &= P_t - L_{ft} + G_t - L_s + \\ &\quad G_r - L_{fr} - P_n + 10\lg\frac{B}{R_b},\end{aligned}$$

where, P_s and P_n are the signal and noise power in dBwatts at the receiver input, respectively; B and R_b are the channel bandwidth and the channel bit rate, respectively; P_t is the transmission power in dBwatts; L_{ft} and L_{fr} are the transmitter and receiver feed line loss, respectively; G_t and G_r are the transmitter and receiver antenna gain, respectively; and L_s is the free-space loss. In the following, the budgets for all links of the ISAT-1 communication system are calculated based on the specifications given in the last section.

1. *Transmission power and noise power.* As specified earlier, the transmission power of all COMM-1 and COMM-2 transmitters is 2 watts, *i.e.*, $P_t \cong 3$ dBwatts. In general, it suffices to assume that the effective noise temperature T_e at the input of a receiver is 1000°K, which corresponds to an average noise figure of about 5 dB. Therefore, the noise power at a receiver input is $P_n = 10\lg kT_eB \cong -156.56$ dBwatts, where k is the Boltzmann's constant.

2. *Feed line losses.* Usually, a 0.5 dB insertion attenuation of both transmitted and received signals would be incurred by a duplexer. Also, a 3 dB insertion attenuation of the transmitted signal would be incurred by a combiner that combines two signals. Consequently, we have the feed line loss of

   - 3.5 dB for the onboard transmitters,
   - 0.5 dB for the onboard receivers,
   - 3.5 dB for the ground station transmitters,
   - 0.5 dB for the ground station receivers,
   - 0.5 dB for the RDCS transmitters,
   - 0.5 dB for the RDCS receivers.

3. *Antenna gains.* It has been specified in the last section that the onboard antenna gain, the ground station antenna gain, and the RDCS transponder gains are 4 dB, 12 dB, and 7 dB, respectively.

4. *Free-space losses.* The free-space loss L_s of signal transmission is expressed as

   $$L_s = 10\lg(4\pi D/\lambda)^2,$$

   where D is the transmission distance and λ is the wavelength. Given the selected carrier frequencies in Table 2 and the maximum contact distances in Table 3, it can be calculated that the free-space loss is about

   - 143.36 dB for COMM-1 uplink,
   - 152.90 dB for COMM-1 downlink,
   - 144.03 dB for COMM-2 uplink from the ground station to the satellite,
   - 141.12 dB for COMM-2 uplink from the RDCS transponders to the satellite,
   - 153.57 dB for COMM-2 downlink from the satellite to the ground station,
   - 150.66 dB for COMM-2 downlink from the satellite to the RDCS transponders.

5. *Link budgets.* Based on all the above calculation results, we come up with the link budget of

   - 30.02 dB for COMM-1 uplink,
   - 20.66 dB for COMM-1 downlink,
   - 29.53 dB for COMM-2 uplink from the ground station to the satellite,
   - 30.44 dB for COMM-2 uplink from the RDCS transponders to the satellite,
   - 19.99 dB for COMM-2 downlink from the satellite to the ground station,
   - 17.90 dB for COMM-2 downlink from the satellite to the RDCS transponders.

From the above calculation results, it can be seen that as long as the communication system meets the specifications presented in Section 3, the ratio of the energy per bit to the noise PSD at the detector input of any receiver of the system will be at least 17.9 dB. This ratio has a positive margin of about 6 dB compared to 12 dB which is required for the CP-DFSK (h=0.715) modulation scheme at the transmission bit error rate $P_e = 10^{-6}$. It can therefore be concluded that the required transmission error performance is achievable with the specifications.

5. COMM-2 Multiple Access Scheme and Protocol

Since the COMM-2 unit involves 100 RDCS transponders which would be competing with each other for data transfer in a single channel, an effective and reliable multiple access scheme and a practical protocol are required in order to efficiently utilize the communication resources and to optimize the performance-to-cost ratio. In this section, several candidate multiple access schemes are first described. The implementation requirements and complexities of these schemes are then summarized; and based on the summary the most appropriate scheme is chosen for our specific application. A preliminary design of protocol corresponding to the selected scheme is also presented.

Three multiple access schemes have been considered potentially suitable for data exchange between the COMM-2 terminals. They are respectively Bent-Pipe Frequency Division Multiple Access (BP-FDMA), Bent-Pipe Code Division Multiple Access (BP-CDMA), and Command-Driven Time Division Multiple Access (CD-TDMA) [3]. In the following, these schemes are described and their relative merits and demerits are evaluated.

Bent-Pipe Frequency Division Multiple Access

In BP-FDMA scheme, all of the 100 transponders will transmit data simultaneously at a low rate r_b, on the order of few ten bps. Each of the transponders, however, will be assigned a sub-carrier with distinct frequency, and will transmit data by first modulating the data onto the sub-carrier with BPSK or BFSK, and then modulating the resulted signal onto the common COMM-2 uplink carrier with CP-DFSK. The separation between the sub-carrier frequencies of any two transponders should be at least $2r_b$. The onboard COMM-2 receiver will receive the signals from all the transponders together as in a single band, and will convert the entire band to the COMM-2 downlink frequency band. The converted signal will be then fed to the onboard COMM-2 transmitter for retransmission to the ground station. At the ground station the COMM-2 receiver will have a total of 100 narrowband filters, each corresponding to one of the 100 sub-carrier frequencies. With these filters the receiver will split the received signal into 100 different sub-bands and then demodulate the signals and detect the data being transmitted.

The advantage of BP-FDMA scheme is that each transponder will have its own communication channel, which prevents data clash between different transponders. Due to the low transmission data rate, the transponders could be made quite simple and their transmission power could be very low. This scheme, however, suffers severely from the Doppler frequency shift effect, which is caused by the movement of the satellite with respect to the stationary ground terminals. The level of the effect varies with different passes of the satellite over the sight of the terminals as well as different locations of the terminals. With reference to Figure 3, the maximum Doppler frequency shift of the uplink signal from a transponder to the satellite can be evaluated by using the following approximate formula

$$\Delta f_{max} = \frac{\nu_{d,max}}{c} f_{U2} = \frac{\nu \sin \phi_z}{c} f_{U2}$$
$$= \frac{\nu}{c} \sin \left[\cos^{-1} \frac{(R_e + H)^2 + D_T^2 - R_e^2}{2(R_e + H) D_T} \right] f_{U2}$$

where, ν is the moving velocity of the satellite and is about 7504.5 km/sec; $\nu_{d,max}$ is the maximum projection of ν on the radical direction of the transponder; c is the speed of light; R_e is the radius of the earth; H is the orbital altitude of the satellite; D_T is the maximum contact distance of the transponder; and f_{U2} is the COMM-2 uplink carrier frequency. By substituting the appropriate values, it can be calculated that $\Delta f_{max} \cong 3223$ Hz. Apparently, to cope with this larger frequency shift effect, the separation between any two of the 100 sub-carrier frequencies must be on the order of kilohertz, which leads the overall bandwidth of the COMM-2 uplink signal to more than 100 KHz. In addition, due to the bent-pipe operation mode, low efficiency linear power amplifier is required for the onboard transmitter. Therefore, it is expected that BP-FDMA scheme will not be suitable for our application.

Bent-Pipe Code Division Multiple Access

In this scheme, each of the 100 transponders will have a distinct spread spectrum code sequence of length L_{seq} more than or equal to 100 bits, and all will transmit data simultaneously at a low rate r_b with the common COMM-2 uplink carrier frequency. The spread spectrum code sequences are orthogonal to each other and can be generated by using, for example, the Hadamard matrix method. To transmit each data bit, a transponder will first modulate the data bit onto the code sequence assigned to it, then modulate the entire sequence onto the common carrier using CP-DFSK, and finally feed the modulated signal to the transmitter for transmission up to the satellite. Similar to the FDMA scheme, the onboard COMM-2 receiver will receive the signals from all the transponders together as a single signal and will translate the signal to the COMM-2 downlink frequency band. The converted signal will be then fed to the onboard COMM-2 transmitter for re-transmission to the ground station. The ground station COMM-2 receiver will have 100 correlators, *i.e.*, matching filters, corresponding to the 100 spread spectrum code sequences. With these filters the receiver will first demodulate the received signal from the carrier and then detect the data being transmitted by matching the demodulated signal with the 100 code sequences.

With BP-CDMA scheme, the overall channel data rate of the COMM-2 uplink from the transponders to the satellite is $L_{seq}r_b$ while the overall source data rate is $100r_b$. It should be mentioned that due to the mutual orthogonality of the 100 code sequences, the matching filter/detector at the ground station COMM-2 receiver will be able to detect the data being transmitted correctly even when the signal-to-noise ratio at the detector input is low or, equivalently, when some errors occur in the received data sequence. This error robustness in turn allows the onboard COMM-2 transmitter to reduce its transmission power while maintaining enough link budget. In addition, like BP-FDMA scheme, the transmission power of the transponders could be very low due to the low transmission data rate; and no data clash would occur since each transponder once again has its own communication channel. The main disadvantage of this scheme is that the ground station COMM-2 receiver will be very complex and costly because of the use of 100 correlators. Also, low efficiency linear power amplifier is required in the onboard transmitter for bent-pipe operation; and to ensure correct signal detection, automatic transmission power control is required in the transponders such that the energy level difference of signals from different transponders be kept within a reasonably small range.

Command-Driven Time Division Multiple Access

In CD-TDMA scheme, the 100 transponders will sequentially transmit data at the channel rate 9,600 bps, with the COMM-2 uplink carrier frequency, upon reception of commands from the ground station. More specifically, when the satellite passes the sight of the transponders, the ground station computer will decide which transponder to transmit data and send a command up to the satellite via the COMM-2 uplink. The command will be broadcast by the onboard COMM-2 transmitter to all the transponders; and the transponder that is requested will then start data transmission. The onboard COMM-2 receiver will demodulate the received signal from the carrier frequency, detect the data being transmitted, and meanwhile, modulate the detected data onto the COMM-2 downlink carrier for retransmission to the ground station. After receiving the entire data block from the particular transponder, the ground station computer will then determine which transponder to transmit data next, and send out the command. This procedure will be repeated until every transponder gets at least one chance to release the data in its storage. As mentioned in Section 3, the volume of the RDCS data is quite limited compared to the selected channel bandwidth and the available communication time. Therefore, the above procedure should be completed in reasonably short time during each pass of the satellite in the sight of the transponders.

With CD-TDMA scheme, transmitters and receivers of all the onboard and ground terminals can be identically designed using well developed technology and assembled with standard off-the-shelf products. Also, with the scheme, the overall transmission error will be the accumulation of bit errors that occur in the uplink and downlink transmissions. This overall error is usually smaller than that due to the channel noise accumulation happening in bent-pipe schemes, which in turn helps to reduce the power consumption requirement of the onboard COMM-2 transmitter. The main disadvantage of CD-TDMA scheme is that some amount of communication time will be wasted due to the two-way simplex mode, in which both the ground station COMM-2 and the transponders are operating, as well as the data/command exchange between the ground station computer and the transponders. However, it can be easily evaluated that this disadvantage is quite limited.

Comparison

A comparison between the three multiple access schemes is given in Table 5. From the table, it can be easily seen that both the channel bandwidth requirement and the transmission efficiency of CD-TDMA scheme are reasonable while the equipment complexity and cost for the scheme are much less than the other two schemes. As a result, it is concluded that CD-TDMA scheme is most suitable for data exchange between the COMM-2 terminals.

Multiple Access Protocol

Using the CD-TDMA scheme described in the above, the multiple access protocol would be quite simple since the number of terminals (*i.e.*, the RDCS transponders) that need to exchange data with the ground station is fixed and no contention of transferring data by the transponders would occur over the communication channel due to the command driven channel access mode. However, there are several matters that still need to be taken into account in the design of the protocol. First, it is very likely that differences exist between clocks of different transponders. Therefore, commands from the ground station must include some synchronization signal such that the

Table 5: Comparison between multiple access schemes.

	BP-FDMA	BP-CDMA	CD-TDMA
Required Channel Bandwidth	>16 KHZ	16 KHz	16 KHz
Required Onboard COMM-2 Transmission Power	>2 watts	≈1 watt	≈2 watts
Key Equipment Requirement, Major Advantage, or Disadvantage	Doppler effect on channel bandwidth and transmission power	100 correlators required for the ground station COMM-2 receiver	technology well developed and off-the-shelf products available
Complexity and Cost of Equipments	complex and expensive for the ground station COMM-2 receiver	complex and expensive for the ground station COMM-2 receiver	simple and cheap for all terminals involved

transponders can synchronize with the ground station and detect the incoming command data correctly. Second, signals to and from different transponders may have different transmission delays due to their spread locations. Correspondingly, some sort of separation masks and boundary delimiters must be placed in the command/data string to be transmitted to and from different transponders.

With all the above considerations in mind, a byte-oriented frame format (shown in Figure 6) similar to the IEEE 802.3 frame format [4] has been chosen for use in the data exchange among all COMM-2 terminals, including the ground station terminal and the onboard terminal. In this format, the length of a frame must be at least 16 bytes and at most 1024 bytes long, from destination address to checksum. If the data portion of a frame is less than 6 bytes, the pad field is used to fill out the frame to the minimum size. The data field in a frame for commands from the ground station may include reception acknowledgement, transmisssion request, and some other ACK/REQs.

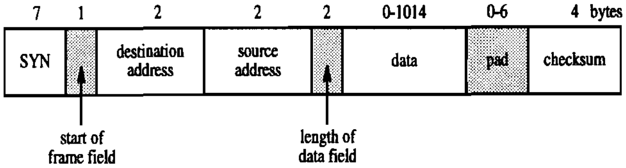


Figure 6: Frame format for data exchange among all COMM-2 terminals.

6. Design of Antennas

Onboard Antenna

The design of the onboard antenna should be under the guideline of the specifications given in Section 3. Particularly, more attention should be paid to the specification of two beams for the COMM-1 uplink and downlink and the specification of beamwidth. To meet the specifications, the antenna will consist of two to four sets of elements, with one set serving as driver and the others as reflectors/directors. Each set comprises four dipole elements of length approximately equal to one quarter wavelength at an uplink carrier frequency (or three quarter wavelength at a downlink carrier frequency), *i.e.*, about 550mm, and is arranged as shown in Figure 7a. The exact lengths of the elements as well as the inter-set distances and the attachment angles are to be adjusted and determined in order that the specifications be satisfied. Moreover, in order to realize cross polarization, a (0°, 90°, 180°, 270°) phase shifter is needed to connect the duplexer to the driver of the antenna.

It should be mentioned that the wavelength at frequency around the uplink carrier frequencies, *i.e.*, about 400 MHz, is comparable with the physical dimension of the satellite. Consequently, the effects of the satellite body on the beam shape and the antenna gain must be taken into consideration; and simulation needs to be pursued before actually designing the antenna. It is preferred that the onboard antenna be attached at the bottom of the satellite. However, since the upper beam may be reflected by the satellite body and may effectively cancel the lower beam, one set of the quarter wavelength dipole elements might need

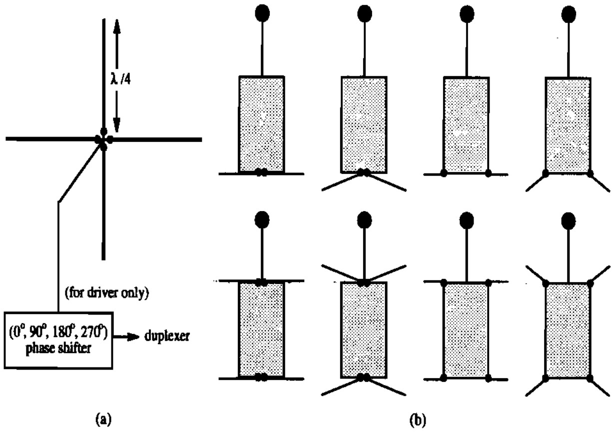


Figure 7: Onboard antenna: (a) arrangement of quarter wavelength dipoles, and (b) the most probable placements and attachments.

to be placed at the top of the satellite, or even some other location. The most probable placements and attachments of the antenna are shown in Figure 7b.

Ground Station Antenna

Since the ground station antenna will have tracking capability, the most important specification for the antenna would be the high directional gain of 12 dB. To meet this specification, six to seven set of elements will be used for the antenna, with one serving as driver, one as reflector, and the remaining as directors, and are attached as shown in Figure 8b. Each set once again consists of four dipole elements with length roughly equal to one quarter wavelength at a uplink carrier frequency, and is arranged as shown in Figure 8a. Also, the exact lengths of the elements and the distances between different element sets are to be adjusted and determined to meet the specifications.

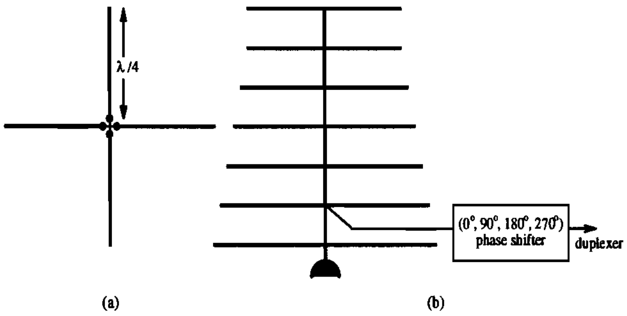


Figure 8: Ground station antenna: (a) arrangement of quarter wavelength dipoles, and (b) the attachment.

RDCS Transponder Antennas

The design of these antennas is very similar to that of the ground station antenna, except that fewer (three or four) sets of elements are needed in correspondence with the wider beamwidth requirement.

7. Design of Transmitters, Receivers, and Modems

The designs and specifications, except the carrier frequencies, of transmitters/receivers/modems for all the onboard and ground terminals of the ISAT-1 communication system will be exactly the same, and will be conformed as much as possible to the standard of the mobile communication systems that use the CCIR 25 KHz channel space separation technology. In this approach, no special parts or devices will be required for the system, which will therefore make the assembling of the system easier and also help to reduce the cost.

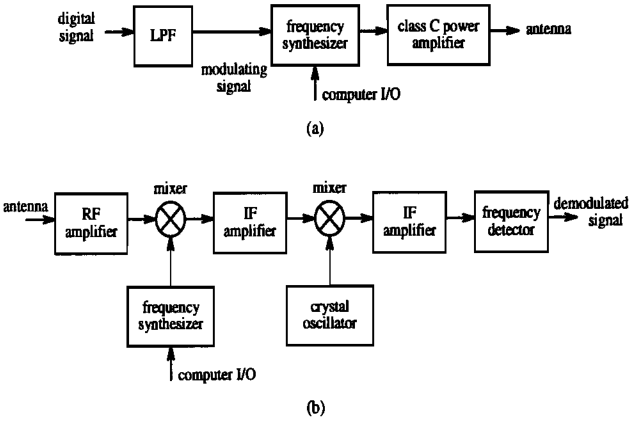


Figure 9: Block diagram of (a) the transmitter and (b) the receiver.

A widely adopted design of frequency modulation transmitter and receiver for mobile communication systems [2] is depicted in Figure 9. In this design, both the transmitter and receiver use a frequency synthesizer, where a voltage control oscillator (VCO), a variable frequency divider, and some other components are arranged in a phase-locked loop (PLL) structure (Figure 10), as a key component for carrier modulation/demodulation. An advantage of this design over many other designs is that the transmitter/receiver will be able to adjust the carrier frequency to other values within a range of several megahertzs in case where the pre-selected carrier frequency happens to be interfered by some other communication system. The adjustment is made possible by incorporation of the variable frequency divider into the PLL arrangement of the frequency synthesizer, and can be accomplished through the control of the frequency divider by a computer. Also, since the frequency synthesizer can be fabricated using CMOS technology, transmitters and receivers with this design will have better functioning characteristics in many aspects than those with other designs, and consume less power as well.

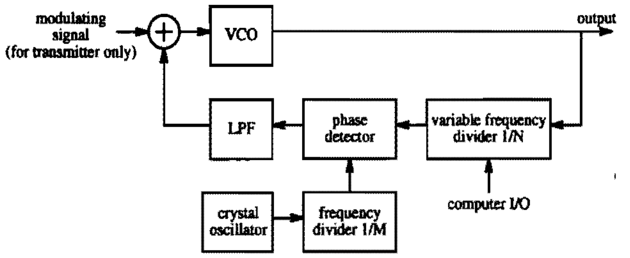


Figure 10: Frequency synthesizer in a phase-lock loop structure.

With the design of transmitter/receiver pair described above, the modem will consist of only the baseband component and could be combined as a part into the transmitter/receiver. More specifically, since the baseband component of the modulator is nothing but a lowpass filter used to smooth input digital signals, and the filtering output level is closely related to the required modulation index h, it will be easy and appropriate to combine the component into the transmitter. Meanwhile, the baseband component of the demodulator includes a matching filter and a synchronization circuit (see Figure 11 for detailed block diagram), with the former being used to improve the signal-to-noise ratio at the input of the thresholding detector. This baseband component can be realized using several IC chips and will be therefore appropriate to be combined into the receiver.

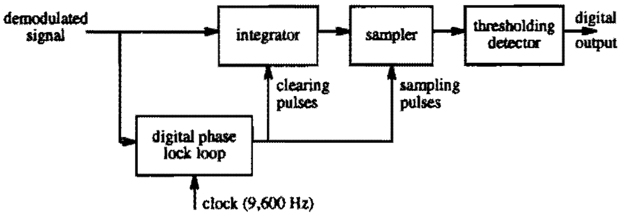


Figure 11: Baseband component of the demodulator.

8. Other Issues and Summary

General specifications and preliminary designs of most operation blocks of the ISAT-1 communication system have been presented in this paper. It can be noticed that, however, an important constituent part of the system, the ground station and the flight computer systems, has not been addressed. This is so because the computer systems are themselves an issue in the entire ISAT-1 project important enough that needs be addressed separately. Currently, it has been decided that two 16 MHz 80C286 single board computers be used in the flight compter system, one being the backup of another; and it is believed that the system will have sufficient computation and I/O interface capability to perform all operations required for the functioning of the communication system and other bus health testing and payload experiment systems, such as the control of their operations, and the processing of the relevant commands and data.

As the communication system is the only link between the ground station and the satellite, it is expected that some data, such as the commands and control data from the ground station and the bus health status data from the satellite, may require stricter error protection in their transmission. To provide this protection, some sort of error control coding may be utilized; and it is anticipated that the Forward Error Correction (FEC) coding and the Cyclic Redundancy Checking (CRC) coding [5] would be most appropriate for the purpose. The two specific codings can be easily realized by either running suitable computer softwares or incorporating dedicated hardwares into the transmitters and receivers.

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