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Low Cost Approaches to Personal Communications Satellites

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Abstract

Over the next few years several communications satellite constellations will become operational, each promising some form of wireless voice or data communication available globally. These systems offer high throughput two-way communications, but at a cost of one to fifteen billion dollars in capital investment. This makes entry into the personal communication satellite market difficult, if not impossible, for the small spacecraft industry. However, AeroAstro has determined that constellations of microspacecraft can still provide services in this market, at a fraction of the investment. The key is to identify niche markets that are not being served by the larger constellations and target those markets for low cost service. This paper will detail one such system, providing one way, and limited two way, messaging from distributed remote sensors back to their owners. A description of the system design will be provided, emphasizing those aspects specific to the microspacecraft mission. Furthermore, AeroAstro has developed several unique approaches that allow these missions to be performed at a reasonable cost. This paper will discuss the use of scanning high gain antennas in combination with linear repeaters to provide global coverage and strong RF linka. Additionally, the use of CDMA technologies in this system is discussed.

Introduction

Over the next few years several communications satellite constellations will become operational, each promising some form of wireless voice or data communication on a global scale. These systems offer high throughput two-way communications, but at a cost of one to fifteen billion dollars in capital investment. This makes entry into the personal communication satellite market difficult, if not impossible, for the small spacecraft industry. However, AeroAstro has determined that constellations of microspacecraft can still provide services in this market, at a fraction of the capital investment. The key is to identify niche markets that are not being served by the larger constellations and target those markets for a unique brand of low cost service.

AeroAstro has identified low data rate one-way communications as such a niche. It is assumed that a number users will send small data packets from unsophisticated, remotely operated, globally distributed remote terminal units (RTU's) to a centrally located data clearinghouse. For example, the messages may be 128 to 1024 bits in length and require transmission at an average rate of once per day or slower. At an average data rate of just one bit every 100 seconds, millions of users could be supported with a simple global communications system. Such a system could track shipping containers and other mobile assets, monitor remote equipment, and perform a host of other duties.

In order to reduce initial capital costs and minimize development time, such low-cost communications systems will need to rethink the frequency allocation problem. Much of the spectrum available to communications satellites in L-band has already been allocated while RF components in K-band are (for the time being) expensive. Furthermore, the process of petitioning for and receiving a license for sole use of any frequency is a costly affair that can take several years. This is going to push small communications systems into sharing frequency allocations with larger, established communications systems (e.g. at GEO). This will require the smaller communications system to limit the transmitted power by using code domain multiple access (CDMA) techniques to spread the data across a larger bandwidth than that require by the data alone.

Then, any LEO communications system that is to provide a low-cost solution to this problem (with low capital investment) must have the following characteristics:

1. Be able to collect CDMA encoded data from multiple remote sensors distributed globally and pass that information to the appropriate customers. The data path from the RTU to the customer is referred to as the inlink.
2. Be able to control the function of the sensors and associated RTU's by passing limited commands (as opposed to data) from the customers to their RTU's. The command path from the customer to the RTU is referred to as the outlink.
3. Near real-time data transfer is desirable, although for some applications may not be necessary
4. Provide position data on mobile remote sensors to the customer
5. Guarantee message receipt without message verification
6. Operate with limited RF power due to licensing agreements and RTU power limitations
7. Minimize the complexity of the RTU

AeroAstro has developed several baseline designs for such communications systems and has two patents pending covering key enabling technologies. A general low-cost communications system consists of three key components:

1. A remote terminal unit (RTU) that is the source of the data to be transferred
2. A constellation of satellites for relaying the data to and from the Ground Station (GS)
3. A series of Ground Stations to collect the data, issue RTU commands and monitor and command the satellites

System Design Issues

Having established the basic system requirements, a series of system concepts can be formulated. In general, this communications system can decode the messages on the spacecraft (on-board processing) and then transmit the message data to the ground or it can act as a linear repeater, retransmitting all of the RTU signals back down to the ground where the messages are then decoded (bent-pipe system). Furthermore, the decoding process can be done either by using a series of CDMA decoders on the raw signal (analog option) or the signal can be digitized (at a sample frequency faster than the chip rate) and stored in memory where the messages can be extracted by software algorithm (digital option).

This leads to four general communications system concepts that have been identified:

1. Analog Bent-Pipe: The spacecraft acts as a linear repeater with no processing performed on the spacecraft. This approach will provide coverage only when the RTU and a Ground Station are in the service area of a satellite simultaneously. Processing of the RTU signals is performed at the GS.
2. Digital Bent-Pipe: The spacecraft digitizes the RTU signal before sending it to the ground. This improves the SNR of the system by reducing noise from the spacecraft to GS leg. Again, this approach will provide coverage only when the RTU and a Ground Station are in the service area of a satellite simultaneously and processing of the RTU signals is performed at the GS.
3. Analog On-board Processing: Rather than send all of the encoded RTU messages and their associated noise, a series of analog CDMA decoders are used to decode the RTU messages. Only the messages are passed to the GS. If a GS is not in view when a message is decoded, that message can be stored for later downlink. Note, however, that the total

message throughput is limited to one message per decoder at any time. So, messages transmitted nearly simultaneously to multiple RTU's may get lost.
4. Digital On-board Processing: Similar to the Analog On-board Processing approach, the RTU signal is digitized on the spacecraft where it can be decoded in software. This allows a single microprocessor to remove several simultaneous RTU messages from the signal without limiting system throughput.

The performance of the system can be reflected by several relevant figures-of-merit (FOM's) that are important to its operation:

1. Total number of data and command messages (System Throughput)
2. System signal-to-noise ratio (SNR) from the RTU to the Ground Station
3. RTU localization (the ability to geolocate the RTU from the transmission signal only)
4. Data and command message latency
5. System expandability, operability and reliability
6. Probability of data and command message transfer

Each of the four approaches was ranked according to its performance based on each FOM.

Table 1: System Trades for LEO Communications Systems

System	A	B	C	D
Signal Form	Analog	Digital	Analog	Digital
Message Path	Bent Pipe	Bent Pipe	On-Board	On-Board
Data Thruput	1	1	4	3
Command Thruput	1	1	1	1
System SNR	4	3	1	1
Localization	4	3	2	1
Command Latency	1	1	1	1
Data Latency	3	3	2	1
System Xpansion	1	1	4	4
System Operability	1	1	1	1
System Reliability	1	2	3	4
Xfer Prob	4	1	1	1

This analysis yields several interesting results:

1. The analog on-board decoding approach is the most limited in terms of system throughput. It is limited to processing a single message per decoder for the entire duration of the message.
2. The digital on-board decoding approach is only slightly better, with its ability to decode messages limited by on-board processor power.
3. Both of the bent-pipe schemes are limited by the total signal-to-noise ratio from the RTU to the GS. The digital scheme has a slight advantage in that digitizing the broadband signal at the spacecraft effectively eliminates the noise from the spacecraft to the GS. However, the total signal to noise ratio is dominated by the RTU to spacecraft link as the GS is assumed to have a tracking dish with very high gain.
4. Our analyses indicate that the analog bentpipe approach provides excellent link margin for a range of potential data rates and frequency co-allocation schemes.
5. The on-board processing systems are limited both in reliability and in their ease of expansion. Placing a large amount of complicated infrastructure in low earth orbit where it is susceptible to radiation damage, extreme thermal cycling and cannot be easily repaired is probably not a cost effective solution. Furthermore, the capacity and capability of the bentpipe systems can be expanded by modifying and improving ground systems. The initial capital investment then is low and further investments can be made as the market expands.
6. The bentpipe approaches are limited in their operation to service areas that are in view of a ground station.
7. The analog bentpipe approach is most limited in its ability to guarantee message transfer as it has the lowest signal-to-noise ratio and is susceptible to simultaneous messages being blocked out.

While many of the innovations described here can be applied to any of the four system approaches, the analog bentpipe is considered for its low initial capital investment, high system throughput and high reliability and expandability. The inability of this system to store messages on-board is eliminated by adding a single CDMA decoder on the spacecraft. Thus, in areas where RTU distribution is sparse (particular at the introduction of the system) the spacecraft can decode and store a small number of message for later downlink. Where the number of RTU's is large (or as the system grows in popularity), a ground station can be placed to provide the bentpipe service. Note than some form of CDMA decoder must be carried on the spacecraft so that it can decode commands sent to it be the ground stations. This system is shown in Figure 1.

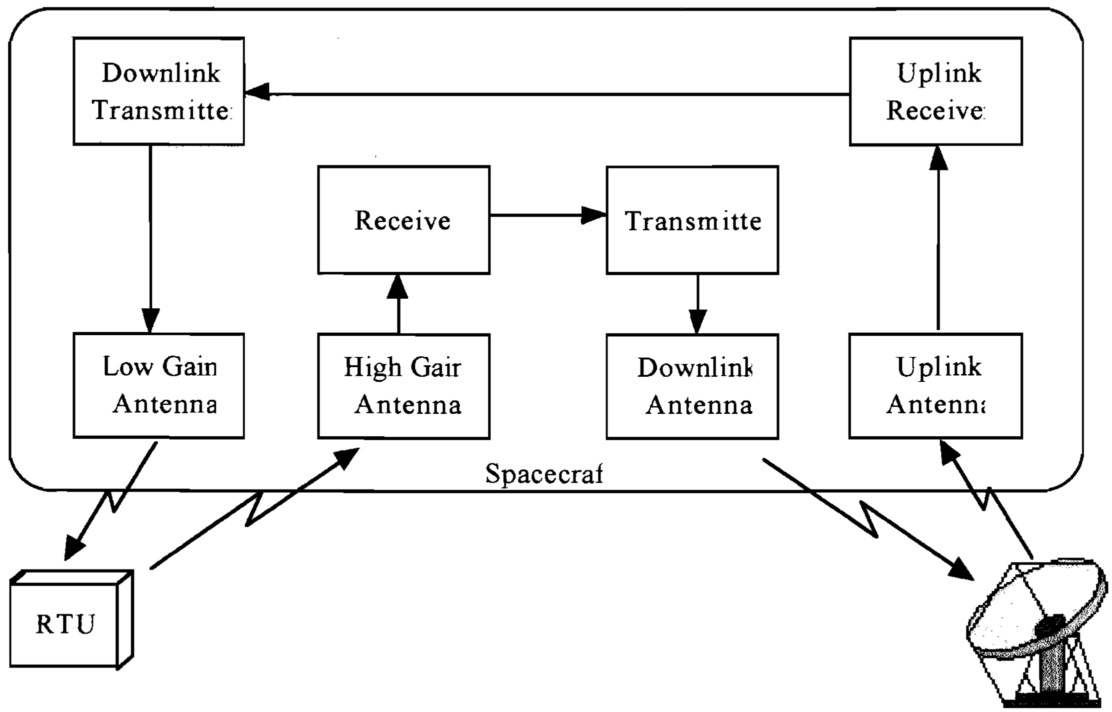

Figure 1: Analog Bentpipe Communications Concept

A fundamental characteristic of these low-cost communications systems is the low transmit power allowed under frequency sharing arrangements. Typically, the secondary user (in this case the low-cost communications system) is required to keep its total power across the allocated spectrum below the primary user's noise floor. In this case, the gain on the transmitter serves no purpose other than to limit the power consumed by the RTU transmitter. That is, if a high gain antenna is used, the power out of the transmitter must be reduced to meet the power output limitations. There is no net effect on the system SNR. Furthermore, placing a directional antenna on the RTU will make it necessary for the RTU to point in the direction of the spacecraft before it transmits. This increases the complexity of the very component that must, by its very nature, be as simple as possible. The key to increasing SNR is to increase the gain of the receive antenna, but a high gain antenna (HGA) has (by its very nature) a small field of view. Then multiple HGA's must be used to cover the service area of a single satellite. In a bentpipe system, these signals must be retransmitted to the ground, again within a limited bandwidth and limited power output. In order to maximize SNR, the signal from the HGA's must be sent down at maximum power, one at a time. This also eliminates the need for multiple transponders, simplifying spacecraft design.

The centerpiece of AeroAstro's innovations is the use of a scanning high gain antenna to provide nearly continuous coverage to an array of low-power, low-cost RTUs (Figure 2). There are four ways to sweep the high gain antenna over the service area:

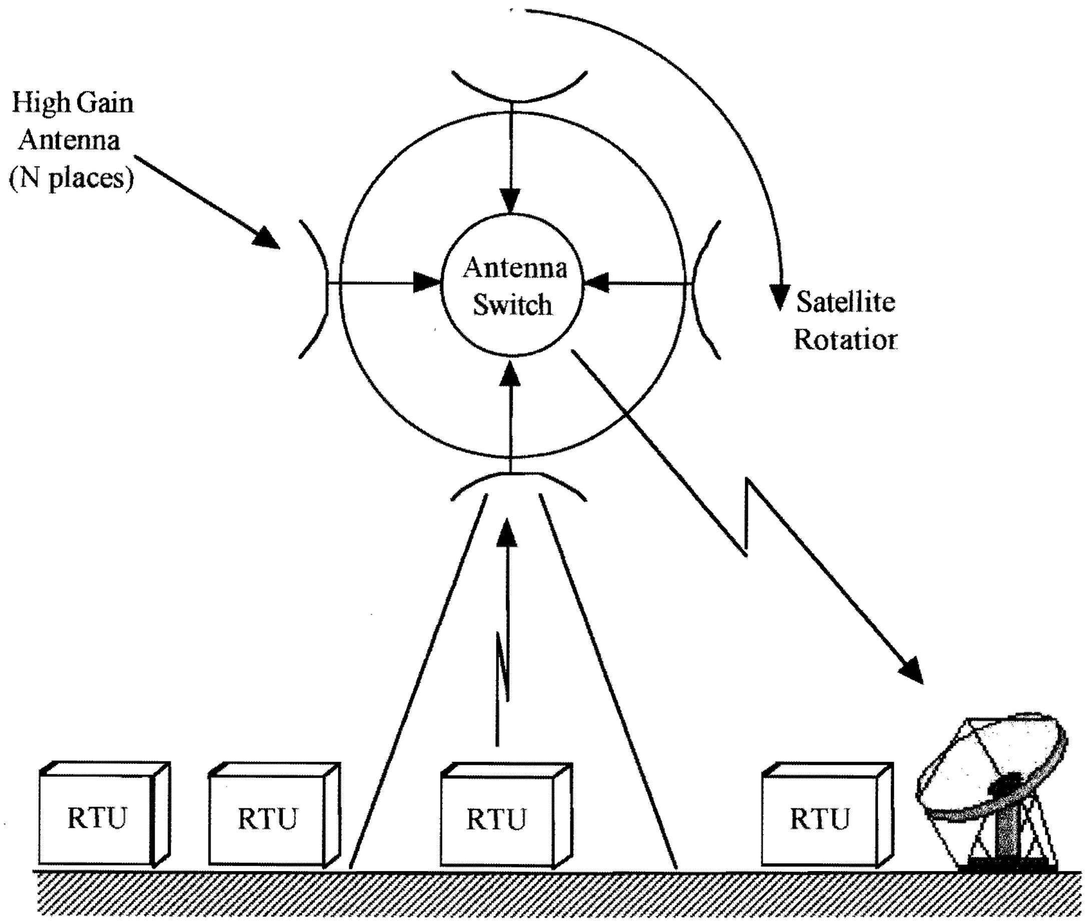

Figure 2: Scanning High Gain Antenna Concept (Spin Stabilized Option)

1. Spin the satellite such that the spin axis is colinear with the orbit normal, orienting the HGA with its boresight normal to the spin axis. As the satellite spins, the HGA is swept over the service area. This also provides attitude stabilization to the spacecraft. Multiple HGA's can be placed around the body to provide continuous or near-continuous coverage. An RF switch is then used to select an antenna pointed "down".
2. Use a nadir pointed satellite with multiple HGA's and switch between them to scan across the service area.
3. Use a nadir pointed satellite with a single HGA that can be mechanically or electronically scanned across the service area.
4. Use a nadir pointed satellite with a single HGA that is fixed in the body and allow the orbital motion of the vehicle to slowly scan the HGA across the service area.

Using a scanning HGA to provide coverage of the service area creates periods of illumination and non-illumination for the RTU's. Messages then must be short in comparison to the period of illumination. Of course, message that are longer than can be fit into a single illumination can be broken into shorter, more manageable messages and reconstructed at the GS. There are two ways that the system can be managed to guarantee that data messages get from the RTU to the GS: a generic tone can be sent by the spacecraft through the HGA letting RTU's know when they are illuminated or the RTU's can simply broadcast "in the blind" a sufficient number of times to guarantee receipt. Either of these approaches are acceptable and each has advantages. Using a tone to "wake up" the RTU's reduces their power consumption and limits the radiated power density in the neighborhood of the transmitters. However, it requires all RTU's be fitted with a receiver, which may not be appropriate for the market being targeted. Having the RTU's broadcast "in the blind" by some repetition algorithm limits the complexity of the system, but results in higher power needs by the RTU's and may require extensive modeling of the radiated power to ensure that the system does not violate the strictures of its frequency use agreement. Having the RTU's broadcast multiple times does not seriously affect the total system throughput. If the algorithm is properly designed each message will find its way into the system no more than twice. Any transmission where the RTU in not in the field of view of an HGA will have no effect on system SNR or throughput - it does not get into the system.

Note that the scanning HGA limits the effect of the "near-far problem". The "near-far problem" is characteristic of CDMA systems where two signals of widely varying power are trying to pass information simultaneously. That is, when one is "near" and one is "far", the weaker signal often gets lost in the noise of the strong signal (often many tens of dB). In terrestrial systems, this is often overcome by active power compensation. In this case, the GS senses the relative levels of the incoming signal and directs the stronger signal to reduce its power. Obviously, this adds complexity to the system and requires active two-way communications. By properly shaping the HGA and using active gain control on the repeater, the near-far problem is reduced. Figure 3 shows the relative size of the illuminated area to the service area as it is scanned across the service area. The gain of the HGA is shaped such that the gain is increased for signals coming from positions where the distances from the RTU's are greatest. The maximum variation in signal strength due to distance is then 3 dB plus whatever error there is in the shaping of the antenna. Changes in the signal strength due to distance variations in the scan direction are compensated by active gain control in the satellite to GS link.

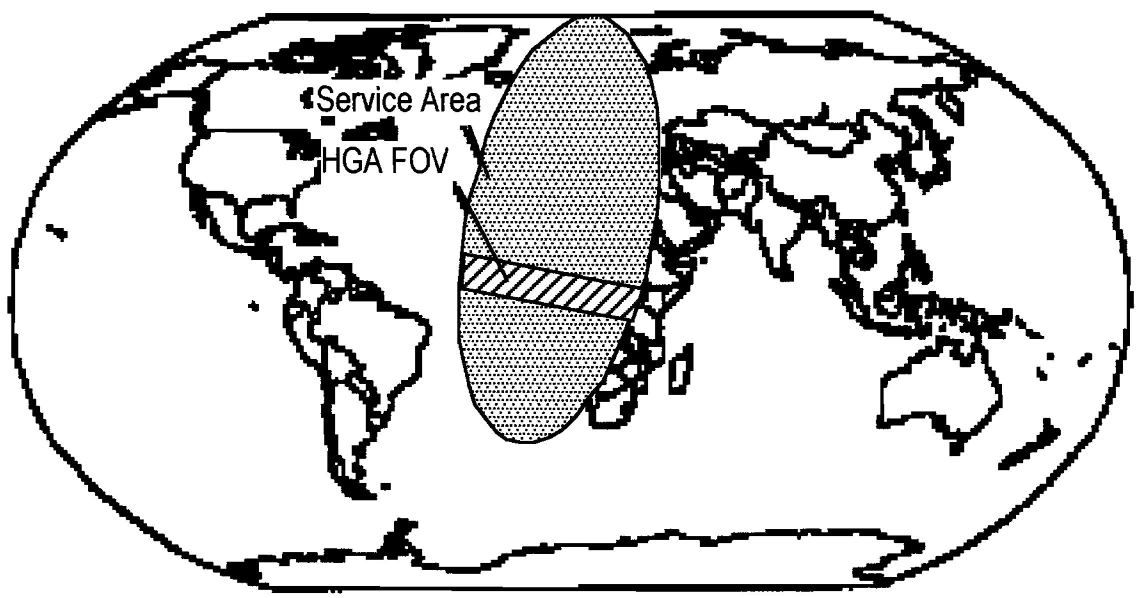

Figure 3: Satellite Service Area of Field of View of the Scanning High Gain Antenna

System Components

Now that the overall system architecture has been defined, the operation of specific components can be discussed.

Remote Terminal Unit

The RTU is the "front" of the communications system. It is the source of the data to be transmitted. Since there will be millions of RTU's spread throughout the world, its design must be robust, low cost, and easy to use. This leads to the use of an antenna with a hemispherical pattern. An RTU should be capable of transmitting data for a number of reasons:

1. Transmission is triggered by an event at the RTU
2. Transmission is timed to occur at some predetermined rate (e.g. once per week)
3. A transmission is requested by a radio command (transceive RTUs only)

This system is capable of supporting RTU transmissions without the RTU acknowledging that its message was received. The RTU guarantees message receipt by transmitting the message multiple times. There are several factors that can prevent a message from successfully passing through the system:

1. There is not a spacecraft within view of the RTU at the time of transmission
2. The spacecraft is in view, but its high-gain receive antenna is not pointed at the RTU
3. The RTU-spacecraft line-of-sight is partially occluded by buildings, foliage or the like
4. There is a collision with another RTU broadcast

Furthermore, the RTU should be as low-power as is feasible, for extended life as a battery-operated unit and capable of running off a portable power supply, battery or solar array. The standard data message from the RTU is short, but they can be strung together to form larger messages.

Satellite Constellation

The function of the satellite constellation is to relay data between the GS's and RTUs: as much intelligence as can be reasonably taken from the spacecraft and kept on the ground, should be. The linear translator directly transfers the spectra surrounding the uplink frequency to the same area surrounding the downlink frequency, amplifies it, and retransmits it: this functions both as the means to transfer data from the RTUs to the GS, and from the GS to any RTU in the service area. The satellites' responsibility is therefore primarily to remain functional in orbit, spread out in an evenly distributed constellation, with the repeater powered. A store and forward capability is also provided by a single decoder channel on the spacecraft. This allows the system to provide limited service to areas not in the vicinity of a GS. The messages from the RTU's will be stored on the spacecraft for downlink to the GS later in the orbit. Similarly, commands to the RTU's can be stored on-board for later downlink.

Ground Stations

Each ground station will receive RTU messages and spacecraft telemetry. The GS must decode discernible transmissions in this spectrum, record their individual Doppler shifts, check message integrity, and pass these messages along to the customer. The GS must also encode and transmit messages to the spacecraft, both for relay to an RTU and to command the spacecraft itself. By using four separate gold codes for each of these types of transmission: to and from RTUs; and to and from a spacecraft itself. The GS must be able to encode or decode each of these, as applicable. The GS also includes an algorithm to order the RTU commands to maximize command throughput. Because there are a limited number of gold codes, each RTU must monitor all of the commands receieved and identify commands to it by means of an identification code. The simplicity of the RTU design requires that it have only one CDMA decoder and so, can only extract one message at a time, locking up the decoder for the duration of the command message and thus limiting command throughput. An innovative allocation of RTU identifiers and innovative ordering of the outgoing commands allows each RTU to quickly recognize that a particular message is not for it and move on to decode the next message.

Conclusions

AeroAstro has been a leader in the small satellite industry for the past eight years with such programs as ALEXIS, HETE and TERRIERS, amongst others. Over the past few years we have developed a number of innovative solutions to the problems posed to low earth orbit communications systems. We believe that these technologies will enable a new class of LEO communications constellations that can service important and lucrative niche markets not served well by the larger constellations now coming on line. These innovations include, but are not limited to:

1. An RTU powered by a portable source, battery or solar array, capable of transmitting low data rate traffic through a simple hemispherical antenna
2. A method of transmitting short data messages or long messages broken into multiple smaller messages
3. A series of algorithms to guarantee transmission of data messages in a system with a scanning high gain antenna and the illumination and non-illumination periods inherent in such a system
4. A method of providing limited two-way communications such that commands can be issued to RTU's without requiring all RTU's to have receivers
5. A concept for managing RTU transmission in a scanning HGA system by means of a transmitted wake-up call via the HGA
6. Ordering of outbound messages to maximize command throughput
7. A system capable of providing both bentpipe and store-and-forward capability on the spacecraft, reaping the benefits of both systems without a significant increase in cost
8. The use of a scanning high gain antenna to provide near-realtime coverage to RTU's with inherently weak signals
9. A method to reduce the "near-far problem" by antenna shaping and automatic gain compensation