Mobile Telephony Through LEO Satellites: To OBP or Not

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GLOBALSTAR is a satellite-based mobile communications system that is interoperable with the current and future Public Land Mobile Network (PLMN) and Public Switched Telephone Network (PSTN). The selection of the transponder type, bent-pipe or on-board processing (OBP), for GLOBALSTAR is based on many criteria, each of which is essential to the commercial and technological feasibility of GLOBALSTAR. This paper describes the trade study that was done to determine the pros and cons of a bent-pipe transponder or an on-board processing transponder.

The design of GLOBALSTAR's telecommunications system is a multi-variable cost optimization between the cost and complexity of the individual satellites, the number of satellites required to provide coverage to the service areas, the cost of launching the satellites into their selected orbits, the ground segment cost, user equipment cost, satellite voice channel capacity and other issues. This paper focuses on the cost and complexity of the individual satellites, specifically the transponder type and the impact of the transponder type on satellite and ground segment cost, satellite power and weight, and satellite voice channel capacity.

Introduction to GLOBALSTAR

GLOBALSTAR is a satellite system which offers global mobile voice and data services and radio-determination satellite services (RDSS) to and from hand-held and vehicle-mounted transmit and receive devices. By combining the use of low-earth orbit (LEO) satellites with existing terrestrial communications systems and innovative, highly efficient spread spectrum techniques, the GLOBALSTAR system provides users throughout the world with low-cost, reliable communications. The system uses a constellation of 48 operating LEO satellites to provide optimum global coverage.

Because 90 percent of all traffic from a given point will be accommodated by a single gateway, GLOBALSTAR has been configured to link the mobile unit to a terrestrial gateway through a single satellite so that the system requires no satellite traffic crosslinks. GLOBALSTAR incorporates existing terrestrial communications facilities into its overall configuration through gateway earth station interfaces. The interoperability of GLOBALSTAR with the PSTN enhances the system's reliability and decreases costs to the end user by decreasing the complexity of the space segment. By complementing rather than supplanting existing carriers' networks and by sharing revenues with existing carriers, GLOBALSTAR can achieve rapid adoption throughout the United States and the world.

GLOBALSTAR proposes three alternative spectrum plans. For brevity, this paper will use only the one employing L-band with C-band feeder links. This system makes bidirectional use of the allocated RDSS spectrum in the L-band (1610-1626.5 MHz).

The GLOBALSTAR system is designed to operate compatibly with other LEO satellite systems providing RDSS, voice and data services and can operate without causing harmful interference to geostationary, RDSS systems, radio navigation systems and GLONASS. Moreover, the capacity of the GLOBALSTAR system will be only slightly degraded by operations from those systems.

Criteria & System Definition

The selection of transponder type, bent-pipe or OBP, was based on the simultaneous solution of many criteria: the complexity and cost of the individual satellites, the weight of the communications payload, the power requirements of the communications payload, the availability of equipment (or the amount of development required), satellite voice channel capacity, security (both for privacy and for fraud), and quality of service. There is also a trade-off in cost and complexity between the satellite and the gateways.

The 48-satellite constellation is the Walker 48/8/1 constellation (ref. 1) at an altitude of 1389 km. (750 nm.) with an inclination of 52 degrees. This constellation has 48 satellites in eight orbit planes, all with an inclination of 52 degrees. The phasing of the satellites from one plane to another is shifted by 7.5 degrees. This 48 satellite constellation provides 100% single coverage from the 65 degrees south latitude to 65 degrees north latitude with a minimum elevation angle (the angle from the horizon to the line of sight between the user and the satellite) of 10 degrees and provides 100% double coverage of the continental United States with a minimum elevation angle of 10 degrees with one satellite at a higher elevation angle than 15 degrees.

With the satellite constellation in a non-polar, inclined orbit, the coverage is constantly changing for a particular point on the earth (although it is predictable): sometimes the covering satellite is moving northeast, sometimes southeast; sometimes there are three or four satellites in view. As the coverage areas for the satellites move across one another, there will be self-interference (or the system has to be tightly controlled to prevent it). This will be taken into consideration in determining the transponder. There might also be interference from other operators.

With the satellite constellation defined, the satellite lifetime defined (7.5 years), input from market studies and input regarding the usage of cellular phones, a program was run to see the maximum number of circuits required during the busy hours in the seventh year of operation. In the seventh year, there will be approximately 1.5 million users which will require a satellite capacity of 1900 channels during the busy hour.

Code Division Multiple Access (CDMA) is the access of choice. CDMA achieves its high capacity by achieving more effective frequency reuse than other methods. This technique allows a statistical averaging principle known as the "Law of Large Numbers" to come into effect with the result that frequency reuse is more efficient than with Frequency Division Multiple Access (FDMA) or Time Division Multiple Access (TDMA) techniques. The CDMA technology used in this system exploits the following techniques in obtaining high spectral efficiency: voice activity, error detection and correction, efficient demodulation, antenna directivity (spot beams) and multiple satellites.

Spot beams are required to deliver the capacity required to and from the mobiles. GLOBALSTAR uses six elliptically shaped spot beams. The major axis of the elliptical beams are aligned with the velocity vector of the satellite movement in order to decrease the number of inter-beam handoffs. Figure 1 shows the six spot beams illuminating the United States.

The spot beams are designed to compensate for the difference in the satellite-to-user link losses between the "near" and "far" users, so that the power flux density of the "far" users is about the same as the "near" users (*isoflux* design). This antenna design reduces the near-far problem, decreases the range of power control required for CDMA and increases the capacity of the system. Figure 2 shows a cross cut of the antenna pattern.

Typical isoflux coverage.
Beams 2 and 5 (shaded) are illuminated
in pairs, as are beams 1–4 and 2–5.

Figure 1 **Spot Beams on the US**

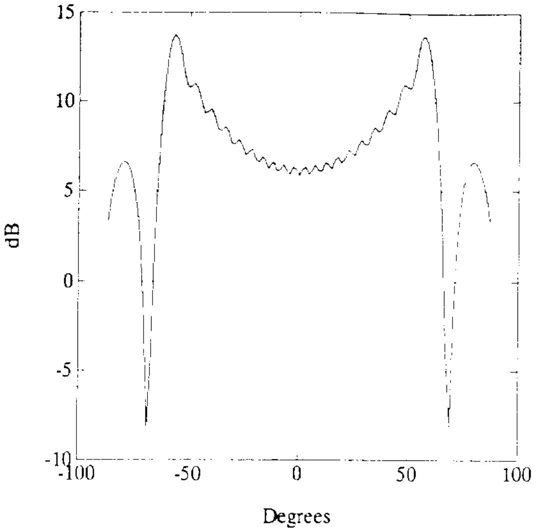

Figure 2 **Isoflux Antenna Pattern**

The multiple access technique used for the system is Time Domain Duplex-Frequency Division-Code Division Multiple Access (TDD-FD-CDMA). The most efficient method of using L-band in both the user-to-satellite and satellite-to-user directions is TDD. The 16.5 MHz at L-band is divided into 13 sub-bands of 1.25 MHz CDMA channels with each channel being TDD. There are multiple CDMA users in a 1.25 MHz channel. The frequency plan of how the user uplinks are translated to the gateway downlinks is shown in Figure 3. Beam hopping is used to minimize the interference from one beam to another beam and decrease the interference to/from other systems. The system has a 60 msec TDD frame with six 10 msec time slots. Three time slots are allocated for transmit and three time slots are allocated for receive. Within an individual time slot, the signals will either transmit or receive two of the six beams (e.g. beams one and four, or beams two and five, or beams three and six). This is shown in Figure 4.

The system trade-off left the following limits on the satellites: the cost could not be more than $10 million per satellite; the DC power required by the communications payload could not be more than 750 watts; the satellite could not weight more than 500 kilograms.

A block diagram was designed for the transponders (shown in Figure 5) which shows where the OBP equipment would be placed.

Link Budgets

Link budgets were produced for the bent-pipe satellite and the OBP satellite to compare the capacity and power consumption of the two different transponders. The bent-pipe link budget is shown in Figure 6 and the OBP link budget is shown in Figure 7.

Each Figure has both the forward path (Gateway to User - columns B and H) and the return path (User to Gateway - columns C and G) as both paths need to be examined to see the trade-offs in the system regarding the link budgets. Lines six through 15 calculate the EIRP. In the ground to space links,

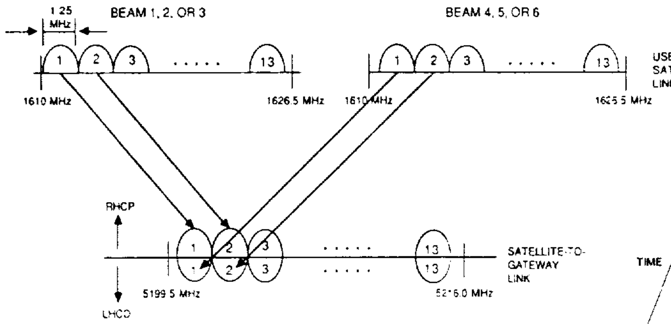

Figure 3 **Frequency Plan**

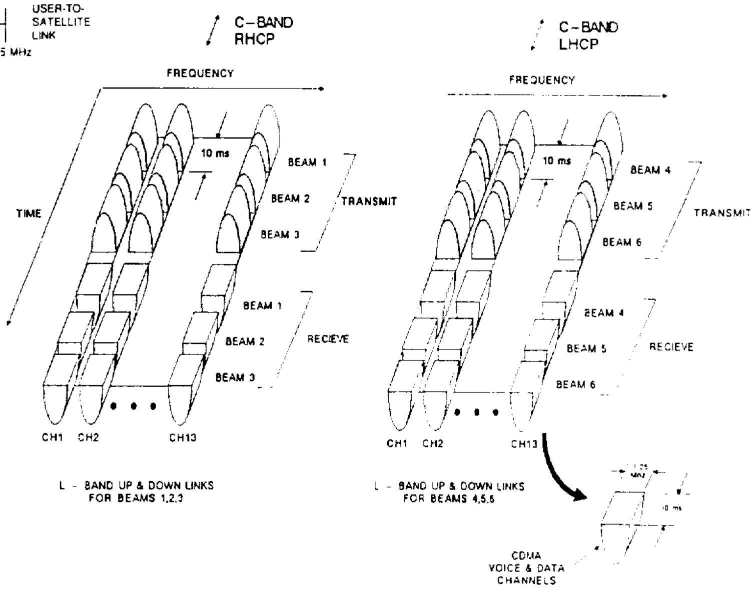

Figure 4 **TDD-FD-CDMA**

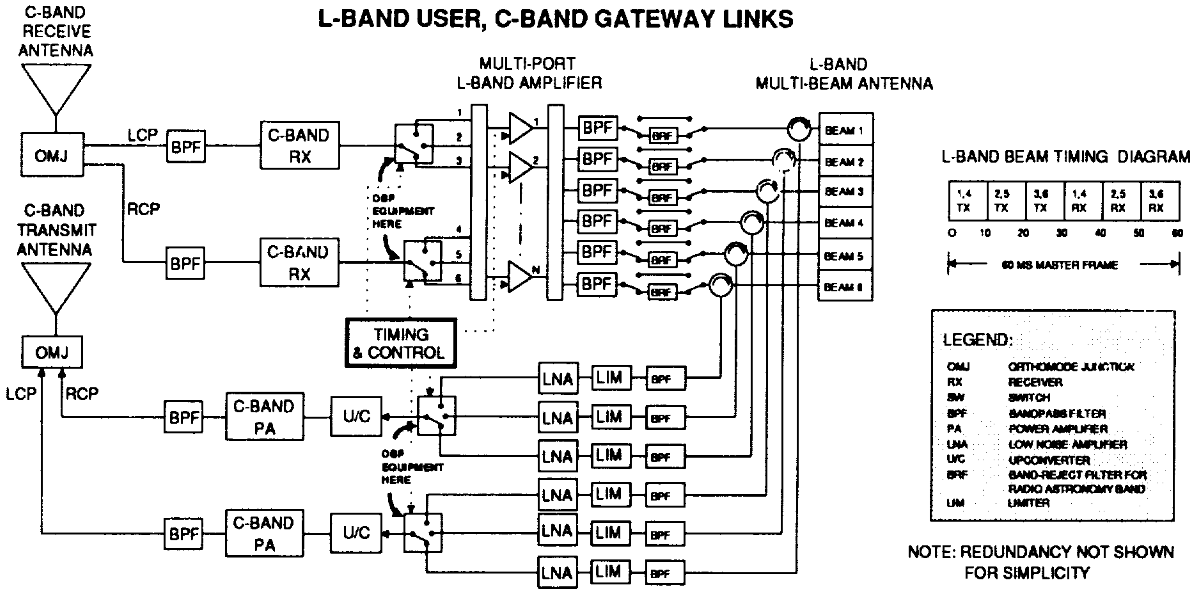

Figure 5 **Transponder Block Diagram**

the power is EIRP/user whereas in the space to ground links the power is EIRP/1.25 MHz channel. The number of users denoted is the number of users in a 1.25 MHz channel. Due to the beam hopping and TDD operation, a transmitter is only on for 1/6 of the time, therefore the transmitter power shown is the power required when the system is transmitting - not the average power.

As spacecraft antenna are isoflux, the elevation angle does not affect antenna gain minus space loss. The antenna gain increases as the space loss increases. The antenna gain shown is the gain with regard to the space loss at nadir (that is why the space loss used is the loss at nadir). There are three antennas at each gateway and each of the antennas track a specific satellite in view. A 1 dB tracking loss is taken. The transmitted data rate is six times the actual data rate due to the beam hopping and TDD operation.

All the links are chip synchronous CDMA except for the user to satellite links. Orthogonal codes are used so there is literally no self-interfence in those links. There are 128 orthogonal codes based on Walsh functions. There is very little self-interference on the gateway to satellite uplink. The gateways and satellites (in the OBP case) use convolutional, rate 1/2, constraint length 9 encoders with interleaving. The user unit uses a convolutional, rate 1/3, constraint length 9 encoder. There is a 1.3 dB interference margin required for the fading, blockage and power control. In the bent-pipe user to gateway link, a 1.0 dB modem/Doppler loss is taken due to the Doppler estimation required by the gateway. This is much more accurate in the OBP user to satellite link because the satellite can make faster and more accurate Doppler estimations.

	A	B	C	D	E	F	G	H	I
1									
2		ES to	User to				Satellite	Satellite	
3		Satellite	Satellite				to ES	to User	
4									
5	Frequency	6530.0	1625.0	MHz		Frequency	5205.0	1625.0	MHz
6	RF Power/User (peak)	0.2	6	Watts		RF Power/sub-band (peak)	1.2	16	Watts
7		-7.0	7.8	dBW			0.8	12.0	dBW
8	Power Loss	-1.0	-1.0	dB		Power Loss	-1.5	-2.2	dB
9	Antenna Gain	40.2	2.0	dBi		S/C Ant. Gain (Isoflux)	1.0	6.5	dBi
10	EIRP	32.2	8.8	dBW		EIRP	0.3	16.3	dBW
11	No. Users, u	25.0	25.0			Pilot Power	0.0	-0.2	dB
12	Voice Duty Cycle	37.5	37.5	%		No. Users & Interferers, u	27.0	25.0	
13	-10*log (u*d)	-9.7	-9.7	dB		Voice Duty Cycle, d	37.5	37.5	%
14						-10*log (u*d)	-10.1	-9.7	dB
15						EIRP/channel	-9.8	6.4	dBW
16									
17	Satellite Altitude-750 NM	1389.0	1389.0	km		Satellite Altitude-750 NM	1389.0	1389.0	km
18	Elevation Angle	90.0	90.0	degrees		Elevation Angle	90.0	90.0	degrees
19	Range	1389.0	1389.0	km		Range	1389.0	1389.0	km
20	Free Space Loss	-171.6	-159.5	dB		Free Space Loss	-169.7	-159.5	dB
21	RX Signal Strength	-139.4	-150.8			RX Signal Strength	-179.4	-153.1	
22	Polarization Loss	-1.0	-0.5	dB		Polarization Loss	-1.0	-0.5	dB
23	Tracking Loss	-1.0	0.0	dB		Tracking Loss	-1.0	0.0	dB
24	S/C Ant. Gain (Isoflux)	1.0	6.5	dBi		Antenna Gain	38.2	2.0	dBi
25	RX Line Losses	-1.2	-1.0	dB		RX Line Losses	-1.0	-0.5	dB
26	Data Rate, Rb	28800.0	28800.0	bps		Data Rate, Rb	28800.0	28800.0	bps
27	-10*log(Rb)	-44.6	-44.6	dB/Hz		-10*log(Rb)	-44.6	-44.6	dB/Hz
28	Eb	-186.2	-190.4	dBW/Hz		Eb	-188.8	-196.7	dBW/Hz
29									
30	LNA Temp.	170.0	75.0	degree K		LNA Temp.	65.0	75.0	degree K
31	Ant. Noise	290.0	290.0	degree K		Ant. Noise	150.0	200.0	degree K
32	Total Thermal Noise	460.0	365.0	degree K		Total Thermal Noise	178.8	264.0	degree K
33	Thermal Noise Density, No	-202.0	-203.0	dBW/Hz		Thermal Noise Density, No	-206.1	-204.4	dBW/Hz
34									
35	Single Interferer Power	-141.6	-145.8	dBW		Single Interferer Power	-144.2	-152.1	dBW
36	Equivalent # of Interferers	0.0	2.0			Intra/InterBeam Interference	-134.3	-148.4	dBW
37	Self Interference	-155.0	-147.0	dBW		InterSatellite Interference	0.0	25.0	%
38	Other System Interference	-155.0	-155.0	dBW		Self Interference	-134.3	-145.8	dBW
39	Total Interference	-152.0	-146.4	dBW		Other System Interference	-155.0	-155.0	dBW
40	Spreading Bandwidth	1.25	1.25	MHz		Total Interference	-134.3	-145.4	dBW
41	-10*log(spreading BW)	-61.0	-61.0	db/Hz		Spreading Bandwidth	1.25	1.25	MHz
42	Pseudo-Noise Density, Io	-213.0	-207.3	dBW/Hz		-10*log(spreading BW)	-61.0	-61.0	dB/Hz
43						Pseudo-Noise Density, Io	-195.3	-206.3	dBW/Hz
44									
45	Thermal, Eb/No	15.8	12.6	dB		Thermal, Eb/No	17.3	7.7	dB
46	Pseudo Noise, Eb/Io	26.8	17.0	dB		Pseudo Noise, Eb/Io	6.4	9.6	dB
47	Uplink Eb/(No+Io)	15.4	11.3	dB		Downlink Eb/(No+Io)	6.1	5.5	dB
48						C/I (Intermodulation)	23.0	15.0	dB
49						Overall Thermal, Eb/No	11.3	7.0	dB
50						Overall Interference, Eb/Io	6.4	8.8	dB
51						Overall Eb/(No+Io+M)	5.2	4.7	dB
52									
53	Number of L Band Beams		6			Modem Implem/Doppler Loss	-1.0	-0.5	dB
54	Number of SubBands		13			Eb/(No+Io) Required	3.0	3.5	dB
55	C Band Amplifier Efficiency		18	%		Interf/Power Control Margin	1.3	1.3	dB
56	L Band Amplifier Efficiency		35	%		Thermal Noise Margin	1.0	1.0	dB
57	Number of Beams Transmitting at Once		2			DC POWER		681.0	Watts
58						TOTAL Mobile BW		16.50	MHz
59						TOTAL USERS		1950.0	

	A	B	C	D	E	F	G	H	I
1									
2		ES to	User to				Satellite	Satellite	
3		Satellite	Satellite				to ES	to User	
4									
5	Frequency	6530.0	1625.0	MHz		Frequency	5205.0	1625.0	MHz
6	RF Power/User (peak)	0.1	3.5	Watts		RF Power/channel (peak)	0.1	15	Watts
7		-10.0	5.4	dBW			-10.0	11.8	dBW
8	Power Loss	-1.0	-1.0	dB		Power Loss	-1.5	-2.2	dB
9	Antenna Gain	40.2	2.0	dBi		S/C Ant. Gain (Isoflux)	1.0	6.5	dBi
10	EIRP	29.2	6.4	dBW		EIRP	-10.5	16.1	dBW
11	No. Users, u	25.0	25.0			Pilot Power	-0.2	-0.2	dB
12	Voice Duty Cycle	37.5	37.5	%		No. Users & Interferers, u	25.0	25.0	
13	-10*log (u*d)	-9.7	-9.7	dB		Voice Duty Cycle, d	37.5	37.5	%
14						-10*log (u*d)	-9.7	-9.7	dB
15						EIRP/channel	-20.4	6.1	dBW
16									
17	Satellite Altitude-750 NM	1389.0	1389.0	km		Satellite Altitude-750 NM	1389.0	1389.0	km
18	Elevation Angle	90.0	90.0	degrees		Elevation Angle	90.0	90.0	degrees
19	Range	1389.0	1389.0	km		Range	1389.0	1389.0	km
20	Free Space Loss	-171.6	-159.5	dB		Free Space Loss	-169.7	-159.5	dB
21	RX Signal Strength	-142.4	-153.1			RX Signal Strength	-190.1	-153.4	
22	Polarization Loss	-1.0	-0.5	dB		Polarization Loss	-1.0	-0.5	dB
23	Tracking Loss	-1.0	0.0	dB		Tracking Loss	-1.0	0.0	dB
24	S/C Ant. Gain (Isoflux)	1.0	6.5	dBi		Antenna Gain	38.2	2.0	dBi
25	RX Line Losses	-1.2	-1.0	dB		RX Line Losses	-1.0	-0.5	dB
26	Data Rate, Rb	28800.0	28800.0	bps		Data Rate, Rb	28800.0	28800.0	bps
27	-10*log(Rb)	-44.6	-44.6	dB/Hz		-10*log(Rb)	-44.6	-44.6	dB/Hz
28	Eb	-189.2	-192.7	dBW/Hz		Eb	-199.5	-197.0	dBW/Hz
29									
30	LNA Temp.	170.0	75.0	degree K		LNA Temp.	65.0	75.0	degree K
31	Ant. Noise	290.0	290.0	degree K		Ant. Noise	150.0	200.0	degree K
32	Total Thermal Noise	460.0	365.0	degree K		Total Thermal Noise	178.8	284.0	degree K
33	Thermal Noise Density, No	-202.0	-203.0	dBW/Hz		Thermal Noise Density, No	-206.1	-204.4	dBW/Hz
34									
35	Single Interferer Power	-144.6	-148.1	dBW		Single Interferer Power	-154.9	-152.4	dBW
36	Intra/InterBeam Interference	0.0	20.0	dBW		Intra/InterBeam Interference	-152.1	-149.7	dBW
37	Self Interference	-155.0	-138.2	dBW		InterSatellite Interference	0.0	25.0	%
38	Other System Interference	-155.0	-155.0	dBW		Self Interference	-152.1	-146.1	dBW
39	Total Interference	-152.0	-138.1	dBW		Other System Interference	-155.0	-155.0	dBW
40	Spreading Bandwidth	1.25	1.25	MHz		Total Interference	-150.3	-145.9	dBW
41	-10*log(spreading BW)	-61.0	-61.0	db/Hz		Spreading Bandwidth	1.25	1.25	MHz
42	Pseudo-Noise Density, Io	-213.0	-199.1	dBW/Hz		-10*log(spreading BW)	-61.0	-61.0	dB/Hz
43						Pseudo-Noise Density, Io	-211.3	-206.9	dBW/Hz
44									
45	Thermal, Eb/No	12.8	10.3	dB		Thermal, Eb/No	6.6	7.4	dB
46	Pseudo Noise, Eb/Io	23.7	6.4	dB		Pseudo Noise, Eb/Io	11.8	9.9	dB
47	C/I (Intermodulation)	50.0	50.0	dB		C/I (Intermodulation)	23.0	15.0	dB
48	Uplink Eb/(No+Io+M)	12.4	4.9	dB		Downlink Eb/(No+Io+M)	5.4	4.9	dB
49									
50	Modem Implem/Doppler Loss	-0.5	-0.5	dB		Modem Implem/Doppler Loss	-0.5	-0.5	dB
51	Eb/(No+Io) Required	3.7	3.2	dB		Eb/(No+Io) Required	3.7	3.7	dB
52	Interf/Power Control Margin	0.5	1.3	dB		Interf/Power Control Margin	0.5	1.3	dB
53	U/L Thermal Noise Margin	6.5	1.0	dB		D/L Thermal Noise Margin	1.5	1.0	dB
54									
55	Number of L Band Beams		6			DC POWER		564.4	Watts
56	Number of SubBands		13			TOTAL Mobile BW		16.50	MHz
57	C Band Amplifier Efficiency		18	%		TOTAL USERS		1950.0	
58	L Band Amplifier Efficiency		35	%					
59	Number of Beams Transmitting at Once		2						

Figure 6 **Bent-Pipe Link Budget**

Figure 7 **OBP Link Budget**

For the bent-pipe links, the user to satellite has an additional 10% of the users due to interbeam and intersatellite interference. Also note that this additional power is used on the satellite to gateway downlink because it is a bent-pipe (all that is received is transmitted). The satellite to user downlink has 20% of intra-satellite interference and 25% inter-satellite interference. The satellite to gateway link is the limiting link due to the fact that the users within a channel are not chip-synchronous. This self-interference is the limiting factor for the bent-pipe transponder. The bent-pipe satellite can support 1950 simultaneous duplex calls and required 681 watts of DC power (while transmitting).

For the OBP links, the user to satellite path has an additional 10% interference along with the non-synchronous users in each channel. As in the bent-pipe case, this link is the limiting path. The satellite to user downlink and the satellite to gateway downlink have 20% if intra-satellite interference while the satellite to user path has an additional 25% due to inter-satellite interference. The OBP satellite can support 1950 simultaneous duplex calls while requiring only 565 watts of DC power for the transmitters. This does not take into account the additional power required for the OBP digital equipment and control.

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However, the OBP satellite is not limited to 1950 calls. The OBP satellite can serve up to 2300 duplex calls until the user to satellite path self-interference limits the number of users (the required communications payload power is 720 watts).

Comparison

The link budgets show that the OBP transponder is more RF power efficient than the bent-pipe transponder (0.29 watts/call versus 0.35 watts/call for the bent-pipe transponder, an 18% savings). However, the power required for the digital equipment of the OBP transponder is not taken into account. For 1950 duplex calls, 2000 to 3900 modems are required depending on the design of the satellite-to-gateway links (only 2000 modems if TDMA is used for the satellite-to-gateways links). For the OBP transponder to be more power efficient than the bent-pipe transponder, the D.C. power of modem needs to be less than 0.06 watts each. It is not believed that this can be achieved until after the mid 1990's. Currently, this type of CDMA modem requires a power consumption of approximately 0.5 watts. This raises the call power from 0.29 watts/call to over 1.2 watts/call. This higher call power is 368% more than the bent-pipe transponder. Therefore, the bent-pipe transponder is more power efficient than the OBP transponder when the power for the OBP equipment is added.

There is more volume required for the OBP payload than the bent-pipe payload and the OBP payload dissipates more power. This extra dissipation could present a problem for small spacecraft. The OBP satellite will be more complex than the bent-pipe satellite, requires more design effort, and the risk is higher.

The OBP transponder does have advantages. The OBP transponder makes better use of the satellite's EIRP by only transmitting the signals of the calls going through **that** satellite (whereas a bent-pipe satellite transmits everything it receives). This gives an increase in call capacity for a given region due to decreased interference and the OBP satellite is able to make better use of satellite double coverage. For CDMA operation, the OBP transponder will have better power control. Also with an OBP transponder, the call set-up procedure can be moved to the satellite.

The cost and complexity of the OBP satellite gateways versus the bent-pipe satellite gateways depends on the design of the OBP gateway-to-satellite links. By using TDMA links, the OBP gateway costs might be higher than the bent-pipe solution. By using CDMA links, the OBP gateway costs might be lower than the bent-pipe gateway costs, but doubles the number of modems in the satellite from 1950 to 3900. The price of a space qualified CDMA modem is not available today since no qualified unit exists. However, it is obvious a cost increase will be incurred with an OBP transponder. For example, 3900 CDMA modems reduced to a single VLSI chip when space qualified would be on the order of $500 each. At this cost, the price of a satellite chip set is nearly two million dollars not including other OBP equipment, integration, and test. A 48 satellite set would incur additional costs of $100 million not including the additional satellite cost of the increased power requirements.

Another decisive factor is the non-standardization of the cellular systems in the world today. The GLOBALSTAR system must be compatible with many types of mobile operations. Europe, the United States and Japan all have different standards. A bent-pipe transponder allows for these different standards to be used with the satellite. There is not enough flexibility in an OBP transponder to handle the different standards and protocols.

Conclusions

The first generation GLOBALSTAR satellite will be bent-pipe due to the flexibility of the transponder to handle different signal formats. A bent-pipe transponder offers inexpensive capacity to users without the prohibitive research and development, power and cost requirements that would be incurred with an OBP solution. The bent-pipe communications subsystem is a classic repeater which uses existing satellite communications techniques and many off-the-shelf parts. This keeps the nonrecurring research and development costs low as well as keeping the satellite equipment and testing costs low. Table 1 give an overview of the comparison between OBP and bent-pipe.

Table 1
Transponder Comparison

	OBP	Bent-Pipe
Cost/Channel		X
Signal flexibility		X
Payload Complexity		x
Capacity	x	
Use of Multi-coverage	X	
Payload Power		X
Payload Weight		x
Payload Volume		x
Thermal		x
Risk		x
R&D Required		x
Gateway Cost	-	-
Signal Quality†	x	

† at maximum capacity

The return link self-interference due to the non-synchronous CDMA operation limits the capacity of both the bent-pipe and OBP transponders. The OBP transponder is limited to 2300 simultaneous duplex calls while the bent-pipe transponder is limited to 1950 simultaneous duplex calls. However, the OBP transponder will use more power than the bent-pipe transponder, which is critical for this LEO satellite system.

Acknowledgements

The authors wish to express their gratitude to the team of people who contributed to the GLOBALSTAR FCC filing. From Loral Aerospace: Alex Tsao, Randy Tyner, Andy Turner, Steve Ames, Vic Mosley and Dr. Bob Kwan; from Alcatel Espace: Denis Rouffet, Patricia Jung, Jean-Francois Migeon, Frederic Berthault and Yannick Tanguy; from Qualcomm Inc.: Allen Salmasi and Klein Gilhoussen - each person gave technical assistance in developing the GLOBALSTAR system and contributed a significant set of ideas to this paper.

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