GLOBAL MOBILE SATELLITE COMMUNICATIONS: A REVIEW OF THREE CONTENDERS*

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Abstract

The era of satellite-based mobile communications systems started with the first MARISAT satellite which was launched into a geostationary orbit over the Pacific Ocean in 1976 to provide communications between ships and shore stations. The combination of high cost and unacceptably large equipment has kept mobile satellite communications (MSC) systems from appealing to the wider market of personal mobile communications. However, the progress made over the last ten years in digital voice processing, satellite technology, and component miniaturization has resulted in the viability of MSC systems in responding to the growing market in personal mobile communications. Three of the more mature proposed LEO/MEO satellite systems, Globalstar, IRIDIUM, and Odyssey, are addressed in this paper. The system architectures of each system are presented along with a description of the satellite and user handset designs, the multi-access techniques employed, and an analysis of their respective cost structures. It will be shown that, although a number of similarities exist amongst the systems addressed in this paper, each system is unique in a variety of significant design areas. Finally, the regulatory concerns affecting all of the proposed mobile satellite systems will be addressed along with the status of the license applications to the Federal Communications Commission (FCC).

It is concluded in this paper that the technical feasibility of satellite-based mobile communications systems seems to be secure. It will be challenging however, for the vendors to actually develop and deploy these systems in a cost effective, timely, and reliable way that meets a continually evolving set of requirements driven by user expectations fueled by a rapidly changing technology base.

I. Introduction

The era of Mobile Satellite Communications (MSC) systems started with the first MARISAT satellite which was launched into a geostationary orbit over the Pacific Ocean in 1976 to provide communications between ships and shore stations. Two more satellites were launched in 1976 and were located above the Atlantic and Indian Ocean regions. Comsat General Corporation operated those satellites until the L-band capacity was leased to Inmarsat in 1982. The ship stations operated at L-band with a 40W transmitter and a 1.2 meter dish antenna having a gain of 23.5 dBi [1,2].

Up until recently, the primary application for satellite-based mobile communications systems has been in ship-to-shore communications where the price for a basic telephone connection using Inmarsat is on the order of $10 per minute for calls terminating within the United States (US), and using US coastal earth stations [3]. The combination of available technology, acceptable terminal size for shipboard applications, and economic tradeoffs for ship-to-shore use resulted in <u>space-based</u> mobile communications systems whose cost for service and large equipment were unacceptable to the wider

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potential market for personal mobile communications which has, over the last ten years, been finding acceptable service solutions from land-based implementations.

Less than ten years after the introduction of the first personal mobile (or cellular) communications systems, the worldwide cellular market currently stands at more than 10 million subscribers (3 million more than the number anticipated in 1983 to be achieved by the year 2000) and is growing at a significant rate [4]. Until now, all cellular mobile communications systems have been land-based and geared to meeting the increasing demand of large cities and industrial areas. However, MSC systems have recently become technically feasible due to the significant progress made over the last ten years in the areas of digital voice processing, satellite technology, and component miniaturization. The purpose of this paper is to provide a comparison of three such proposed systems, taking into consideration technical, financial, and regulatory issues. The systems addressed are Globalstar, IRIDIUM, and Odyssey[1]. The system architecture of each is presented along with a description of the satellite and user hand-held terminal design, the multi-access technique employed, and an analysis of the proposed cost structure. It will be shown that, although a number of similarities exist amongst the systems addressed in this paper, each system is unique in a variety of significant design areas. Finally, the regulatory concerns affecting all of the proposed mobile satellite systems will be addressed along with the status of the license applications to the FCC.

II. Discussion

General: The MSC systems fielded or imminent utilize satellites in geostationary orbits [2,11,12]. The altitude of a geostationary satellite is almost 36,000 km resulting in a minimum one-way, single hop time delay of approximately a quarter of a second accounting only for the speed of light transmission delay. Signal processing delays further add to the overall delay. Furthermore, the long path lengths associated with geostationary satellites result in the need for either more sophisticated satellite designs (in the areas of increased amplifier power and antenna gain) or more capable user terminals which typically translates into increased size. For these reasons, most of the newly proposed space-based MSC systems involve low Earth orbit (LEO) or medium Earth orbit (MEO) constellation designs. Of the three MSC systems addressed in this paper, the Globalstar and IRIDIUM systems are in the LEO category while Odyssey is a MEO design.

In the parlance of the regulatory community, these three systems, together with Aries and Ellipso, are referred to as Big LEOs since they would provide the full range of mobile satellite services (MSS) including voice and data and operate in the 1 to 3 GHz band[2]. In 1992, the World Administrative Radio Conference (WARC 92) allocated spectrum for MSS in L- and S-bands on a primary worldwide basis thus removing a significant regulatory hurdle facing the proposed Big LEO systems.

The Globalstar system is under development by Loral Qualcomm Satellite Services, Inc. (LQSS) with Loral Aerospace Corporation and QUALCOMM, Inc. each controlling 51% and 49% of the company, respectively. The FCC license application was submitted on 3 June 1991 and, as is the case which each of the other systems, LQSS is awaiting a final decision [5].

The IRIDIUM system is under development by Motorola Satellite Communications, Inc. The FCC license application was submitted on 3 December 1990 [6,7]. The name “IRIDIUM” was chosen since the picture of 77 satellites (the number of satellites in the original IRIDIUM design) in near-polar orbit around the Earth resembled the classical model of an atom surrounded by electrons. The element having an atomic number of 77 is IRIDIUM; however, a recent modification to the IRIDIUM application has changed the number of satellites to 66. There are no plans to change the name to Dysprosium.

Finally, the Odyssey system is under development by TRW, Inc. The FCC license application was submitted on 28 May 1991 [8].

Each of the systems will interface with the Public Switched Telephone Network (PSTN) as well as the Public Land Mobile Network (PLMN). All three of the vendors are quick to point out that they intend to complement and extend the coverage of existing telephone networks and not to compete with them.

The anticipated operational date for each of the systems was originally sometime in calendar year 1998 (CY98) but is likely to be delayed until at least 2000. Motorola applied for and received an experimental license from the FCC. Within the context of this license, Motorola plans to construct and launch five IRIDIUM satellites with the first launch scheduled for CY94 or CY95. TRW plans to perform ground-based demonstrations and testing. LQSS did not apply for an experimental license claiming that the high degree of in-house experience between Loral Aerospace Corporation and QUALCOMM, Inc., relating to both space and ground equipment, precluded the need for testing.

The next several sections provide a more detailed discussion of the system architecture, satellite design, multi-access scheme, user handsets, cost structure, and regulatory issues germane to each of the three systems addressed in this paper.

System Architecture: The primary features of the system architectures are presented in Table 1. Three categories of data are presented which include characteristics pertaining to the constellation design, the frequency plan and selected operational parameters.

The Globalstar system includes 48 LEO satellites at an altitude of 1401 km and equally divided into 8 orbital planes. The orbits are circular with an inclination angle of 52 degrees. The IRIDIUM system includes 66 LEO satellites at an altitude of 785 km and equally divided into 6 orbital planes. Finally, the Odyssey system includes 12 MEO satellites at an altitude of 10,354 km and equally divided into 3 orbital planes. Note that a smaller number of satellites is required to provide global coverage for the Odyssey system since the satellite altitude is significantly higher than either Globalstar or IRIDIUM.

The mobile user frequency plan is the same for Globalstar and Odyssey, with the uplink (i.e., user to satellite) in the 1.610 GHz to 1.6265 GHz band and the downlink (i.e., satellite to user) in the 2.4835 GHz to 2.5 GHz range. IRIDIUM is unique in two ways. First, Motorola plans to use the same frequency range for both uplink and downlink transmissions. Second, a truncated version of the available frequency range is used. That is, the low end of the frequency range is 1.616 GHz versus 1.610 GHz resulting in a 10.5 MHz system bandwidth versus 16.5 MHz for Globalstar and Odyssey. Using the same frequency band on both the uplink and downlink for IRIDIUM is possible since the system employs a time division duplexing scheme of time division multiple access (TDMA) signals to prevent interference. This will be covered in greater detail in the multi-access section.

The IRIDIUM satellite enjoys the largest capacity at 3840 full duplex (FDX) circuits/satellite followed by Globalstar and Odyssey, respectively, with 2800 circuits/satellite and 2300 circuits/satellite. It should be noted that the “per satellite” capacity is not cumulative due to self interference and beam overlap considerations. For example, it is claimed by LQSS that dual satellite coverage for the Globalstar system over the Continental United States (CONUS) will result in a system capacity of approximately 5000 circuits.

The average satellite connection time for a user is similar for Globalstar and IRIDIUM, due to the similarity in orbital altitudes for each system, and is in the 10 minute range. Odyssey, on the other hand, enjoys a two hour average connection time due to the higher constellation altitude. Each of the vendors however, claims that its system will result in "seamless" satellite-to-satellite handovers thereby making the average connection time a moot parameter relative to system performance. The final parameter listed in table 1 is the minimum elevation angle. Again, the Globalstar and IRIDIUM systems exhibit similar performance with a minimum elevation angle of 10 degrees and 8.2 degrees, respectively. The minimum elevation angle for Odyssey is significantly higher at 22 degrees which is again due to the higher constellation altitude. The higher minimum elevation angle for Odyssey could result in a more uniform level of performance, especially in metropolitan and mountainous regions.

Satellite Design: Several of the primary satellite design features of each of the systems are shown in table 2. Each satellite is 3-axis stabilized with a mission life of between 5 and 15 years. The Globalstar and Odyssey satellites include traditional bent-pipe transponders whereas the IRIDIUM satellite would employ on-board processing techniques. This is a major design feature of the IRIDIUM system and is essential to support the satellite-to-satellite crosslinks which will circumvent the need to downlink voice and data traffic to intervening hub stations. IRIDIUM is the only design of the three to include satellite crosslinks. Four crosslinks would exist on each satellite; one forward within a plane, one backward within a plane, and two cross-plane links. The satellite crosslinks would operate at 25 Mbps in the 22.55 GHz to 23.55 GHz frequency range. Satellite tracking may be challenging in this design since satellites in adjacent planes travel in opposite directions. The onboard processing feature, together with the satellite crosslink capability, provide increased flexibility in message routing at the expense of system design complexity. Motorola is aiming to be the first vendor to utilize these techniques in a commercial satellite system.

The dry masses of the satellites are currently estimated to be 704 lbs for Globalstar, 1100 lbs for IRIDIUM, and 2703 lbs for Odyssey. The IRIDIUM satellite is heavier than Globalstar primarily due to the additional crosslink communications payload together with the on-board processing equipment. The larger Odyssey satellite size is driven by: (1) the larger solar arrays and additional component shielding needed to protect the satellite against the increased radiation levels that exist at the higher orbital altitudes, and (2) the larger antennas needed to provide the increased gain requirements that result from a higher orbital altitude and increased path length.

The final component of interest in the satellite designs is the antenna system used to support the mobile user to satellite communications link. Globalstar uses a phased array antenna producing 16 spot beams. IRIDIUM uses three phased array antennas, each producing 16 beams, resulting in a total of 48 beams per satellite. Little additional detail is available on the IRIDIUM antenna design. Finally, Odyssey uses a rigidly mounted, multiple-beam antenna that produces 37 spot beams on the uplink and 32 spot beams on the downlink. The antenna is a "staring" antenna in that the satellite must be repositioned in order to adjust the coverage area. It should be noted that antenna coverage area adjustments are not expected to occur often in the Odyssey design.

Multi-Access Scheme: The multi-access schemes, depicted in figure 1, include some of the most interesting features of the systems studied in this paper. The tradeoffs between multiple access techniques for MSC systems are being actively pursued, with approaches incorporating some form of code division multiple access (CDMA) reflecting the current trend [13-15]. Such is the case with

Globalstar and Odyssey.

The multi-access scheme for Globalstar includes a CDMA signal spread across the entire 16.5 MHz of available bandwidth. It is claimed that this scheme will support a total capacity per satellite of 2808 FDX voice circuits assuming a 4.8 kbps transmission rate and a bit error rate (BER) of 1E-3. It should be noted that the CDMA design used in Globalstar exactly models the QUALCOMM, Inc. design currently used in their terrestrial applications.

The Odyssey multi-access scheme utilizes a combination of CDMA and frequency division multiple access (FDMA). The 16.5 MHz user bandwidth is divided into three 4.83 MHz channels that utilize CDMA to support multiple users per channel. One CDMA channel is assigned to each of the 16 antenna beams resulting in an aggregate capacity of 2300 FDX voice circuits at 4.8 kbps with an achievable BER of 1E-3. The three user channels are assigned distinct frequency bands (shown as A, B, and C in figure 1). The 16 beam pattern is designed such that no two adjacent spot beams (or channels) occupy the same frequency band.

The IRIDIUM multi-access scheme combines the features of both FDMA and TDMA. IRIDIUM is FDMA in that a 12 frequency re-use scheme is proposed over the 10.5 MHz bandwidth. One of the 12 frequencies is assigned to each of the 48 antenna cells/satellite. Frequency coordination is required both within the individual satellite's 48 cell pattern as well as between neighboring satellites. IRIDIUM is also a TDMA system, using a 90 ms TDMA frame to accommodate four 50 kbps user accesses per frame. The throughput calculations provided by Motorola are not fully described for the recently changed 66 satellite system design; however, it has been claimed that each cell supports an average of 80 channels per cell (maximum of 240) with each satellite nominally supporting (48 cells)x(80 channels/cell) or 3840 channels. The nominal global throughput (assuming that IRIDIUM can provide global coverage with 2150 cells as stated in their literature) is (2150 cells)x(80 channels/cell) or 172,000 channels. The relationships between accesses and frames and between accesses and channels are not fully described in the available IRIDIUM literature.

The IRIDIUM system will be required to: (1) coordinate cell utilization (i.e., turn the antenna beams on or off) to account for cell overlap as the satellites travel to the higher latitudes in their orbits, (2) coordinate cell frequency management (i.e., determine which of the 12 frequencies is to be used for each cell taking into consideration the desire to minimize adjacent cell interference) both within the satellite's 48 antenna beams and across satellite boundaries among neighboring satellites in a highly dynamic satellite motion environment, and (3) to accurately provide time synchronization to support the TDMA framing structure. The IRIDIUM system is certainly the most challenging of the three systems, from a multi-access standpoint, and will require sophisticated algorithms to be implemented to ensure proper operation.

Handsets: Several of the key user handset design features for each of the systems are shown in table 3. All three systems employ quadrature phase shift key (QPSK) modulation. Each of the systems employ forward error correction coding (FECC) in the form of convolutional encoding with Viterbi decoding [9,10]. IRIDIUM uses a rate 3/4, constraint length 7, (r=3/4;K=7) convolutional code on both transmission and reception at the user handset. Odyssey also uses the same coding scheme for both transmission and reception; however, the code rate is 1/3 with a constraint length of 7 (r=1/3;K=7). Globalstar, on the other hand, uses a rate 1/3 code rate with constraint length 9 for transmission (i.e., user transmitting to the satellite) and a rate 1/2 code with constraint length 9 for reception.[3]

The projected BER for voice is at worst 1E-3 for Globalstar and Odyssey and 1E-2 for IRIDIUM. It is uncertain how IRIDIUM will be able to provide acceptable voice quality at a BER of 1E-2; however, the voice encoding algorithms under development by Motorola have not been described in the literature to date. The supportable transmission rates for voice (data) are 4.8 kbps (2.4 kbps) for IRIDIUM and 4.8 kbps (1.2 - 9.6 kbps) for Odyssey. The Globalstar supportable transmissions rates for voice and data claimed by LQSS are between 1.2 kbps and 9.6 kbps depending upon channel conditions.

All three of the systems evaluated claim that the handsets will be similar in weight and overall dimensions to current terrestrial handsets. Each of the systems employ re-chargeable batteries but the battery lifetimes are described differently as shown in table 3. The Globalstar battery lifetime is the shortest at 8 hours assuming a 5% duty cycle. It is assumed that the limited achievable battery lifetime of 8 hours is directly related to the decision to pursue the smaller pocket calculator design as opposed to the larger cellular phone design approach chosen by Motorola and TRW. All three designs are claimed to support dual mode operations. That is, the handset can be used with the system in question or as a land-based handset directly interfacing with the PLMN.

Finally, the estimated initial prices for the handsets vary considerably as shown in table 3 with Odyssey projecting the least expensive handset selling for under $500, followed by Globalstar at $750, and IRIDIUM at $2000 to $3000. The cost of actually producing the dual mode units in large production quantities is expected to be only slightly higher than the cost of terrestrial cellular hand-held units.

Cost Structure: Since the initial filings with the FCC, the cost estimates for Globalstar and Odyssey have increased to reflect the impact of a larger satellite communications payload. LQSS is estimating that the cost of designing, producing and delivering 48 operational satellites on-orbit, along with the supporting ground segment, will be $1.7 billion in then year (TY) dollars. This is nearly double the original estimate. TRW has increased its original estimate by $200 million to $1.5 billion TY for non-recurring and recurring costs related to the satellite and ground segments, launch and the first year of operations.

Motorola has signed a firm fixed price contract with Iridium, Inc. for $3.37 billion TY to cover the cost of designing, producing and launching the initial constellation of 66 satellites, plus six spares, as well as the design and construction of the ground segments[4]. This figure is actually about $500 million less than the estimate for the former 77-satellite constellation presented in the original FCC filing. The cost to operate and maintain the system for the first five years is projected to be $2.8 billion TY.

In order to field the systems within the estimated cost structures and schedules, each proposer faces difficult challenges. Globalstar and IRIDIUM require the development of satellite production lines capable of delivering one unit per week. It is likely that this could require a larger investment of time and money than either has anticipated. On the other hand, Odyssey employs the fewest satellites and utilizes a standard bus design. While Odyssey's schedule and budget are aggressive, they seem more likely to be achievable without revolutionary changes to spacecraft production and testing methods.

One area that appears to be less developed in each of the proposed systems is the earth station technology. The magnitude of managing these constellations, as well as operating the service, has not been completely addressed by any of the vendors publicly. As such, concern is warranted that the cost and schedule estimates for this area are low.

After the price of the handset, the per minute charge for service is a key determinant in attracting subscribers. LQSS plans to charge $0.30 per minute for the Globalstar service plus about $0.10 per minute for tail charges to connect to local or long distant services. In addition, a monthly service charge of $8 to $10 is anticipated based on current cellular experience. The retail price of Odyssey service is estimated at $0.65 plus about $0.10 per minute for tail charges and a monthly charge of about $24. IRIDIUM plans to charge $3.00 per minute plus tail charges which have not been provided at this time.

Regulatory Issues: WARC 92 granted worldwide primary allocation in the 1 to 3 GHz band for LEO MSS services. Several significant events have transpired since that time that relate to the assignment of this spectrum to the Big LEO systems. Specifically, in August 1992, when the FCC implemented the allocation made at WARC 92, they denied any Pioneer Preference awards to the Big LEO proposers, and they granted experimental licenses, as noted above.

Critical proceedings have begun at the FCC that will lead to a decision on the assignment of spectrum to one or more of the five Big LEO proposers. Negotiated rulemaking was attempted in early 1993 by the FCC to encourage the proposers to reach a consensus on sharing the limited spectrum. Three informal working groups consisting of representatives of all the proposers and other affected parties held a series of meetings over a three month period. While agreement was reached on limiting interference with other services, a scheme for intraband sharing eluded the negotiators. A critical impediment was the inability of a TDMA scheme to share a frequency band with a CDMA scheme. This has pitted Motorola, the sole advocate of TDMA, against the so-called “gang of four” which has embraced CDMA. The failure of negotiated rulemaking has put the burden back on the shoulders of the FCC. If the mutual exclusivity of the applications of the five “Big LEO” proposers cannot be eliminated, then the FCC is authorized by the Omnibus Budget Reconciliation Act of 1993 to use competitive bidding, also known as spectrum auction, to assign frequencies for MSS. On 23 September 1993, the Commission adopted a Notice of Proposed Rulemaking describing its plans for conducting these auctions.

In October 1993, LQSS and Motorola jointly filed a proposal with the FCC to share the allocated spectrum in an attempt to avoid auctions. The essence of their approach is to have the FCC assign the MSS allocation in L-band (1610 to 1626.5 MHz) to the first operational system. As additional systems are fielded, this portion of the spectrum would then be divided equally among the operators. TRW, MCHI and Constellation Communications opposed this formula, suggesting instead that the spectrum be partitioned according to the multiple access scheme to be used.

Compounding the delays that have resulted because of the inability on the parts of the vendors to come to a consensus agreement on spectrum utilization is the fact that the FCC has been slowed by a shortage of staff as well as the absence of a chairman until recently (Mr. Reed Hundt was confirmed as chairman of the FCC in November 1993). In December 1993, the FCC allocated the 1610 to 1626.5 MHz and 2483.5 to 2500 MHz bands for MSS but postponed action on assigning spectrum to any of the proposers. The commission offered a compromise to the proposers in January 1994 that imposes strict financial qualifications, and technical and service standards. The comment period is to end in May 1994 and licenses may be granted during the first quarter of 1995.

No notable progress has been made in obtaining international approval to operate a Big LEO system worldwide. Each proposer, however, is seeking partnerships outside the US that will facilitate obtaining regulatory approval abroad, on a country by country basis. There is currently no straightforward mechanism in place by which any proposer can obtain worldwide spectrum allocation or landing rights since these must be negotiated individually with each sovereign state.

III. Summary And Conclusions

The progress made over the last ten years in digital voice processing, satellite technology, and component miniaturization has resulted in the viability of satellite-based mobile communications systems to meet the growing market in personal mobile communications using handsets similar to those currently in use with land-based cellular systems. Globalstar, IRIDIUM, and Odyssey, three of the more mature Big LEO satellite systems, were addressed in this paper. It was shown that, although a number of similarities exist amongst the designs, each system exhibits unique qualities in a number of significant areas.

Of the three systems discussed, it is clear that IRIDIUM will be the most challenging to deploy due to the inclusion of on-board processing techniques within the satellite communications payload together with a high data rate satellite crosslink capability. Furthermore, the FDMA/TDMA multi-access scheme proposed for IRIDIUM presents a number of complex issues involving cell utilization, cell frequency management, and time synchronization. The Globalstar system seems to be well postured, from a technical standpoint, due to the in-house experience of QUALCOMM in the area of CDMA/cellular applications. However, Odyssey may be in the best position to achieve its stated cost and performance objectives since the small number of satellites required in the design along with the use of a proven communications bus onboard the satellite reduces cost uncertainties.

In conclusion, while the technical feasibility of Big LEO systems seems to be secure, their economic viability is somewhat more questionable. What remains to be done is the actual full scale development, deployment, and operation of such systems in a cost effective, timely, and reliable way to meet a market demand that cannot be guaranteed. The long development time of satellite-based systems will only add to the uncertainty concerning which system design is optimal in terms of meeting a set of continually evolving requirements that are driven by user expectations fueled by a rapidly changing technology base as well as competing service offerings coming on-line with land-based systems. Compounding the financial and programmatic challenges are the difficult regulatory issues, both domestic and international, that are likely to linger for at least several more years. This uncertainty alone can discourage investment of the magnitude required to field these systems.

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[1] These systems form a subset of the five for which applications have been filed with the Federal Communications Commission (FCC). They were specifically selected in this study because of the fact that they were proposed by well established corporations with significant experience in satellite communications. The two systems not considered (i.e., Aries by Constellation Communications, Inc. and Ellipso by Mobile Communications Holdings, Inc. (MCHI)) have been proposed by entrepreneurial organizations.

[2] In contrast, Little LEOs are systems that provide non voice, store-and-forward mobile satellite services and operate at a frequency below 1 GHz.

[3] One reason for the higher constraint length by Globalstar, relative to IRIDIUM and Odyssey (i.e., 9 versus 7), might be to provide support for the higher transmission rate of 9.6 kbps versus 4.8 kbps since the higher constraint length code will result in a higher coding gain.. Also, the use of a more powerful code during uplink transmissions (i.e., rate 1/3 versus 1/2) makes sense to overcome the limited effective isotropic radiated power (EIRP) available from the user handset.

[4] Iridium, Inc. is a spin-off of Motorola that would own and operate the IRIDIUM system

Table 1: Comparison of the System Architectures

		Globalstar	IRIDIUM	Odyssey
Constellation	# Satellites	48	66	12
	Orbit/Inclination	Circ/52°	Circ/86.4°	Circ/55°
	# Planes	8	6	3
	Altitude (km)	1401	785	10,354
Frequency	Mobile User Uplink (GHz) Downlink (GHz)	 1.610-1.6265 2.4835-2.500	 1.616-1.6265 1.616-1.6265	 1.610-1.6265 2.4835-2.500
	Gateway Terminal Uplink (GHz) Downlink (GHz)	 C-band C-band	 27.5-30.0 18.8-20.2	 29.5-30.0 19.7-20.2
Connectivity	FDX Circuits/Sat	2800	3840	2300
	Average Satellite Connection Time	10-12 min.	9 min.	2 hours
	Min Elevation Angle	10°	8.2°	22°

Table 2: Comparison of the Satellite Designs

	Globalstar	IRIDIUM	Odyssey
Stabilization	3-axis	3-axis	3-axis
Transponder	Bent pipe	Processing	Bent Pipe
Mission Life (yrs)	7.5	5	15
Dry Mass (lbs)	704	1100	2703
Mobile User Segment Antenna Design	16-beam phased array	3 16-beam phased array antennas	Rigidly mounted 37(up) /32(dn) beam "staring" antenna
Crosslinks	No	Yes; 4 crosslinks at 25 Mbps; 22.55-23.55 GHz	No

Table 3: Comparison of the Mobile User Handsets

	Globalstar	IRIDIUM	Odyssey
Modulation	QPSK	QPSK	QPSK
FECC	Convolutional Xmit: (r=1/3;K=9) Rcv: (r=1/2,K=9)	Convolutional (r=3/4;K=7)	Convolutional (r=1/3;K=7)
BER	1E-3 (Voice) 1E-5 (Data)	1E-2 (Voice) 1E-5 (Data)	1E-3 (Voice) 1E-5 (data)
Supportable data rate (Kbps)	1.2-9.6 (Voice & Data)	4.8 (Voice) 2.4 (Data)	4.8 (Voice) 1.2-9.6 (Data)
Weight (lbs) Dimensions (in)	"Similar to current terrestrial cellular handsets"	"Similar to current terrestrial cellular handsets"	"Similar to current terrestrial cellular handsets"
Battery Lifetime	24 hrs standby; 8 hrs @ 5% duty cycle	24 hrs: 1hr talk, 23 hrs standby	30 minutes talk time; 48 hrs standby
Proposed Price	$750	$2,000 - $3,000	<$500

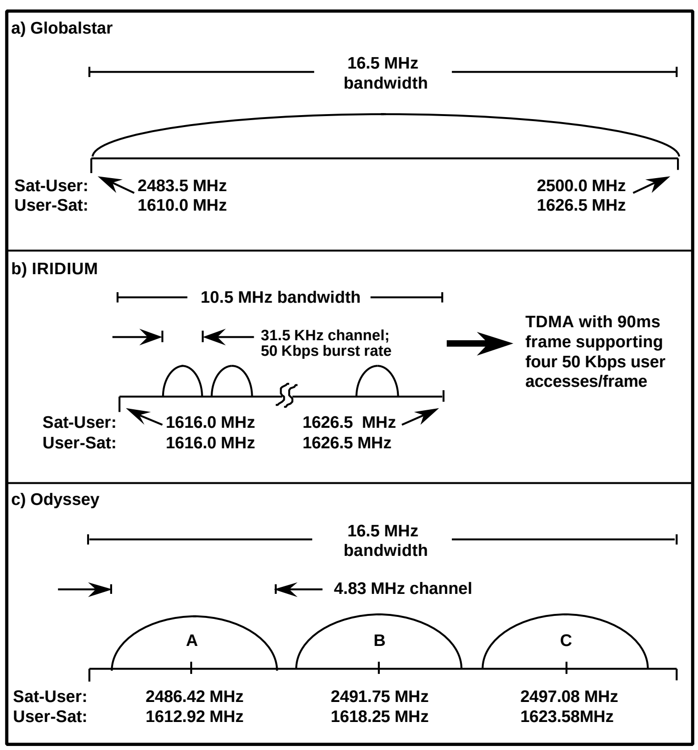

Figure 1: Comparison of the Multi-Access Schemes