Satellite Systems for Personal Communications

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A number of industry groups are planning to construct satellite systems that will provide personal communications services (PCS's) (typically voice, data, and fax) to users over small, handheld, cellular-type telephones. Some of these systems (e.g., Iridium and Globalstar) will be constructed using satellites in low earth orbit. Two (Ellipso and ICO) will employ medium earth orbit (3–8-h period), and still others (ACeS and Agrani) will operate from geostationary altitude. The origin and evolution of mobile satellite communications is discussed first, including the Inmarsat system and several land-based mobile satellite systems currently in operation. The rival approaches to the PCS market are then described, and some of the technical challenges inherent in each are indicated. This paper concludes with speculation on the factors influencing the likelihood of business success for the various PCS systems.

Keywords*—*Land mobile radio, propagation, satellite antennas, satellite communication, satellite mobile communication, satellites.

I. Introduction

Mobile satellite communications for commercial (i.e., nonmilitary) users is evolving rapidly toward personal communications services (PCS) systems capable of providing basic telephone, fax, and data services essentially anywhere on the globe at a per-minute cost that may be as little as three to four times that of regular wireless cellular service (see, for example, a survey by Wu *et al.* [1]). This paper traces the origins of commercial mobile satellite communications, beginning with the introduction of the Marisat system in 1976, which led to the creation of Inmarsat in 1979. The more recently completed land-mobile systems operating in the United States, Canada, and Australia are then described briefly. All of these systems employ geostationary satellites with modest effective isotropically radiated power (EIRP), which restricts their use to mobile terminals with an antenna gain of approximately 8 dB (considerably more than can be achieved with a handheld unit, which might be only on the order of 2 dB). These terminals are most frequently mounted on vehicles, although fixed and transportable versions can also be provided.

True personal communications using small, cellular-like telephones will become available after about 1998, when a number of new competing systems are scheduled to be brought into service. Regional systems are to be deployed over Asia, Africa, and the Middle East. These are planned to operate from geostationary satellites employing very-large-diameter reflector antennas to create a large number of small, fixed beams (in order to secure adequate link margins for handheld terminals).

Global satellite systems are also being built for personal communications. In the United States, the Federal Communications Commission (FCC) licensed five such systems: Iridium, Globalstar, Odyssey, Ellipso, and ECCO. Of these, only the first two appear to be well under way, and both expect to be in operation by 1999. TRW, however, has abandoned its plans to build the Odyssey system. In Europe, a spinoff from Inmarsat called ICO-Global is building a system known as ICO, which should be in operation by 2000–2001. Some of the technical difficulties that must be overcome in fielding these systems are discussed, including propagation effects, satellite antenna design, onboard processing, handoff, and network control.

This paper concludes with a few personal observations on the factors that are likely to influence the business success of these systems.

II. Inmarsat

The commercial use of satellites for mobile communications began with the COMSAT/Marisat system in 1976 [2]. Satellites operating at ultrahigh frequency (UHF) and L-band were launched on February 19 and June 9 of that year into positions over the Atlantic and Pacific Oceans, respectively. The UHF capacity was utilized by the U.S. Navy, while the L-band capacity was intended to inaugurate a commercial service for mariners. Shipboard terminals typically consisted of an above-deck 1-m-diameter antenna gimballed to remain locked on the satellite and protected from the elements by a radome, while below decks would be a telephone handset, fax, and/or teleprinter terminal (Fig. 1). Feeder links for these satellites were provided at C-band via "coast" earth stations at Southbury, CT, and Santa Paula, CA, which were connected to the public switched network.

The system subsequently became global with the addition of a third satellite over the Indian Ocean and, in 1979, was turned over to the newly formed Inmarsat international

Manuscript received October 12, 1997; revised January 21, 1998.
The author is with COMSAT Corporation, Bethesda, MD 20817 USA.
Publisher Item Identifier S 0018-9219(98)04238-8.

Fig. 1. Shipboard Inmarsat terminal radome-enclosed antenna.

organization to manage. Inmarsat, which is headquartered in London, is a treaty organization with 81 members. Initially, it leased its satellite capacity from COMSAT and from the European Space Agency MARECS satellites [3]. During the latter half of the 1980's, capacity was provided by INTELSAT, which added maritime packages to some of its V-series satellites.

In 1991, Inmarsat deployed four Inmarsat-2 satellites constructed to its own specifications [4]. Two were placed over the Atlantic Ocean and became known as Atlantic East and Atlantic West (see Fig. 2) to handle the large amount of traffic in that ocean region. These satellites, like their predecessors, employed a single L-band global beam for servicing mobile users. This, combined with the limited band of frequencies (28 MHz) available for this service at L-band, restricted the number of simultaneous users. In response to the growth in traffic, two approaches have been taken to increase the availability of a circuit. One involves terminal design and the other entails frequency reuse.

The original (Inmarsat-A) terminal employed analog (FM) modulation of the L-band signals and 50-kHz channel spacing. About 20 000 such terminals are currently installed on vessels around the globe. Some terminal manufacturers repackaged their products for use on land (Fig. 3), and about 5000 of these are also in existence today. They are often used in remote locations, disaster situations, or peacekeeping operations, but their purchase price and high operating cost have discouraged more widespread use. This has, however, created a market for smaller, lighter weight, less-expensive terminals. To satisfy this demand, as well as to create more channels, Inmarsat introduced three new services known as Inmarsat-B, -C, and -M [5], as described in Table 1. The Inmarsat-B terminal is viewed as a replacement for Inmarsat-A. It employs digital [offset quadrature phase shift keying (O-QPSK)] modulation of the carrier with 20-kHz channel spacing. Voice is carried using adaptive predictive coding at a 16-kb/s rate, and most terminals can be operated at 64 kb/s for data. The Inmarsat-M terminal uses a voice codec to provide synthesized speech at 4.8 kb/s, which, with error protection, is transmitted at 6.4 kb/s in a 10-kHz-wide channel. The Standard-C terminal provides only data at 300 b/s, (which, with error protection, is transmitted at 600 b/s) and is useful for functions such as low-rate messaging and position reporting. The Inmarsat-M terminal can be built into a regular-size briefcase, and approximately 10 000 of these units have been sold at prices ranging between one-half and one-third the cost of the original Inmarsat-A.

In 1996, the first two of five Inmarsat-3 satellites were launched. These satellites reuse the authorized frequencies in up to five "spot" beams, which can be selected for their coverage over land (Fig. 4). These spot beams provide higher EIRP, making it possible for still smaller terminals to operate within the system, and a "mini-M" terminal the size of a laptop computer was made available in January 1977. It sells for about $3000, with a usage charge (fully terminated) of $3.00 per minute. The owner/operators of the Inmarsat system hope this service will attract a large number of new users (consumers), as distinct from the commercial accounts that currently make up the bulk of the revenue.

III. Existing Land-Based Mobile Systems

Several regional mobile satellite communications systems have recently been established; these are summarized below.

A. North American MSAT System

The most advanced satellite system providing mobile satellite communications over land is a system implemented by the United States and Canada that covers those two countries (including Alaska), Mexico, and the Caribbean using two essentially identical satellites. In Canada, studies on the design of a mobile satellite (MSAT) system were performed for the Department of Communications by Canadian industry, augmented by the Communications Research Center [6], [7]. In the United States, the National Aeronautics and Space Administration (NASA) supported studies via the MSAT-X program managed by the Jet Propulsion Laboratory [8]. Early designs focused on a UHF system; however, an FCC proceeding concluded that any U.S. system should operate at L-band. Moreover, since the mobile terminals could not readily discriminate between satellites placed in the longitude sector that covers North America, there could only be a single system. The contenders to provide this service were thus forced into a consortium, which became known as the American Mobile Satellite Corporation (AMSC) [9], [10]. In Canada, Telesat Mobile, Inc. (TMI) was licensed to provide service, and these two companies agreed on a common set of specifications and an arrangement for sharing the available bandwidth [11]–[14].

The arrangement between TMI and AMSC is such that each satellite can act as a spare for the other, should one fail. The parameters of this system are listed in Table 2. Fig. 5 shows the outlines of the shaped beams used to cover the service areas. The AMSC satellite was launched during

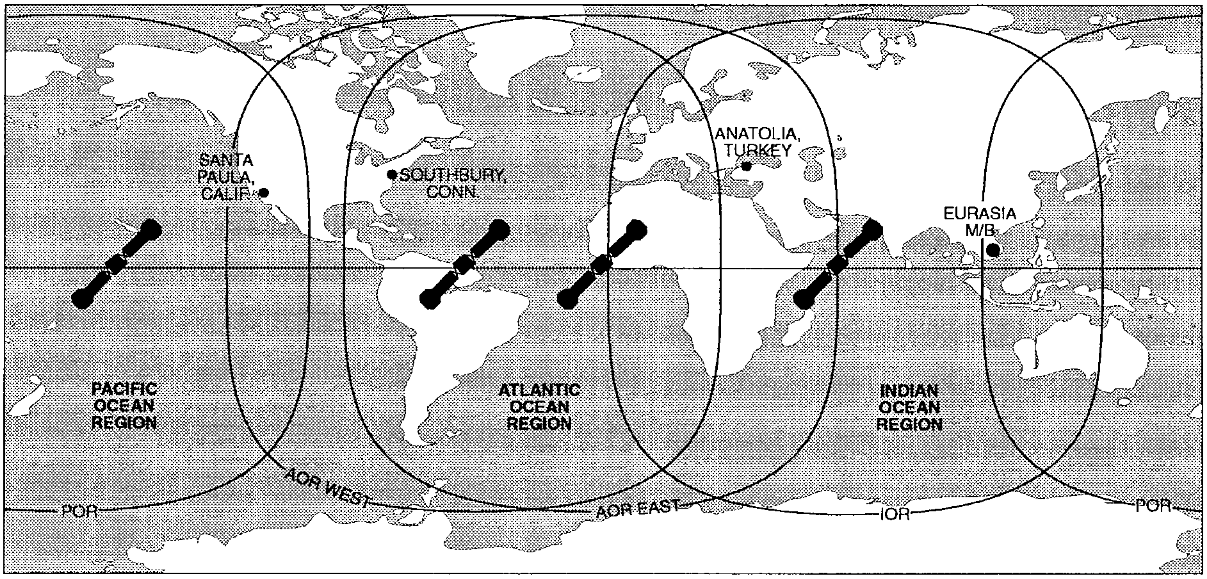

Fig. 2. Coverage patterns of the Inmarsat-2 satellites and locations of the coast earth stations operated by COMSAT.

Fig. 3. Inmarsat-A terminal used on land.

1995, and the TMI satellite early in 1996. These launches were somewhat later than planned owing to difficulties in securing the large 6 $\times$ 5-m (elliptical) reflector antennas. (As in the case of the Inmarsat satellites, separate transmit and receive antennas are employed to circumvent passive intermodulation problems.) Originally, it was intended to use unfurlable mesh antennas [15], [16]; however, these proved impractical, and single-piece graphite-epoxy antennas had to be built instead. These were made sufficiently flexible that they could be wrapped around the satellite bus to fit within the shroud of the launch vehicle [17].

The ground segment for the AMSC/TMI system [18] is depicted in Fig. 6. It differs from that employed in the Inmarsat system in that provision is made for separate earth stations providing public switched network services, private network services, and data services, all under the command of a network control center.

B. Australian Mobile Satellite System (OPTUS)

Australia has implemented a mobile satellite service using an L-band transponder carried on the Aussat-B series

Table 1 Comparison of Inmarsat Voice Systems

Features	Inmarsat-A	Inmarsat-B	Inmarsat-M	"Mini"-M
Mobile To/From Satellite, L-Band (GHz)	1.6/1.5	1.6/1.5	1.6/1.5	1.6/1.5
Fixed To/From Satellite, C-Band (GHz)	6/4	6/4	6/4	6/4
Minimum Channel Spacing (kHz)	50	20	10	5
Users per Carrier	1	1	1	1
Access Method	FDMA	FDMA	FDMA	FDMA
Modulation	Companded FM	O-QPSK	O-QPSK	O-QPSK
FEC Coding Rate	N/A	3/4	3/4 (for subband bits)	2/3 (for subband bits)
Speech Coding Algorithm	N/A	Adaptive predictive coding (APC)	Improved multiband excitation (IMBE)	Advanced multiband excitation (AMBE)
Voice Coding Rate (kb/s)	N/A	16	6.4 (incl. error correction bits)	4.8 (incl. correction bits)

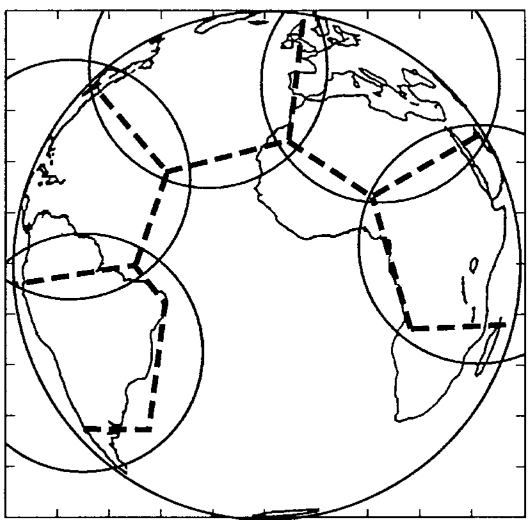

Fig. 4. Beam patterns of an Inmarsat-3 satellite system, showing five possible spot beams, four of which can be activated to provide coverage of land areas.

spacecraft (two Hughes HS-601 satellites) [19], [20]. Table 3 summarizes the performance characteristics of these satellites' L-band mobile service links and their Ku-band feeder links. Fig. 7 shows the coverage afforded by the B-1 satellite using a single spot beam. Owing to Australia's relatively high latitude, the elevation of the satellite as seen from the more populated parts of Australia will exceed about 40°, somewhat simplifying the design of the mobile antenna. The services offered by this system include telephony using 4.8-kb/s voice encoding in 5-kHz channels (similar to the Inmarsat-M system), as well as a data service at 2.4 kb/s and fax at 4.8 kb/s.

C. Japanese N-Star Mobile Communications System [21]

The Japanese NTT Mobile Communications Network, Inc. (NTT DoCoMo) initiated mobile service in March 1996 using the N-Star satellite. N-Star-a (launched in August 1995 into 132°E longitude) and N-Star-b (launched in February 1996 into 136°E latitude) are multipurpose satellites offering both fixed and mobile services. These satellites provide mobile services to the Japanese islands and surrounding waters via four 1200-km-diameter spot beams, as illustrated in Fig. 8. The service links to subscribers are at S-band (2.6/2.5 GHz), while the feeder links are at C-band (6/4 GHz).

Three kinds of mobile terminals have been developed: portable, maritime, and car mounted. The maritime terminals use the satellite exclusively, and the car-mounted terminals provide access to both the terrestrial cellular network and the satellite system. The portable units are available in this dual-mode version also, or in a satellite-only version. The portable unit is about the size of a briefcase.

The system provides voice service using a 5.6-kb/s codec, which, with rate 1/2 convolutional coding, results in a transmission rate of 14 kb/s. Fax and data are sent at 4.8-kb/s rates. Channel spacing is 12.5 kHz. Each of the two satellites is accessed by separate base stations, each of which has dual redundant equipment for high reliability.

D. Other Mobile Satellite Systems

Mexico is in the process of implementing a mobile satellite service employing L-band transponders on each of two Solidaridad satellites (also Hughes HS-601) launched in 1994 [22]. To take advantage of the work performed by AMSC/TMI in developing their system and associated terminals, it is understood that the Mexican system will provide the same types of service using essentially identical equipment.

India is planning a mobile satellite service using an S-band (2-GHz) transponder placed on the INSAT 2 spacecraft. This service will consist of voice, data, and fax using essentially the same parameters as the Inmarsat-M service (Table 1).

Table 2 Parameters of L-Band AMSC Satellite Links

Parameter	Link: 4.7-m FES Antenna-to-Mobile	Link: Mobile-to-4.7-m FES Antenna
Uplink		
Frequency (GHz)	13.2	1.65
Uplink EIRP/Voice-Activated Carrier (dBW)	47.2	14.5
Path Loss (dB)	206.8	188.7
Satellite G/T (dB/K)	-3.0	2.8
Required Flux Density/Voice-Activated Carrier (dBW/m^2)	-115.7	-148.4
C/N_0 Thermal (dB-Hz)	66.0	57.2
Downlink		
Frequency (GHz)	1.545	11.3
Required EIRP/Voice-Activated Carrier (dBW)	30.0	8.6
Path Loss (dB)	188.2	205.8
Receive Terminal G/T (dB/K)	-15.0	28.2
C/N_0 Thermal (dB/Hz)	55.4	59.6

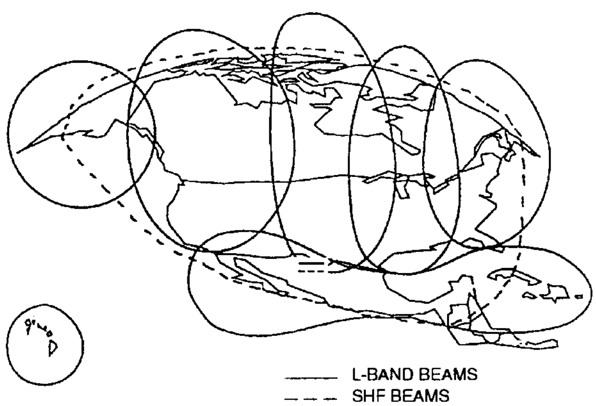

Fig. 5. Beam patterns of the AMSC/TMI satellites.

IV. New Regional Personal Communications Systems

Two U.S. companies (Hughes and Lockheed Martin) and the French company Matra Marconi are seeking to develop regional mobile satellite systems capable of providing mobile services to customers who carry only handheld (cellular radio-like) transceivers. Table 4 lists those systems that have been reported in the trade press; however, little has been published thus far in the technical literature. It would appear that each venture is in the process of seeking financing and regulatory approvals.

The Asia Cellular Satellite (ACeS) system is intended to cover southern China, Thailand, Indonesia, and the Philippines and is owned by partners from the latter three countries. Lockheed Martin is building the satellite for this system, which will be placed in geostationary orbit (GEO) and will employ as many as 150 narrow spot beams to achieve link margins adequate to operate with handheld telephones based on the global system for mobility [23].

The Satphone and Africom systems appear to be similar to ACeS (and each other) in concept and may be merged into a three-satellite system also employing Lockheed Martin A2100 spacecraft.

Hughes has won a contract with China and Singapore (Asia Pacific Mobile Telecommunications), and with a partnership backed by the government of the United Arab Emirates to build a system, called Thuraya, to serve the Middle East and North Africa.

Coordination among these regional systems could be difficult were they all to be built. The dates for launch (given in Table 4) are probably optimistic in all cases.

V. Global Personal Communications Systems

A large number of companies (almost all of them in the United States) have announced plans to construct and operate satellite communications systems that would provide personal communications around the globe, and a number of these systems have been discussed and compared in the literature [24], [25]. Much of this activity was spurred by a bold plan put forth by Motorola—to create a global personal satellite communications system called Iridium, employing 77 (later changed to 66) satellites in low earth orbit (LEO). Other proposals for LEO systems followed, causing Inmarsat to consider what type of personal communications system it might launch. Guided to some extent by design studies performed by TRW, Inmarsat adopted a system employing satellites placed in 6-h orbits at 10 000-km altitude (i.e., above the Van Allen radiation belts). This system is now being built by an affiliate company called ICO-Global.

Fig. 9 shows the amount of the earth's surface visible from LEO, intermediate circular orbit (ICO) or medium earth orbit (MEO), and GEO. The higher the satellite altitude, the fewer satellites are required to provide global coverage. However, to preserve the link margin on the handheld-to-satellite link, the spot size of the beam on the earth's surface must be kept small. This requires that larger satellite antennas be employed the further out the satellites are placed, and each antenna must form a greater number of spot beams in order to maintain overall coverage.

Thus, LEO satellites tend to be smaller, lighter, and cheaper than MEO spacecraft, which in turn are likely

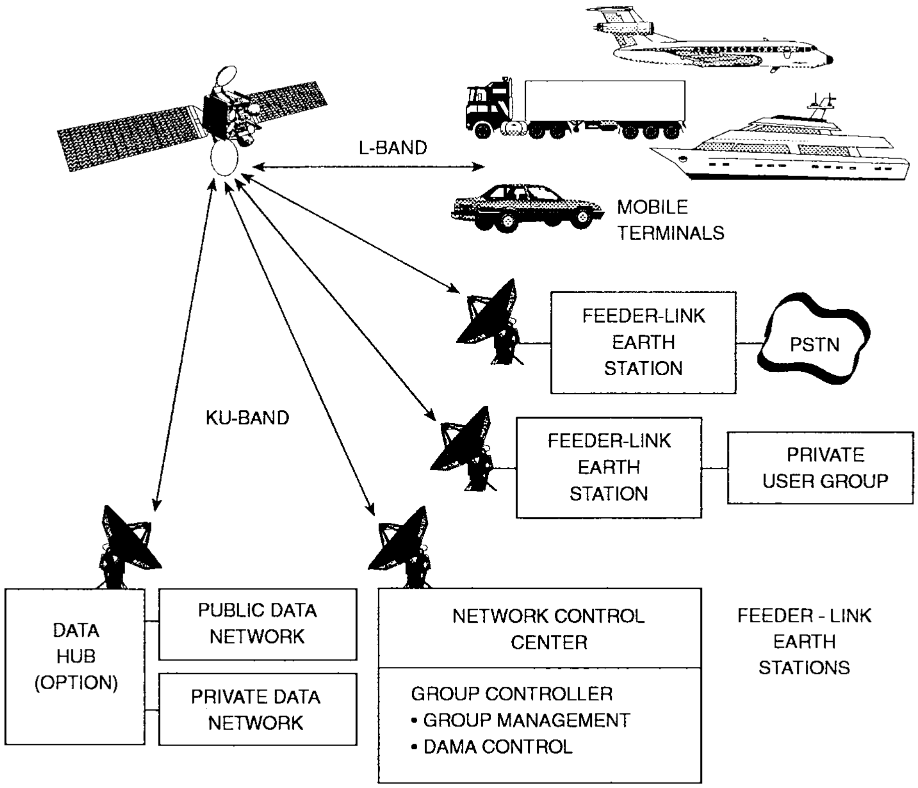

Fig. 6. Arrangement of the ground segment for the AMSC/TMI system.

Table 3 Parameters of the Australian OPTUS System

Parameter	Value
Ku- to L-Band Repeater	
Receive Band (GHz)	14.0115–14.0255
Transmit Band (GHz)	1.5450–1.5590
Receive *G/T* (dB/K)	1.0* or -1.5**
L-Band EIRP (dBW)	48.0
Ku-Band Antenna, Receive Polarization	Vertical
L-Band Antenna, Transmit Polarization	RH circular
L- to Ku-Band Repeater	
Receive Band (GHz)	1.6465 to 1.6605
Transmit Band (GHz)	12.2635 to 12.2775
Receive *G/T* (dB/K)	-1.5
Ku-Band EIRP (dBW)	38.0* or 34.0**
L-Band Antenna, Receive Polarization	RH circular
Ku-Band Antenna, Transmit Polarization	Horizontal

*Within the capital cities.

**Within 90% of the Australian coverage.

to be less expensive than GEO spacecraft. This offsets to some extent the benefit of developing systems with fewer satellites. (We return to this issue in the next section.)

Market studies performed by the proponents of these systems have identified four potential markets:

i) *international business travelers:* primarily business travelers from the developed world traveling to less-developed countries;

ii) *national roamers:* primarily business travelers who need mobile communications in their own countries but who travel beyond the reach of terrestrial cellular systems;

iii) *national rural fixed service:* an extension of the national fixed services to regions where they are presently unobtainable;

iv) *government agencies:* law enforcement, fire, public safety, and other services.

The designs of the global systems to be discussed represent different assumptions concerning the business to be attracted from these four segments. The regional systems discussed previously cater largely to markets ii)–iv), since international business travelers are believed to require a single phone that will work anywhere.

The subsections that follow discuss the five systems that appear to be proceeding. Of these, the Iridium, Globalstar, and ICO systems appear to have the best chance of being fielded, while the financing of the others remains to be completed. Table 5 summarizes the parameters of these five systems, and Table 6 gives the characteristics of the communications links (where known).

A. Iridium

From a technical standpoint, the Iridium system—proposed by Motorola and currently being constructed by that company in conjunction with Lockheed Martin, Raytheon, and other contractors—is the most ambitious of the five to be discussed [26]. The system

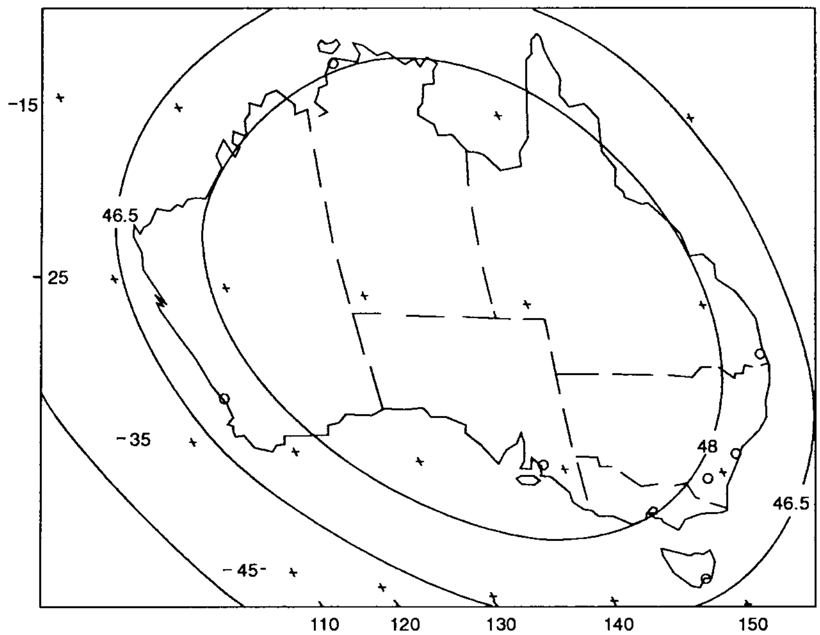

Fig. 7. Coverage of Australia afforded by the Aussat B-1 satellite [19].

Table 4 Proposed New Regional Mobile Satellite Communications Systems

System	Manufacturer	No. of Satellites	Launch Date
Agrani	Hughes	2	1998
APMT	Hughes	2	1998
ACeS	Lockheed Martin	2	1998
Satphone	Lockheed Martin	2	1998
Africom	Lockheed Martin	2	1998
Thuraya	Hughes	2?	2000
EAST	Matra Marconi	1	2000

is being purchased and will be operated by a separate company (Iridium, Inc.), which has secured investment from many parts of the world [27]. The design employs 66 satellites placed in circular polar orbits at 780 km altitude. The satellites will be deployed into six equispaced orbital planes, with 11 satellites equally separated around each orbit. Satellites in adjacent planes are staggered with respect to each other to maximize their coverage at the equator, where a user may be required to access a satellite that is as low as 10° above the horizon.

Users employ small handsets operating in frequency-division-multiplexed/time-division multiple access (FDM/TDMA) fashion to access the satellite at L-band. Eight users will share 45-ms transmit and 45-ms receive frames in channels that have a bandwidth of 31.5 kHz and are spaced 41.67 kHz. That is, users are synchronized so that they transmit and receive in the same time windows alternately. This approach is necessary because (three) phased-array antennas are used for both transmitting and receiving. Fig. 10 is a sketch of the satellite, and Fig. 11 shows the 48 spot beams formed at L-band projected onto the earth at the equator.

The Iridium system requires onboard processing in order to demodulate each arriving TDMA burst, determine how to route it, and then retransmit it to its next destination. This can be to the ground if a gateway earth station is in view or, failing that, to one of the four nearest satellites: the one ahead or behind in the same orbital plane, or the nearest in either orbital plane to the east or west. These satellite cross links operate at 23 GHz, while the links to the gateway earth stations are at 20 GHz. Fig. 12 shows these pathways schematically.

The use of cross links greatly complicates the design of the system but allows global service to be provided with a small number (11 are planned) of gateway earth stations. To properly route traffic, each satellite must carry a set of stored routing tables from which new routing instructions are called every 2.5 min.

The cross links to the satellite ahead and behind are the easiest to implement, since those satellites remain at a fixed distance and in a fixed viewing direction. The cross-links to the satellites in the adjacent orbital planes have constantly changing time delays and antenna pointing requirements. To mitigate this problem a circular polar orbit (actually an inclination of 86.5°) was chosen. Even so, these cross links are dropped above 68° latitude, as the angular rates for the tracking antennas become high and little traffic is expected at these latitudes.

The onboard processor is being constructed using very-large-scale integrated circuits designed specifically for the project. It includes 512 demodulators, which, via the signaling channel, can center the arriving handheld bursts in frequency and time. The observed Doppler shift of these arriving bursts is routed to the intended destination gateway earth station to determine the user's location. Service is then provided (or denied) based on country-by-country service

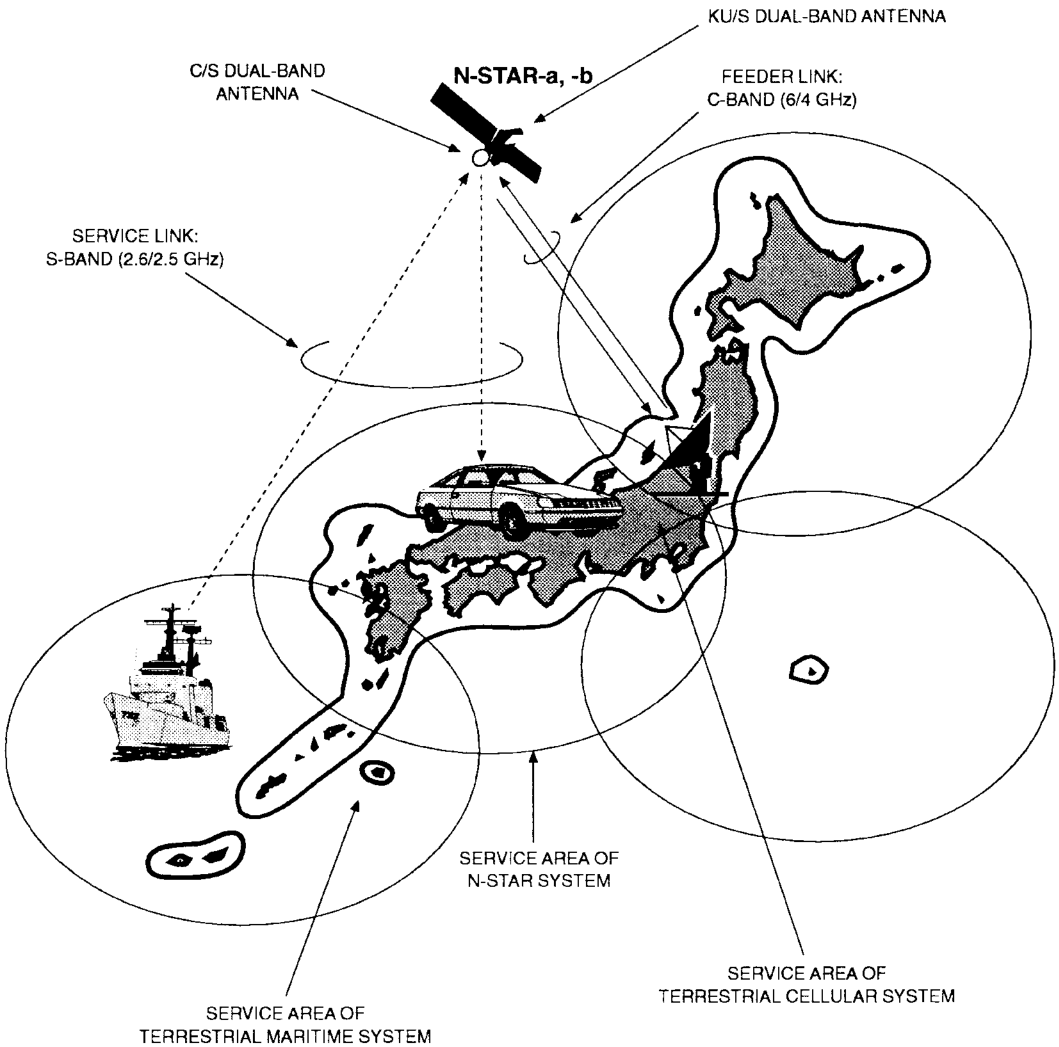

Fig. 8. Overview of the Japanese N-Star mobile communications system.

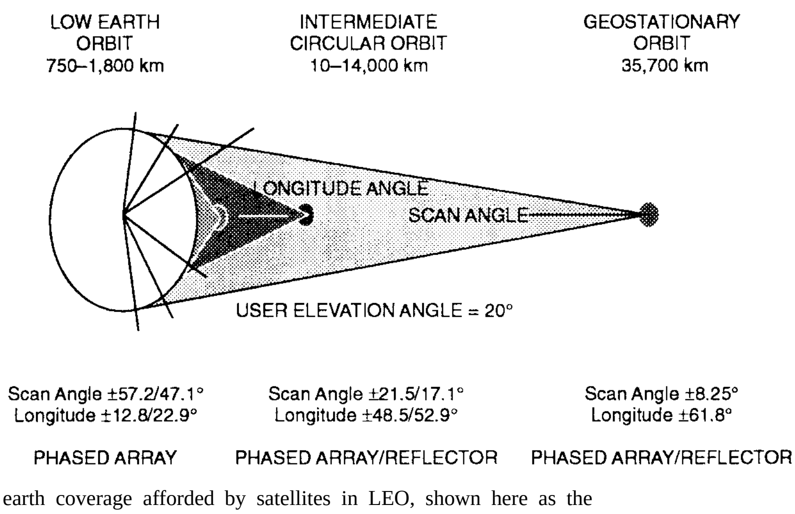

Fig. 9. Relative amounts of earth coverage afforded by satellites in LEO, shown here as the closest satellite position; ICO, shown as the next closest satellite to the earth; and GEO, shown as the most distant satellite location.

agreements. Each satellite is capable of handling as many as 1100 simultaneous calls.

A model of the Iridium handheld terminal is depicted in Fig. 13. Services to be provided include voice (probably at 2.4-kb/s encoding, although Table 5 lists 4.8 kb/s), data at 2.4 kb/s, and high-penetration paging, which affords 11 dB more power than the regular signal. The design, however, already provides a link margin (∼16 dB) that is higher than any of the competing systems. This is because Motorola required that the handheld unit be usable

Table 5 Proposed New Global Satellite PCS Systems

Parameter	Iridium	Globalstar	ICO-Global	Ellipso	Aires (ECCO)
Company	Motorola	Loral/ Qualcomm	ICO-Global	Mobile Communication Holdings, Inc.	Constellation Communications, Inc.
No. of Active Satellites	66	48	10	17	46
Orbit Planes	6 circular polar (86.5°)	6 circular inclined (52°)	2 circular inclined (45°)	2 elliptical inclined (116.6°) 1 circular equatorial	7 circular inclined 1 circular equatorial
Orbit Altitude (km)	780	1,414	10,355	N.A. 8,060 equatorial	? 2,000 equatorial
Satellites per Orbit Plane	11	8	5	5 in each ellliptical orbit 7 in equatorial orbit	5 in each inclined orbit 11 in equatorial orbit
Beams per Satellite	48	16	163	61	1
Reported Cost ($B)	4.7	2.5	4.6	0.56	1.15

Table 6 Communications Characteristics of the Proposed New Satellite PCS Systems

Parameter	Iridium	Globalstar	ICO-Global	GEO Regionals
Mobile User Link				
Frequency, Up/Down (GHz)	1.62135–1.6265	1.6100–1.62135/ 2.4835–2.49485	1.980–2.010/ 2.170–2.200	1.525–1.559/ 1.6265–1.6605
Bandwidth (MHz)	5.15	11.35	30	34
Spot Beams per Satellite	48	16	163	>240
Voice Bit Rate, (coded) (kb/s)	4.8 (6.25)	1–9	4.8 (6.0)	3.6 (5.2)
Feeder Link				
Frequency Up/Down (GHz)	30/20	5.1/6.9	5.2/6.9	14/12
Gateway Antenna *G/T* (dB/K)	24.5	28.5	26.6	37.0
User Terminal				
Multiple-Access	TDMA-FDMA	CDMA-FDMA	TDMA-FDMA	TDMA-FDMA
Carrier Bandwidth (kHz)	TDD, 31.5	1250	25.2	27
Carrier Bit Rate (kb/s)	50	2.4	36	45
Modulation	DQPSK	PN/QPSK	QPSK	QPSK
RF Power (W)	0.45	0.5	0.625	0.5
G/T (dB/K)	-23.0	-22.0	-23.8	-23.8
Nominal Link Margin (dB)	16.5	11	10	10
Nominal Capacity per Satellite (ckts)	1,100	2,400	4,500	16,000

from inside a vehicle (e.g., a taxi), a capability dictated by the business plan, which depends heavily on serving international business travelers.

One of the complicating aspects of the Iridium system is the need to hand off a subscriber from beam to beam as a satellite flies by. Since a typical satellite pass takes less than 9 min, and the average international call duration is about 7 min, there is also a need to hand off some calls to the next satellite to appear above the horizon. This will be in one of the adjacent orbits and hence in a somewhat different direction from the first, raising the possibility of the call's being dropped if buildings block the view. This issue has been examined at Inmarsat [28], by Carter and Beach [29], and by others. Other systems (e.g., Globalstar) attempt to exploit dual-satellite visibility as a means of mitigating shadowing effects and claim that this is preferable to designing for high link margins.

The Iridium satellites are station-kept using onboard propulsion in order to overcome atmospheric drag and have sufficient fuel for an eight-year life. Four telemetry, tracking, and control facilities are being built to manage satellite operations (in Hawaii, at Yellowknife and Iqualvit in Canada, and at Eider in Iceland), as well as a separate engineering facility to diagnose problems that may arise (e.g., the failure of a cross link). The Master Control Facility is in Lansdowne, VA, with a backup in Rome, Italy.

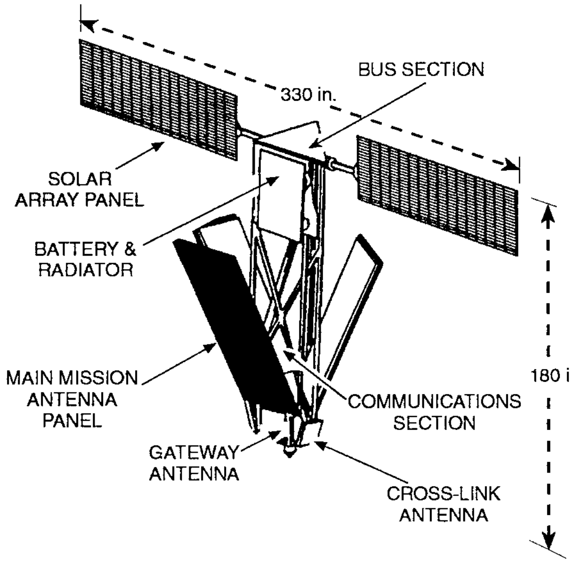

Fig. 10. Sketch of the Iridium system satellite. The 48 spot beams (see Fig. 11) are formed by the three phased-array antennas cantilevered from the three sides of the spacecraft. (Courtesy of Motorola Corporation.)

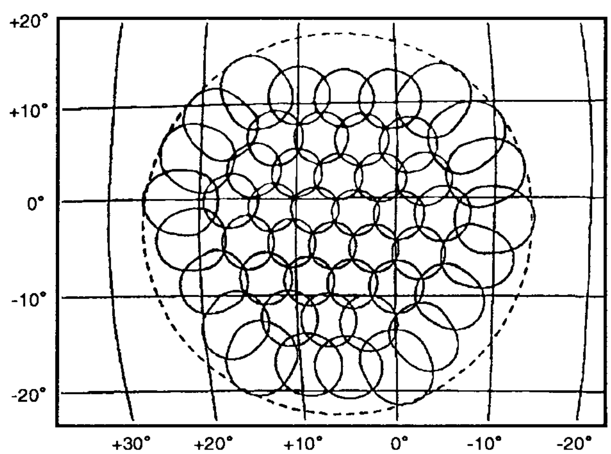

Fig. 11. Service (L-band) spot beams formed by an Iridium satellite over the equator.

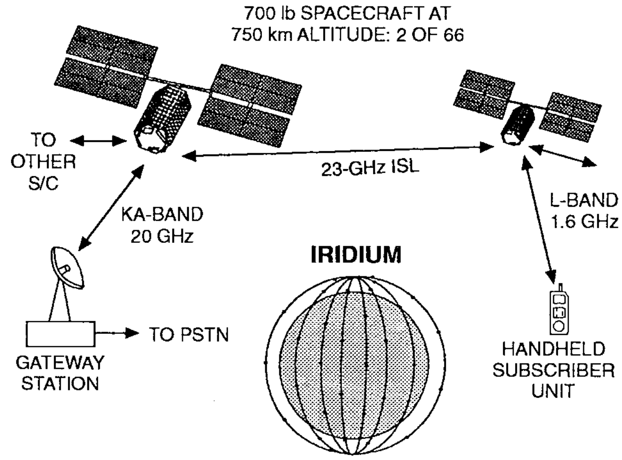

Fig. 12. Connections possible in the Iridium system between users, the satellite, and the ground.

Fig. 13. Model of a handset proposed for the Iridium system. (Courtesy of Motorola Corporation.)

To date, Motorola has launched two-thirds of its satellites, and plans to have the entire system in operation in the fourth quarter of 1998. Satellites are currently being built at a rate of one per week, and launch contracts have been secured in the United States (Delta), Russia (Proton), and China (Long March) to place the remaining satellites in orbit.

B. Globalstar

The Globalstar system is being purchased by a limited partnership in which Loral and Qualcomm of the United States are principal partners. The satellites are currently being assembled in Italy (by Alenia Spazio), while Qualcomm has developed much of the ground segment [30], [31].

Unlike the Iridium system, which offers a true *global* service, Globalstar's business plan calls for launching the space segment and franchising its use to partners in different countries. Over 90 such relationships have been established.

The Globalstar system will employ 48 satellites organized in eight planes of six satellites each (Fig. 14). The satellite orbits are circular, at 1414 km and 52° inclination. The use of an inclined orbit concentrates the available satellite capacity at lower latitudes where the largest populations exist; little or no coverage is provided beyond ±70° latitude (Fig. 15). As can be seen in Fig. 15, two or more satellites are visible (above 10° elevation) between 25° and 50° latitude at all times, and from the equator to 60° latitude 80% of the time. Like the Iridium satellites, the Globalstar spacecraft are three-axis-stabilized, with a mission life of 7.5 years (minimum).

Because the Globalstar system does not employ satellite cross links, a subscriber can gain access to the system only when a satellite in view can also be seen by a gateway earth station. Typically, this means that service areas are within

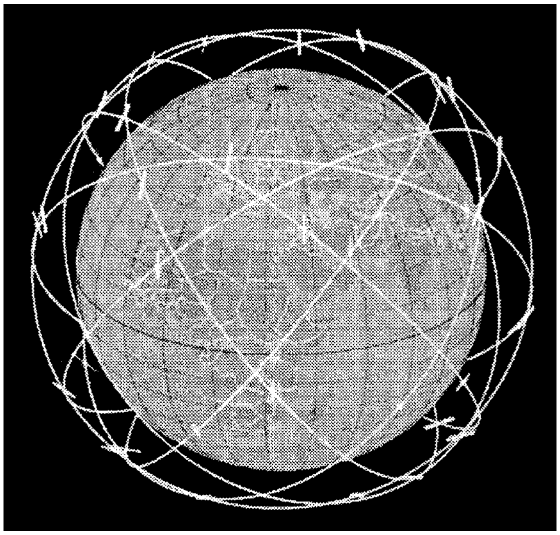

Fig. 14. The Globalstar constellation [31].

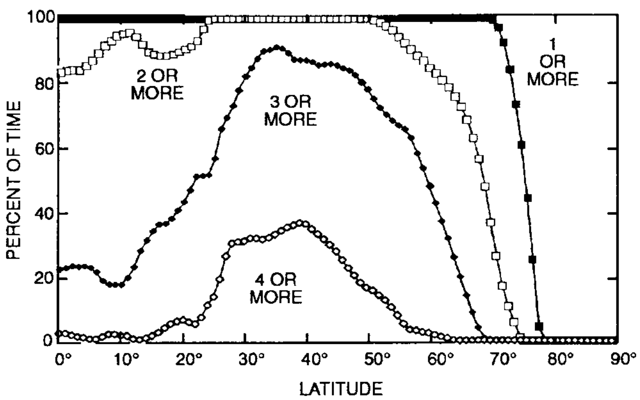

Fig. 15. Multiple-satellite coverage provided to users (at elevations above 10°) by Globalstar [30].

1000 miles of each gateway earth station. To achieve truly global coverage would require the construction of more than 200 earth stations, which seems unlikely to happen. Thus, Globalstar is more likely to serve national roamers than international business travelers.

In contrast to Iridium, each Globalstar satellite covers a comparable area of the earth's surface with only 16 spot beams. This, together with the sharing of the receive channels on board the satellite by many more users, reduces the available link margins to about 3–6 dB, although for a small number of users, this can be increased to 11 dB. Access to and from the satellite is at L- and S-band, respectively (Table 6), utilizing code-division multiple access (CDMA) in channels that are 1.25 MHz in bandwidth. Voice is encoded at rates of 1–9 kb/s, depending on speaker activity. The satellites employ simple "bent pipe" transponders, with the feeder links at C-band [32].

A problem for this type of system is that while frequency reuse can be employed at L- and S-band, the feeder links must occupy the full band of all of the signals that can be transmitted through the satellite. Therefore, securing an adequate feeder link allocation becomes almost as critical as an L- and S-band allocation.

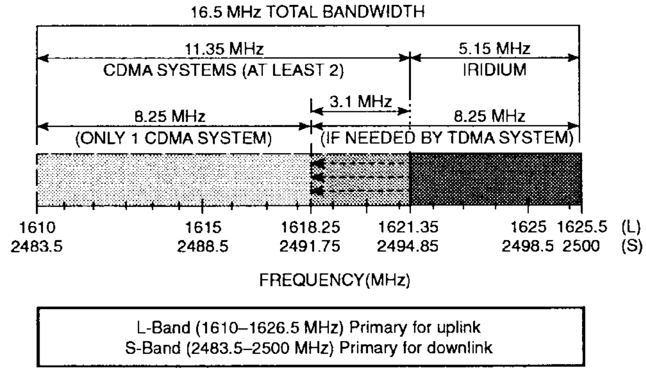

Fig. 16. FCC-mandated frequency-sharing arrangements for Iridium, Globalstar, and Odyssey.

The early contention among Iridium, Globalstar, and Odyssey for L-band frequencies (ICO intends to operate entirely at S-band) resulted in the FCC's allocating 5.15 MHz to Iridium and 8.25 MHz to the first operational CDMA system (presumably Globalstar), as shown in Fig. 16. If a second CDMA system (at one time expected to be Odyssey [33]) were built, it would share a band with Globalstar that is 11.35-MHz wide. If a second system is not built, then Iridium will be allowed to expand to occupy a band of 8.25 MHz.

Since all 16 beams of all of the 48 satellites are always active, each satellite that is in view of a subscriber will pick up the subscriber's signal and retransmit it in its feeder link. Thus, by tracking the several satellites that are in view of a given gateway earth station, two channels can be kept open to the subscriber. The channel providing the stronger signal can then be selected for connection to the public-switched network. This feature should mitigate blocking by buildings and provides an automatic "soft" handoff from satellite to satellite. The advantage afforded by diversity routing was examined by Akturan and Vogel [34] and found to be considerable for urban environments. Globalstar hopes to have its system in operation by early 1999. While none of the 48 satellites has been launched so far, the first was scheduled for launch in February 1998.

C. ICO

ICO-Global is a spinoff from Inmarsat, which owns 15% of the corporation. The remainder is presently owned by Inmarsat signatories and by Hughes (the builder of the spacecraft) and TRW.

ICO-Global has chosen an intermediate circular orbit for its system (10 355 km altitude), with ten satellites arranged five in each of two inclined circular orbits. The inclination of the orbits is 45°—making it the lowest of the systems described. This reduces the coverage at high latitudes but allows for the smallest number of satellites. (Actually, 12 satellites are to be launched in order to provide a spare in each orbital plane.) The design of the ICO system (initially called Inmarsat-P) involved several teams, and several options were considered before the final design was adopted [35].

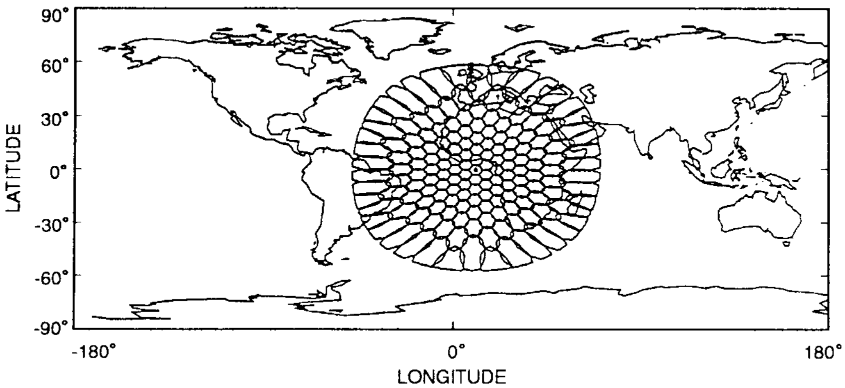

Fig. 17. Coverage provided by the 163 spot beams of an ICO satellite over the equator.

To improve the link margins on the ICO satellites, Inmarsat chose a satellite design that employs 163 spot beams (Fig. 17). Routing the signals to the correct spot beam then becomes extraordinarily difficult to accomplish with analog (e.g., SAW) filters, and instead will be performed using a digital filter bank [which performs a fast Fourier transform on the signals arriving from the gateway earth station]. Therefore, to access a given spot beam, the gateway earth station must transmit at a particular frequency.

Given that a large digital signal processor is required onboard the ICO satellites, it was decided to form the 163 beams by phase-combining the signals digitally rather than in a microwave matrix. While this further complicates the onboard processor, it is expected to greatly simplify the checkout and calibration of the antenna systems. In principle, this arrangement would also permit the beams to be steered to increase the amount of time a given subscriber remains in a given spot beam.

ICO differs from both Iridium and Globalstar in that a true TDMA scheme has been adopted for the service links, with six subscribers multiplexed into channels 25.2 kHz in width at a bit rate of 36 kb/s. A disadvantage of this access scheme is that a soft handoff (e.g., from beam to beam) is not automatic, and it is more difficult to exploit dual-satellite visibility. One method being considered would be to send a burst via an alternate satellite (say) every fifth burst. By noting the strengths of the regular and alternate bursts, the subscriber terminal could determine which satellite presently affords the best path to the gateway earth station and could adjust its own burst time and frequency to select that satellite.

The ICO satellites are being built by Hughes Space and Communications Division, and the ground segment by a team consisting of NEC, Eriksson, and Hughes Network Systems Division. ICO hopes to have its system in operation in the 2000–2001 time frame.

D. Ellipso

The Ellipso system [36], [37] differs from all the others in that satellites will be deployed into elliptical orbits (Table 5). This design takes advantage of the fact that most of the world's population lies in the northern hemisphere. The system is to be built by Mobile Communications Holdings, Inc. (MCHI) of Washington, DC, and claims to be a very-low-cost approach to the market.

The space segment of the Ellipso system consists of 16 satellites arranged in three orbital planes. All three planes remain approximately edge-on to the sun, thereby simplifying control of the solar panels. Six satellites are placed in a circular orbit above the earth's equator at 8060 km (4.8-h period) altitude. This constellation can serve users between 40°S and 40°N latitudes. Higher northerly latitudes will be served by two inclined elliptical orbits separated by 180° in which there are five satellites, each with a 3-h period. Fig. 18 shows this arrangement. The apogee of these elliptic orbit satellites will be near 7800 km.

The satellites will be similar to those used by Globalstar, having simple repeater transponders and employing CDMA transmissions. Each subscriber's signal will occupy the full 16 MHz assigned at L-band.

The satellites are oriented to face the earth and provide coverage via 61 spot beams. They are expected to weigh 700 kg and have a lifetime of five to seven years.

In an order released on July 1, 1997, the Ellipso system was awarded a license by the FCC following a decision by AMSC to withdraw its application for a second-generation system. That same order also awarded a license to the Aries system, which will be discussed next.

E. Aries

The Aries system is a proposal put forth by Constellation Communications, Inc. (CCI), based in Reston, VA. As originally proposed, the system would employ 48 lightweight satellites arranged in four circumpolar orbit planes (12 satellites per plane) at an altitude of 1020 km [38]. Each satellite would use a single beam to serve subscribers, and each subscriber would be allocated one of 50 frequency-division multiple access (FDMA) L-band carriers operating at up to 7 kb/s. The S-band signal delivered to the subscriber would be time-division multiplexed at 110 kb/s and spread by a pseudorandom sequence over the full 16 MHz of the assigned band.

Subsequent changes to the design of the Aries system have included a new constellation plan employing 46 satellites. Eleven satellites are placed in a circular equatorial

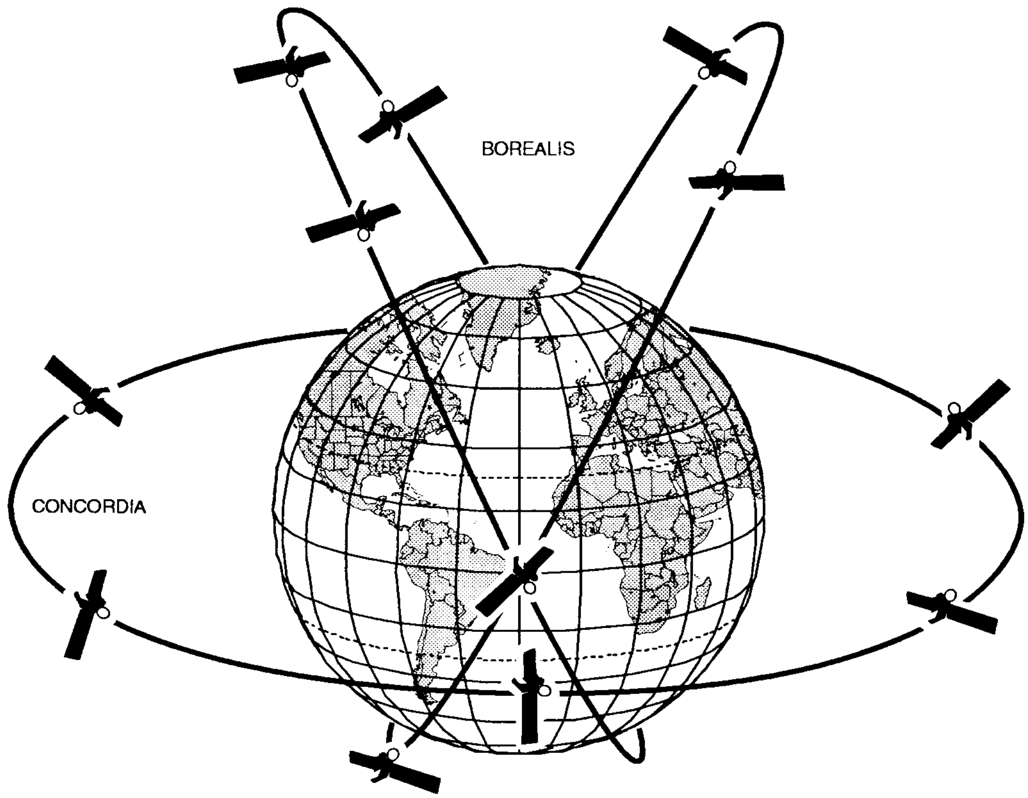

Fig. 18. Arrangement of orbits in the Ellipso system [37].

orbit at 2000 km altitude, and five are placed in each of seven inclined orbits. The equatorial portion, which is to be completed first, is known as ECCO. The ECCO system will be capable of providing service up to 23° north and south of the equator. The goal of the system is to provide rural telephony (at 2.4 kb/s) and fax (at 4.8 kb/s) using CDMA encoding.

VI. Technical Challenges

This section discusses some of the technical challenges facing the five systems described above, as well as the new regional systems outlined in Section V.

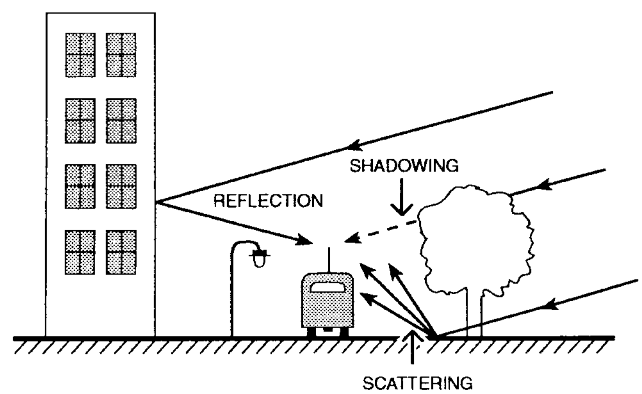

Fig. 19. Propagation effects encountered in a mobile satellite system.

A. Propagation Effects

A principal problem for satellite communications systems that provide land-mobile service is poor propagation. As illustrated in Fig. 19, signals can arrive at the subscriber terminal via multiple paths. Fortunately, the high elevation of the source makes the time dispersion of the signals much less of a problem than is encountered in terrestrial cellular systems. The chief difficulty instead is shadowing or blockage of the direct ray. Fig. 20 shows an example of the fading encountered along a tree-lined road. The problem has been studied extensively (for example, by Vogel and Goldhirsh [39]) at a wide range of frequencies. At L-band, absorption by foliage is a relatively small effect (~2 dB) compared with the scattering caused by branches, which creates deep nulls (Fig. 20). Fortunately, these are quite localized, so that a subscriber on foot could readily find a better location; however, vehicle-mounted terminals may experience temporary losses of signal.

Signal blockage by buildings has also been studied by various groups (see, for example, [28]). Fig. 21 shows model results obtained at COMSAT Laboratories for the average length of a call (placed randomly during a satellite pass) before it is dropped owing to shadowing (of either the original or the following satellite) for a hypothetical 12-satellite ICO system and a 35-satellite LEO system. Dual visibility was not exploited for either system. The results shown are for an urban environment. The situation that was modeled involved a midlatitude subscriber placing a call from a corner at the intersection of two streets lined with two-story buildings. It can be seen that the

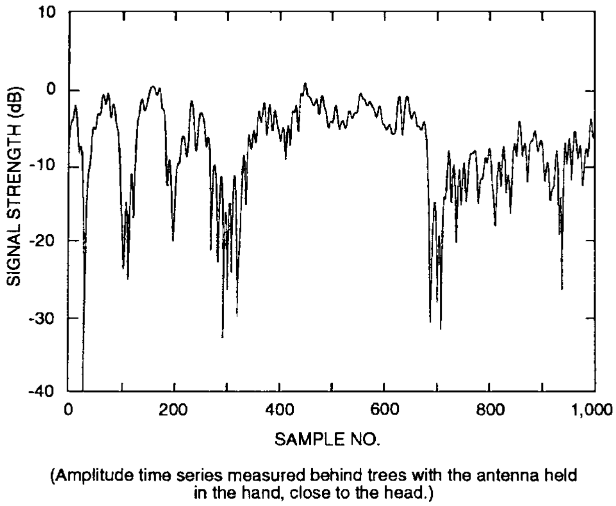

Fig. 20. Example of fading encountered along a tree-lined road at L-band.

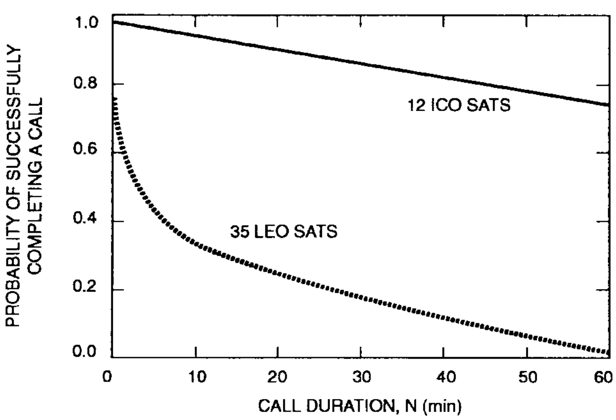

Fig. 21. Model results obtained at COMSAT Laboratories for the probability of completing calls of N-minutes duration in an urban environment. (W. Sandrin, private communication.)

intermediate circular orbit offers the better approach for such an environment.

B. Antenna Design

The design of antennas for mobile service to handheld units is particularly critical for geostationary satellites. Typically, separate transmit and receive antennas are used to avoid passive intermodulation problems. Reflector antennas with diameters on the order of $\geq$10 m or larger are necessary to achieve adequate link margins, and these must be fed with a phased array of some type to form the requisite number of beams. An offset-fed arrangement is preferable to avoid blockage, but requires that these (two?) large reflectors be supported at some distance from the main body of the spacecraft [40].

Such large reflectors must be folded in some fashion and then deployed in orbit. A variety of deployment schemes have been developed, but all are difficult to test on earth in a way that matches the weightless conditions encountered on orbit. Another difficulty is that in order for the reflector to conform to the required surface, it is preferable to use a knitted or woven mesh material (such as beryllium-copper) that is springy and can be stretched tightly across the ribs [40]. The mesh, however, can snag on itself, preventing proper deployment. Coating it with a thin layer of plastic material to prevent this is undesirable, since dielectric materials can become charged in sunlight, causing electrostatic discharges to occur [17].

C. Onboard Processing

To date, the only satellites that have been flown in which any significant digital onboard processing was employed were the NASA Advanced Communications Technology Satellite (ACTS) and two experimental Italian (ITALSAT) spacecraft. The large amount of processing required by the Iridium and ICO designs represents a risk area from several standpoints. First, there is the danger that the size and power consumption of the processor will increase as development proceeds, affecting the overall power budget of the spacecraft. A second concern is for the long-term reliability of a large digital signal processor placed in orbit and possibly subject to radiation damage over time.

D. Handoff

Handoff from beam to beam is necessary in each of the five global systems described and can be likened to the situation arising in a terrestrial cellular system, only in reverse: the subscriber is essentially stationary and the cells are moving past. Since, by definition, a subscriber who has successfully placed a call is in a known beam, it is possible to manage the beam-to-beam handoff problem in a relatively straightforward way. More difficult is a satellite-to-satellite handoff, which is likely to occur for any LEO system. CDMA systems can allow this to happen in a "soft" fashion (albeit at some loss of capacity), since the transfer need not occur until the subscriber's signal is being received in the following satellite. This is more difficult to accomplish in FDMA/TDMA systems, since the Doppler shifts (relative to the channel width) are quite large and in different directions for the arriving and departing satellites. Also, call transfers must be handled carefully to avoid missing a portion of the conversation or having the terrestrial system erroneously detect a call hangup and take down the call.

E. Network Control

Some form of network control is required for all of the systems described here. Call setup usually entails a signaling channel, which the subscriber unit uses initially to request a call. This is particularly true for TDMA systems, which must be told what burst time to employ. All of the systems require that the call be handled in a different channel from the signaling channel.

Particularly challenging is the network control for the Iridium system, since essentially the largest portion of the network resides in the satellites and their cross links. To

Table 7 Comparison of Orbits for Global Handheld Services

Feature	GEO	ICO	LEO
Satellites	3–4	10–15	40–70
Estimated Space Segment Cost Ratio	1	1.5	2.3
Launches for Continuous Coverage	3–4	~7	~30
Operational Cost/Complexity	Low	Medium	High
Frequency Coordination Complexity	Medium	High	High
Transmission Delay (ms)	370	220	140–220
Cooperative User	Walks	Walks/waits	Walks/waits
Service Limitations	Indoors, high latitude	Indoors	Indoors

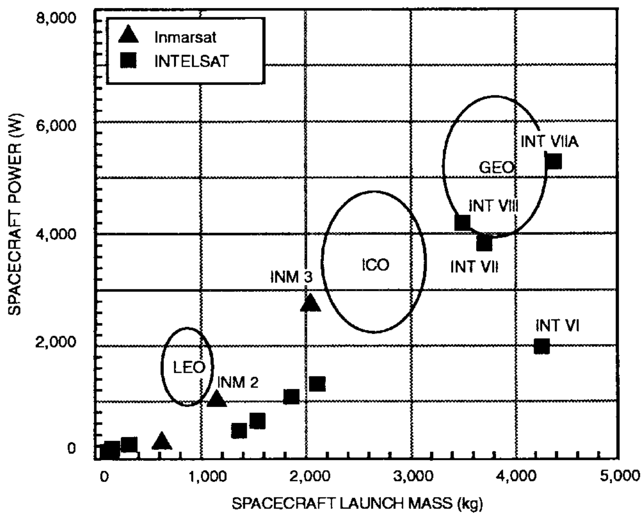

Fig. 22. Mass and power consumption estimates for mobile communications satellites for personal communications placed in LEO, ICO, and GEO orbits. For reference, some of the Inmarsat and INTELSAT satellites are also plotted.

avoid congestion on these links, they must be designed so that each cross link can handle all of the service traffic from a given satellite. In the event that a cross link fails, new routing tables must be delivered to all of the satellites in the vicinity of the failed link. Linking between satellites that are in ascending and descending planes is particularly difficult and may require that packets be routed around the globe in the opposite direction. Last, there is a need to monitor the number of times a packet has been routed via a node and to drop any when this exceeds a certain value, lest the system become clogged with undeliverable traffic.

VII. Prospects for Business Success

The likely business success of the PCS systems described here is difficult to gauge and will depend on a number of factors. These include initial overall system cost, time to market, quality and convenience of the service, value-added features such as paging, and cost to the subscriber for the terminal, monthly subscription fee, and per-minute usage. The relative risks entailed in the five U.S. projects described here have been assessed by Gaffney *et al.* [41].

Table 7 compares some of these features qualitatively. Based on a design methodology similar to that described by Maral [42], COMSAT Laboratories performed studies of the satellite mass (and hence cost) for LEO, ICO, and GEO spacecraft. The results are shown in Fig. 22. It appears that the greater cost of the ICO and GEO satellites is more than offset (even when launch costs are factored in) by the smaller number required. Provided they can be fielded in the same time frame and the large-antenna problem can be solved, the regional systems (discussed in Section V) would appear to be a distinct threat to all of the global systems.

Of the global systems, Globalstar would seem to offer good prospects for a successful business because of the low cost of its space segment and because the cost of the ground segment is borne by the franchised operators of the system.

Most risky from all standpoints would appear to be the Iridium system, which is the most expensive and the most technically complex. Moreover, the Iridium business plan seems to depend a great deal on a million or so international business travelers, whose needs might be served in other ways—either by one of the regional systems or by cellular phones designed to operate in several modes to meet different standards around the globe.

All of the remaining systems, while less complex than Iridium, may suffer because they may not reach the marketplace until two to three years after the first entrants. Moreover, it may be difficult for Ellipso and Aires to secure adequate financing given the head start of Iridium, Globalstar, and ICO.

Complicating all of this speculation is uncertainty regarding the attitude of potential subscribers. Accustomed to the high quality and high penetration of cellular systems, some may forego altogether the use of satellite phones, with their weaker link margins, while others may opt to buy a satellite (or cellular/satellite) phone as an insurance measure (for example, to deal with a situation in which they encounter vehicle problems in a remote area of the country).

One thing that does seem certain is that the very large amounts of capital being raised to build these systems make for interesting times for those in the communications satellite field.

ACKNOWLEDGMENT

The author wishes to thank many colleagues at COMSAT—and particularly those with COMSAT Laboratories—for helpful discussions on these topics. He is particularly gratefully to A. Williams for furnishing some of the material used in this paper.

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