AN INTEGRATED SATELLITE-CELLULAR LAND MOBILE SYSTEM FOR EUROPE

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Abstract

Recently the standards of a Pan european digital cellular mobile system have been agreed upon and the implementation of the system will start in the early 1990's. The initial deployment will cover the major cities and traffic routes. To achieve a faster wide area coverage, the cooperation of a satellite system with the terrestrial cellular network appears an interesting solution, provided that as far as possible the same protocols can be used in the two environments. This paper proposes an approach to the close integration of a satellite system with the cellular network, aiming at a solution using the same protocols except the RF part of the physical layer and the synchronization strategy in the access phase. This approach, using essentially the same mobile terminal equipment for both the satellite and the cellular systems, would lead to a cost effective and efficient technical solution for the land mobile communications towards the 21st century. Moreover the system here proposed can be extended to aeronautical and maritime mobiles, so that a unified integrated land-aeronautical--maritime (LAM) system can be conceived for all mobiles.

1. INTRODUCTION

Recently the CEPT Study Group on Mobiles has defined the specifications about the standards of the new generation of a Pan European Cellular Mobile Communication System (the so called GSM System) [1]. This system had to fulfill the following main requirements:

- to provide a full roaming capability in all participating networks (countries).
- to provide basic telephone services as well as a wide choice of non-voice services.
- to offer a traffic capacity higher than that in existing systems.
- to be compatible with the ISDN, where and when it will be available.

The GSM system foresees a complete coverage of the interested areas by means of cells and does not take into consideration any possible role of a mobile satellite system cooperating with the terrestrial GSM network to provide a wider and quicker area coverage. The role of a satellite system integrated with the terrestrial GSM system appears to be a reasonable choice, taking into account that:

- the deployment of the GSM system will be necessarily slow and at the early stages of implementation (about 1995) limited to some specific areas (larger cities, main routes,..);
- the technical specifications proposed for the GSM system could be used to design a satellite system closely integrated with the terrestrial mobile network.

The aim of this paper is to outline the structure of such a satellite system and to preliminarily assess its performance. After briefly recalling in sect. 2 the structure and the characteristics of the GSM network, sect. 3 proposes an approach for a satellite system closely integrated with the terrestrial GSM network outlining the main problems to be solved and the alternatives towards this solution and sect. 4 presents the achievable performance for a presently reasonable choice of the system parameters.

2. GSM SYSTEM ARCHITECTURE

The main building blocks of the GSM system, which are indicated in Fig. 1, are [1]:

- the Mobile Station (MS)
- the Base Station (BS), to which the MS is connected through a radio link; a BS controls a number of cells.
- the Mobile-services Switching Centre (MSC), to which the BS's are connected through a terrestrial link; the MSC is the interface between the fixed terrestrial network and the GSM network.

The correct operation of the GSM system requires exchanging informations during a call to/from a mobile and during the periods when the mobile is idle. The GSM network must keep track of the location of each mobile both when it is idle and when a call is in progress; in the latter case also a dynamic routing of the call in progress must be implemented to guarantee connecting the mobile going from one cell to another (handover). All the signaling informations related to these functions are provided accordingly as close as possible to the CCITT Signaling System No. 7 (with the use of the Mobile Application Part).

The specifications for the proposed GSM system are the following:

- Digital transmission for voice and non-voice services;
- Frequency bandwidths: 25+25 MHz (890-915 and 935-960 MHz bands);
- Carrier spacing: 200 kHz, providing 125 available carriers in 25 MHz bandwidth;
- Frequency reuse: 9 groups of carriers for the cellular operation;
- Multiple access: TDMA with 8 channels per carrier;
- TDMA frame format (Fig. 2):
  frame length 4.615 ms
  slot duration 577 μs
  guard times 30 μs
  frame bit rate 270.833 kb/s;
- Channel data rate: 22.8 kb/s (informations plus coding);
- Cell capacity: about 112 channels per cell;
- Modulation: Gaussian Minimum Shift Keying (GMSK);
- Voice coding: 13 kb/s Linear Predictive Coding;
- Data: 300 to 1200 b/s asynchronous, 1200 to 9600 b/s synchronous;
- Circuit-switched and packet-switched services to be provided.

3. INTEGRATED SATELLITE/GSM SYSTEM

From the user's point of view a communication system for mobiles employing both a satellite network and the GSM network is fully integrated when the user is not aware whether the actual connection goes through the satellite or the GSM networks. In such a system the MS must be able to use the satellite or the GSM facilities in a transparent way to the user (Fig. 1).

From a system point of view the integration of the satellite and GSM networks requires the use in both networks of the same protocols for the mobile terminals and for the fixed stations.

Of course the RF part of the MS transmitter and receiver must be separated for the satellite and the GSM networks. Thus a technically efficient approach would be to think of a MS having the same protocols (i.e. the same hardware and software equipment) with the exception of the RF part.

The operation of the MS should be to select at any instant of time which one of the two links (satellite or GSM) has better characteristics, for example comparing the levels of the signals received from the satellite and from the GSM base station. Note that the MS, even when idle, receives signals from the GSM network and that the selection of the link is already foreseen in the GSM system for the managing of handover and location informations; thus the operation of a MS is an extension of existing functions for the inclusion of a satellite system.

The main procedures from a network point of view for the integrated satellite/GSM system are:

a) location registration
b) call handling
c) handover
d) synchronization of the TDMA access.

One interesting outcome of. the analysis reported in [2] is that the same protocols of the GSM network can be used to implement the first three procedures and that the Earth Stations (ESs) of the satellite system play the role of the MSCs and their associated BSs. Differently, the synchronization procedure requires some adaptations.

3.1 Synchronization strategy

For the synchronization strategy of the TDMA access both in the GSM system and in the satellite system we must distinguish two states (modes of operation):

i) normal state, which is present during the call already in progress;
ii) access state, which is present in the call setup request phase, e.g. at the start of a new connection or at handover.

i) Normal State

In the GSM system during normal operations (e.g. during the call in progress) the BS continuously monitors the delay from the MS and, when the delay changes, communicates the variation to the MS, that accordingly updates its transmission time instant. In that way the burst transmitted by a MS is always correctly positioned within the assigned timeslot and a guard time of about 30 μs is sufficient for any cell size.

The same procedure can be applied in a satellite system, performing the measurements on board or at an earth station. Therefore no change in the GSM synchronization procedure is necessary in this state.

ii) Access State

In the GSM access state, the MS sends an Access Burst (AB) of 88 bits (0.325 ms) with a guard time of 68.25 bits (0.252 ms). In this state the MS has no information on its position relative to the BS, but the guard time is sufficient to allow for a maximum cell radius of about 35 km. Thus in the GSM system the duration of one slot is sufficient even in the access state.

In a satellite system with multiple spot beams we have to cope with spot radius of about 1000 km. A guard time of 7.2 ms is therefore necessary, corresponding to 1950 bits. Of course, in this case one slot is not sufficient and even one frame (4.615 ms) is shorter than the necessary guard time. An even longer guard time is necessary when using a satellite with a single beam covering Europe (Eurobeam). Therefore a different approach is required in the access state of the satellite system. Two alternatives are possible.

1) Carrier reservation for the access state

We shall consider here the case of a satellite system with multiple spot beams. The extension of the synchronization procedure to a Eurobeam system is straightforward.

A complete carrier is reserved for the access procedure in the satellite system for each spot (Access Carrier). This Access Carrier is subdivided in Access Timeslots corresponding to two GSM frames, whose duration of 9.23 ms is sufficient for the necessary guard time and the Access Burst duration. The Access Timeslots are simply derived by the MS terminal from the received timing signals from the satellite, for example detecting the start of even (or odd) frames. Successively, the satellite system receiving the Access Burst measures (on board or at an earth station) the estimated round trip delay (satellite-MS-satellite) and sends the corresponding information to the MS, that can thus start using the burst format of the GSM system.

2) Cooperation with a positioning system

If an autonomous positioning system (e.g. like the Global Positioning System or a similar one) is available at the MS, the mobile position can be known with a sufficient accuracy (i.e. within a radius of about 35 km) to allow for the use of the same GSM procedure in the access state.

3.1.1 Performance Analysis of the Satellite Access Procedure with Carrier Reservation

The Access Burst is transmitted by the MS after the detection of the start of the even (or odd) frames. Due to the random spreading of the mobiles throughout the spot, the starts of transmission of the Access Burst are likely to be random points within the two frame period of the Access Timeslot. Therefore, as a first order approximation, we can assume the Aloha model to represent this transmission procedure.

The GSM Recommendations assume as a reference load for the traffic model for MS originating calls an average BHCA (Busy Hour Call Attempt) ranging from 1.2 to 4. Taking a mean value of 2.4 BHCA, this corresponds to $0.666\ 10^{-3}$ attempt/s for each MS. The Access Burst duration is 0.325 ms. This leads to an

Access Traffic/Subscriber: 0.216 μErl/Sub

The maximum throughput of an Aloha system is 0.18 [3]. Therefore in the Access State the satellite system has the

Capacity: $0.18/0.216\ 10^{6} \approx$ 830 000 subscribers

The average time required to successfully transmit the Access Burst is given by

$$T \approx d + b + R_x\, d$$

where

d is the collision detection delay,
b is the burst transmission time (= 0.325 ms),
R_x is the average number of retransmissions.

In the above formula the contribution of the retransmission time interval in case of collision has been neglected, as in satellite system it is much smaller than the collision detection delay (a few milliseconds with respect to hundreds milliseconds).

In practice a satellite system will operate in a low traffic load, i.e. with a throughput less than 0.1. For low traffic intensity, the average number of retransmissions can be estimated to be less than 0.25 [3]. The approximate value of d is 260ms if the round trip delay is measured on board or 520ms if it is measured at an ES. Therefore the average delay time is in the two cases respectively

$$T \approx 325 \text{ ms} \quad \text{or} \quad 650 \text{ ms}$$

3.2 Satellite configurations

Different scenarios can be envisaged for a satellite system integrated with the terrestrial GSM network: transparent satellite, satellite with limited on board processing and satellite with enhanced on board processing.

The three alternatives have different operational capabilities and can be assumed as three possible steps for the implementation of a satellite system integrated with the GSM network, based on the available technology.

3.2.1 Transparent satellite

A number of different architectures can be envisaged. They all assume a single beam for the fixed Earth Stations (ESs) [2].

A1 - Only one ES for the whole system; a single Eurobeam for mobiles.
A2 - Only one ES; multiple spot beams for mobiles.

In both solutions the ES is the unique interface with the terrestrial GSM network: all the traffic to/from mobiles that uses the satellite passes through this station, whose role is similar to a GSM Base Station (with its associated MSC) that now controls all the spot beams instead of the cells. It must be noted that these solutions have very long terrestrial tails from the ES to the end users and may not be acceptable for the management problems associated with the presence of the different Administrations in Europe. In addition solution A1 can provide a limited capacity.

B1 - Multiple ESs in the single beam (e.g. as many as the number of spots for mobiles); multiple spot beams for mobiles.
This solution assumes that the traffic directed to mobiles of a given spot pass through the ES located in (or closest to) that spot. The satellite simply acts as a repeater connecting a MS in a given spot with its closest ES, which again performs the functions of a GSM BS now controlling only one spot. In this case, too, we have long terrestrial tails for traffic directed outside the spot of the MS. However, due to the traffic distribution [2][6], they are likely to occur infrequently and may become acceptable.

B2 - Multiple ES's; multiple spot beams for mobiles.
To reduce the terrestrial tails this solution assumes that the mobiles are connected to the ES closest to the end user. To simplify the constraints on the synchronization procedure among all the ESs accessing the satellite in TDMA, a fixed number of carriers can be assigned to each combination of ES-spot. This fixed assignment may lead to an inefficient system if a small number of carriers is available through the satellite.

B3 - Multiple ESs; multiple spot beams for mobiles.
The inefficiency of solution B2 can be eliminated using an unconstrained TDMA access from ES to MS: this however increases the complexity of the ES [2].

As a final remark, in any configuration the transparent satellite alternative simply substitutes the GSM network link MS-BS-MSC with the satellite link MS-ES. All the network functions remain under the responsibility of the terrestrial GSM network.

The transparent satellite alternative allows for the communication with mobiles in areas covered by the satellite and not by the GSM network, but, for practical reasons, it cannot be used for direct MS-to-MS communication through the satellite.

3.2.2 Satellite with limited on board processing (C)

In addition to multiple ESs and multiple spot beams for mobiles, we assume a satellite with a base-band on board processing in charge of switching the calls. All the functions required for call routing and system management can be provided on ground at a control center through a double-hop connection.

The uplinks and downlinks between the satellite and the MSs are in TDMA on multiple carriers, as in the GSM system. The uplinks and downlinks between the satellite and the fixed ESs are in TDMA on a high-rate unique carrier. The on board switching function provides for the correct connections between the links on the ES side and the links on the MS side. This technical solution simplifies the complexity of the ES. It also provides end-to-end connections with relatively short terrestrial tails and allows for direct MS-to-Ms communications through the satellite.

Moreover a reallocation of resources (channels) among the various ESs to improve the system efficiency is now possible through the ground control station and it is very easy to increase the number of fixed ESs as required.

3.2.3 Satellite with enhanced on board processing (D)

With respect to C, this solution adds other processing capabilities on board in order to reduce the double-hop connection for some signalling functions required by the integrated system. This is of course the most powerful system with optimized performances, avoiding the delay of the double hop connection for signaling information management. At the moment this solution can be considered as a long term solution, whose feasibility and convenience will depend on the advances of the on board processing technology and the integrated system operational requirements.

4. SATELLITE SYSTEM PERFORMANCE

The performance of a satellite system cooperating with the terrestrial GSM network is reported, as an example, considering the present bandwidth allocation for a land mobile satellite system 7 MHz at L band [4]. The different alternatives described in sect. 3 will be evaluated with the following assumptions:

- Bandwidth: 7 MHz (full duplex) at L band;
- Carrier spacing: 200 kHz
- Beam configurations: Eurobeam, 7 spot beams, 12 spot beams (Figs. 3 and 4)
- Frequency reuse (spot beams cases): 3 groups of carriers
- Multiple access: TDMA with 8 channels per carrier, with the same format as the GSM system;
- Subscriber traffic intensity: 20 mErl/sub.
- The system capacity is assumed to be limited only by the number of available channels to/from mobiles: in other words the link to/from the ESs is assumed to have the necessary bandwidth (operating at Ka or Ku band) and a full connectivity is assumed on board the satellite.

Table 1 shows the performance of each satellite configuration. Greater details are reported in [2].

The number of subscribers refers to a blocking probability (grade of service) of 2%, according to the Erlang-B formula [5]. The last column (system R) gives the maximum capacity of the system when bandwidth reallocation among the spot beams for mobiles is employed: the result refers to the limiting case of maximum reallocation of the available channels. The result for the system alternative B2 has been obtained assuming a traffic distribution of 95% in the same spot and 5% uniformly distributed among the other spots

[6].

Peak power indicates the RF power required at the MS during the burst transmission in the TDMA frame. The mean RF power required at the mobile transmitter is therefore approximately 1/8 of the peak power.

CCITT Recommendation G.114 suggests a maximum delay for speech of 400ms. GSM Recommendations assume a delay of approximately 90ms for the speech transmission between the MS and the BS (or the MSC), including signal processing and transmission. With 260ms of signal delay through the satellite, CCITT Recommendation can be satisfied only avoiding a double 90ms contribution to the overall delay. As shown in [2], only configurations B2, B3, C, D and R can avoid the double contribution.

5. CONCLUSIONS

The basic idea for a satellite system integrated with the terrestrial GSM network is to provide as far as possible commonality of functions between the equipment of the GSM system and the one of the satellite system.

In the proposed alternatives this has been achieved by using as far as possible the same protocols for the satellite and the GSM systems. The common protocols include all the functions at layers 2 and 3 and the majority of functions at layer 1. The differences at layer 1 between the two systems are the RF band used and the synchronization procedure for the random access protocol employed in the call setup request phase. Therefore the MSs and the ESs can share the equipment for the common protocols and different implementations are limited to the RF part and the random access synchronization protocol.

The results suggest some of the proposed alternatives as feasible solutions for the integration of a satellite system with the terrestrial GSM network for land mobile communications.

The main technical advantages are:

- only one mobile terminal is required for the satellite and the GSM systems, making it attractive for its potential low cost;
- the ESs of the satellite system are similar to the GSM BS and MSC switching centres: this avoids an expensive development for the ESs that can be adapted from the GSM BS and MSC stations and may even be colocated with some of them saving the common parts.

The main operational benefits that could be achieved are the extension of the mobile services with the GSM standards to:

- not yet covered Western Europe areas;
- Eastern Europe and North Africa areas;
- aeronautical and maritime mobiles, so that a unified integrated land/aeronautical/maritime system (LAM system) could be conceived for all mobiles.

On the basis of the subscribers capacity offered by the systems and RF power required at the mobile terminals, the following conclusions can be drawn:

i) Solution A1, the simplest one, may be considered only for a demonstration mission, but it is not adequate for an operating system.

ii) Solutions B2 and B3 can be selected for an operating system using a transparent satellite, as they also can cope with the management problem associated with the presence of several different Administrations in Europe.
It must be recalled that these solutions do not allow a direct MS-to-MS connection through the satellite. For calls between two MSs using both the satellite and the GSM systems, a delay smaller than 400 ms for speech can be guaranteed with the configuration B3. However, considering also that a call between two MSs is likely to occur relatively infrequently, both solutions can be used for a first generation of a satellite integrated mobile communication system.

iii) Solution C with on board baseband switching functions is more attractive in many respects: it allows direct MS-to-MS connection (guaranteeing a delay for speech smaller than 400 ms), simplifies the TDMA part of the ES and is more flexible, as new ESs may be added as required (further reducing the terrestrial tails) and the reallocation strategy becomes easier and more efficient (granularity of one channel).
Due to the additional cost of the satellite payload, Solution C may be more adequate for a system providing larger subscribers capacities (e.g. those operating with larger bandwidths for mobiles) and can be more attractive for a second generation of a satellite integrated mobile communication system.

It is clear that, with the current frequency allocation at L band, a mobile satellite system can only serve a small fraction of the potential users of the GSM system (estimated in the order of millions subscribers). Nevertheless, the capacity of the satellite system can be sufficient to meet the needs of users roaming through areas not covered by the GSM network, at least in early stages of development of the land mobile communication system. At later stages, when the increased demand for mobile communication services will require higher capacity to the satellite system, larger bandwidths will be necessary at L band or at Ka or Ku bands.

For the integrated LAM system even with the current frequency allocation at L band the capacity provided by a satellite system could be satisfactory for the smaller communities of aeronautical and maritime users.

Of course, many problems are to be solved for the integrated satellite-GSM system to become a reality. Among the main technical problems we can mention the multipath fading, the staggering of the transmission and reception at the MS to avoid the use of a duplexer, the transmission interface at the ES to avoid the double protocol conversion between GSM and terrestrial networks standards and the antenna characteristics at the MS. All these aspects need further detailed studies.

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REFERENCES

[1] GSM Recommendations, CEPT Study Group on Mobiles, CEPT/CCH/GSM/PN, February 1988.

[2] E. Del Re, "Satellite systems integrated with the terrestrial cellular network for mobile communications", European Space Agency, STR 228, March 1989.

[3] M. Schwartz, Telecommunication networks, Addison-Wesley Pub. Co., Reading, MA, 1987.

[4] World Administrative Radio Conference for the Mobile Services, Geneva, 14 Sept.-16 Oct. 1987.

[5] L. Kleinrock, Queueing Systems, John Wiley & Sons, New York, 1975.

[6] J. M. Casas, P. Bartholome', "Some aspects of the implementation of an integrated space/terrestrial network for Europe", in E. Del Re, P. Bartholome', P.P. Nuspl, Eds., Satellite Integrated Communications Networks, North-Holland, Amsterdam, The Netherlands, 1988.

SYSTEM	A1	A2,B1	B3,C,D	B2	R
DIRECT MS-to-MS COMMUNICATION (N=No, Y=Yes)	N	N,N	N,Y,Y	N	Y
NO. OF SUBSCRIBERS					
Eurobeam	12888				
7 spot beams		24045	24045	8729	33885
12 spot beams		41220	41220		56475
MS PEAK RF POWER (W)					
Eurobeam	60				
7 spot beams		6	6	6	6
12 spot beams		3	3	3	3
SPEECH DELAY (ms)	440	440	350	350	350

Table 1 - Performance of satellite configurations

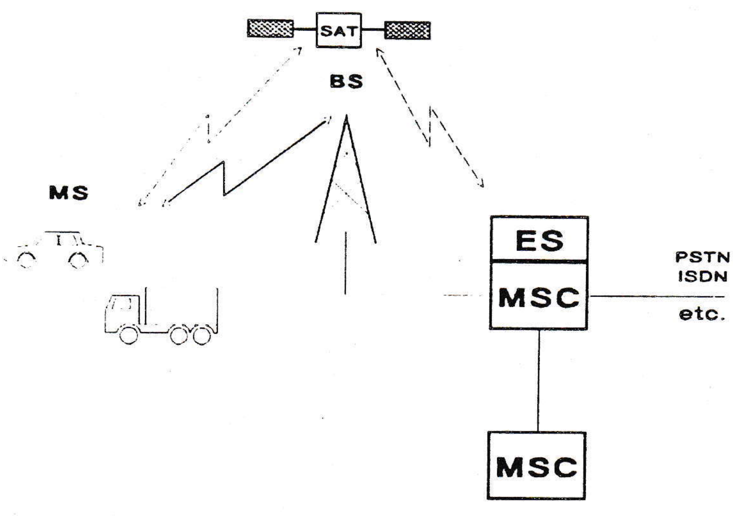

Fig. 1 - Integrated satellite-GSM system

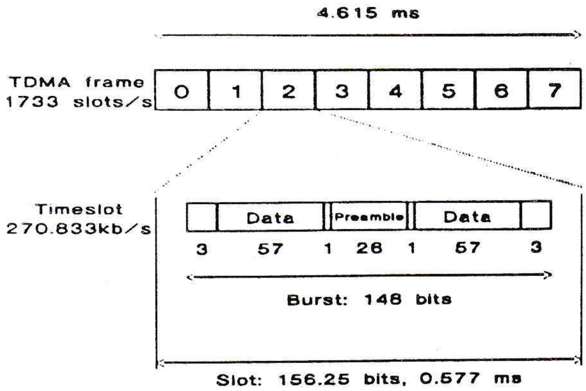

Fig 2 – Basic burst and TDMA frame structures

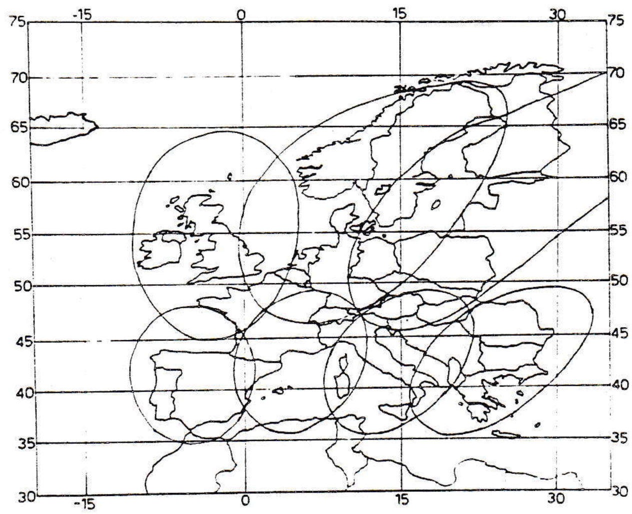

Fig. 3 – 7 spot-beam system for Europe

(courtesy of ESA)

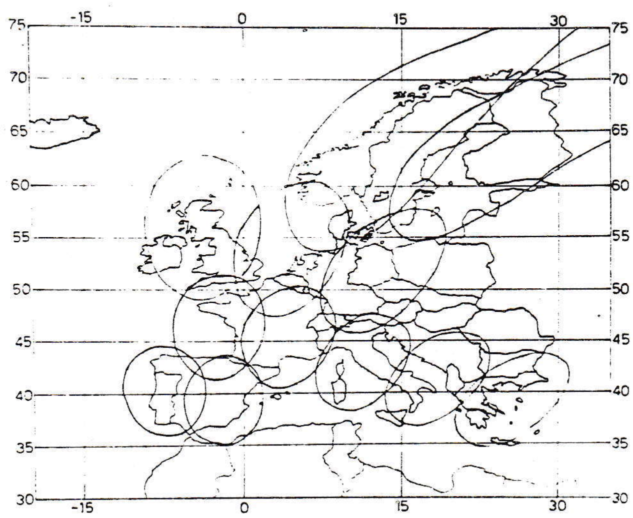

Fig. 4 – 12 spot-beam system for Europe

(courtesy of ESA)