SATELLITE COMMUNICATION AND NAVIGATION FOR MOBILE USERS

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When people think in terms of satellite communication they probably think of a very large fixed-earth station. But there is another class of user, typified in Figure 1. It is the individual highly mobile user, in this case, an Air Force KC-135. As opposed to the fixed-earth station, he might have only very low-rate teletype communications to be broadcast back to some central facility, or air-to-air communications.

Obviously, it is rather impractical to put a 60-ft dish antenna on an aircraft. Instead, as can be seen on the figure, a very small blade antenna is ordinarily used for aircraft communication. This breakthrough in satellite communications has been made possible by advances in the last 6 years or so. Most of the applications that have been looked at have been for the military, although NASA performed some communication experiments with ground stations and commercial airliners with their Applications Technology Satellite (ATS-I).

A large number of uses for satellite communications to mobile users in the civilian section is seen in Figure 2. A problem, for instance, exists with transoceanic airline communications. When a commercial airliner is on a long-distance flight from this country to Europe, or especially over the Pacific, it has to rely on what is called high-frequency (HF) communications, which, although it provides considerable range, is somewhat dependent on the sunspot cycle, the weather, the day of the week, the hour, etc.; and communications are not highly reliable. A satellite always hovering overhead, however, would provide a reliable link. The same fact holds for ships; they too have to rely on HF for their long-range communications, and the satellite would be benefiting them also. All types of emergency communications in inaccessible regions, such as jungles, or any sort of disaster area where communications are needed in a hurry, can be set up quickly with the types of satellites I will discuss in the following. As I mentioned before, the military has been the most interested party in satellite communications for mobile users.

Satellite communications for mobile users have a number of characteristics in the type of communication that are different from the types that the Commercial Satellite (COMSAT) has to deal with or the type of communication that NASA requires, getting information back and forth from astronauts in orbit or around the moon. Figure 3 shows a number of characteristics that would be typical of the mobile user. First of all, there would be a large number of intermittent users. We are not talking about a user who is on the air all the time; he is someone who will want to "push-to-talk," as they say. He just wants to get a quick message over and back. Of course, the satellite ground stations themselves are very numerous. We are not just talking about a few large stations that can cooperate with each other in terms of sharing the power of the satellite or its bandwidth; thus, we are dealing with a large number of intermittent users, and the equipment that these users are going to have must be easy to use and inexpensive. The operators of this equipment will not be trained satellite communicators; more typically, they will be radio operators. The communication facilities should be as easy to use as a radio set now; and obviously, the cost is going to have to be kept down. The operating frequency directly determines the type of antenna that can be used on these terminals. On the aircraft, I indicated the blade antenna, as it is called. It is most appropriate in the UHF, the frequency band just below the microwave frequencies for satellite communication, which are also typical of current air-to-ground communications. Any frequency higher than that would involve larger antennas, which, in addition, would have to be pointed. I think you can see the rather difficult problems that an aircraft would have constantly changing its antenna just to keep it pointed at the satellite. Another very interesting technical point which will determine the sort of signal design that we could use with satellites is that we have to allow for multipath propagation over water. Later I will have a little bit more to say about that aspect. Last, there is an ecology issue with the radio spectrum. The usefulness of the VHF and UHF bands for air-to-ground communications and other types of communications has been recognized for quite a while, and it has become a very crowded portion of the frequency spectrum, so that we will have to be careful to allow shared usage and not to dominate the band.

A number of experimental programs aimed at solving a number of problems suggested by these characteristics have been conducted in the past. I mentioned NASA's ATS-I satellite which was used for tests between some commercial airliners and a ground station. I have been more involved with the Lincoln Experimental Satellites and the ground equipment that has been used with them. The Lincoln Experimental Satellite (LES-III) was used for propagation measurements, trying to investigate the mechanism of how signals would propagate from very high altitudes down to an airplane. LES-V and -VI were communication satellites; they demonstrated with our ground equipment, which we call the Tactical Transmission System (TAT), that a number of multiple-access techniques or a large number of users could efficiently use these rather simple satellites. Figure 4 indicates just what one of these satellites looks like. The satellite is on the left, in this case, the LES-VI. It is the most recent of the Lincoln Satellites, and it was launched about 3 years ago. It broadcasts in the UHF frequency band, the band which could easily be used on aircraft, ships, or any other sort of small terminal. Just a few quick items of interest on the satellite are: the dark blue material wrapped around it are actually the solar panels; the sun's energy hits the solar panels and generates roughly a kilowatt of raw dc power, which is converted into radio-frequency energy and is transmitted by the small antennas shown. Another benefit of using this lower frequency band is that the satellite, itself, is quite simplified.

Figure 5 shows what the inside of LES-VI looks like. What appears to be gold-covered boxes is just that: they are boxes with a very thin gold coating on the outside for excellent thermal and electromagnetic shielding. As a matter of fact, the thermal shielding is so good — after very careful design — the electronics inside these boxes actually stay at room temperature, plus or minus a few degrees. Considering the extremely hostile environment in space, that says quite a bit about the thermal design engineers.

What does one of these satellites do? Its function is very simple: it just listens to signals on a given frequency band, amplifies anything that comes in on that band, then moves those incoming frequencies to a slightly different frequency, amplifies them, and broadcasts them out again. You have to change the frequency a little bit, because if the satellite broadcasts on the same frequency that it receives on, it would just be talking to itself and get caught up in the loop. As a result, it would just sit there and behave like a bit oscillator — a very expensive one, too. LES-VI, as a matter of fact, was the very first of the automatically stationkeeping synchronous satellites. This meant that without commands from ground stations, LES-VI remains hovering over one point on the earth. Previous synchronous satellites required ground commands for stationkeeping. Figure 6 depicts, in a rough way, how LES-VI did that. It depicts the earth and the pointing direction to the sun. As we all know by now, a synchronous satellite always stays above one point on the earth because as the earth rotates, so does the satellite. The satellite senses the sun and the earth, and if it knows what time it is, it knows where the sun and the earth ought to be. If they are not sensed where they should be, the satellite moves itself slightly by applying a sharp electrical pulse to a little piece of Teflon-type material, which vaporizes slightly and causes a plasma jet to move the satellite over, just a little bit, until the error is corrected. The satellite, in order to make its orbit even more stable, spins around itself at about 8.5 revolutions per minute as it slowly moves around its orbit about the earth.

Figure 7 shows one of the problems with this sort of spin-stabilized satellite. For greater efficiency, we would like to be able to broadcast our energy in a fairly narrow beam toward the earth. Why broadcast energy all over into space when you just want the energy beamed down to earth? LES-VI used a so-called electronically despun antenna system. This system activates only those antennas which are looking at the earth at any instant of time. The electronics, thus, switch between antennas at just the right rate to compensate for the spin of the satellite, so LES-VI is always looking down at the earth. The fascinating thing about this is that LES-VI actually generates only about 50 watts of radio-frequency power, or one-half the amount of power in a light bulb. This beaming adds another effective factor of 10, so altogether LES-VI is broadcasting only 500 watts down toward the earth but it can serve a significant number of users. I always find that analogy between satellites 22 000 miles up and light bulbs rather amazing.

Now that our satellite has been established in orbit, how do we go about using it? The straightforward way of using the satellite bandwidth, as shown on Figure 8, is to assign channels, similar to the way the spectrum is chopped up for television, radio, or whatever, and to use certain simple modulation techniques, AM or FM. One difficulty with this is that there may be only a few channels, yet very many users, so that we have to figure out a good way to assign the users to the channels on a dynamical basis. It would not be advisable to allocate a fixed frequency to one user because he would keep too much of the satellite occupied. Another interesting problem with frequency-division multiple access is shown in the next slide (Fig. 9). Multiple access means access to the satellite from a multitude of terminals.

Figure 10 shows what the effects of reflective propagation can be. We have a multipath interference pattern where the received power on some frequencies is very low compared to the received power on other frequencies, depending on whether the reflected rays just cancel out the direct rays or whether they actually add to them. That is one problem with frequency-division multiple access, if we consider airborne users. Obviously, ships and other stations that are physically on the ground do not have this problem. One way around that is shown in Figure 11. Instead of assigning people to certain frequencies, we assign them certain slots of time, actually very short slots of time, quick bursts of perhaps a one-millionth or a ten-millionth of a second, and each user takes his turn with his burst. This system is called time-division multiple accessing. Instead of splitting frequency up, we divide time into intervals. However, if you send a very short pulse it will cover, all by itself, the whole frequency band. This system, thus, has the same problem of the echo — echo from channel 1 clobbering channel 2 — and also the dynamic assignment problem.

A third technique (Fig. 12) is called code-division multiple accessing. Here every user is given some frequencies and some times; he transmits on a random pattern, at least, it appears random, and the person that he is trying to talk to is always looking for that type of pattern. With this pattern, we can let everybody talk on top of themselves, while the signals from other people tend to look like noise to the one particular link that is being received from. A particular system, TAT, was developed at Lincoln Laboratories and was pursued by the military. Basically it is a code-division multiple access system, as shown in Figure 13 in block diagram form. Modem, meaning a modulator/demodulator, is the thing that takes the input data and somehow converts them into a signal ready to be used; it is a very fast frequency synthesizer. Thus, the signal can hop from frequency to frequency, covering the whole band. The frequency synthesizer puts out one of a million frequencies and changes frequencies in about ten millionths of a second. By generating a hopping pattern it becomes possible to spread those little bits of energy over the bands and to get around the multipath problem and around the multiassignment problem.

Figure 14 shows a little more specifically what this band spreading, the way you make each and every individual signal cover the whole band in time, would look like. Each user transmits on some sort of a pattern by changing the frequency of the information slightly as he is making these great big hops across the bands. It is called the frequency-hopping type of a multiple access system.

Figure 15 indicates what sort of performance we can get with this system. If we plot the number of people that can use the satellite simultaneously versus the signal-to-noise ratio — and the signal-to-noise ratio is very high — we could get on the order of a dozen high-rate users, certainly not high in the sense of gigabits, but high in the sense of needing only 2400 bits per second to transmit one voice conversation. On the other hand, if these mobile users were satisfied with 75 bits per second, which is more typical with teletype rates, we can get a factor of 32 more users to a satellite. Of course, there is a message here, namely, to make most efficient use of the satellite bandwidth that is available, it would be best if these mobile users were using the lowest data rates that they could possibly get away with. Does an airliner over the ocean really have to talk to his control tower or can he simply teletype his position? This is something to be looked into.

Figure 16, on the TAT system, shows just how big this modulator/demodulator actually is. Depicted is a prototype the Lincoln Laboratory built, consisting of two drawers of equipment and a control panel. When everything is put together, it is really smaller than a television set, and all the operator has to do is to key in his little hopping pattern, which determines how his signal is going to be spread across the band. Or he enters the receive pattern, which determines what signal he is looking for, punches a button or two, and is ready to go. Sylvania built a number of production models of this Modem for the Government, and they got it down to one drawer. Most of the equipment shown on the top of this box are small digital integrated circuits. There seems to be one thing in the country where the prices are dropping and that seems to be digital integrated circuits. That, I would say, is the trend of the future in terms of communication; it will be digital.

Up to now, we have talked only about communications for mobile users. Navigation is also a very clear application of satellites. Since those satellites are always up there in some constellation, why not take advantage of them to find out where you are? Figure 17 indicates the basic way. Basically, there are three transmitters: transmitter zero is a reference and transmitter 1 and transmitter 2 are radio transmitters. The receiver listens to the time delays of the transmissions from transmitter 2 relative to the base and transmitter 1 relative to the base, and these generate so-called reference hyperbolas for a navigation system. The next slide (Fig. 18) shows how you can actually use this information. If I am a receiver, and I know that I am in the same geometric plane as the three transmitters or on the surface of the earth (it just complicates the geometry a little bit more), and if I know that the relative delay between these two transmitters is ΔT_2 or whatever, that tells me I must be on a hyperbola, and if I know the delay between the other two, it tells me I must be on a second hyperbola. If I am on both hyperbolas, I must be at the crossover point. Fundamentally, all radio navigation systems work this way. A rather elegant application of this sort of technique was developed by Johns Hopkins University for the Navy which was called the Transit Navigation System, as indicated in Figure 19. Instead of having three transmitters, why not have one satellite going around so quickly that it might as well be three satellites? Thus, they put the transit satellite about 600 miles above the earth, in a polar orbit. If I am a ship and willing to wait essentially in one position for a couple of minutes, I can have the benefit of three different transmissions. Johns Hopkins developed some rather clever techniques for the ship to measure the distance that the satellite has gone in orbit. From the three points and from the knowledge where the satellite is, the ship can at once tell where it is — to within a very small fraction of a mile to within hundreds of feet. This system has been in use for quite a while and has worked exceedingly well.

Knowing your position to within hundreds of feet implies that you know the satellite's position to within some hundreds of feet. However, we are dealing with some very interesting geophysical interactions since the satellite does not travel in a perfectly circular orbit. The earth itself is not perfectly circular and the satellite is drawn a little this way and a little that way. Thus, in doing this experiment they learned quite a bit about the shape of the earth.

How about future applications for navigation satellites? One area, aside from the obvious one of letting a ship or plane know where it is, will be in air traffic control. One of the problems is to let someone else know where you are. Figure 20 shows how such a system could work. In order to get its position, the airplane needs four satellites, not just three, as the ship. The ship knew it was on the surface; the airplane has the fourth variable of altitude. If it knows its altitude exactly, it can get away with three satellites, but if it has one more unknown, it needs one more satellite position. We can picture a constellation of four satellites, for instance, that either beam down to the airplane which then makes those hyperbolic calculations that I mentioned, or the airplane could transmit up to the four satellites and down to a ground station. The ground station could do all the calculations for it and transmit back again. There are all sorts of permutations and combinations on this. At least, the figure indicates the idea.

In conclusion, I have tried to relate some of our past efforts in communication and navigation and to indicate some future developments that we might be able to expect in this very fertile area in which space technology can really benefit us in finding some solutions to these very down-to-earth problems.

Transcribed from tape

Figure 1. KC-135 with blade antenna for satellite communication.

- Airline Transoceanic Communication
- Reliable Long-Range Ship-Shore Communication
- Emergency Communication in Regions With Rough Terrain
- Military

Figure 2. Some applications of satellite communication for mobile users.

- Large Number of Intermittent Users
- Equipment Must Be Easy to Use and Inexpensive
- Operating Frequency Must Allow for Simple Antennas on Terminals
- Must Allow for Multipath Propagation Over Water
- Must Be Compatible With Other Electromagnetic Spectrum Allocations

Figure 3. Characteristics of satellite systems for mobile users.

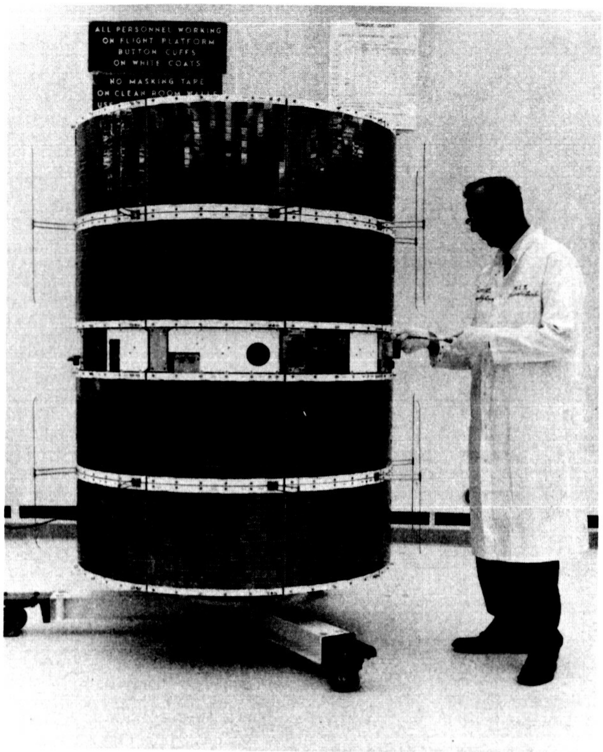


Figure 4. LES-VI external view.

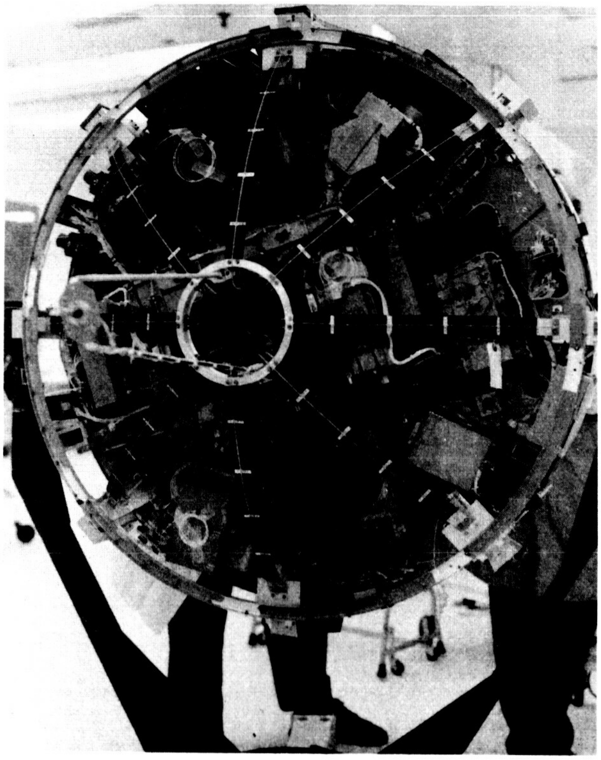


Figure 5. LES-VI internal view.

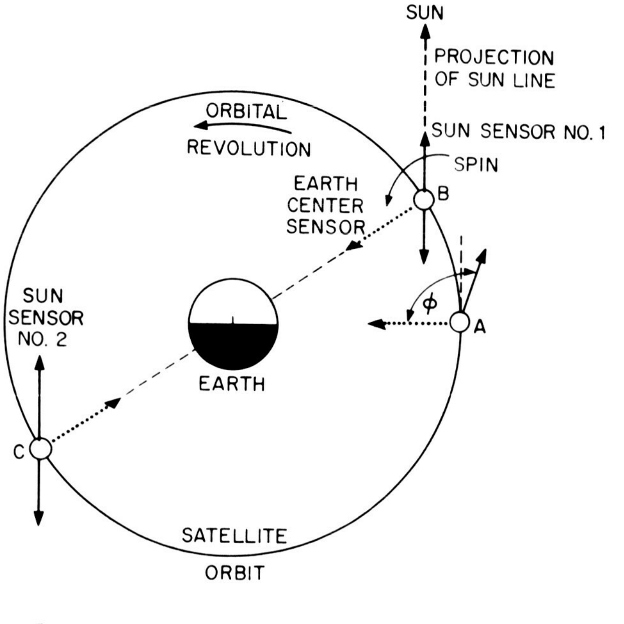


Figure 6. Determination of satellite position.

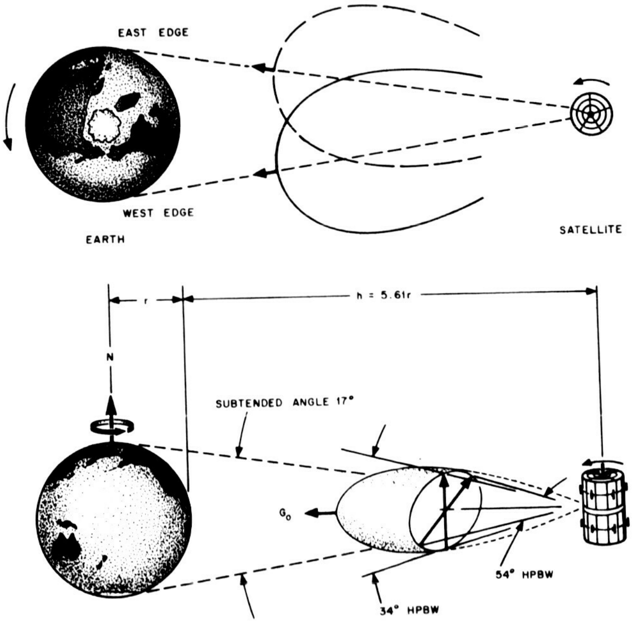


Figure 7. LES-VI antenna patterns.

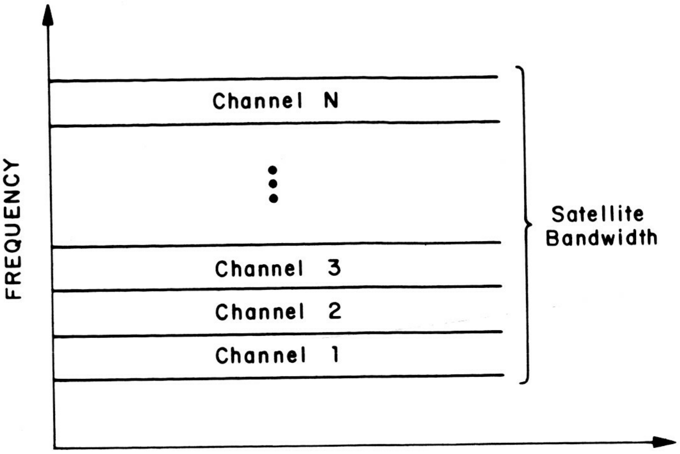


Figure 8. Frequency-division multiple access.

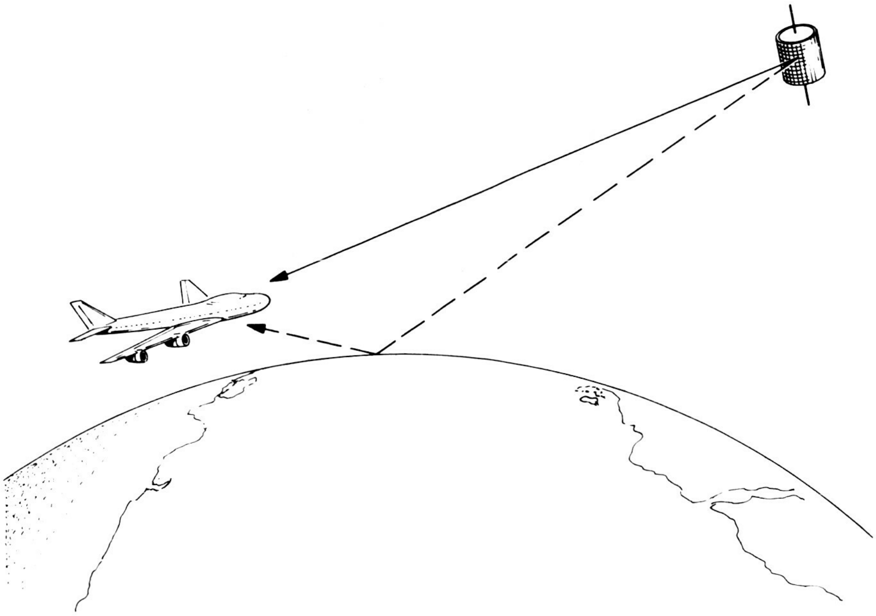


Figure 9. Multipath progagation.

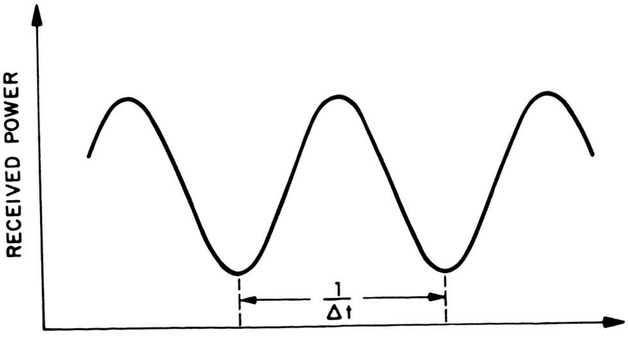


Figure 10. Multipath interference pattern.

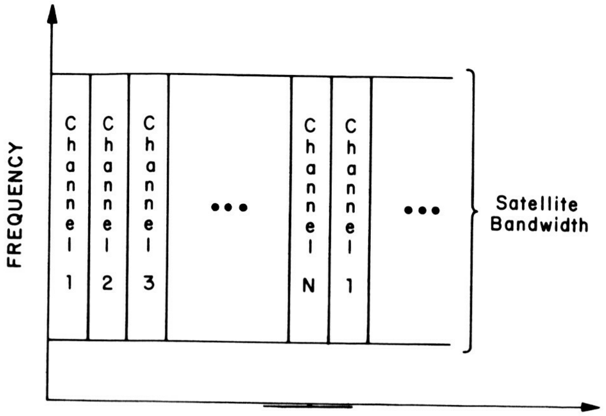


Figure 11. Time-division multiple access.

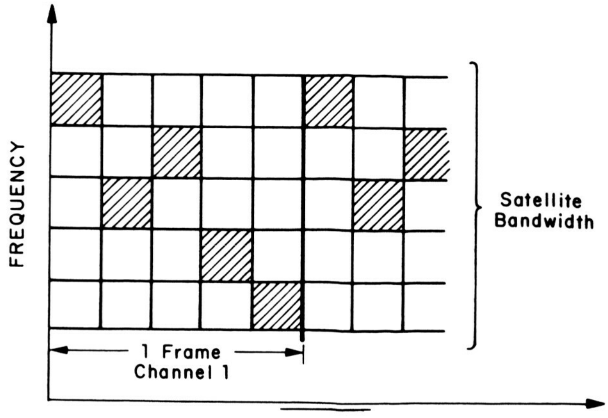
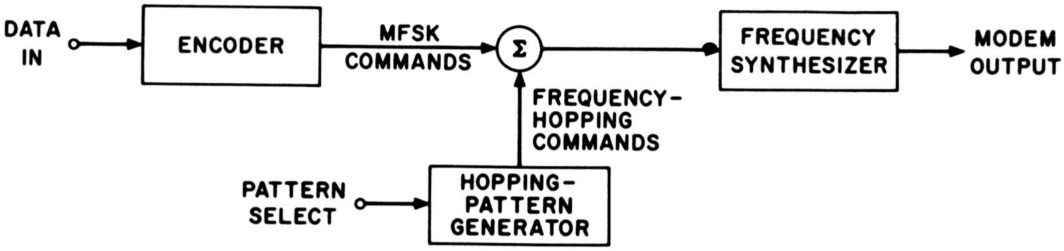
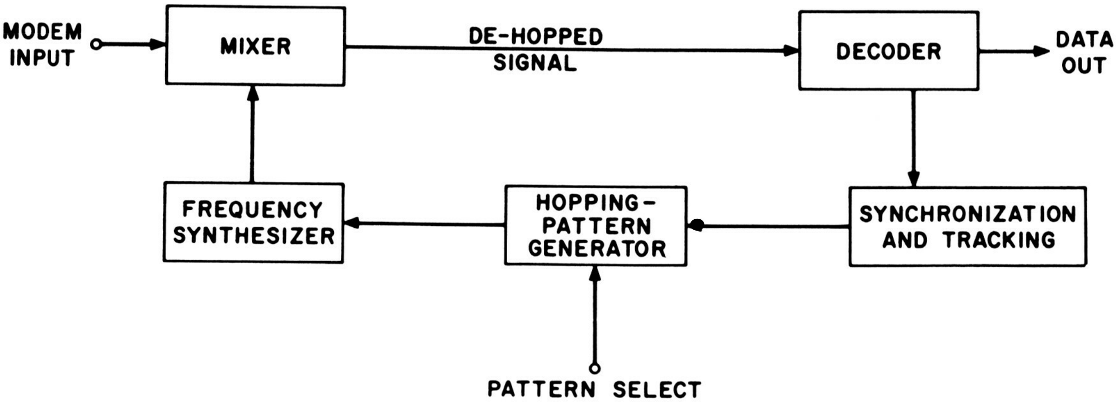


Figure 12. Code-division multiple access.



(a) TRANSMITTER



(b) RECEIVER

Figure 13. TATS Modem block diagrams.

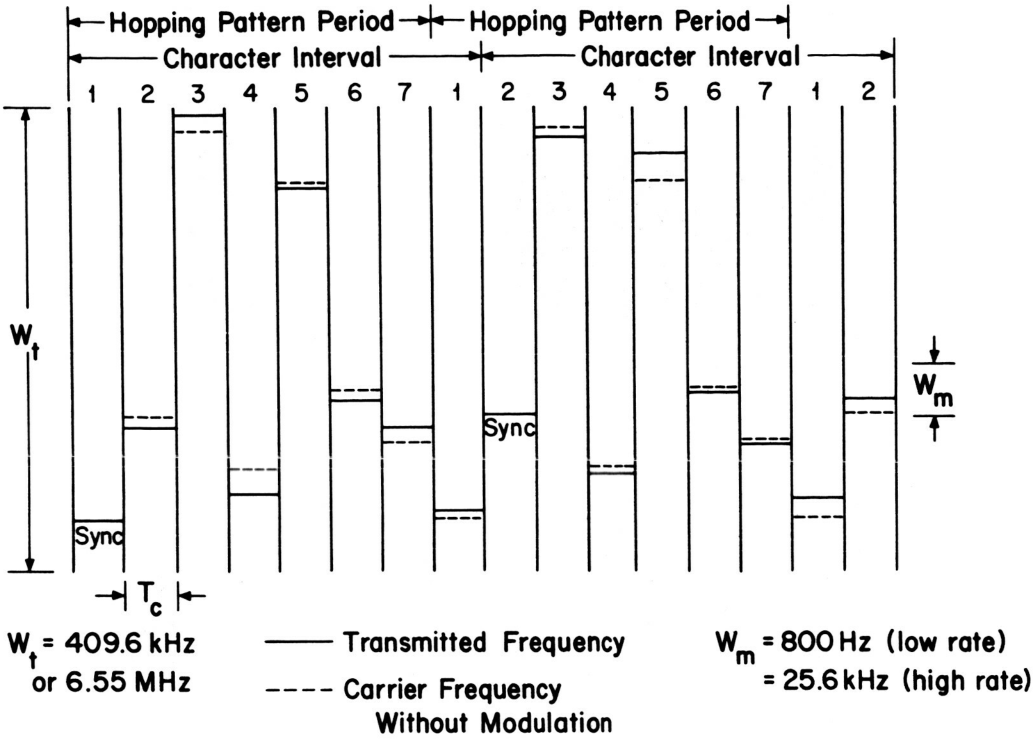


Figure 14. TATS bandspread signal format-fixed pattern.

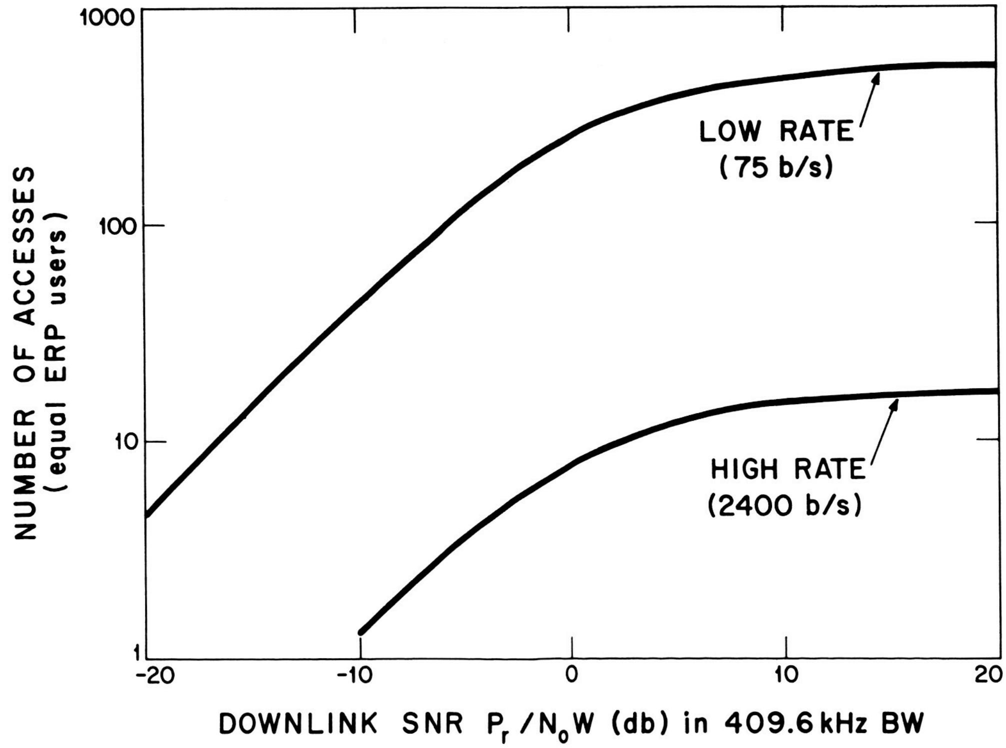


Figure 15. TATS multiple access capacity.

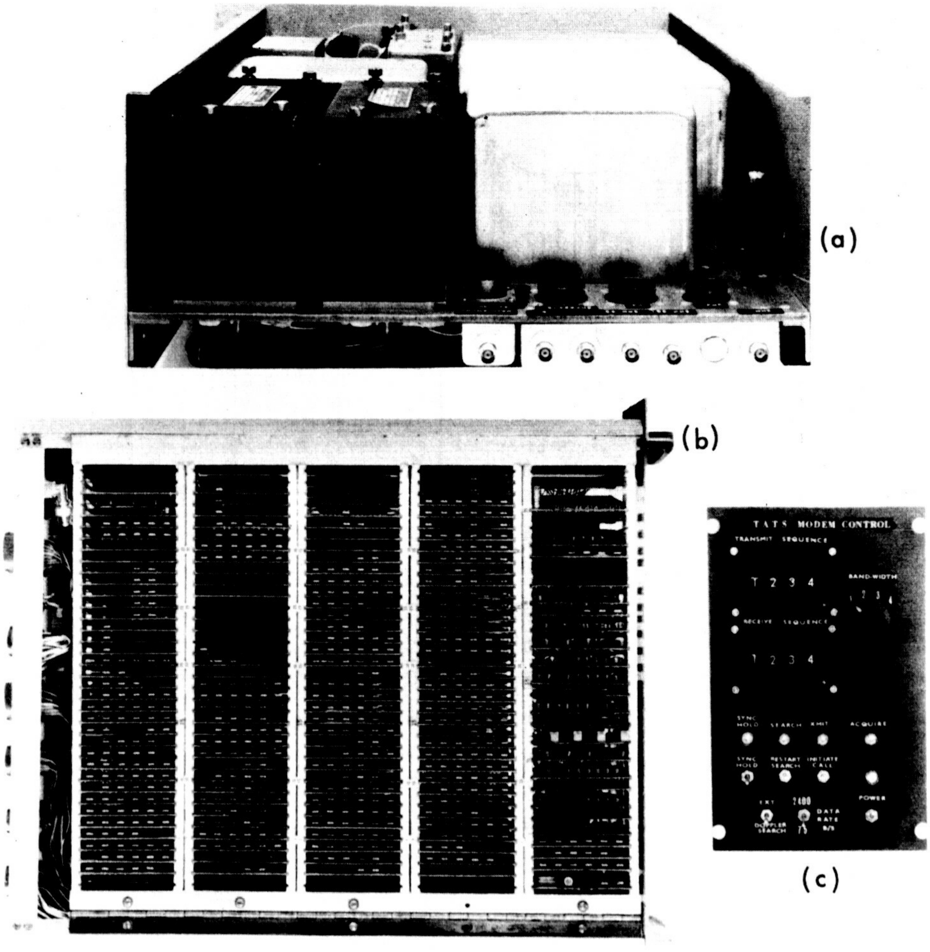


Figure 16. Lincoln Laboratory prototype TATS Modem.

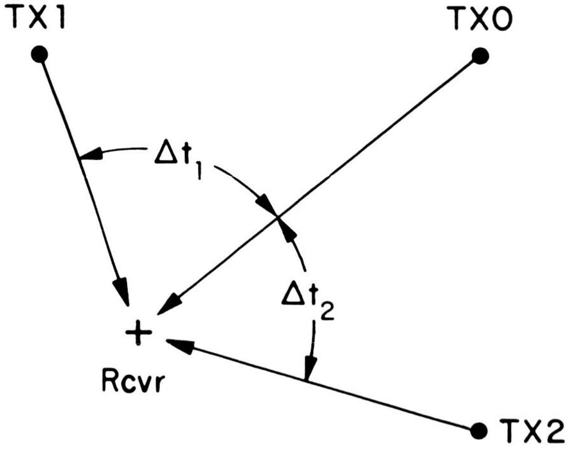


Figure 17. Radio generation of reference hyperbolas for position finding.

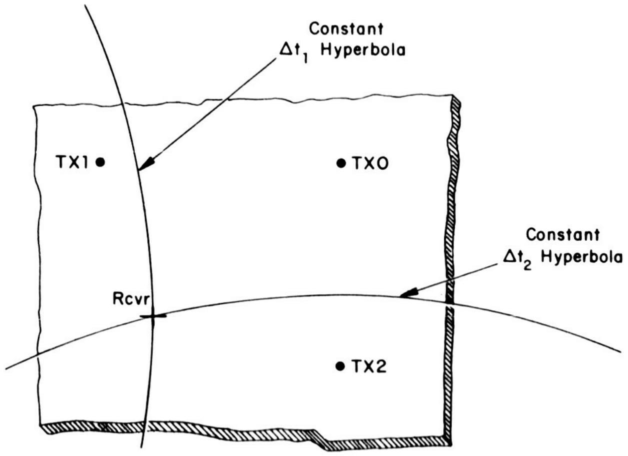


Figure 18. Hyperbolic position finding.

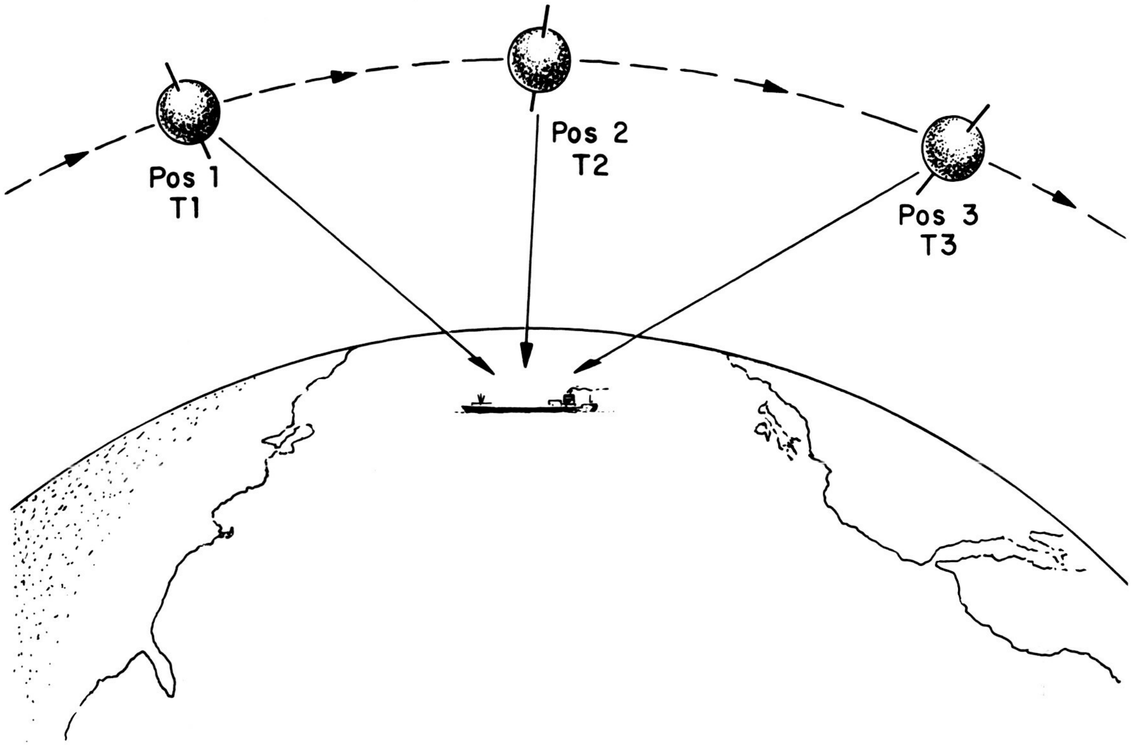


Figure 19. Transit navigation satellite concept.

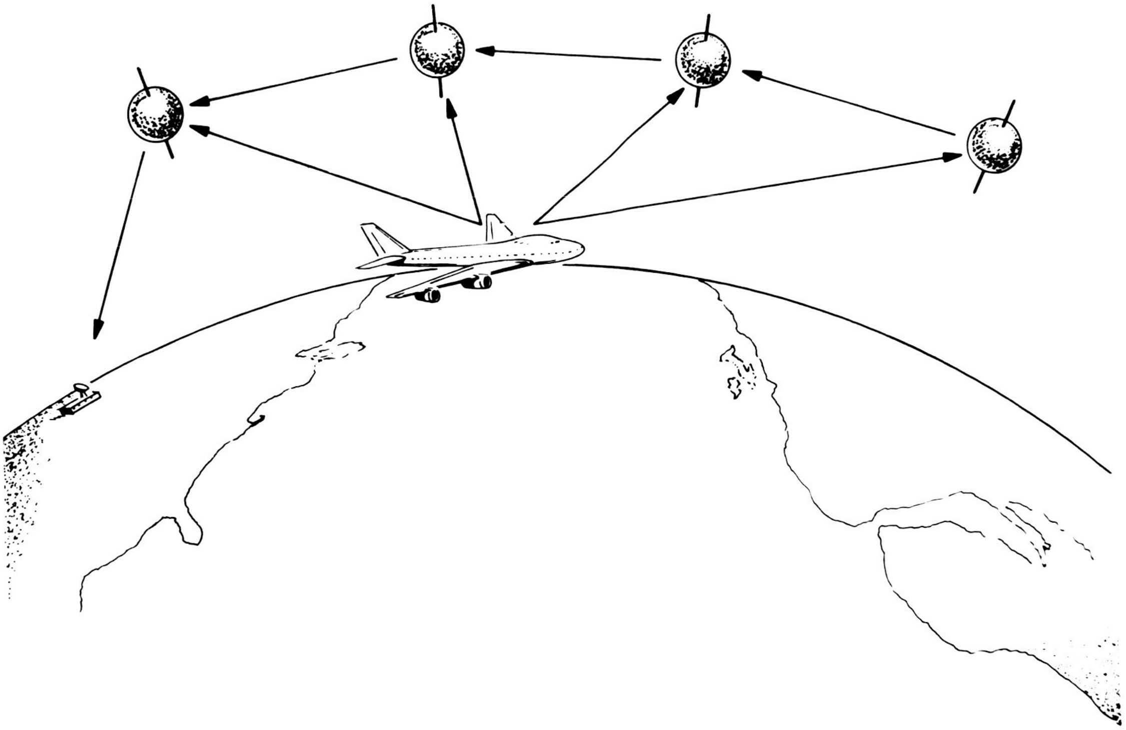


Figure 20. Aircraft navigation satellite system.