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Abstract

The interference problems faced by nongeostationary satellites may be of major significance. A general discussion indicates the scope of the problems and describes several configurations of importance. Computer programs are described, which are employed by NASA/JPL and the U.S. Air Force Satellite Control Facility to provide interference-free scheduling of commands and data transmission. Satellite system mission planners are not concerned with the precise prediction of interference episodes, but rather with the expected total amount of interference, the mean and maximum duration of events, and the mean spacing between episodes. The procedures in the theory of probability developed by the author which permit calculation of such quantities are described and applied to several real cases. It may be anticipated that the problems will become steadily worse in the future as more and more data transmissions attempt to occupy the same frequency band.

Introduction

Most investigations of radio-frequency interference between satellites deal with geostationary communications satellites. There are many other satellites in earth orbit, however, and they also are subject to potential signal interference. The communications circuits with these satellites carry commands on the uplinks and data, tracking codes, and beacons on the downlinks. Since there are many more satellites using certain frequency bands than there are communications channels, the interference problems may be significant.

What investigation techniques are available to treat these interference problems? There are two different procedures, which would be applied by different people.

The personnel who actually operate satellite systems, or collect and interpret the data, are concerned with the specific times and places of interference episodes. They therefore employ computer programs, which produce such answers as "There will be interference between satellite A and satellite B when viewed from ground station C at 3:30 pm local standard time next Wednesday." At least two such programs are currently operational. One, at the Jet Propulsion Laboratory in Pasadena, California, predicts interference for the deep-space net. The other, at the Air Force Satellite Control Facility in Sunnyvale, California, predicts interference for the numerous U.S. military satellites. Computer programs such as these are necessary for satellite network control.

The personnel who plan satellite missions or devise new satellite programs have a different viewpoint. They do not need precise prediction of interference occasions. In fact, they may not even know the launch date. They are concerned with such questions as: How much total interference can be expected? How long will it last when it occurs? How often does it occur? Is there a real interference problem, which perhaps should be solved before launch? For such questions, computer programs do not provide appropriate answers; the methods of the theory of probability are more effective.

To place the situation in perspective, consider Table 1. This table shows that the geostationary communications satellites constituted

Table 1

SATELLITES ORBITED: 1981-82

	USSR	U.S. & Other	Combined
Geostationary communications	10	21	31
Geostationary noncommunications	0	5	5
Molniya type	23	0	23
Low circular, < 30 days	69	4	73
Low circular, 30 days-1 year	14	4	18
Low circular, long life	108	11	119
High circular and other	4	6	10
Manned program	13	5	18
Total	241	56	297

only about 10 percent of the total number of satellites orbited in the years 1981 and 1982. The other satellites fall into several classes. There are geostationary satellites used for other purposes, such as the synchronous meteorological satellites. The Soviet Union has launched many satellites into the Molniya-type orbit (highly elliptical, 12-hour period, 63 deg inclination). Most of these are communications satellites, but some have different purposes. The USSR and the United States have launched a large number of satellites into low earth orbits (apogee below 1500 km), with low eccentricity (< .01). These may be separated by their orbital lifetimes. The 69 short-life (< 30 days) satellites launched by the USSR are associated with their military space program. There are usually two or three of them in space at any time. The intermediate lifetime (30 days to one year) satellites are mostly scientific. The long lifetime (one year to 1000 years) satellites have a variety of purposes. This class includes 48 Soviet communications satellites launched in six groups of eight during 1981-82.

In addition to the satellites listed in Table 1, many satellites launched in previous years are still transmitting. In August 1981, NASA was monitoring the transmissions of 10 satellites in earth orbit and nine deep-space vehicles. The U.S. military was monitoring at least 20 satellites, and the Soviet Union was certainly monitoring more than that. The possible RF interferences between satellites depend upon their orbital and signal characteristics.

Geostationary satellites appear at fixed points in the sky with respect to ground stations. Hence, any interference between them will not be dependent on time. Various interference reduction techniques, such as polarization discrimination, antenna beam shaping, and use of efficient modulation schemes, have been developed. When these techniques are applied, it may be possible to reduce the interference to an acceptable value.

In contrast, interference between nongeostationary satellites is strongly time-dependent. It can only occur when the satellites are in a common antenna beam. Such events are rare, but predictable since the satellite ephemerides can be accurately calculated. When the interference does occur, it may be quite disruptive.

These satellites receive commands on their uplinks. If a pair of satellites are in such directions from their ground stations that a command intended for satellite A is received by satellite B, then the possibility of a false command exists. If both ground stations are transmitting commands, the interference may cause the satellites to fail to receive their proper commands. Since the command interval is usually short compared to the time each satellite is in the field of view of its ground station, the commands may be deferred or repeated until they are properly acknowledged. Hence, uplink interference problems should not be too serious.

The downlink problems are more important. Most of the existing and planned satellites use the 2200-2300 MHz band for data transmission. This band contains 20 channels, each 5 MHz wide. Most satellites have low power levels, and the low-orbit satellites (the vast majority) carry earth coverage antennas. Thus, the power density at the ground from the desired and undesired satellites is comparable. If they are in the same antenna beam, serious interference may result. This may take the form of excess bit error rate and consequent loss of data during the interference interval. Worse, if the communications link employs a phase-locked loop, the interference may cause the lock to break, so that after the interference ceases, the desired signal must be reacquired and the lock reestablished. Still worse, if the interfering signal is somewhat stronger than the desired, it is possible for the antenna tracking system to be captured, so that after the satellites separate in direction, the antenna follows the interferer. Worst of all are the problems of the deep-space tracking net. The receiving systems are so sensitive, and the interferers have such a range advantage (low earth to planetary distances) that a deep-space tracking station may be completely incapacitated if an interferer is anywhere above the horizon, since the interference will come in on the sidelobes.

Since there are many more satellites than there are channels, interference may be quite likely. There are three possible configurations. In the first, a low altitude satellite is being tracked, and the tracking antenna beam crosses the location of a geostationary satellite. In the second, the converse of the first, communication is taking place between the ground and a geostationary satellite, and a low altitude satellite enters the beam of the ground-based antenna. This situation is the one most likely to produce antenna capture. For the third configuration, while a low altitude satellite is being tracked, another low altitude satellite enters the beam, producing a short episode of serious interference.

The determination of when these episodes occur reduces to finding when a low altitude satellite, moving on the surface of an imaginary sphere, enters the cone which defines the critical offset angle of the earth-based antenna beam. The locus of intersection is determined by a complicated mathematical expression which for small antenna beamwidth reduces to an ellipse. The specific times of intersection may be found by a computer program, or the probability of intersection may be found by analytic procedures. We shall describe the two techniques.

Computer Programs

Computer programs for calculating interference involving both geostationary and nongeostationary satellites are in operation. The NASA/Jet Propulsion Laboratory Deep Space Network determines interference using a program (DSIP2) developed by JPL, with software support from Computer Sciences Corporation, and maintained and operated by JPL. The U.S. Air Force Satellite Control Facility, Sunnyvale, CA, uses a program (MILESTONE 4) developed by Data Dynamics, Inc. and maintained and operated by the Lockheed Corporation. The programs are used for day-to-day scheduling of command and telemetry transmissions by their respective users. The programs employ the same basic logic, but differ considerably in detail.

The programs first investigate if the satellites have common frequencies (common means lying within the same bandwidth). Since the satellilte times of transmission are under ground control, the programs then consider the location of the satellites' ground stations, to determine whether satellite A is transmitting when it is in view of a ground station associated with satellite B. If the answers to these questions are negative, the satellite pair is scratched from the list of potential interferers.

Each program uses an ephemeris generator to determine as a function of time the coordinates of each spacecraft under consideration. The rise and set times of each spacecraft at each ground station are found. If there are common visibility intervals, the antenna offset cone angles are calculated to establish whether the interferer comes within the critical cone angle. The JPL program calculates signal level to determine whether any threshold (symbol signal-to-noise ratio degradation, telemetry drop lock, receiver interference, and receiver drop lock) is exceeded.

The outputs from the programs give the time of occurrence of each interference episode, and for JPL the degree of interference. The Air Force program also provides a wall-mounted multichannel strip chart. Time is horizontal, and each ground station is assigned to a vertically displaced parallel channel. Each satellite is associated with a color. The rise and set times for each satellite at each station are then used to mark an interval along the corresponding channel with the appropriate color. This enables the user to obtain very easily both an overall picture of the operations and an indication of the times of radio frequency conflict.

Both the JPL and Air Force programs are usually run weekly, with more frequent operation at critical time periods. The JPL program during 1981 was evaluating interference among nine spacecraft, ten potential interferers, and three ground stations. The Air Force program handled 20 satellites and 12 ground stations. Each program is capable of treating greater numbers.

Since these programs are employed to provide information to field personnel concerning potential interference and consequent loss of operation, action is required if interference is indicated. The first action is to inform the user when an interference episode may be expected. He may be able to defer his operation to a noninterfering time. This is especially useful for commands. Then, if the interference episode is very short, the interference may simply be accepted and the information lost. This is only reasonable if the information is not critical. If the signal from Voyager had been interfered with for a particular 45 seconds, the only picture which contained a previously unknown moon of Jupiter would have been lost. If the information is critical, the operator of the interfering satellite may be persuaded to command it off. This was actually done during the Voyager I flyby of Saturn. A Soviet Cosmos satellite, which could have interfered drastically with the Voyager data transmission, was turned off by the Russians during the critical periods.

These computer programs work quite well for the ascertainment of possible interference, determination of when it may occur, and action procedures. There is a difficulty at present in the Air Force operation in that there is no feedback from the field, so it is not known whether the action procedures are effective. This is an operational problem rather than a matter of principle. It appears that both programs provide interference warnings with sufficient lead time.

Probability Considerations

The mission planner is interested in such quantities as the expected fraction of the time there will be interference, the mean and maximum duration of such occurrences, and the mean spacing between episodes. He would like an analytic treatment, with the results given as simple equations from which he can draw qualitative and quantitative conclusions, rather than a computer program which will give him excessive information about special cases. We have developed such results, valid under the restrictions of narrow antenna beams and near-circular orbits. These restrictions are satisfied for most cases of interest. They are not satisfied for the deep-space net. Although they use very narrow antennas, the great receiver sensitivity and the range advantage of the interferer permits sidelobe interference. The theory may be adapted to cover this situation. Also, the Molniya-type orbits cannot be handled by these analytic procedures.

Recall that the condition for interference is that the two spacecraft be in the same antenna beam. Suppose satellite A is being tracked. If all orbits are approximately circular, satellite B is moving on a sphere of radius r_B. The beam from the ground station to A intersects the sphere of radius r_B in a complicated curve which for small antenna beamwidths reduces to an ellipse. If the nodal crossing of the orbit of B is properly located, the orbit track will pass through the ellipse, and if the time of the nodal crossing of B is properly related to the time of the nodal crossing of A, satellite B will actually pass through the beam. The time that B spends in the beam can be calculated. The value of beamwidth is selected by a "cookie-cutter" model, such that there is interference if B is inside, and non-interference if B is outside. The JPL and Air Force computer programs use a beamwidth of 5 deg, which is small enough to meet the requirement that the intersection curve be an ellipse. The duration of interference is to be averaged over the position and time of the nodal crossing to give the mean duration of interference, which is equivalent to the long-term probability of interference. The maximum duration of interference occurs for episodes near the edge of the field of view, for which the ellipse is largest.

There are several possible configurations. The interference may be between a low-altitude satellite and a geosynchronous satellite, in which case interference may occur on either northbound or southbound passes of the low-altitude satellite. If both satellites are low-altitude, their periods may be unrelated, in which case interference may occur for either northbound or southbound passes of either satellite. If two low-altitude satellites have related periods, as occurs for the sun-synchronous satellites, then there is only one possibility for interference, which must be determined separately for each example.

A low-altitude (below 1500 km) satellite of sufficient inclination will make one northbound and one southbound pass through the field of view of a ground station each day. If the ground station is tracking a geosynchronous satellite, then there will be interference if the low-altitude satellite has its nodal crossing in the proper range. The mean time between episodes of interference will be the nodal crossing width which corresponds to entering the field of view divided by the nodal crossing width which corresponds to entering the beam. The result is the same if the low-altitude satellite is being tracked. If the satellites are both low altitude, then the interval between episodes of interference is directly proportional to the synodic period of the satellites, that is, the time for the faster satellite to gain one orbit on the slower, and inversely proportional to the product of the angular widths along the equator such that either satellite enters the field of view. In general, the probability of interference is proportional to the square of the beamwidth, while the maximum duration of interference is proportional to the beamwidth.

The general theory has been applied to several examples of real satellites, listed in Table 2. These satellites were selected because the information about orbits, frequencies, and other parameters was unclassified and because they display all the indicated interference behavior. Other satellites might have been preferred, such as a Soviet satellite, but the information was not generally available. It is noted

Table 2

SATELLITES TREATED

Satellite	Altitude (km)	Inclination (deg)
1. Desired signal Defense Meteorological Support Program (DMSP)	825	98.65
2. Geostationary interferer GOES-4	35,790	0.2 (95°W)
3. Low-altitude random P-80	740	72.5
4. Low-altitude synchronized Landsat-3	919	99.11

that Soviet satellites will usually not be transmitting when they pass over the United States, and thus will not cause interference, but they might interfere with U.S. or other receivers in Europe.

The interference between a Defense Meteorological Support Program (DMSP) satellite and the geostationary meteorological satellite GOES-4 is summarized in Table 3. They have a common frequency, or rather their center frequencies lie well within the 5 MHz bandwidth. Their ground stations are so located that DMSP is commanded on when it is within range of the GOES-4 station, and GOES-4 is always in the sky at the DMSP station. The table shows the interference is at the .01 percent occurrence level, which is comparable to that required of communications

Table 3

DMSP AND GOES-4

Common frequency:	2207.5 MHz (DMSP)	2209 MHz (GOES-4)
Stations:	Loring AFB, Caribou, ME	DMSP
	Wallops Station, VA	GOES-4

GOES-4 interferes with DMSP 52 min/yr

	Northbound	Southbound
Episodes per year	48	40
Mean duration	32 sec	39 sec
Max duration	42 sec	50 sec
Episode spacing	4, 5, or 9 days	9 days

DMSP interferes with GOES-4 27 min/yr

	Northbound	Southbound
Episodes per year	32	30
Mean duration	25 sec	28 sec
Max duration	32 sec	36 sec
Episode spacing	9 or 14 days	9 or 14 days

satellites, and lasts about 1/2 minute per episode. The 9-day period is the synodic period for DMSP to recur within the nodal crossing range required by the ellipse size. The ellipse is so oriented in the sky at Loring AFB that there are additional northbound episodes of short duration. The ellipse is higher in the sky at Wallops Station than it is at Loring, so it is smaller in size and there is less interference, as shown by all the numerical values.

The interference between two randomly related satellites, DMSP and P-80, is shown in Table 4. The interferer, P-80, is a satellite in the Air Force Satellite Test Program which has not yet been launched, but for which information has been released. These satellites have a common frequency and a common ground station. As can be seen, the interference is rare, but when it occurs, the duration is appreciable. For this pair of satellites, each has a nodal crossing width of slightly below 60 deg for it to come into the field of view northbound, and another of the same length for southbound passes. The synodic period is 61 orbits, or about 4 1/4 days. The product of factors gives the 40-day mean spacing,

Table 4

P-80 INTERFERING WITH DMSP

Nodal positions and times random
Common frequency: 2207.5 MHz
Common station: Vandenberg AFB, CA

Probability of interference -- 2.15 min/yr

Episodes per year	9
Mean duration	14 sec
Max duration	30 sec
Mean spacing	40 days

which was then checked by detailed calculations. The probability was calculated using a computer program for the HP-34C hand calculator. This probability would most likely not be regarded as significant.

The third case is the interference between DMSP and its fellow sun-synchronous satellite Landsat-3 (L-3), shown in Table 5.

The times when these satellites cross the equator are so adjusted that they will always be in the proper time phase for interference at 10:30 am local time, at which time both are near 60° N. For interference to occur, their nodal crossings must be so arranged that L-3's southbound crossing is about 38° W of DMSP's northbound crossing. They have a common frequency, and a pair of ground stations such that both can be commanded on and viewed during potential interference intervals. The nodal crossings, separated as above, must be placed so the interference location lies within the mutual field of view. These nodal crossing combinations are quite rare, so the total interference is

Table 5

LANDSAT-3 INTERFERING WITH DMSP

DMSP crosses equator northbound at 11:30 am local time
L-3 crosses equator southbound at 9:30 am local time
Interference only possible with satellites near 60°N

Common frequency:	2267.5 MHz (DMSP), 2265 MHz (L-3)
Stations:	Fairchild AFB, Spokane, WA (DMSP)
	Fairbanks, Alaska (L-3)

Probability of interference -- 0.88 min/yr

Episodes per year	3
Mean duration	18 sec
Max duration	30 sec
Mean spacing	127 days

small, less than 1 minute per year. However, the duration may be significant, since a full picture may be lost. The mean duration is longer for the case of Table 5 than for Table 4, because the interference episodes for Table 5 all occur in the outer portion of the field of view.

It may be concluded that nongeostationary satellite interference problems are sufficiently important that there are current and planned major field operations for handling them. Existing computer programs provide interference flags with sufficient lead time. Effectiveness of action programs is uncertain at present, because of lack of feedback from the field. Probability considerations enable mission planners to determine if they may be confronted with significant interference problems.

There are so many satellites and ground stations that the total effect on a program may be significant, even though the individual interference episodes are rare, and it may be anticipated that the problems will become steadily worse in the future as more and more data transmissions attempt to occupy the same frequency band.