RECOMMENDATION ITU-R F.1107-1*

Probabilistic analysis for calculating interference into the fixed service from satellites occupying the geostationary orbit

(Question ITU-R 223/9)

(1994-2002)

The ITU Radiocommunication Assembly,

considering

a) that the World Administrative Radio Conference for Dealing with Frequency Allocations in Certain Parts of the Spectrum (Malaga-Torremolinos, 1992) (WARC-92) has allocated to a number of satellite services, operating in the geostationary orbit, spectrum that is also allocated to the fixed service (FS);

b) that emissions from space stations operating in the geostationary orbit and sharing the same spectrum may produce interference in receiving stations of the FS;

c) that it may be impractical to coordinate between the many terrestrial stations and the many space stations, and that, therefore, sharing criteria should be established to preclude the need for detailed coordination;

d) that in devising such sharing criteria, account needs to be taken of the operational and technical requirements of networks in the satellite service as well as of the requirements of the FS and measures available to them;

e) that it has been determined that a probabilistic basis for developing sharing criteria results in a more efficient use of the spectrum than from criteria developed using worst case analysis;

f) that it is difficult and burdensome to assemble sufficient statistically accurate information about real existing and planned terrestrial and satellite system stations;

g) that computer simulations of FS and satellite services operating in the geostationary orbit can generate statistically accurate information suitable for determining sharing criteria for a wide variety of sharing scenarios,

recommends

1 that information derived from computer simulations of FS and satellite services operating from the geostationary orbit and using the same spectrum may be acceptable for developing sharing criteria;

2 that when deriving information for developing sharing criteria the material in Annex 1 should be taken into account;

3 that when developing sharing criteria with respect to digital systems in the FS, the material in Annex 2 should be taken into account.

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[*] This Recommendation should be brought to the attention of Radiocommunication Study Groups 4 (WP 4-9S), 6 (WP 6S) and, 7 and 8 (WP 8D).

ANNEX 1

Method of developing criteria for protecting the fixed service from emissions of space stations operating in the geostationary orbit

1 Introduction

WARC-92 allocated to the broadcasting-satellite service (TV and sound), the mobile-satellite service and the space science services spectrum which is also shared by the FS. WARC-92 also approved several Resolutions and Recommendations that requested the ITU-R resolve the sharing issues resulting from the various allocations. This Annex describes a methodology that will aid in the development of sharing criteria between the FS and those satellite services provided from the geostationary orbit.

Recommendation ITU-R SF.358 proposes power flux-density (pfd) protective levels for the FS for some portions of the spectrum. Similarly Table 21-4 of Article 21 of the Radio Regulations provides definitive pfd limits for similar bands. Neither reference, however, addresses all the bands indicated by WARC-92 nor do they provide sufficient information on how to extend the criteria, other than by extrapolation, to different fixed and satellite service sharing scenarios.

Appendix 1 to Annex 1 of Recommendation ITU-R SF.358 does indicate that statistical simulation methods for determining pfd levels to protect the FS from satellites operating in the geostationary orbit are acceptable but it does not provide a detailed methodology for developing the data. This Annex describes the geometric considerations needed to calculate the data. It also provides a description and the basic language source code for a program that can generate data representative of many of the sharing scenarios that currently exist or will result from the WARC-92 allocations. The resulting program data can be analysed to determine the effects of satellite pfd levels on the FS for a variety of scenarios. Scenario differences can be determined by user input parameters to the program. Some examples are provided in Appendix 1 to this Annex of how the data from the simulation program can be utilized to help resolve WARC-92 or similar issues.

2 Geometric considerations

In order to calculate the interference into a fixed wireless network from satellites in the geostationary orbit, it is necessary to identify all satellites visible to each fixed wireless station. This may be accomplished by determining the limits of the visible geostationary orbit for each station and accordingly all satellites between those limits would be visible.

Figure 1 provides a representation of the geometry of the geostationary orbit and a fixed wireless station. Some of the important parameters needed to calculate interference into the fixed wireless station are:

θ : elevation angle of the satellite above the horizon

β : spherical arc subtended by the sub-satellite point, S', and the fixed wireless station, P

Ω : angle subtended by β as viewed from the satellite, S.

If the radio-relay antenna has 0° elevation and diffraction is ignored then the azimuth displacement, A, measured from South, to the intersection of the horizon with the geostationary orbit can be calculated as:

$$|A| = \cos^{-1}\left(\tan\varphi/(K^2 - 1)^{1/2}\right) \tag{1}$$

where:

$K = R/a$

a: radius of the Earth

R: radius of the geostationary orbit

φ: latitude of the fixed wireless station.

The relative longitudinal separation between the fixed wireless station and the horizontal plane/geostationary orbit intercept can be expressed as:

$$\lambda = \sin^{-1}\left(\sin A(1 - K^{-2})^{1/2}\right) \tag{2}$$

Since the visible stationary orbit is symmetrical around the 0° azimuth line the total number of satellites visible to the station will appear in the longitudinal span of the orbit equal to 2λ.

The azimuth A_z to each visible satellite is:

$$A_z = \tan^{-1}(\tan\lambda_r / \sin\varphi) \tag{3}$$

where λ_r is the difference between the longitude of the satellite and the fixed wireless station, i.e. the relative longitude.

The ITU-R customarily limits or defines pfd levels from a satellite as a function of the elevation angle, θ. The angle can be determined as follows:

$$\theta = (\pi/2) - (\beta + \Omega) \tag{4}$$

where:

$$\beta = \cos^{-1}(\cos\varphi\cos\lambda_r) \tag{5}$$

$$\Omega = \tan^{-1}(\sin\beta/(K - \cos\beta)) \tag{6}$$

Generally pfd is defined in the form:

$$F(\theta) = \begin{cases} pfd_{low} & \text{for} \quad 0° \le \theta \le 5° \\ pfd_{low} + 0.05\,(pfd_{hi} - pfd_{low})\,(\theta - 5) & \text{for} \quad 5° \le \theta \le 25° \\ pfd_{hi} & \text{for} \quad 25° \le \theta \le 90° \end{cases} \tag{7}$$

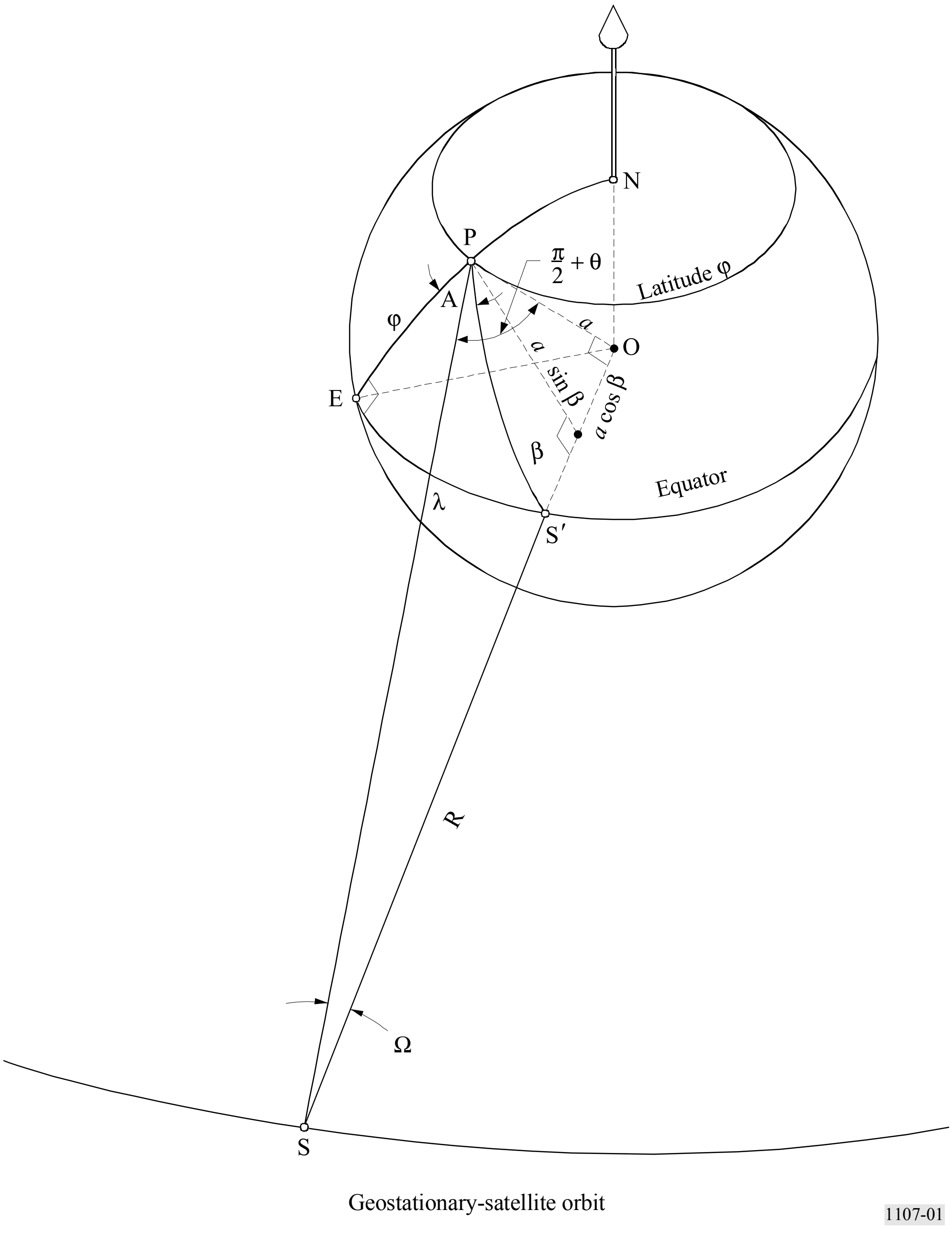
where:

pfd_{low}: allowable level for low angles of arrival, usually expressed in dB(W/m^2) in a 4 kHz band

pfd_{hi}: allowable level for high angles of arrival also expressed in dB(W/m^2) in a 4 kHz band.

FIGURE 1

Geometry of the geostationary-satellite orbit and a fixed wireless station



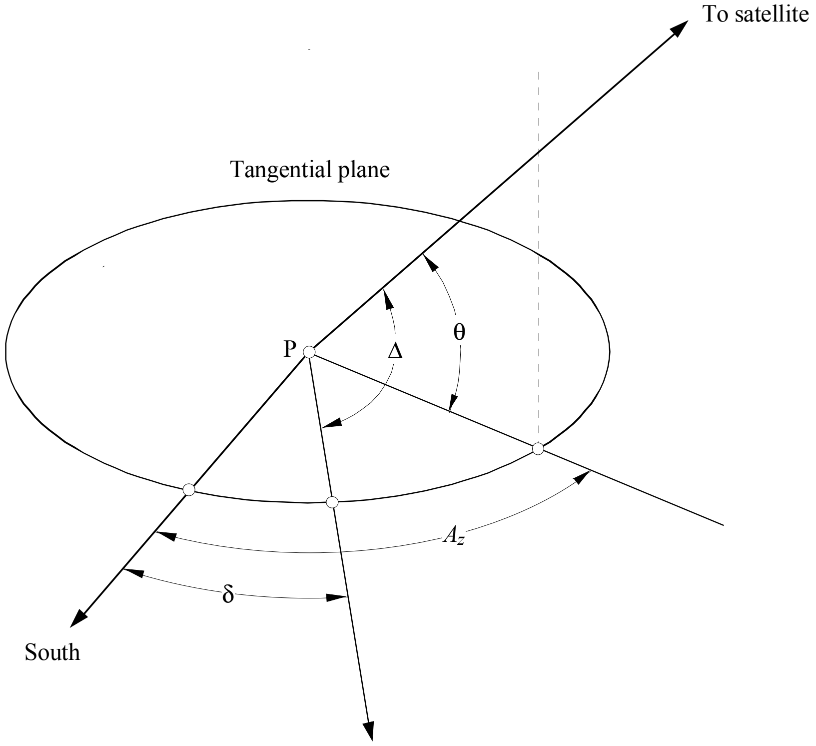
Finally the angle Δ between the incidence of the interfering satellite pfd level and the pointing direction of the fixed wireless station receiver (Fig. 2) can be determined by:

$$\Delta = \cos^{-1} (\cos\theta \cos (A_z - \delta)) \tag{8}$$

where δ is the pointing direction of the fixed wireless station receiver relative to South.

FIGURE 2

Geometry determining the off-beam angle to a satellite



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If the fixed wireless receive antenna gain is assumed to be equal in all planes (horizontal to vertical) then the gain in the direction of the interfering satellite, $G(\Delta)$, may be determined from the antenna gain pattern equations in Recommendation ITU-R F.699.

3 Interference calculations

The total interference power received at the fixed wireless receiver can be determined by summing the contributions from each visible satellite. Each contribution can be determined as follows:

$$I_B = f(\theta) \times g(\Delta) \times \lambda^2 / 4\pi h \tag{9}$$

where:

$$f(\theta) = 10^{F(\theta)/10} \tag{10}$$

$$g(\Delta) = 10^{G(\Delta)/10} \tag{11}$$

λ: wavelength of the carrier

h: feeder loss.

Equation (9) contains the factor $\lambda/4\pi h$ because $f(\theta)$ is in units of W/(m$^2 \cdot$ 4 kHz).

4 Network simulation for interference determination

The selection of a methodology to select pfd values for protecting the FS is limited by very practical considerations. For example, it is theoretically possible to determine the interference effects of a satellite service on the FS by performing an exact calculation involving the convolution of all existing and planned transmissions of the satellite service against all existing and planned receptors of the FS while taking into account temporal, spatial and spectral factors. The practical considerations, however, in accumulating the requisite data for such a calculation, for even one type of sharing scenario, generally preclude this possibility.

Other methods of calculating protective criteria such as using “worst case” analysis may in certain cases be conservative for determining the use of a valuable and limited resource. Additionally, laboratory experiments do not lend themselves to convenient solutions for spatial and quantitative reasons. Finally, because of the uncertainty of being able to anticipate all of the situations which may develop, concerning new services or where continual evolution of existing services takes place, the results of any of the above techniques are subject to continual re-evaluation.

For these reasons, an analytic computer simulation of the problem is the most expedient method of getting useful results. Computer simulations using Monte Carlo methods for generating representative service implementations can create simulated data which can be used in place of actual or measured databases.

Appendix 1 provides a listing and description of a Monte Carlo implemented computer simulation that allows a variety of FS/satellite scenarios to be examined. The program can be used to test specific FS systems performance with specific satellite configurations emitting specific pfd levels. Iterative runs of the program can be used to determine the trade-offs of system parameters that would allow sharing.

Figures 3-7 provide results of appropriate example FS/satellite service sharing scenarios.

APPENDIX 1

TO ANNEX 1

Description of an example computer simulation program

1 Network assumptions

The satellite and fixed wireless models implemented in the program assume that:

- the orbit is completely filled with uniformly spaced platforms, operating with the same level of effective radiated power and producing the same pfd on the earth surface; and
- the fixed wireless network is composed of 50 hop routes randomly distributed over an approximately 65° by 22.5° longitude by latitude surface. All receivers have the same noise temperature, antenna characteristic (Recommendation ITU-R F.699), and spacing (50 km);
- free-space calculations are used. Atmospheric and polarity advantages are not considered.

2 Input/output

The simulation program allows operator selection and control of the following input parameters:

- latitude of the centre of the routes (trendline);
- receiver noise temperature;
- maximum receive antenna gain;
- number of fixed wireless routes to be analysed;
- satellite spacing;
- orbit avoidance;
- low angle pfd;
- high angle pfd.

The program produces two output files containing databases that the user can analyse.

The first database (RAD_RTS.DAT) would appropriately be used to analyse the interference effects of analogue fixed wireless networks for various satellite network configurations. The file is a series of records where each record gives the total baseband interference (pW) in a 4 kHz bandwidth for a 50 hop fixed wireless route. The data could most typically be used to provide cumulative distribution graphs showing the amount of interference impairment that percentages of the analogue networks would experience as a function of the interference levels. The size of the file is twice the number of fixed wireless routes analysed, since there are two directions for each route. The maximum size file will be 600 records and is a function of the maximum number of routes that can be handled by the program which is 300.

The second database file (RAD_STE.DAT) can similarly be used to analyse the effects of satellite interference on digital FS networks. Each record in the file is the interference (I) (W) input into a fixed wireless site receiver. The records are arranged in groups of 50, so that analysis for each complete 50 hop route, in both directions, can be performed. Each route will produce 100 records (50×2). The maximum size file will contain 30 000 records ($50 \times 2 \times 300$).

In the event that the maximum size files from one computer run is not a sufficiently large enough sample of data, the program can be re-run and the subsequent data will be automatically appended.

3 Program operation

The program begins by selecting the user-specified latitude for the centre of the fixed wireless route and then proceeds to calculate the longitude as a random variable (bounded by the 65° surface limits) of the centre of the route. The azimuth (relative to South) of the route direction or trendline, is calculated as a random variable with a uniform distribution between 0 and 2π. The location of the first fixed wireless site is determined from the latitude, longitude and trendline angle. The sum of the interference into the site receiver from all visible satellites is then calculated and stored for further use.

The location of the next site on the route is determined by assuming that its direction is a uniformly distributed random variable within ±25° of the route trendline and that the route length is 50 km. Interference into the new site receiver from all visible satellites is again calculated as described above.

Next site selection and interference calculations are repeated for all 50 hops in the route wherein a new route is randomly selected and the interference calculation process is repeated for up to 300 times. In the event that orbit avoidance is to be considered (user option), the program tests each site to determine if the site direction falls within the range to be avoided. If it does, the site location is discarded and a new direction and site is chosen.

The stored interference information is used to create the output files (RAD_RTS.DAT, RAD_STE.DAT).

In the case of analogue networks the baseband interference is the desired information. The program derives this information by assuming that there is a linear relationship between the receiver input interference-to-noise ratio and the baseband interference-to-noise ratio as follows:

$$i_c / n_c = i_b / n_b \tag{12}$$

or:

$$i_b = (i_c / n_c) \; n_b \tag{13}$$

The receiver input interference is determined by the network characteristics as explained above is in main § 3 of Annex 1. Therefore:

$$i_c = I_s \ \text{(see equation (9))}$$

The receiver thermal input noise is a function of the fixed wireless receiver noise temperature

$$n_c = k \, T_s \, b$$

where:

k: Boltzmann's constant

T_s: system noise temperature

b: voice channel bandwidth (4 kHz).

Recommendation ITU-R SF.358 indicates that for an appropriate fixed wireless model the channel thermal noise power is:

$$n_b = 25 \text{ pW0p}$$

The program uses this value to determine the baseband interference for each site receiver per equation (13) and sums all 50 site interferences for each route to determine the total interference per route.

The second file (RAD_STE.DAT) created by the program is a compilation of the I_s values calculated.

Calculations made by the program are constrained by the following factors:

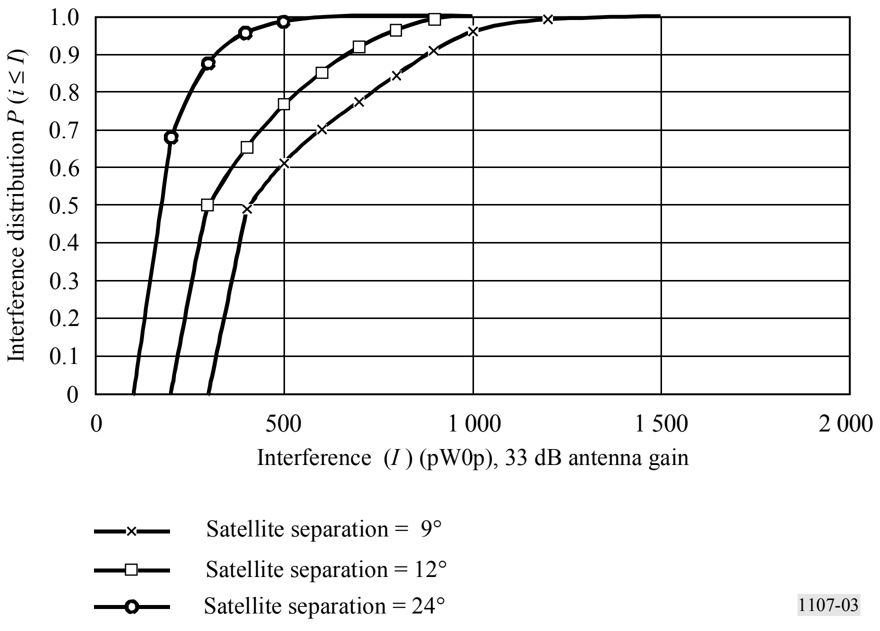
- The centre point of a route must lie between 15° and 70° latitude.
- The program assumes satellites are in exact equatorial planes, and does not allow for inclined orbits.

4 Sample scenario results

Figure 3 gives the results of an analysis of the RAD_RTS.DAT data for three 2 GHz sharing scenarios. All fixed systems were assumed to be 50 hop FDM routes implemented with 33 dB gain receive antennas and receivers with noise temperature of 1 750 K. These FS parameters are representative of those described in Recommendation ITU-R F.758. The three satellite network models considered limit pfd levels to –154 to –144 dB(W/m^2) in 4 kHz and differ only in maximum orbit occupancy (9°, 12° and 24° spacing).

FIGURE 3

2 GHz interference distribution
40° latitude, pfd = –154/–144 dB(W/(m² · 4 kHz))



The results indicate that, for satellite spacings of 6° or more, the FDM FS systems would experience interference less than 1 000 pW in about 95% of the routes, assuming a uniform distribution of route directions. It also suggests that the FS might accept higher pfd levels from satellites with reduced orbit occupancy and still meet the 10% criteria.

Figure 4 illustrates the results of an analysis of the RAD_STE.DAT data. Here the resultant interference database was applied to an assumed FS system sharing spectrum with 2 GHz, 64-QAM, space diversity, digital FS routes typical of Recommendation ITU-R F.758. Using techniques described in Recommendation ITU-R P.530, graphs depicting the cumulative effect on unavailability (the amount of time that the error ratio was less than 1 in 10^{-3}) were derived. The abscissa of Fig. 4 is a factor that increases unavailability of space diversity 50 hop digital routes as a result of the satellite interference. For example, about 80% of the routes experiencing interference from the satellite constellation with 24° separation would have less than a 50% increase in unavailability. This analysis gives some insight as to the apparent sensitivity of fixed digital systems and suggests that the impact on sharing be understood when changes to the definition of unavailability (i.e. ITU-T Recommendation G.826) for digital systems are being considered.

FIGURE 4

2 GHz unavailability distribution
40° latitude, pfd = –154/–144 dB(W/(m² • 4 kHz)),
Antenna gain: 33 dB/space diversity

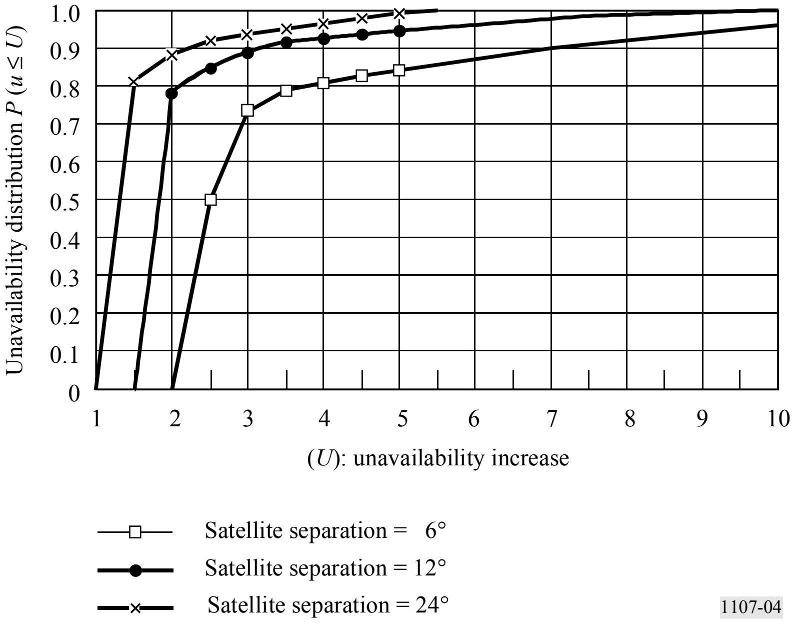


Figure 5 shows the results of sharing spectrum between an assumed satellite system spaced at 60° (possibly broadcasting-satellite service (BSS) (sound) or mobile-satellite service (MSS) systems) and a representative fixed analogue system configuration in the 1.5 GHz band. The allowable satellite high angle pfd level is assumed to be –135 dB(W/m^2) in 4 kHz. The low angle pfd was kept at –154 dB(W/m^2). The high angle pfd is 9 dB higher than pfd levels in adjacent bands. The results (from RAD_RTS.DAT) indicate over 85% of the fixed systems would have less than 1 000 pW of interference for that configuration.

Figures 6 and 7 give the results of a partial study. The purpose of the study was to analyse in a quantitative manner the sensitivity of the interference distributions of the FS to changes in satellite pfd levels and to changes in the band of operation, assuming all other parameters in the sharing scenario were kept constant. The results suggest that the FS systems selected for operation in a shared environment have to be chosen with care if the same level of performance is to be maintained in all bands.

FIGURE 5

Interference distribution, satellite separation = 60°
1.5 GHz, pfd = –154/–134 dB(W/(m² • 4 kHz)), 25° latitude

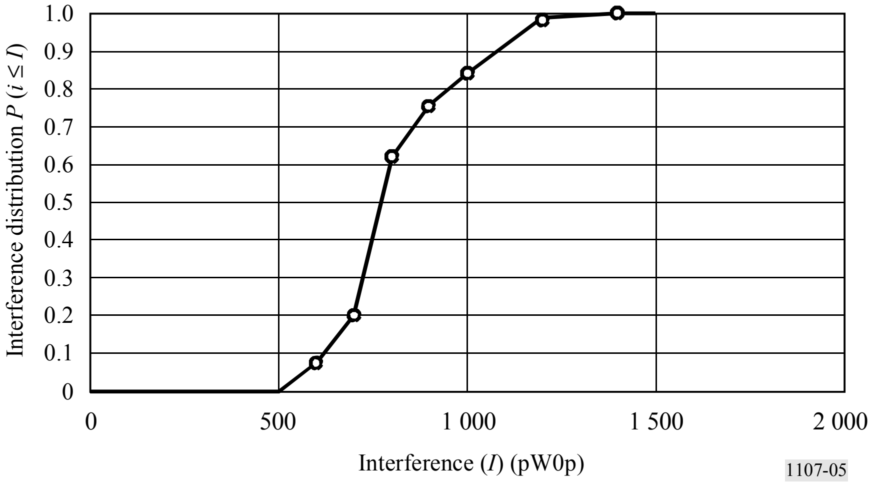


FIGURE 6

1.5 GHz, satellite/FS interference study
40° latitude, satellite separation = 45°, pfd = dB(W/(m² • 4 kHz))

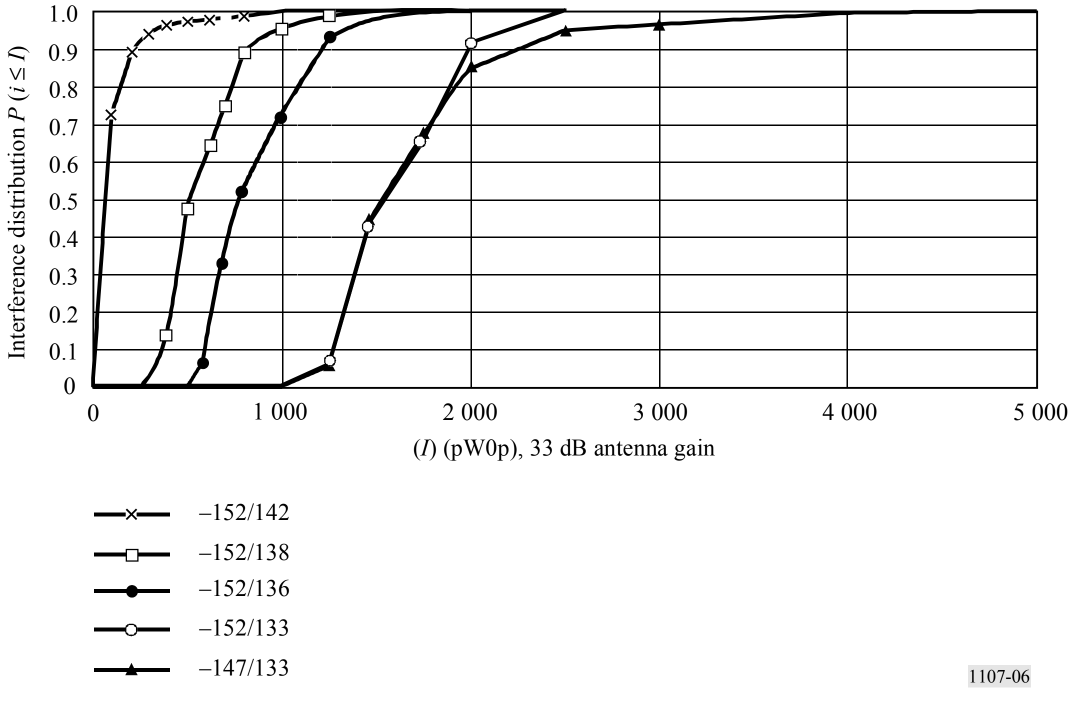
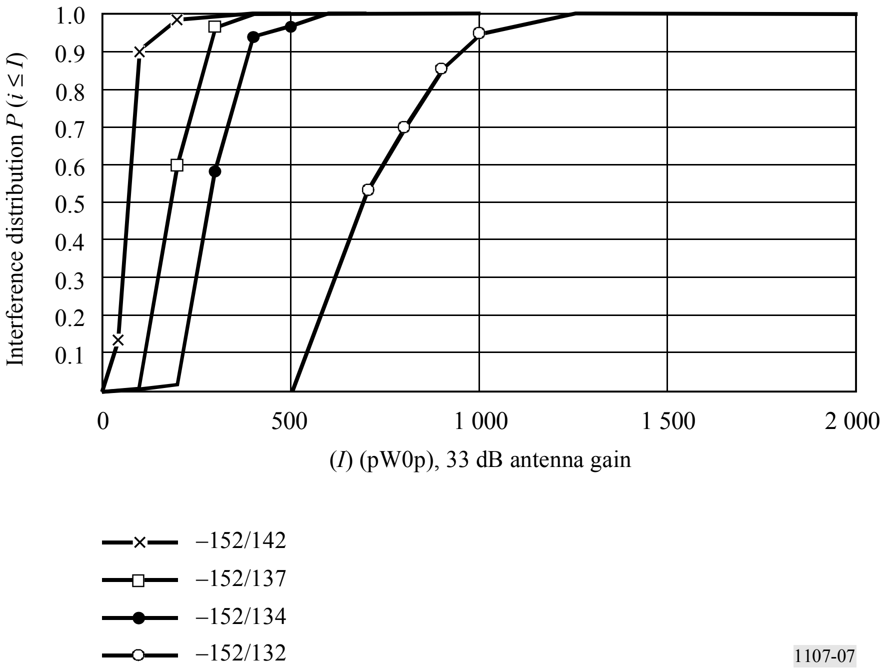


FIGURE 7

2.5 GHz, satellite/FS interference study
40° latitude, satellite separation = 45°, pfd = dB(W/(m² · 4 kHz))



5 Listing OF RAD_REL.BAS

The following listing has been successfully compiled with a commercial compiler (Microsoft QuickBasic versions 4 and 4.5). Other compilers may require some modification of the code for proper operation. As indicated in § 1 of this Appendix, network parameters can be adjusted for both the fixed wireless and satellite networks so that a variety of sharing situations can be analysed.

Care should be taken that the below numbered statements having more than one line of code be entered without control characters i.e. no “carriage return” or “line feed”.

REFERENCE: A.S. MAY AND M.J. PAGONES. MODEL FOR COMPUTATION OF INTERFERENCE FROM GEOSTATIONARY SATELLITES. BSTJ, VOL. 50, NO. 1, JANUARY 1971, PP81-102.

```
'       MAINPROGRAM

100     CLS : SCREEN 9

155     RANDOMIZE TIMER: RTS = 49:
        STS = 50'RTS=# RR ROUTES, STS=# STATION SITES PER ROUTE

160     CLS : PI = 3.141593: RA = .01745329#:
        DE = 57.29578: T = 22.48309
'       T = MAXIMUM GREAT CIRCLE LENGTH (DEG) OF ONE 50 HOP ROUTE

162     K = 6.629957: K2 = K * K: K4 = 1 / (K2 – 1) ^ .5:
        K2I = 1 / K2: PI2 = PI / 2

165     GOSUB 1650'ENTER LATITUDE OF SYSTEMS

170     GOSUB 1700'ENTER FREQUENCY
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175     GOSUB 1750'ENTER RR RECEIVER NOISE TEMP

180     GOSUB 1800'ENTER RR RECEIVE MAXIMUM ANTENNA GAIN

185     GOSUB 3000'ENTER # OF RR ROUTES

190     GOSUB 4000'ENTER AMOUNT OF ORBIT AVOIDANCE

195     GOSUB 5000'ENTER SATELLITE ORBIT SEPARATION

200     GOSUB 6000'ENTER LOW/HIGH ANGLE PFD LIMIT VALUES

210     GOSUB 7000'MAKE REVISIONS OF ABOVE ENTRIES

215     PF = .005 * (PFH – PFL): PFDL = 10 ^ (.1 * PFL):
        PFDH = 10 ^ (.1 * PFH)

220     CLS : DIM A!(RTS, STS): DIM B!(1 + 2 * RTS): DIM C!(RTS, STS)

225     FOR Q = 0 TO RTS: FOR V = 0 TO STS: A(Q, V) = 0: C(Q, V) = 0:
        NEXT: NEXT

227     FOR Q = 0 TO (1 + 2 * RTS): B(Q) = 0: NEXT

230     MU = 1.6212E+18 / (FREQ ^ 2 * NTEMP)

235     MU1 = kTbl/Nc

'       MU=Nc((c/FREQ)^2/4Pi)/kTbl, MU1 = kTbl/Nc

'       Where:

'                              Nc=voice channel noise power

'                                 =25 picowatts

'                       c/FREQ=transmission wavelength

'                                 k=Boltzmann’s constant, 1.3805E-23

'                                 T=receiver noise temp. in Kelvin s

'                                 b=channel bw, 4KHz

'                                 l=feeder loss,3dB

'       START ROUTE CALCULATIONS

240     FOR M = 0 TO RTS

243     LOCATE 13, 1: PRINT STRING$(30, 0)

244     LOCATE 13, 1: PRINT "CALCULATING ROUTE"; M

245     LONGREF = T * (2 * RND - 1)
'       LONGREF is longitude of middle of reference

250     TAU = 90 * RND: TAURA = TAU * RA
'       TAU is the direction of RR network trendline

260     LATR0 = (((T / 2) * COS(TAURA)) + LATREF)

265     LONGR0 = -((T / 2) * SIN(TAURA) + LONGREF)
'       LATRO, LONGRO is latitude, longitude of the 1st RR site.

275     'X = 319.5 + ((LONGR0 * 319.5) / (1.5 * T)):
        'Y = (1 - COS(TAURA)) * 77.5

'       X, Y= SCREEN COORDINATES FOR PLOTTING THE SITES. REMOVE "'"
'       FROM 275, 530 - 550 FOR GRAPHIC REPRESENTATION OF ROUTES.
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```
'       Find satellite horizon from 1st RR site

300     A = K4 * TAN(LATR0 * RA): A2 = ((1 - A * A) ^ .5) / A

305     AZMUTH = ATN(A2)

'       Azmuth= angle to horizon from south at RR point

310     AZ = SIN(AZMUTH) * ((1 - K2I) ^ .5)

315     LONGHOR = ATN(AZ / ((1 - AZ * AZ) ^ .5))

'       LONGHOR is the longitude difference between the RR and
'       horizon/orbit intercept

320     LONHOR = LONGHOR * DE

'       Calculate interference from all visible sats into a RR site
'       on a route.

330     LONGR = LONGR0: LATR = LATR0: LONS = 0

'       LONGR=Longitude of RR, LATR=Latitude of RR, LONS=longitude of
'       next visible sat.

'       Do the interference calculation for each site

335     FOR N = 0 TO STS

340     RR = (TAU + 25) - (50 * RND): RRD = RR * RA
'       RR, RRD is the pointing direction to the next site

'       Calculate location of next RR site

'       Find most easterly visible satellite.

350     DO WHILE LONS <= LONHOR + LONGR

360     LONS = LONS + SEP: LOOP

364     LONS = LONS - SEP

370     'Do the interference calculation per site.

380     DO WHILE LONS >= LONGR - LONHOR

390     GOSUB 2360

395     IF GAMMAW < AVOID OR GAMMAE < AVOID
        THEN A(M, N) = 0: C(M, N) = 0: GOTO 340

400     LONS = LONS - SEP: LOOP

'       Calculate location of next RR site

411     J = LONGR: L = LATR

420     P = (SIN(LATR * RA)) * COS(.4496 * RA) -
              (COS(LATR * RA)) * (SIN(.4496 * RA)) * (COS(RRD))

430     Q = P / (1 - P * P) ^ .5

435     LATR = DE * ATN(Q) 'LATITUDE OF THE NEXT RR SITE

440     R = SIN(.4496 * RA) * SIN(RRD) / (1 - P * P) ^ .5:
        S = R / (1 - R * R) ^ .5: DELLONGR = ATN(S) * DE
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```
450     LONGR = LONGR + DELLONGR 'LONGITUDE OF NEXT RR SITE
'       Calculate satellite horizon for the new RR site
470     A = K4 * TAN(LATR * RA): A2 = ((1 - A * A) ^ .5) / A
480     AZMUTH = ATN(A2)
        'Azmuth= angle to horizon from south at RR point, South reference
490     AZ = SIN(AZMUTH) * ((1 - K2I) ^ .5)
500     LONGHOR = ATN(AZ / ((1 - AZ * AZ) ^ .5))
'       LONGHOR is the longitude of the RR horizon/orbit intercept
520     LONHOR = LONGHOR * DE
'       Print RR route on screen
530     'Y1 = ((L - LATR) / T) * 155: X1 = (DELLONGR / (3 * T)) * 480
540     'LINE (X, Y)-(X + X1, Y + Y1)
550     'X = X + X1: Y = Y + Y1
555     NEXT ' Do next RR site
560     NEXT ' Do next RR route
'       Calculate the output files
600     FOR M = 0 TO RTS
610         FOR N = 1 TO STS
620             B(M) = B(M) + A(M, N)
630         NEXT N
640     NEXT M
650     FOR G = 0 TO RTS
660         FOR H = 0 TO STS - 1
670             B(RTS + 1 + G) = B(RTS + 1 + G) + C(G, H)
680         NEXT H
690     NEXT G
700     OPEN "RAD_RTS.DAT" FOR APPEND AS #1
710     FOR M = 0 TO 1 + (2 * RTS)
720     'PRINT "ROUTE"; M; : PRINT "="; B(M)
725     PRINT #1, B(M)
730     NEXT
735     CLOSE #1
740     OPEN "RAD_STE.DAT" FOR APPEND AS #2
750     FOR M = 0 TO RTS: FOR N = 0 TO STS
755     A(M, N) = A(M, N) * MU1
760     PRINT #2, A(M, N): NEXT: NEXT
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765     PRINT #2, 0

770     FOR M = 0 TO RTS: FOR N = 0 TO STS

775     C(M, N) = C(M, N) * MU1

780     PRINT #2, C(M, N): NEXT: NEXT

790     CLOSE #2

830     'PRINT "PROGRAM COMPLETED, PRESS ANY KEY TO END"

840     A$ = INKEY$: IF A$ = " " THEN 840

850     IF A$ = "r" OR A$ = "R" THEN LOCATE 14, 1:
        PRINT STRING$(70, 0): GOTO 225 'REPEAT DATA BASE CALC.

860     IF A$ = "e" OR A$ = "E" THEN CLS : GOTO 1000

870     GOTO 830

1000    END ' END OF RAD_REL.BAS

'Subroutine for entering RR route latitude

1650    LOCATE 4, 1: PRINT STRING$(78, 0): LOCATE 5, 1:
        PRINT STRING$(20, 0)

1660    LOCATE 4, 1: PRINT "1) ENTER NETWORK LATITUDE (15 to 70) "

1670    INLEN% = 6: GOSUB 14000

1680    LATREF = VAL(BUFF$)
        'LATREF is the latitude at the centre of the trend line

1690    IF (LATREF > 70! OR LATREF < 15!) THEN LOCATE 22, 1:
        PRINT "Out of Range, RE-ENTER, ": FOR C = 1 TO 100000:
        NEXT: LOCATE 22, 1: PRINT STRING$(40, 0): GOTO 1650

1695    RETURN

'Subroutine for entering frequency of operation

1700    LOCATE 6, 1: PRINT STRING$(78, 0): LOCATE 7, 1:
        PRINT STRING$(20, 0)

1710    LOCATE 6, 1: PRINT "2) ENTER TRANSMIT CARRIER FREQUENCY <GHz>"

1720    INLEN% = 6: GOSUB 14000

1730    FREQ = VAL(BUFF$)'FREQ = FREQUENCY OF SHARING SCENARIO IN GHZ

1740    IF FREQ <= 0! OR FREQ > 100! THEN LOCATE 22, 1:
        PRINT "OUT OF RANGE, RE-ENTER,": FOR C = 1 TO 100000: NEXT:
        LOCATE 22, 1: PRINT STRING$(78, 0): GOTO 1700

1745    RETURN

'Subroutine - enter RR receiver noise temp.

1750    LOCATE 8, 1: PRINT STRING$(78, 0): LOCATE 9, 1:
        PRINT STRING$(20, 0)

1760    LOCATE 8, 1:
        PRINT "3) ENTER AVE. VALUE OF RR RECEIVER NOISE TEMP <DEG
        KELVIN>"
```

```
1770    INLEN% = 6: GOSUB 14000

1780    NTEMP = VAL(BUFF$)'NTEMP=NOISE TEMP OF RR RECEIVERS

1790    IF NTEMP <= 0 THEN LOCATE 22, 1:
        PRINT "OUT OF RANGE, RE-ENTER,": FOR C = 1 TO 100000: NEXT:
        LOCATE 22, 1: PRINT STRING$(78, 0): GOTO 1750

1795    RETURN

'Subroutine - enter RR receive antenna gain and calculate
                intermediate parms.

1800    LOCATE 10, 1: PRINT STRING$(78, 0): LOCATE 11, 1:
        PRINT STRING$(20, 0)

1805    LOCATE 10, 1:
        PRINT "4) ENTER MAX RADIO-RELAY RECEIVE ANTENNA DB GAIN"

1810    INLEN% = 6: GOSUB 14000

1820    GMAX = VAL(BUFF$)'GMAX is MAX RR rec. Antenna gain

1830    IF GMAX < 0 OR GMAX > 99 THEN LOCATE 22, 1:
        PRINT "OUT OF RANGE, RE-ENTER": FOR C = 1 TO 100000: NEXT:
        LOCATE 22, 1: PRINT STRING$(40, 0): GOTO 1800

1840    DLAMBDA = 10 ^ ((GMAX - 7.7) / 20)
        'DLAMBDA=RATIO OF REC. ANT DIA./ WAVELENGTH

1850    G1 = 2 + 15 * (LOG(DLAMBDA) / LOG(10))
        'PRINT "DLAMBDA="; DLAMBDA

1860    PHYM = (20 / DLAMBDA) * (GMAX - G1) ^ .5

1870    RETURN

'       This Subroutine to calculate RR/sat elevation and
        separation angles and interference

2360    W = (LONS - LONGR):
        ASAT = ATN((TAN(W * RA)) / SIN(LATR * RA)): ASAT1 = ASAT

'       ASAT=AZMUTH ANGLE TO SUBSAT REFERENCED TO SOUTH

2370    U = COS(LATR * RA) * COS(W * RA):
        BETA = ATN((1 - U * U) ^ .5 / U)

2380    OMEGA = ATN(SIN(BETA) / (K - COS(BETA)))

2390    THETAR = PI2 - (BETA + OMEGA): THETA = THETAR * DE
        THETA=ELEVATION ANGLE TO SAT FROM RR

2400    VW = (COS(THETAR)) * COS(ASAT - RRD):
        GAMMAW = (PI2 - ATN(VW/SQR (1 - VW * VW)) * DE
'       GAMMAW = ANGLE BETWEEN SATELLITE AND WEST POINTING RECEIVER

2415    GAMMAE = 180 - GAMMAW
'       GAMMAE = ANGLE BETWEEN SATELLITE AND EAST POINTING RECEIVER

2420    IF GAMMAW < 0 THEN GAMMAW = 180 + GAMMAW
```

```
2425    IF GAMMAE < 0 THEN GAMMAE = 180 + GAMMAE

2430    IF (GAMMAW <= AVOID) OR (GAMMAE <= AVOID) THEN RETURN

2440    IF THETA >= 0 AND THETA < 5 THEN PFD = PFDL: GOTO 2500

2450    IF THETA >= 5 AND THETA < 25 THEN
        PFD = (10 ^ (PFL * .1 + PF * (THETA - 5))): GOTO 2500

2460    IF THETA >= 25 THEN PFD = PFDH

2500    IF GAMMAW >= 0 AND GAMMAW <= PHYM THEN GTHETAW
        = 10 ^ (.1 * (GMAX - .0025 * (DLAMBDA * GAMMAW) ^ 2)):
        GOTO 2540

2510    IF GAMMAW >= PHYM AND GAMMAW < (100 / DLAMBDA) THEN
        GTHETAW = 10 ^ (.1 * G1): GOTO 2540

2520    IF GAMMAW >= (100 / DLAMBDA) AND GAMMAW < 48 THEN
        GTHETAW = 10 ^ (.1 * (52 - 10 * (LOG(DLAMBDA)) / LOG(10) -
        25 * (LOG(GAMMAW)) / LOG(10))): GOTO 2540

2530    IF GAMMAW >= 48 AND GAMMAW ≤ 180 THEN
        GTHETAW = 10 ^ (1 - (LOG(DLAMBDA)) / LOG(10))

2540    SINTW = MU * PFD * GTHETAW:
        IF N > 0 THEN A(M, N) = A(M, N) + SINTW
'       SINTW = INTEFERENCE INTO WEST POINTING RECEIVERS

2550    IF GAMMAE >= 0 AND GAMMAE <= PHYM THEN GTHETAE
        = 10 ^ (.1 * (GMAX - .0025 * (DLAMBDA * GAMMAE) ^ 2)):
        GOTO 2590

2560    IF GAMMAE >= PHYM AND GAMMAE < (100 / DLAMBDA) THEN
        GTHETAE = 10 ^ (.1 * G1): GOTO 2590

2570    IF GAMMAE >= (100 / DLAMBDA) AND GAMMAE < 48 THEN
        GTHETAE = 10 ^ (.1 * (52 - 10 * (LOG(DLAMBDA)) / LOG(10) -
        25 * (LOG(GAMMAE)) / LOG(10))): GOTO 2590

2580    IF GAMMAE >= 48 AND GAMMAE ≤ 180 THEN
        GTHETAE = 10 ^ (1 - (LOG(DLAMBDA)) / LOG(10))

2590    SINTE = MU * PFD * GTHETAE: IF N < 50 THEN
        C(M, N) = C(M, N) + SINTE
'       SINTE = INTERFERENCE INTO EAST POINTING RECEIVERS

2600    RETURN

'Subroutine - ALLOWS ENTRY OF # RR ROUTES (RTS)

3000    LOCATE 12, 1: PRINT STRING$(78, 0): LOCATE 13, 1:
        PRINT STRING$(20, 0)

3010    LOCATE 12, 1:
        PRINT "5) ENTER NUMBER OF RADIO-RELAY ROUTES <300 MAX>"

3020    INLEN% = 3: GOSUB 14000

3030    RTS = VAL(BUFF$)

3033    IF RTS > 300 OR RTS < 1 THEN LOCATE 22, 1:
        PRINT "Out of Range, RE-ENTER": FOR C = 1 TO 100000: NEXT:
        LOCATE 22, 1: PRINT STRING$(40, 0): GOTO 3000
```

```
3035    IF RTS <= 300 THEN RTS = RTS - 1: RETURN

'Subroutine to specify orbit avoidance

4000    LOCATE 14, 1: PRINT STRING$(78, 0): LOCATE 15, 1:
        PRINT STRING$(20, 0)

4040    LOCATE 14, 1:
        PRINT "6) ENTER ORBIT AVOIDANCE ANGLE, DEG. <ENTER>"

4050    INLEN% = 4: GOSUB 14000

4060    AVOID = VAL(BUFF$)

4070    IF AVOID < 0 THEN LOCATE 22, 1:
        PRINT "Out of Range, RE-ENTER": FOR C = 1 TO 100000: NEXT:
        LOCATE 22, 1: PRINT STRING$(40, 0): GOTO 4000

4080    RETURN

'Subroutine to determine satellite orbit separation

5000    LOCATE 16, 1: PRINT STRING$(78, 0): LOCATE 17, 1:
        PRINT STRING$(20, 0)

5010    LOCATE 16, 1:
        PRINT "7) ENTER SATELLITE ORBIT SEPARATION (2 MIN), DEG.
        <ENTER>"

5060    INLEN% = 5: GOSUB 14000

5070    SEP = VAL(BUFF$)

5080    IF SEP < 2 THEN LOCATE 22, 1: PRINT "Out of Range, RE-ENTER":
        FOR C = 1 TO 100000: NEXT: LOCATE 22, 1: PRINT STRING$(40, 0):
        GOTO 5000

5090    RETURN

'Subroutine - Enter low/high angle pfd value

6000    LOCATE 18, 1: PRINT STRING$(78, 0): LOCATE 19, 1:
        PRINT STRING$(20, 0): LOCATE 20, 1: PRINT STRING$(78, 0):
        LOCATE 21, 1: PRINT STRING$(20, 0)

6010    LOCATE 18, 1:
        PRINT "8A) ENTER MAXIMUM LOW ANGLE (0 <= THETA < 5°) PFD
        LEVEL"

6020    INLEN% = 5: GOSUB 14000

6030    PFL = VAL(BUFF$)

6040    IF PFL > 0 THEN LOCATE 22, 1:
        PRINT "OUT OF RANGE, ENTER NEGATIVE VALUE":
        FOR C = 1 TO 100000: NEXT: LOCATE 22, 1: PRINT STRING$(50, 0):
        GOTO 6000

' - Enter high angle pfd value

6500    LOCATE 20, 1: PRINT STRING$(78, 0): LOCATE 21, 1:
        PRINT STRING$(20, 0)
```

```
6510    LOCATE 20, 1:
        PRINT "8B) ENTER MAXIMUM HIGH ANGLE ( THETA >= 25°)
        PFD LEVEL"

6520    INLEN% = 5: GOSUB 14000

6530    PFH = VAL(BUFF$)

6540    IF PFH > 0 THEN LOCATE 22, 1:
        PRINT "OUT OF RANGE, ENTER NEGATIVE VALUE":
        FOR C = 1 TO 100000: NEXT: LOCATE 22, 1: PRINT STRING$(50, 0):
        GOTO 6500

6545    PF = .005 * (PFH - PFL): PFDL = 10 ^ (.1 * PFL):
        PFDH = 10 ^ (.1 * PFH)

6550    RETURN

7000    LOCATE 22, 1: PRINT STRING$(78, 0): LOCATE 23, 1:
        PRINT STRING$(20, 0)

7010    LOCATE 22, 1:
        PRINT "REVISIONS? ENTER '1 - 8' OR '0' IF NONE "

7020    A$ = INKEY$: IF A$ = "" THEN 7020

7030    IF A$ = "0" OR A$ = CHR$(13) THEN RETURN

7040    IF A$ = "1" THEN GOSUB 1650: GOTO 7000

7050    IF A$ = "2" THEN GOSUB 1700: GOTO 7000

7060    IF A$ = "3" THEN GOSUB 1750: GOTO 7000

7070    IF A$ = "4" THEN GOSUB 1800: GOTO 7000

7080    IF A$ = "5" THEN GOSUB 3000: GOTO 7000

7090    IF A$ = "6" THEN GOSUB 4000: GOTO 7000

7100    IF A$ = "7" THEN GOSUB 5000: GOTO 7000

7110    IF A$ = "8" THEN GOSUB 6000: GOTO 7000

7200    GOTO 7000

'Subroutine for entering numeric data

14000   TRUE = -1: FALSE = 0'Formated numeric input subroutine

14005   POINT. = FALSE: DEC.CNT = 0: BUFF$ = " ":
        ERA$ = CHR$(29) + CHR$(95) + CHR$(29):
        PRINT STRING$(INLEN%, CHR$(95)); STRING$(INLEN%, CHR$(29));

14010   W$ = INPUT$(1): IF W$ >= "0" AND W$ <= "9" THEN 14100

14020   IF W$ <> CHR$(8) THEN 14040

14030   IF BUFF$ = "" THEN 14010 ELSE W$ = RIGHT$(BUFF$, 1):
        BUFF$ = LEFT$(BUFF$, LEN(BUFF$) - 1): PRINT ERA$; :
        IF W$ = "." THEN POINT. = FALSE: DEC.CNT = 0

14035   IF POINT. THEN DEC.CNT = DEC.CNT – 1: GOTO 14010 ELSE 14010

14040   IF W$ = CHR$(13) THEN RETURN
```

```
14070   IF W$ = "." THEN IF POINT. THEN 14010 ELSE IF
        LEN(BUFF$) = INLEN% THEN 14010 ELSE POINT. = TRUE: GOTO 14100

14080   IF W$ = "-" OR W$ = "+" THEN IF BUFF$ > " " THEN
        14010 ELSE 14100

14090   GOTO 14010

14100   IF LEN(BUFF$) = INLEN% OR DEC.CNT = 3 THEN
        14010 ELSE PRINT W$; : BUFF$ = BUFF$ + W$:
        IF POINT. THEN DEC.CNT = DEC.CNT + 1: GOTO 14010 ELSE 14010

'Subroutine - Enter alphanumeric data (not used)

14300   BKSPC$ = CHR$(8): CR.RET$ = CHR$(13):
        ERA$ = CHR$(29) + " " + CHR$(29) 'String input routine

14305   BUFF$ = " "

14310   W$ = INPUT$(1): IF W$ >= "a" AND W$ <= "z" THEN
        W$ = CHR$(ASC(W$) - 32): GOTO 14350

14315   IF W$ >= " " AND W$ <= CHR$(127) THEN 14350

14320   IF W$ = BKSPC$ THEN IF BUFF$ = " " THEN 14310 ELSE
        BUFF$ = LEFT$(BUFF$, LEN(BUFF$) - 1): PRINT ERA$; :
        GOTO 14310

14340   IF W$ = CR.RET$ THEN RETURN ELSE 14310

14350   IF LEN(BUFF$) = INLEN% THEN 14310 ELSE PRINT W$; :
        BUFF$ = BUFF$ + W$: GOTO 14310
```

ANNEX 2

Information for assessing the interference into digital fixed service systems from emissions of space stations operating in the geostationary orbit

1 Introduction

Annex 1 to this Recommendation describes a method of developing criteria for protecting mainly long-haul analogue FS systems. However, currently most FS systems employ digital modulation. Many basic elements described in Annex 1 are applicable to the method of developing criteria for protecting these FS systems. This Annex presents additional information that is necessary for assessing the interference into such FS systems.

The methodology provides statistics for both the interference-to-noise ratio (I/N) values of individual stations and the fractional degradation of performance (FDP) values of routes. The methodology employed for assessing the route FDP as described in Section 3 is only valid when the I/N of a receiver station of that route is not so large as to drive the receiver into a non-linear range. The user is therefore encouraged to assess the I/N per receiver statistics, as described in Section 2, before assessing the FDP statistics on a multihop basis, as described in Section 3.

This Annex applies to digital FS systems where multipath fading generally predominates and does not apply to those systems where precipitation attenuation generally predominates.

2 Station-by-station analysis

In the case of analogue FS systems, the interference from geostationary satellites is evaluated in terms of channel interference noise in pW (see Appendix 1 to Annex 1). However, in the case of digital point-to-point (P-P) and point-to-multipoint (P-MP) FS systems, it is appropriate to evaluate interference in terms of FDP as defined for the time varying interference from non-geostationary satellites in Annex 3 to Recommendation ITU-R F.1108. As an analogy, when there is only one FS station, FDP_{hop} due to interference entries from geostationary satellites can be defined at the input of a receiver as follows, taking into account that the interference level is almost time-invariant:

$$FDP_{hop} = \frac{I}{N_T} \tag{14}$$

where:

I: aggregate interference (W/MHz) from visible satellites into the FS receiver

N_T: receiver thermal noise (W/MHz).

A methodology proposed in Appendix 2 of this Annex may be used for evaluating the I/N statistics.

When it is necessary to determine the effect of interference on digital FS receivers employing diversity, a different formula may be more appropriate for evaluating FDP_{hop} as described in Annex 4 to Recommendation ITU-R F.1108.

3 Multi-hop P-P FS systems

For digital FS systems with n hops operating at frequencies where multipath fading generally predominates and acknowledging that, in general, the performance objectives for multi-hop P-P FS systems are specified on a route basis, two probabilistic assessment methods may be employed. One is described in Section 2 and another is to evaluate the FDP for the route defined as the ratio of total interference power to total noise power for one direction of a route as follows:

$$FDP_{route} = \frac{\sum_{k=1}^{n} (I_k)}{n \times N_T} \tag{15}$$

where I_k is the aggregate interference falling into the k-th receiver from visible satellites.

It should be noted that equation (15) is based on the assumptions that:

- the digital signal is regenerated at each repeater; and
- the fading has Rayleigh characteristics.

It should also be noted that, for evaluating FDP_{route} for digital FS systems employing diversity, an appropriate formula different from equation (15) should be used. Further studies are required.

Although there are a variety of fading types, Rayleigh fading is regarded as the most severe fading encountered in line-of-sight paths and is a determining factor in the evaluation of FS system performance. The feature of Rayleigh fading is that the probability of 10 dB deeper fading, for example, becomes smaller by a factor of 1/10. Therefore, if there exists a time-invariant interference in a hop whose level is equal to the thermal noise level ($I/N = 0$ dB), the probability of severely errored seconds (or the probability of unavailable time) will become twice as much as that of the case where there is no interference.

The FDP concept has certain limitations, the most important assumption is that the FS receiver operation remains within a linear response range. If there is an exceptionally high level of interference so that the FS receiver operation falls into a non-linear response range, the FDP concept will not apply or will underestimate the effect of interference (see paragraph following equation (16) in Annex 3 to Recommendation ITU-R F.1108). However, as long as the FS receiver operation is maintained within a linear response range, equation (15) is valid for multi-hop FS digital systems.

The discussion in the preceding section does not result in a conclusion that only FDP should be evaluated on a route basis. Station basis evaluation of FDP will be also useful for understanding the effects of interference.

A typical hop distance of long haul systems in Appendix 1 to Annex 1 is assumed to be 50 km, but a shorter hop distance may be appropriate for short haul systems, depending on various factors including the operating frequency and propagation effects. For example, in the case of an operating frequency in the 1-3 GHz range, random selection between specified limits (e.g. between 10 and 30 km) may be appropriate as typical hop distances.

FS routes under survey should be selected according to the Monte Carlo simulation approach, as described in Appendix 1 to Annex 1 to this Recommendation with the route starting point randomly selected within a user specified test box identified by latitude and longitude limits.

In performing route analysis for digital systems subject to multipath fading, it may not be necessary that each individual hop meets the I/N criterion. The overall route performance, however, must meet the fractional degradation of performance criterion. This issue is explained below.

Where multipath is the dominant fade mechanism, Recommendation ITU-R P.530 relates the probability of an outage on a hop $P(hop\ outage)$ to the link thermal fade margin (TFM):

$$P(hop\ outage) = K \cdot d^{3.6} \cdot f^{0.89} \cdot (1 + |h_r - h_e|/d)^{-1.4} \cdot 10^{-TFM/10}$$

where:

K: geoclimatic factor

d: link length (km)

f: frequency (GHz)

h_r and h_e: transmit and receive antenna heights (metres above sea level or another common reference)

TFM: thermal fade margin on a hop (dB)

$$TFM = 10 \log\left(\frac{C}{N_T}\right) - CNC$$

where:

$10 \log\left(\frac{C}{N_T}\right)$: unfaded carrier-to-noise ratio (C/N) (dB)

CNC: value of C/N at which the performance criterion is just met (dB).

Setting $K \cdot d^{3.6} \cdot f^{0.89} \cdot (1 + |h_r - h_e|/d)^{-1.4} \cdot 10^{-CNC/10} = \gamma$

Then:

$$P(hop\ outage) = \gamma \cdot N_T/C$$

Thus

$$P(hop\ outage\ before\ satellite\ interference) = \gamma \cdot N_T/C$$

$$P(hop\ outage\ after\ aggregate\ satellite\ interference) = \gamma \cdot (N_T + I)/C$$

where C, N_T and I are in consistent power units.

If it is assumed that:

- each hop is designed to have a similar nominal probability of outage before satellite interference; and
- hop fades are independent and sufficiently rare that the outage probabilities may be added,

then the net nominal probability of outage for the route is:

$$P(route\ outage) = \Sigma\ (P(hop\ outage))_{number\ of\ hops\ in\ route}$$

Thus, the fractional increase in the probability of a route outage due to a degraded fade margin on each hop within the route is simply:

$FDP(route\ outage)$

$$= \frac{P(route\ outage\ with\ interference) - P(route\ outage\ without\ interference)}{P(route\ outage\ without\ interference)}$$

$$= \frac{\Sigma\ (\gamma \cdot (N_T + I)/C) - \Sigma\ (\gamma \cdot N_T/C)}{\Sigma\ (\gamma \cdot N_T/C)}$$

$$= \frac{\Sigma\ I}{\Sigma\ N_T}$$

i.e. the route FDP is the total route interference power divided by the total route noise power:

$$= \frac{\Sigma\ I}{n \cdot N_T} \qquad \text{as a power ratio}$$

$$= 100 \frac{\sum I}{n \cdot N_T} \qquad \%$$

Thus the FDP approach for the assessment of the impact of interference on a FS route and the usage of percentages (rather than dB) is appropriate.

In P-MP systems, most links are single hop therefore equation (14) would apply. In P-P systems, multihop deployments are typical, therefore equation (15) will apply.

4 P-MP FS systems

Interference to hub stations in P-MP systems should be evaluated according to Section 2 in the case of digital modulation, but it should be noted that these stations employ omnidirectional or sectoral antennas. Reference radiation patterns in the elevation plane for such antennas are described in Recommendation ITU-R F.1336. If appropriate, the effect of downward beam tilting of the antennas may be evaluated in the interference assessment.

Interference into subscriber stations in P-MP FS systems should also be evaluated according to Section 2 in the case of digital modulation. For this case, it is generally assumed that the azimuthal directions of subscriber station antennas are uniformly distributed over 0°-360° noting that, in general, orbit avoidance is not feasible for these systems.

5 Test area

A large number of FS routes and stations (to ensure stability and convergence of the statistics) are randomly distributed in latitude, longitude and azimuth in a user-defined test area. To ensure a uniform exposure to all arrival angles, the test area longitude dimension should be an integral multiple of the satellite spacing in the case of uniformly spaced satellites and the latitude dimension of the test area should be sufficiently large. Alternatively, the test area can be defined to encompass an administration’s territory so that parameters specific to that administration’s systems may be evaluated. In this case, the satellite locations may be specified.

6 Satellite constellation

A full orbit of equally spaced satellites is usually assumed when investigating a new satellite service. Alternatively, user-defined satellite locations should be accommodated. Another option would permit random locations within a specified orbital arc.

The model should permit orbit avoidance in those situations where this technique is practical for the FS. In general, ubiquitous deployment FS systems cannot take advantage of this technique.

7 pfd mask

All satellites are assumed to transmit the maximum levels allowed by the assumed pfd mask. This is a conservative assumption with respect to the level of interference. The mask consists of straight-line segments of pfd versus arrival angle (from 0° to 90°). The model should allow multiple segments to be specified.

Statistical pfd masks to account for satellite service area coverages may also be derived. Further studies are required.

8 FS parameters

The noise figure (or thermal noise floor) and feeder loss common to all FS stations in the computer simulation must be specified. In addition, the common antenna gain and pattern must be specified. The following default patterns could be included in an antenna file for selection by the user, for example:

- Recommendation ITU-R F.1245, *recommends* 2, for P-P systems co-polar with the interferers.
- Recommendation ITU-R F.1245, Note 7, for P-P systems with linear/circular discrimination in main beam-to-main beam coupling conditions.
- Recommendation ITU-R F.1245, Annex 1, for P-P systems with a sine squared structure in the side lobes.
- Recommendation ITU-R F.699 for P-P systems co-polar with the interferers.
- Recommendation ITU-R F.1336 for P-MP systems hub station antennas.
- Recommendation ITU-R F.1336 for P-MP systems subscriber station antennas.

In addition, the algorithm should accept user-defined patterns that could consist, for example, of a main lobe defined by the 3 dB beamwidth with the discrimination varying as the square of the off-axis angle and the transition to a piecewise linear side-lobe region (on a logarithmic off-axis angle scale). These user-defined patterns could be entered into an antenna pattern file library for future applications.

9 Other considerations

9.1 Interference criteria

For bands where the fading is controlled by multipath, Recommendation ITU-R F.758 states that, in principle, the interference level relative to receiver thermal noise should not exceed –10 dB (or –6 dB). In the case of digital FS systems, these values correspond to a FDP_{hop} of 10% (or 25%), respectively. It is recommended that, if possible, the –10 dB value be adopted. However, in certain difficult sharing situations, it was found extremely difficult to apply the –10 dB requirement from the viewpoint of facilitating frequency sharing. For example, Recommendations ITU-R M.1141 and ITU-R M.1142 dealing with frequency sharing between FS systems and space stations (geostationary or non-geostationary) in the MSS in the 1-3 GHz range are based on the –6 dB requirement.

In a statistical interference assessment, it is necessary to establish a certain allowable percentage of stations or routes for which the aggregate interference may exceed the interference criterion. It is preferable that this percentage should be as small as possible, but, in certain difficult sharing situations, it was found extremely difficult to adopt a very small allowable percentage. For example in such situations, 10% of FS receivers under survey might be prepared to accept interference exceeding the preferred interference criterion. In a similar manner, a certain allowable percentage of routes for which the fractional degradation of performance may exceed the FDP criterion may be defined.

Thus two pairs of performance criteria are specified:

Receiver *I*/*N* objective	Per cent of receiving stations allowed to exceed receiver objective
Route FDP objective	Per cent of routes allowed to exceed route objective

Either or both of these performance criteria pairs may be applicable in a given situation.

9.2 Propagation attenuation

Minimum propagation attenuation due to atmospheric gases for use in frequency sharing studies between FS systems and satellites in various space services is given in Recommendations ITU-R SF.1395 and ITU-R F.1404.

9.3 Slightly inclined orbits

Satellite service to near omnidirectional antennas permits the satellite operators to take advantage of the fuel savings afforded by relaxed North-South station keeping and allows the satellites to employ slightly inclined orbits. This causes the interference arrival angles to terrestrial networks to vary on a daily basis, in effect extending the orbital arc below the static radio horizon for part of the time and increasing the arrival angle (and hence the pfd) of interference of satellites above the horizon for another part of the time. A simple mechanism for evaluating this effect is to modify, for calculation purposes, the latitude of the FS station: nominal station latitude, nominal station latitude plus maximum orbit inclination, and nominal station latitude less maximum orbit inclination can be determined (see also Recommendation ITU-R SF.1008 on this subject).

10 Output results

The probability distribution functions of the aggregate *I*/*N* or FDP for the individual FS stations (FDP_{hop}) and of the route FDPs (FDP_{route}) are the required outputs. Optional outputs include {*I*/*N*, azimuth}, {*I*/*N*, arrival angle} for presentation in scatter diagrams. The latter output is useful in synthesizing a pfd mask. These optional outputs require no additional processing since the parameters are already computed.

APPENDIX 1

TO ANNEX 2

Software model for probabilistic interference assessment on a multi-hop P-P basis

1 Introduction

In frequency bands where the probabilistic interference methodology is intended to be exercised, the FS is the existing service while the satellite service is the unknown incoming system. It is thus logical, when assigning parameters in the software model, to fix as many of the FS parameters as possible and to vary the satellite parameters.

In this model, an area coverage approach is combined with statistical interference analyses of a set of individual stations and routes. The primary satellite deployment is a uniformly spaced deployment of satellites with uniform pfd masks. This deployment may be assumed for simplicity noting that this is a conservative approach. User-defined satellite locations or random deployment could be options. Simple straight line, smooth spherical earth, geometry is assumed.

2 Input parameters for model

2.1 Satellite parameters

– pfd mask {arrival angle break points/pfd levels}; linear segments assumed, number of break points user specified, common to all satellites.

– Uniform geostationary-satellite orbit spacing (must be an integer divisor of 360°), full orbit; (optionally, defined orbit locations can be input or satellites can be randomly located in a specified orbital arc).

– Orbit inclination (e.g. 0° or 5°), applies to all satellites.

2.2 FS performance criteria

– Required protection level (e.g. $FDP_{route} = 10\%$ or 25%, station $I/N = -10$ dB or –6 dB).

2.3 FS test area parameters

– Longitude limits, latitude limits.

– Atmospheric loss model (selection from a menu relating atmospheric loss to be applied to the interference power based on arrival angle and geoclimatic region, zero if none).

– Refraction model (selection from a menu of models relating maximum refraction angles, latitude, and geoclimatic region, zero if none).

- Rain fade model if applicable i.e. if rain fading is to be applied to the interference power (selection from a menu of the rain fade levels to be applied, the arrival angle, and off-axis angle dependencies, and geoclimatic region, zero if none).

  (Further study is required to generate suitable menus of the above models of low arrival angle phenomena based on ITU-R Recommendations bearing in mind that, in general, these phenomena affect only near-worst-case exposures in a substantial way and that these exposures are reduced in significance by the probabilistic approach.)

2.4 FS station parameters

- Orbit avoidance angle (zero if none).
- Number of routes in victim area:
  - Minimum and maximum number of hops per route: the resulting total number of stations ($\Sigma_{all\ routes}$ (number of stations per route)); should be as large as computer memory and speed limitations allow.
  - Minimum and maximum hop lengths (not required for single station analysis).
  - Maximum azimuth variation about route trend line (not required for single station analysis).
- Station parameters, different types of station require separate runs. Within a run, the following parameters are common to all stations:
  - Antenna gain and pattern (from built-in list (including options such as linear to circular discrimination and side lobe structure), facility for entering other antennas into list should be provided).
  - Feeder loss.
  - Noise figure.
  - Elevation angle distribution quantized function (e_{i-1} to e_i, probability). Assume a maximum of 100 pairs of elevation angle range and probability of occurrence values for each distribution ($i = 1$ to I_{elev_max}) noting that different types of station will probably have different elevation angle statistics (large antennas are usually employed where high gain is required to compensate for the high losses of long path lengths, long path lengths imply low elevation angles). The elevation angle distribution should be symmetric about zero degrees elevation.

3 Parameter selection process

Set up a hundred-entry weighted list (to correspond to percentage values) for the elevation angle distribution. A uniformly distributed random pointer selects the elevation angle of each station.

(The symbol "⇒ **< 1 >**" indicates the start of loop 1; "*RANDx*" = uniformly distributed random number between 0 and 1.)

⇒ **< 1 >** Choose route starting points and trend lines (randomization of parameters):

– $latitude = latitude(min) + RAND1 * (latitude(max) – latitude(min))$;

– $longitude = longitude(min) + RAND2 * (longitude(max) – longitude(min))$;

– trend_line_azimuth = $RAND3$ * 360 if only one direction of transmission is subject = 90 + $RAND3$ * 180 if both directions of transmission are subject to satellite interference from the same satellite service; the "go" direction route (trend line azimuth 90° through 180° to 270°) is reversed for the "return" direction of transmission (270° through 0° to 90°) and the larger of the two degradations determines the route performance;

– $number\ of\ hops = hop(min) + RAND4*(hop(max) – hop(min))$.

(For single-station analysis only (i.e. minimum number of hops = maximum number of hops = 1), the trend line azimuth is the station azimuth and the station is assumed to be a receiver.)

Choose station locations:

– first station location is the same as the route starting point; the first station is assumed to be a transmitting station in this context unless there is only one station in the route.

⇒ **< 2 >** for second and subsequent stations in route:

– *azimuth* = trend_line_azimuth + (2 * *RAND*5-1) * max hop_azimuth_variation;

– *elevation angle* = mid value of range pointed to by "Nearest_integer{100 * RAND6}"

Check if orbit avoidance applies (noting that stations with elevation angles above zero may intercept orbit above the horizon). If avoidance applies and station main beam direction is within the avoidance angle, reject station, go to **< 2 >**;

– $hop\ length = hop\ length(min) + RAND7 * (hop\ length(max) – hop\ length(min))$;

– determine latitude and longitude of station.

If station is outside test area, reject station location. Go to **< 2 >**.

Repeat for all hops in route. Go to **< 2 >**.

Repeat for all routes in the specified area. Go to **< 1 >**; note that, if interference in both directions of transmission is to be assessed, the "return" direction of the route has the reverse list of station locations, complement azimuths and complement elevation angles from the "go" direction route parameters.

Store set of FS station parameters {{FS}} = {{type (antenna gain and pattern, noise figure, feeder loss), route number, station location(latitude, longitude), azimuth, elevation angle}}.

For equally spaced satellites, the constellation reference longitude is expressed relative to the mid longitude of the test area "$long_{mid}$". Generate satellite locations.

– *satellite longitude* $long_m = long_{mid} +$ m*(360/number_of_satellites),

m = 0 to (number_of_satellites – 1)

For randomly located satellites:

- *satellite longitude* $long_m$ = *min arc longitude* + *RAND*8*(*max arc longitude* – *min arc longitude*)

⇒ **<3>** For each route

⇒ **<4>** For each station in route

⇒ **<5>** For each satellite in constellation.

- compute nominal arrival angle to satellite, compute arrival angles at maximum and minimum excursions of orbit inclination allowing for refraction;
- if any of these arrival angles are more negative than the refraction angle attach "ignore" marker for future computations. If all of these arrival angles are more negative than the refraction angle, go to **<5>** to select next satellite, else
- compute off-axis angles, antenna gains, compute maximum of the three $I/N|_{single\ entry}$ values {as power ratios} taking account of atmospheric attenuation (function of arrival angle) and rain fade (function of off-axis angle and arrival angle) if appropriate.

Go to <**5**>, next satellite

- compute $I/N|_{aggregate} = \Sigma_{all\ satellites}\ (I/N|_{single\ entry})$, $I/N|_{station} = 10\ \log(I/N|_{aggregate})$ (dB)

  NOTE 1 – Appendix 2 to this Annex describes the derivation of $I/N_{aggregate}$ in greater detail.

Go to **<4>**, next station in route

- compute $FDP_{route} = \Sigma_{all\ stations}\ (I/N|_{aggregate})/n$ ......sum over all stations n in route.

Go to **<3>**, next route

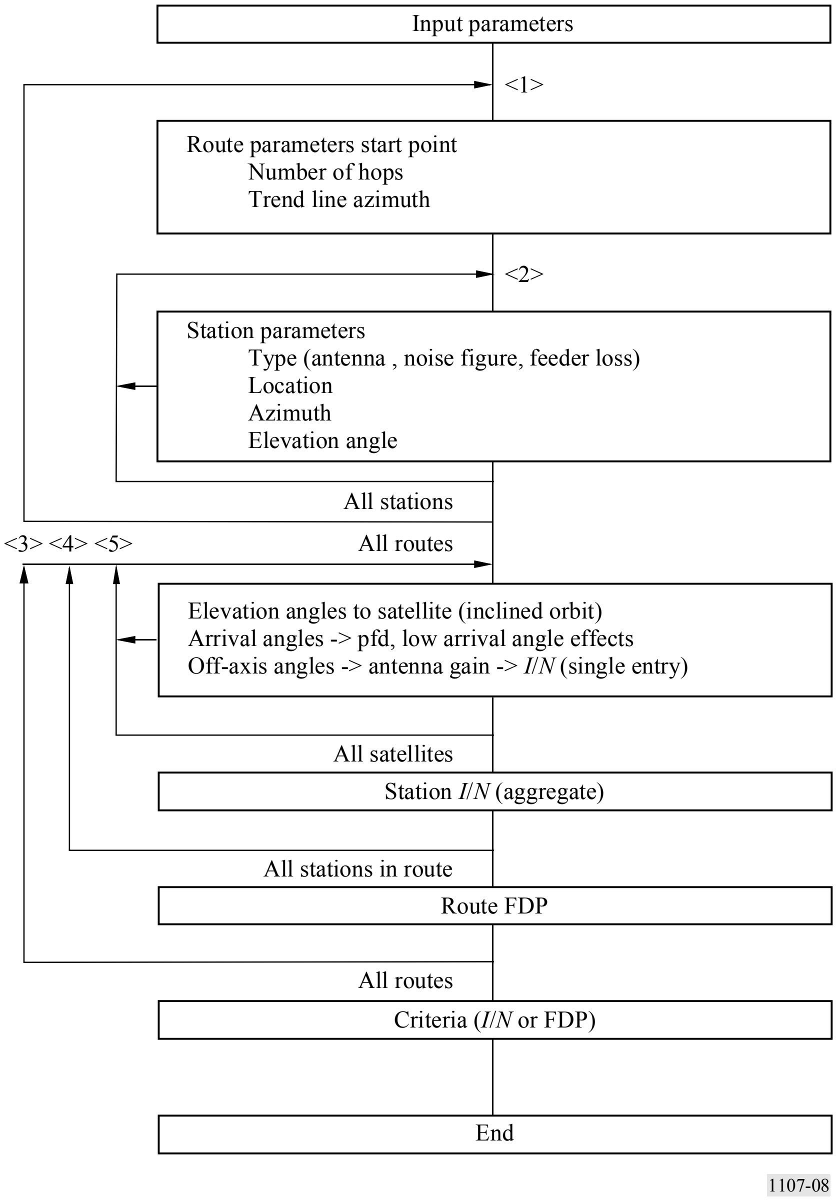
- generate probability distribution function (pdf) of station $I/N|_{aggregate}$ values by creating an ordered list of values from high to low, numbering the list of entries, i.e. $(j, I/N|_j : j = 1 \text{ to } J)$ then $\{100^*j/J\}$ is the percentile corresponding to $I/N|_j$ whereby all subsequent stations have a performance better (less) than $I/N|_j$. Generate pdf of route FDP in a similar fashion;
- determine from the pdfs,
  - the per cent of stations or routes as appropriate at the associated performance criterion ("$\%_{stations}$_at_I/N$_{criterion}$" and "$\%_{routes}$_at_FDP$_{criterion}$"); and
  - the value of *I*/*N* or FDP as appropriate at the defined percentage of stations or routes, respectively ("I/N_at_P$_{station}$" and "FDP_at_P$_{route}$");
- output the station *I*/*N* and route FDP probability distribution functions: {*I*/*N* value, probability *I*/*N* is exceeded}: {FDP value, probability FDP is exceeded} for presentation as a graph. Output the above derived values: "$\%_{stations}$_at_I/N$_{criterion}$", "$\%_{routes}$_at_FDP$_{criterion}$", "I/N_at_P$_{station}$" and FDP_at_P$_{route}$".

4 Commentary

A flow chart of the above process is given in Fig. 8.

FIGURE 8

Simplified flow chart algorithm



The test criterion “I/N_at_P$_{\text{station}}$” indicates by how much the pfd mask may need to be reduced. For example, assuming the original low arrival angle pfd level to high arrival angle pfd level transition is to be maintained, if the acceptable performance is 90% of stations should have an *I*/*N* less than or equal to –10 dB and if the test criterion “I/N_at_P$_{\text{station}}$” (dB) exceeds this value, the pfd mask should be reduced by the difference {“I/N_at_P$_{\text{station}}$” – (–10)} to meet the criterion. Similarly, if the acceptable performance is 90% of routes should have a FDP less than or equal to 25% and if the test criterion “FDP_at_P$_{\text{route}}$” (%) exceeds this value, the pfd mask should be reduced by the difference {10 log(“(FDP)_at_P$_{\text{route}}$/100”) – 10 log(0.25)} to meet the criterion.

A scatter diagram of the calculated I/N values against arrival angle would permit a different transition to be developed if required.

It should be fairly straightforward to input an actual database of FS receive stations and/or a known satellite constellation instead of the random set of stations and the uniform constellation in order to obtain a real-life picture if required. Allowance for these options would have to be made in the data input routines of course.

APPENDIX 2

TO ANNEX 2

Derivation of $I/N_{aggregate}$ for individual FS receivers

The methodology is based on the following algorithm:

- considering a given spacing between geostationary satellites, $Long_{ref} = 360/\text{nb\_sat}$
- considering a given pfd mask applicable to each geostationary satellite;
- considering a given latitude and longitude of the FS system:
  - for each FS pointing azimuth (varying from 0° to 360°);
  - for each satellite constellation relative longitude ($\Delta long$ varying from 0° to $Long_{ref}$);
- calculation of the aggregate interference at the FS receiver entrance from all visible geostationary satellites;
- calculation of the resulting I/N at the FS receiver

$$\frac{I}{N}(azimuth, \Delta long) = \frac{1}{N}\sum_{i=1}^{vis}\left(pfd_i(\Delta long) + G(\theta_i(azimuth, \Delta long)) + 10\log\left(\frac{\lambda^2}{4\pi}\right) - FL\right)$$

where:

$\frac{I}{N}(azimuth, \Delta long)$: resulting aggregate I/N from all visible geostationary satellites at the FS receiver, $\Delta long$ being the relative longitude of the satellite constellation and *azimuth* the pointing azimuth of the FS station antenna

$pfd_i(\Delta long)$: pfd at the FS station from visible geostationary satellite i

$\theta_i(azimuth, \Delta long)$: off-axis angle between the FS antenna pointing direction and the direction under which the i-th satellite is seen from the FS station (in the case of hub stations of P-MP systems $\theta_i(azimuth, \Delta long)$ should be replaced by $elev_i(\Delta long)$ which is the difference between the pointing elevation of the FS antenna and the elevation under which the i-th satellite is seen. Where directional FS stations have elevation angles other than zero, the off-axis angle is modified accordingly

$G(\theta)$: gain of the FS antenna for the off-axis θ

λ: wavelength

FL: FS feeder loss

vis: number of visible satellites from the FS station

N: FS receiver thermal noise.

This enables one to determine a table of I/N values (or FDP) at the FS receiver station as a function of the pointing azimuth of the FS station and relative longitude of the satellite constellation, and hence a probability density function of the FS station I/N or FDP_{hop} or route FDP_{route} (all routes located within a given test area) for a given pfd mask and geostationary satellite spacing.