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Technical Basis for the Geostationary Satellite Orbit Analysis Program (GSOAP) Version 2

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CCIR	International Radio Consultative Committee
CIR	carrier-to-interference ratio
CPA	co-polar attenuation
CPM	Conference Preparatory Meeting
EIRP	equivalent isotropically radiated power
FCC	Federal Communications Commission
FSS	Fixed-Satellite Service
GSOAP	Geostationary Satellite Orbit Analysis Program
IRAC	interdepartment Radio Advisary Committee
ITU	International Telecommunication Union
NTIA	National Telecommunications and Information Administration
NRP	normalized received power
RARC	Regional Administrative Radio Conference
RARC-BS-R2	Regional Administrative Radio Conference for the Planning of the Broadcasting-Satellite Service in Region 2
WARC	World Administrative Radio Conference
WARC-BS	World Administrative Radio Conference for the Planning of the Broadcasting-Satellite Service
XPD	cross-polarization discrimination

TECHNICAL BASIS FOR THE GEOSTATIONARY SATELLITE ORBIT ANALYSIS PROGRAM (GSOAP) - VERSION 2

Hiroshi Akima*

The Geostationary Satellite Orbit Analysis Program (GSOAP) is computer software that analyzes system performance and mutual interference of communication satellites using the geostationary satellite orbit. Calculation of the CIR (carrier-to-interference ratio) margins is an essential part of GSOAP. It involves a variety of technical problems, i.e., earth-station and satellite antenna radiation patterns, radio wave propagation models, and related problems such as the polarization angles of linearly polarized emissions, combining of the transmitting and receiving antenna gains, percent of the time for which the CIR is to be protected, and so forth. Various transponder arrangements in the satellites may contribute to the complexity of the calculation. Some of the methods for solving such problems are taken from the ITU (International Telecommunication Union) and CCIR (International Radio Consultative Committee) documents, while others have been developed in the present study. GSOAP is still under development. This report describes the technical basis for GSOAP, Version 2.

Key words: antenna gain pattern; CIR (carrier-to-interference ratio); CIR margin; geostationary satellite orbit; GSOAP (Geostationary Satellite Orbit Analysis Program); radio-wave propagation model

1. INTRODUCTION

The National Telecommunications and Information Administration (NTIA), U.S. Department of Commerce, is developing computer software called the Geostationary Satellite Orbit Analysis Program (GSOAP). The objective of this development effort is to develop a computer analytical model to characterize the physical and electromagnetic phenomena involved in the computation of system performance and mutual interference among geostationary-satellite radio communication systems in the Fixed-Satellite Service (FSS). The analytical model will be used in conjunction with an existing communication satellite data base to assess inter-satellite interference, in particular FSS systems in Region 2, which will be used to assist in the development of

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the U.S. policy and proposals for the 1985/1988 ITU World Administrative Radio Conference on the use of the geostationary-satellite orbit and the planning of space services utilizing it (85/88 ITU SPACE WARC).

GSOAP calculates the CIR (carrier-to-interference ratio) margins for all uplink or downlink paths and for all satellite networks. (The CIR margin is the CIR less protection ratio. A satellite network consists of a satellite and all uplink and downlink earth points associated with the satellite.) GSOAP calculates, for each path and for each satellite network and for each of the transponders of the wanted satellite, the margins corresponding to the single-entry CIR's (ratios of the wanted carrier power to powers of individual interferers) and the total CIR (ratio of the wanted carrier power to total interference power).

This report describes the technical basis for GSOAP, Version 2. GSOAP is still under development.

For simplicity, Version 2 of GSOAP is based on the rectangular emission spectrum and pass-band approximations; it assumes that, for the signal passing through each transponder, the shapes of both the signal spectrum and receiver pass band are rectangular and their bandwidths are identical. The CIR is calculated as the ratio of the wanted signal power to the portion of the interfering signal power intercepted by the receiver pass band for the wanted carrier.

GSOAP, Version 2, assumes, also for simplicity, that a satellite or an earth station in an uplink or a downlink path in a satellite network has a single set of antenna type and dimension and has a single set of values of the bandwidth and EIRP (equivalent isotropically radiated power) for a transponder.

The ITU (International Telecommunication Union) is one of the most important sources of technical information for developing GSOAP. The ITU Radio Regulations (ITU, 1982) and the final acts of the world and regional administrative radio conferences of the ITU (1977, 1983) contain various provisions on technical aspects as well as political aspects. Because each document has the status of an international treaty, the technical provisions such as the antenna radiation patterns and propagation models in each document have been implemented in GSOAP at the minimum.

Another important source of technical information is the CCIR (International Radio Consultative Committee), which is a technical arm of the ITU. The CCIR is making continuous efforts to establish and improve technical standards for various radio service operational problems. The recommendations and reports adopted by the Plenary Assembly of the CCIR are published periodically (about 3- to 4- year periods) as the so-called CCIR Green Books. Out of more than 10 volumes of the latest version of the Green Books (CCIR, 1982a), Volume IV-1 (Fixed-Satellite Service), Volume V (Propagation in Non-Ionized Media), and Volume X/XI-2 (Broadcasting-Satellite Service) are of interest to this study. The CCIR also holds a preparatory meeting for an administrative radio conference of the ITU, usually one year before the conference, to develop recommendations on technical matters for the conference. Of particular interest in this study is the Report of the Conference Preparatory Meeting SAT-R2 (for the 1983 RARC-BS) (CCIR, 1982b).

Other sources of technical information are the U.S. Committee for the CCIR, the IRAC (Interdepartment Radio Advisory Committee) ad hoc committees for the ITU conferences, FCC (Federal Communications Commission), technical journals, etc. Even with the information from these sources, there are still unresolved problems for which original studies are required.

Main areas of this development effort include antenna radiation patterns, radio wave propagation models, calculation of received powers by calculating and combining antenna gains and propagation phenomena, and calculation of CIR's from the received powers. They are addressed in Section 2, 3, 4, and 5, respectively, of this report.

2. ANTENNA RADIATION PATTERNS

GSOAP implements the antenna radiation patterns adopted by the ITU or recommended by the CCIR, some with slight modifications. The radiation patterns of the earth-station and satellite antennas are described in Subsections 2.1 and 2.2, respectively, of this report. In addition to these patterns, GSOAP implements two new types of satellite antenna patterns, each developed to approximate a shaped-beam antenna pattern. These patterns are described in Subsections 2.3 and 2.4.

Each pattern consists of a pair of gain curves that represent the copolar and crosspolar gains, respectively. Each curve is given as a function of the off-axis angle or its equivalent. Each pattern is given a name that is a string of six characters.

In this section, we use the following symbols to describe the antenna radiation patterns:

D = diameter of a circular antenna in meters,

G_c = copolar gain, relative to the copolar on-axis gain, in decibels (dB),

G_ℓ = constant term for the linear portion of the gain curve, relative to an isotropic antenna gain, in decibels above isotropic (dBi),

G_r = residual antenna gain (i.e., the gain at a far distant angle) relative to an isotropic antenna gain, in dBi,

G_x = crosspolar gain, relative to the copolar on-axis gain, in dB,

G_0 = copolar on-axis gain, relative to an isotropic antenna gain,

G_1 = first sidelobe level, relative to an isotropic antenna gain, in dBi, in Subsection 2.1, and

= gain corresponding to the first contour, relative to the copolar on-axis gain, in dB, in Subsections 2.3 and 2.4,

R = D/λ,

r = ϕ/ϕ_0,

r' = $(\phi - 0.5\phi_0)/\phi_r + 0.5$ for fast roll-off pattern, and

= $\phi'/\phi_r + 0.5$ for polygon pattern,

λ = wavelength of the radio wave in meters,

ϕ = off-axis angle in degrees,

ϕ' = angle off 3-dB contour in degrees,

ϕ_a, ϕ_b

= major-axis and minor-axis beamwidths of the 3-dB contour of an elliptical beam antenna in degrees,

ϕ_r = reference beamwidth in degrees,
ϕ_0 = 3-dB beamwidth in degrees.

We also use symbols max {...} and min {...} to represent "the maximum of" and "the minimum of" the quantities enclosed in the braces. Use of these symbols together with the use of r and r' in the above list sometimes enables us to re-write the gain equations in a more compact manner than in the source documents.

Constant values for the patterns in the source documents have been checked for the continuity of the gain curves. Some of the values have been slightly modified for better continuity.

2.1. Earth-Station Antenna Patterns

Currently, GSOAP implements the following 12 antenna patterns as the earth-station antenna patterns:

EFC391 -- FSS earth-station antenna pattern, based on CCIR Report 391-4 (CCIR, 1982a). The main-beam portion of the copolar curve and the entire crosspolar curve are supplemented based on the Final Acts of the 1983 RARC-BS-R2 (ITU, 1983).

G_c = max {$-0.0025\ R^2\phi^2$,
min {G_1, max {G_ℓ - 25 log (ϕ), -10}} - G_0}.
G_x = min {-30, max {G_c - 10, - 10 - G_0}}.
G_0 = 8 + 20 log (R).
G_1 = 2 + 15 log (R).
G_ℓ = max {32, 52 - 10 log (R)}.
R: input argument.

EFC465 -- FSS earth-station antenna pattern, based on CCIR Recommendation 465-1 (CCIR, 1982a).

The pattern is the same as EFC391 except that
G_ℓ = 32.

EFC580 -- FSS earth-station antenna pattern, based on CCIR Recommendation 580 (CCIR, 1982a). This pattern is recommended for antennas with R $\geq$ 150.

The pattern is the same as EFC391 except that
$G_\ell = 29$.

EFFC25 -- FSS earth-station antenna pattern, based on Part 25 of the FCC Rules and Regulations (FCC, 1984). The main-beam portion of the copolar curve and the distant-angle portion of the crosspolar curve are supplemented.

$$
\begin{aligned}
G_c &= \max\{-0.0025\, R^2\phi^2, \\
&\quad \min\{G_1, \{29 - 25\log(\phi)\} - G_0\} && \text{for } 0 \le \phi \le 6.9183, \\
&= 8 - G_0 && \text{for } 6.9183 \le \phi \le 9.1201, \\
&= 32 - 25\log(\phi) - G_0 && \text{for } 9.1201 \le \phi \le 47.863, \\
&= -10 - G_0 && \text{for } 47.863 \le \phi. \\
G_x &= \min\{-30, \max\{G_c - 10, -10 - G_0\}\}. \\
G_0 &= 8 + 20\log(R). \\
G_1 &= 2 + 15\log(R).
\end{aligned}
$$

R: input argument.

EFFL83 -- FSS earth-station antenna pattern for the feeder link for a broadcasting satellite, adopted by the 1983 RARC-BS-R2 (ITU, 1983).

$$
\begin{aligned}
G_c &= -0.0025\, R^2\phi^2 && \text{for } 0 \le \phi \le 0.1000, \\
&= 36 - 20\log(\phi) - G_0 && \text{for } 0.1000 \le \phi \le 0.3128, \\
&= 51.3 - 53.2\,\phi^2 - G_0 && \text{for } 0.3128 \le \phi \le 0.5426, \\
&= 29 - 25\log(\phi) - G_0 && \text{for } 0.5426 \le \phi \le 36.3078, \\
&= -10 - G_0 && \text{for } 36.3078 \le \phi. \\
G_x &= -30 && \text{for } 0 \le \phi \le 35.4813/R, \\
&= 9 - 20\log(\phi) - G_0 && \text{for } 35.4813/R \le \phi \le 8.9125, \\
&= -10 - G_0 && \text{for } 8.9125 \le \phi. \\
G_0 &= 8 + 20\log(R).
\end{aligned}
$$

R: input argument.

EFFM83 -- FSS earth-station antenna pattern for the feeder link for a broadcasting satellite, adopted by the 1983 RARC-BS-R2 (ITU, 1983) and modified as described in Appendix A to this report.

G_c for $R \leq 1138.0$

$= -0.0025R^2\phi^2$ for $0 \leq \phi \leq 46.5991/R$,

$= \max\{-0.0025R^2\phi^2, 29 - 25\log(\phi) - G_0\}$ for $46.5991/R \leq \phi \leq 36.3078$,

$= -10 - G_0$ for $36.3078 \leq \phi$.

G_c for $R \geq 1138.0$

$= -0.0025R^2\phi^2$ for $0 \leq \phi \leq 41.6795/R$,

$= 36.0555 - 20\log(\phi) - G_0$ for $41.6795/R \leq \phi \leq 0.003662$,

$= -3237.6\phi^2$ for $0.003662 \leq \phi \leq 0.04095$,

$= 29 - 25\log(\phi) - G_0$ for $0.04095 \leq \phi \leq 36.3978$,

$= -10 - G_0$ for $36.3078 \leq \phi$.

$G_x = -30$ for $0 \leq \phi \leq 35.4813/R$,

$= 9 - 20\log(\phi) - G_0$ for $35.4813/R \leq \phi \leq 8.9125$,

$= -10 - G_0$ for $8.9125 \leq \phi$.

$G_0 = 8 + 20\log(R)$.

R: input argument.

EFWC79 -- FSS earth-station antenna pattern, agreed to by the 1979 WARC and included in Appendixes 28 and 29 of the ITU Radio Regulations (ITU, 1982). It is also described in Annex I to CCIR Report 391-4 (CCIR, 1982a).

$G_c = \max\{-0.0025\,R^2\phi^2,$
$\min\{G_1, \max\{G_\ell - 25\log(\phi), G_r\}\} - G_0\}$.

$G_x = \min\{-30, \max\{G_c - 10, G_r - G_0\}\}$.

$G_0 = 7.7 + 20\log(R)$.

$G_1 = 2 + 15\log(R)$.

$G_\ell = \max\{32, 52 - 10\log(R)\}$.

$G_r = \max\{-10, 10 - 10\log(R)\}$.

R: input argument.

EGSS01 -- General earth-station antenna pattern with sidelobe suppression.

$G_c = \max\{-0.0025\,R^2\phi^2,$
$\min\{G_1, \max\{G_\ell - 25\log(\phi), G_r\}\} - G_0\}$.

$G_x = \min\{-30, \max\{G_c - 10, G_r - G_0\}\}$.

$G_0 = 8 + 20\log(R)$.

R, G_1, G_ℓ, G_r: input arguments.

EGSS02 -- General earth-station antenna pattern with sidelobe suppression with the crosspolar gain curve of the EFFL83 pattern.

The pattern is the same as EGSS01 except that

$G_x = \min\{-30, \max\{9 - 20\log(\phi), G_r\} - G_0\}$.

EBCR77 -- BSS earth-station antenna pattern for community reception, adopted by the 1977 WARC-BS (ITU, 1977) and included in Appendix 30 to the Radio Regulations (ITU, 1982).

$$
\begin{aligned}
G_c &= 0 && \text{for} \quad 0 \le r \le 0.2500, \\
&= -12r^2 && \text{for} \quad 0.2500 \le r \le 0.8584, \\
&= \max\{-10.5 - 25\log(r), -G_0\} && \text{for} \quad 0.8584 \le r. \\
G_x &= -25 && \text{for} \quad 0 \le r \le 0.2501, \\
&= -30 - 40\log(1 - r) && \text{for} \quad 0.2501 \le r \le 0.4376, \\
&= -20 && \text{for} \quad 0.4376 \le r \le 1.3982, \\
&= -30 - 25\log(r - 1) && \text{for} \quad 1.3982 \le r \le 2.0000, \\
&= \min\{-30, G_c\} && \text{for} \quad 2.0000 \le r. \\
G_0 &= 44.447.
\end{aligned}
$$

EBIR77 -- BSS earth-station antenna pattern for individual reception in Regions 1 and 3, adopted by the 1977 WARC-BS (ITU, 1977) and included in Appendix 30 to the Radio Regulations (ITU, 1982).

$$
\begin{aligned}
G_c &= 0 && \text{for} \quad 0 \le r \le 0.2500, \\
&= -12r^2 && \text{for} \quad 0.2500 \le r \le 0.7049, \\
&= -9 - 20\log(r) && \text{for} \quad 0.7049 \le r \le 1.2590, \\
&= -8.5 - 25\log(r) && \text{for} \quad 1.2590 \le r \le 9.5499, \\
&= -33 && \text{for} \quad 9.5499 \le r. \\
G_x &= -25 && \text{for} \quad 0 \le r \le 0.2501, \\
&= -30 - 40\log(1 - r) && \text{for} \quad 0.2501 \le r \le 0.4376, \\
&= -20 && \text{for} \quad 0.4376 \le r \le 1.3982, \\
&= -30 - 25\log(r - 1) && \text{for} \quad 1.3982 \le r \le 2.0000, \\
&= \min\{-30, G_c\} && \text{for} \quad 2.0000 \le r. \\
\phi_0 &= 2.0^\circ.
\end{aligned}
$$

EBIR83 -- BSS earth-station antenna pattern for individual reception in Region 2, adopted by the 1983 RARC-BS-R2 (ITU, 1983).

$G_0 = 0$	for $0 \le r \le 0.2500$,
$= -12r^2$	for $0.2500 \le r \le 1.1302$,
$= -14 - 25 \log(r)$	for $1.1302 \le r \le 14.723$,
$= -43.2$	for $14.723 \le r \le 35.004$,
$= -85.2 + 27.2 \log(r)$	for $35.004 \le r \le 45.124$,
$= -40.2$	for $45.124 \le r \le 70.026$,
$= 55.2 - 51.7 \log(r)$	for $70.026 \le r \le 80.037$,
$= -43.2$	for $80.037 \le r$.
$G_x = -25$	for $0 \le r \le 0.2501$,
$= -30 - 40 \log(1 - r)$	for $0.2501 \le r \le 0.4376$,
$= -20$	for $0.4376 \le r \le 1.2824$,
$= -17.3 - 25 \log(r)$	for $1.2824 \le r \le 3.2210$,
$= \min\{-30, G_c\}$	for $3.2210 \le r$.
$\phi_0 = 1.7°$.	

2.2. Satellite Antenna Patterns

Currently, GSOAP implements eight antenna patterns as the satellite antenna patterns. Five of them, adopted by the ITU or recommended by the CCIR, are described in this subsection. (The remaining three are described in Subsectionss 2.3 and 2.4.)

SFC558 -- FSS satellite antennna pattern, based on CCIR Report 558-2 (CCIR, 1982a). The main-beam portion of the copolar curve is extended to the beam center, and the crosspolar curve is supplemented.

$G_c = -12\, r^2$	for $0 \le r \le 1.2910$,
$= -20$	for $1.2910 \le r \le 3.1548$,
$= \max\{-25 \log(2r), -10 - G_0\}$	for $3.1548 \le r$.

$G_x = \min\{-30, G_c\}$.

$r = \phi/\phi_0$.

$G_0 = 44.447 - 20 \log \phi_0$.

ϕ_0: input argument.

SBFR83 -- BSS satellite antenna fast roll-off pattern, adopted by the 1983 RARC-BS-R2 (ITU, 1983).

$$
\begin{aligned}
G_c &= -12r^2 && \text{for } 0 \le r \le 0.5000, \\
&= -12r'^2 && \text{for } 0.5000 \le r' \le 1.4499, \\
&= -25.227 && \text{for } 1.4499 \le r',\ r \le 1.4499, \\
&= \max\{-22 - 20 \log(r),\ -G_0\} && \text{for } 1.4499 \le r.
\end{aligned}
$$

$G_x = \min\{-30,\ G_c\}$

$G_0 = 44.447 - 10 \log(\phi_a \phi_b)$.

$r' = (\phi - 0.5\phi_0)/\phi_r + 0.5$.

$\phi_r = 0.8°$.

ϕ_a, ϕ_b, ϕ_0: input arguments.

SBFRM1 -- BSS satellite antenna fast roll-off pattern, slightly modified from the SBFR83 pattern listed above. This pattern is the same as SBFR83 except that the first two segments for G_c are replaced by the following.

$$
\begin{aligned}
G_c &= 0 && \text{for } r' \le 0, \\
&= -12r'^2 && \text{for } 0 \le r' \le 1.4499.
\end{aligned}
$$

SBSD77 -- BSS satellite antenna standard pattern, adopted by the 1977 WARC-BS (ITU, 1977) and included in Appendix 30 to Radio Regulations (ITU, 1982).

$$
\begin{aligned}
G_c &= -12r^2 && \text{for } 0 \le r \le 1.5811, \\
&= -30 && \text{for } 1.5811 \le r \le 3.1623, \\
&= \max\{-17.5 - 25 \log(r),\ -G_0\} && \text{for } 3.1623 \le r. \\
G_x &= -40 - 40 \log(1 - r) && \text{for } 0 \le r \le 0.3316, \\
&= -33 && \text{for } 0.3316 \le r \le 1.6684, \\
&= \max\{40 - 40 \log(r - 1),\ -G_0\} && \text{for } 1.6684 \le r.
\end{aligned}
$$

$G_0 = 44.447 - 10 \log(\phi_a \phi_b)$.

ϕ_a, ϕ_b: input arguments

SBSD83 -- BSS satellite antenna standard pattern, adopted by the 1983 RARC-BS-R2 (ITU, 1983).

$$
G_c = -12r^2 \qquad \text{for } 0 \le r \le 1.4499,
$$

$= \max \{-22 - 20 \log (r), - G_0\}$ for $1.4499 \leq r$.

$G_x = \min \{-30, G_c\}$.

$G_0 = 44.447 - 10 \log (\phi_a \phi_b)$.

ϕ_a, ϕ_b: input arguments.

2.3. Satellite Antenna Polygon Pattern

To approximate a shaped-beam pattern of a satellite antenna, we have developed a new type of antenna pattern called the polygon pattern. This pattern is devised for use when only a polygon that closely approximates a gain contour is given either with or without a maximum gain point. We assume that the satellite antenna gain in the direction of an earth point inside and outside the contour increases and decreases, respectively, as a function of the "angle between the earth point and the polygon." The angle between the earth point and the polygon is the minimum value of the distance, expressed in the angle seen from the satellite, between the earth point and a point on the boundary of the polygon.

Using the angle between the earth point in question and the polygon, ϕ', we calculate the modified normalized angle by

$$r' = (-G_1/12)^{1/2} \pm \phi'/\phi_r,$$

where G_1 is the gain corresponding to the contour, relative to the copolar on-axis gain, in dB, and ϕ_r is the reference beamwidth. The upper and lower signs in this equation apply to the cases where the earth point is outside and inside of the contour, respectively. The r' variable is applied to a fast roll-off pattern.

We estimate the effective value of 3-dB beamwidth, ϕ_0, from the copolar on-axis gain, G_0, from the relation

$$G_0 = 44.447 - 20 \log (\phi_0).$$

Then, the effective value of the normalized angle, r, is estimated from the relation

$$r' - 0.5 = (r - 0.5) (\phi_0/\phi_r).$$

The r value thus estimated is used for the gain calculation outside the polygon when the pattern requires its use.

Currently, GSOAP includes two patterns called the SGPP83 and SGPPM1 patterns. Both patterns assume that each vertex of the polygon is represented by the "pitch" and "roll" angles, i.e., by the angles of the vertex seen at the satellite from the line connecting the satellite and its subsatellite point to the east and north directions, respectively. (The subsatellite point of a satellite is an earth point due beneath the satellite. It is also the earth point nearest the satellite.) Both patterns also assume that the vertexes of the polygon are given counterclockwise. They are based on the fast roll-off curve of the SBFR83 and SBFRM1 patterns described in Subsection 2.2 above. Description of the polygon patterns follows.

SGPP83 -- General satellite antenna polygon pattern, based on the gain curves of the SBFR83 pattern described in Subsection 2.2 above.

$$G_c = G_1 \, (d_0/(d_0 + d_1))^2 \quad \text{for} \quad r' \le r_1',$$
$$= 12r'^2 \quad \text{for} \quad r_1' \le r' \le 1.4499,$$
$$= -25.227 \quad \text{for} \quad 1.4499 \le r', \; r \le 1.4499,$$
$$= \max\{-22 - 20 \log (r), \; -G_0\} \quad \text{for} \quad 1.4499 \le r.$$

$$G_x = \min\{-30, G_c\}.$$

$$r' = r_1' \pm d_1/\phi_r.$$

$$r_1' = (-G_1/12)^{1/2}.$$

$$\phi_0 = 10^{(44.447 - G_0)/20}.$$

$$r = (r' - 0.5)\,(\phi_r/\phi_0) + 0.5.$$

d_0 = distance (angle) between the earth point and the maximum gain point in degrees.

d_1 = distance (angle) between the earth point and the polygon.

G_0, ϕ_r: input arguments.

SGPPM1 -- General satellite antenna polygon pattern, based on the gain curves of the SBFRM1 pattern described in Subsection 2.2 above.

This pattern is the same as SGPP83 except that the first two segments for G_c are replaced by the following.

$$G_c = 0 \qquad \text{for} \quad r' \le 0,$$
$$= -12r'^2 \qquad \text{for } 0 \le r' \le 1.4499.$$

2.4 Satellite Antenna Shaped-Beam Pattern

Another way of approximating a shaped-beam pattern of a satellite antenna also has been developed. We assume that several polygons that approximate gain contour lines corresponding to a set of gain values are given with a maximum gain point. When the earth point for which we wish to calculate the antenna gain falls between two polygons approximating two contour lines, we interpolate the gain value from the two gain values corresponding to the two contour lines linearly with respect to the distances to the two polygons. (The distance between a point and a polygon is the minimum value of the distances between the point in question and the points on the sides of the polygon.) When the earth point falls inside the innermost polygon, we interpolate the gain value from the maximum gain value and the gain value for the innermost contour line, assuming that the gain decreases as the square of the distance from the maximum gain point. When the earth point falls outside the outermost polygon, we extrapolate the gain value from the two gain values for the two outermost contour lines linearly until the gain equals the value set for the residual gain.

The antenna gain values resulting from this calculation method are continuous. The gain value for an earth point that lies between two polygons always remains between the two gain values corresponding to the two polygons. One of the disadvantages of the method is that the resulting gain values are not smooth on the sides of the polygons.

Currently, GSOAP includes a pattern called the SGSB01 pattern. This pattern assumes that each vertex of the polygon is represented by the "pitch" and "roll" angles, i.e., by the angles of the vertex seen at the satellite from the line connecting the satellite and its subsatellite point to the east and north directions, respectively. This pattern also assumes that the polygons (or contours) are sorted from the innermost outward and that the vertexes of each polygon are given counterclockwise. Description of the SGSB01 pattern follows.

SGSB01 General satellite antenna shapedbeam pattern.

$G_c = G_1 \; (d_0/(d_0 + d_1))^2$

for inside the innermost contour (the first contour)

$= (G_{i+1}d_i + G_i d_{i+1})/(d_i + d_{i+1})$

for the range between the ith and the (i+1)st contours.

$= \max \{(G_n d_{n-1} - G_{n-1} d_n)/(d_{n-1} - d_n), \min \{-10 - G_0, G_n\}\}$

for outside the outermost contour (the nth contour).

$G_x = \min \{-30, G_c\}$.

G_i: gain corresponding to the ith contour, relative to the copolar on-axis gain, in dB, where i = 1, ..., n.

d_i: distance between the earth point and the ith polygon, where i = 1, 2, ..., n.

n: number of contours.

d_0: distance between the earth point and the maximum gain point.

G_0: input argument.

3. PROPAGATION MODELS

Among several weather effects on a radio wave, two weather effects caused by rain are particularly important in space telecommunications. One is rain attenuation of a radio wave. The other is rain-induced depolarization of a radio wave, i.e., the phenomenon that a crosspolar component is generated by rain. The degree of depolarization is represented by the crosspolarization discrimination, which is the ratio of the copolar component to the crosspolar component.

Currently, GSOAP includes three models for the rain-related propagation phenomena: the 1977 WARC-BS model, the CCIR model, and the 1983 RARC-BS-R2 model. Each model includes a world rain-climate-zone map, which divides the world into several rain-climate zones. Each model gives a procedure for determining the rain attenuation and crosspolarization discrimination for each rain-climate zone and some other parameters.

The 1977 WARC-BS, CCIR, and 1983 RARC-BS-R2 models are outlined in Subsections 3.1, 3.2, and 3.3, respectively. The method of implementing each model in GSOAP is also described in each subsection.

In addition to the rain-related phenomena, a radio wave suffers from molecular absorption, primarily by atmospheric water vapor and oxygen. Currently, GSOAP includes the CCIR model for calculating the gaseous absorption. This model is described in Subsection 3.4.

3.1. 1977 WARC-BS Model

This model was adopted by the 1977 WARC-BS (ITU, 1977) and is now in Appendix 30 to the ITU Radio Regulations (ITU, 1982). It is a simple model. It is intended for use only in the 11 to 12 GHz frequency band. It is presented purely graphically; no formulas are given.

The model divides the world into five rain-climatic zones, indexed as 1 through 5. Zone 1 is the most rainy zone, and Zone 5 is the least rainy zone.

This model gives the rain attenuation values graphically. Four curves of attenuation versus elevation angle of the radio propagation path are given. They are: Curve A for Zone 1, Curve B for Zone 2, Curve C for Zones 3 and 4, and Curve D for Zone 5.

This model gives two values of crosspolarization discrimination regardless of the elevation angle. The discrimination value is 27 dB in Zones 1 and 2, and 30 dB in Zones 3, 4, and 5.

To implement this model in GSOAP, we have read the rain-zone indices at all grid points of 3° intervals both in longitude and latitude from the world rain-zone map. We have stored these index values in data file. We calculate the rain-zone index for a given earth point by finding the square in the 3° grid that includes the earth point, by interpolating the index value from the index values at the four corners of the square with a bilinear interpolation formula with respect to the longtitude and latitude, and by taking the nearest integer to the interpolated result.

We have also read the attenuation values and the slopes of the attenuation versus elevation angle curve at every 10° interval of the elevation angle and stored them. We calculate the rain attenuation for a given elevation angle and a given rain-zone index by finding the interval that includes the given elevation angle, by generating a third-degree (cubic) interpolation formula with respect to the elevation angle for that interval, and by applying the formula to the given elevation angle value.

3.2. CCIR Model

This model is described in CCIR Report 564-2 (CCIR, 1982a), which in turn is based on CCIR Reports 563-2, 721-1, 722-1, and 723-1 (CCIR, 1982a).

This model divides the world into 14 rain zones, Rain Zones A through P (excluding I and O), Rain Zone A is the least rainy zone, and Rain Zone P is the most rainy zone. The world rain-zone map is given in Figures 11 through 13 in CCIR Report 563-2. The values of the rainfall intensity exceeded for a wide range of percentage of time for each rain zone are also listed in the same CCIR report.

The basic methods for estimating the rain attenuation and crosspolarization discrimination are described in CCIR Reports 721-1 and 722-1, respectively. CCIR Report 564-2 summarizes these reports and presents a comprehensive procedure for the estimations. Excerpts from Sections 6 and 8 of CCIR Report 564-2 follow.

6.1.2 Method of prediction

From an examination of the methods discussed in Report 721, the following simple technique appears to yield reasonable agreements with available data.

To calculate the long-term average of the slant-path rain attenuation at a given location, the following parameters are required:

R_p: the point rainfall rate for the location at the required percentage times (mm/h)

h_o: the height above mean sea level of the earth station (km)

θ : the elevation angle (degrees)

ϕ : the latitude of the earth station (degrees).

The proposed method consists of the following steps 1 to 7 for 0.01% of the time, and step 8 for other time percentages.

Step 1. The rain height, h_R, is obtained from (see Report 563):

$$h_R = 5.1 - 2.15 \log \left(1 + 10^{\left(\frac{\phi - 27}{25}\right)}\right) \text{ km} \tag{1}$$

Step 2. The slant-path length, L_s, below the rain height is obtained from:

$$L_s = \frac{2(h_R - h_o)}{(\sin^2\theta + 2(h_R - h_o)/R_e)^{1/2} + \sin\theta} \quad \text{km} \quad \text{for } \theta < 10° \tag{2}$$

where R_e is the effective radius of the Earth (8,500 km).

For $\theta \geq 10°$, equation (2) may be simplified to :

$$L_s = \frac{(h_R - h_o)}{\sin\theta} \quad \text{km} \tag{3}$$

Step 3. The horizontal projection, L_G, of the slant-path length is found from (see Fig. 1):

$$L_G = L_s \cos\theta \quad \text{km} \tag{4}$$

Step 4. The reduction factor, r_p, for 0.01% of the time is calculated from:

$$r_p = \frac{90}{90 + 4L_G} \tag{5}$$

Step 5. Obtain the rain intensity, R_p, exceeded for 0.01% of an average year, (with an integration time of 1 min). If this information cannot be obtained from local data sources, an estimate can be obtained from the maps of rain climates given in Report 563.

Step 6. Obtain the specific attenuation, γ_R, using the coefficients given in Table I of Report 721 and the rainfall rate, R_p, determined from Step 5, by using:

$$\gamma_R = k(R_p)^{\alpha} \qquad \text{dB/km} \tag{6}$$

Alternatively, Fig. 1 or 2 of Report 721 may be used.

Step 7. The attenuation exceeded for 0.01% of an average year may be obtained from:

$$A_{0.01} = \gamma_R L_s r_p \qquad \text{dB} \tag{7}$$

Step 8. The attenuation to be exceeded for other percentages of an average year, in the range 0.001% to 0.1% may be estimated from the attenuation to be exceeded for 0.01% of an average year by using:

$$A_p = A_{0.01} \left(\frac{p}{0.01}\right)^{-a} \tag{8}$$

where a is given by [Fedi, 1981]:

$a = 0.33$	for	$0.001 \leq p \leq 0.01$
$a = 0.41$	for	$0.01 < p \leq 0.1$

The above procedure has been found to give reasonable agreement with available data, in particular in maritime climates. For continental climates and/or for time percentages greater than 0.1%, the procedure may be modified as follows:

(a) in Step 1: obtain the rain height, h_R, for 0.001%, 0.01%, 0.1% and 1.0% of the time using Fig. 17 of Report 563;

(b) Step 2 and Step 3: remain unchanged;

(c) in Step 4: obtain the reduction factor, r_p, for 0.001%, 0.01%, 0.1%, and 1.0% of the time from:

$$r_p = \frac{90}{90 + C_p L_G} \tag{9}$$

using the values of C_p given in Table I.

Table I

Percentage of a year	0.001	0.01	0.1	1.0
C_p	9	4	0.5	0

(d) in Step 5: obtain the rain intensity, R_p, exceeded for 0.001%, 0.01%, 0.1% and 1.0% of the time of an average year;

(e) using Steps 6 and 7 obtain the attenuation exceeded for the four time percentage values using equations (6) and (7);

(f) to calculate path attenuation A_p for an intermediate time percentage, p, between 0.001% and 1.0%, interpolation with the aid of the following approximate formula may be used:

$$\frac{A_p}{A_n} = \left(\frac{p}{p_n}\right)^{-a} \tag{10a}$$

where A_n is the attenuation calculated in step (e) for time percentage p_n, and where:

$$a = -\frac{\log (A_n/A_{n+1})}{\log (p_n/p_{n+1})} \tag{10b}$$

where A_n and A_{n+1} are the attenuations calculated for adjacent time percentages p_n and p_{n+1} respectively.

* * * * * * *

6.1.3 Prediction for worst month

System planning often requires the attenuation value, exceeded for the time percentage p_w of the "worst month."

Using the following approximate relation (see Report 723), the corresponding annual time percentage, p, may be obtained:

$$p = 0.29 \; p_w^{1.15} \; (\%) \qquad (11)$$

The attenuation exceeded for this annual time percentage, p, calculated in step (e) or (f), may then be taken as the attenuation value exceeded for p_w per cent of the worst month.

* * * * * * *

8.2 Prediction techniques for cross-polarization due to hydrometers

Because of the importance of both rain and ice clouds in producing interference due to cross-polarized rain attenuation statistics, an equation of the form:

$$XPD = U - V \log (CPA) \quad dB \qquad (15)$$

can be used for both linear and circular polarizations (see Report 722). The following approximate forms for U and V appear to be in reasonable agreement with existing theory and available data:

$$U = \kappa^2 - 10 \log 1/2 \, [1 - \cos(4\tau) \exp(-\kappa_m^2)] + 30 \log f - 40 \log (\cos \varepsilon) \qquad (16)$$

for $8 \leq f \leq 35$ GHz, and $10° \leq \varepsilon \leq 60°$

$$V = 20 \text{ for } 8 < f \leq 15 \text{ GHz}; \; V = 23 \text{ for } 15 < f \leq 35 \text{ GHz} \qquad (17)$$

where

ε: angle of elevation;

τ: polarization tilt angle with respect to horizontal (for circular polarization $\tau = 45°$);

κ, κ_m: effective parameters of the raindrop canting angle distribution in degrees.

The value of the parameter κ depends not only on meteorological factors discussed in Report 722, but also on elevation angle and the particular statistical relationship being fitted to the experimental data. In accounting for the effects of rain alone, a value of $\kappa = 0$ would appear to be conservative. Positive values of κ^2 have been observed, and are discussed in Report 722.

The second factor in equation (16) is the improvement of linear polarization with respect to circular polarization. A conservative value of $\kappa_m = 0.25°$ is recommended at present. This gives maximum improvement of 15 dB for $\tau = 0°$ or $\tau = 90°$. It should be noted, however, that higher improvements have been observed [Cox, 1981] as described in Report 722.

*   *   *   *   *   *   *

For the frequency band 4 to 6 GHz where attenuation is low, CPA statistics are not as useful in predicting XPD statistics. For frequencies below about 8 GHz, it may be more useful to employ relationships between XPD, point rain rate, and effective path length [Oguchi, 1977; Kobayashi, 1977]. A simple prediction technique to obtain an overall cumulative distribution of XPD, has been suggested [Olsen and Nowland, 1978].

8.3 Frequency and polarization scaling for long-term statistics

Long term XPD statistics obtained at one frequency and polarization tilt angle can be scaled to another frequency and polarization tilt angle using the semi-empirical formula

$$XPD_2 = XPD_1 - 20 \log \frac{f_2 \sqrt{1 - \cos 4\tau_2 \, e^{-\kappa_m^2}}}{f_1 \sqrt{1 - \cos 4\tau_1 \, e^{-\kappa_m^2}}} \qquad \text{for } 4 \leq f_1, f_2 \leq 30 \text{ GHz}$$

where XPD_1 and XPD_2 are the XPD values not exceeded for the same percentage of time at frequencies f_1 and f_2 and polarization tilt angles τ_1 and τ_2, respectively. A measured value for the parameter κ_m should be used if available; otherwise, the value given in 8.2 should be employed.

Equation (18) is based on the same theoretical formulation as equation (15) [Olsen and Nowland, 1978; Chu, 1980; Cox, 1981]. It can be used to scale XPD data that include the effects of both rain and ice depolarization, since it has been observed that both phenomena have approximately the same frequency dependence at frequencies less that about 30 GHz (see Report 722). Equation (18) is provisional and must be used with particular caution for large differences between the respective frequencies and polarization tilt angles.

In GSOAP, we have implemented this model with modifications (a) through (f) so that GSOAP can be used even for time percentage greater than 0.1%. As Equation (10b) indicates, calculations for only two percentage values are sufficient.

To implement this model in GSOAP, we have processed the world rain-zone map in a similar manner as for the 1977 WARC-BS model. We have read the rain-zone indices at all grid points of 3° intervals both in longitude and latitude from the world rain-zone map. We have converted the alphabetic indices A through P (excluding I and O) into numerical indices 1 through 14 and stored the numerical index values in a data file. We calculate the rain-zone index for a given earth point by finding the square in the 3° grid that includes the earth point, by interpolating the index value from the index values at the four corners of the square with a bilinear interpolation formula with respect to the longitude and latitude, and by taking the nearest integer to the interpolated result.

For calculating k and α, to be used in Step 6, we use Equations (2) and (3) given in CCIR Report 721-1. Since the equations require k_H, k_V, α_H, and α_V values, we have included all K_H, k_V, α_H, and α_V, values given in Table I of CCIR Report 721-1 and provided a linear interpolation procedure (on a logarithmic scale of the frequency) for an arbitrary frequency value.

For a circularly polarized radio wave, the polarization tilt angle of the radio wave used for calculating the rain-induced depolarization is set to 45°, as noted in the source document. For a linearly polarized radio wave, it is calculated with the method described by Akima (1984).

3.3. 1983 RARC-BS-R2 Model

This model was adopted by the 1983 RARC-BS-R2 (ITU, 1983). It is a modification of the CCIR model described in the preceding subsection.

This model divides Region 2 into 14 rain zones, Rain Zones A through P (excluding I and O). Rain Zone A is the least rainy zone, and Rain Zone P is the most rainy zone. The Region 2 map in this model is different from the same map in the CCIR model only in Brazil.

Since the description of the model is more comprehensive in the CPM report (CCIR, 1982b) than in the Final Acts of the RARC (ITU, 1983), we first give an excerpt from the CPM report and next describe the changes made on the CPM report by the RARC. An excerpt from the CPM report follows.

> To calculate the long-term average of the slant-path rain attenuation at a given location, the following parameters are required:
>
> R_p: the point rainfall rate for the location at 0.01% of the year (mm/h)
>
> h_o: the height above mean sea level of the earth station (km)
>
> θ : the elevation angle (degrees)
>
> ϕ : the latitude of the earth station (degrees).
>
> The method consists of the following steps:
>
> 1. The rain height, h_R, is obtained from (see Report 563-2):
>
> $$h_R = \rho_p \left(5.1 - 2.15 \log \left(1 + 10^{\left(\frac{\phi - 27}{25}\right)}\right)\right) \quad \text{km} \qquad (1)$$
>
> where the empirical height reduction factor, ρ_p, is given by:
>
> $$\begin{aligned} \rho_p &= 0.6 & \phi &\le 20^\circ \\ \rho_p &= 0.6 + 0.2\,(\phi - 20) & 20^\circ \le \phi &\le 40^\circ \qquad (1a) \\ \rho_p &= 1.0 & 40^\circ &\le \phi \end{aligned}$$
>
> 2. The slant-path length, L_S, below the rain height is obtained from:
>
> $$L_S = \frac{2(h_R - h_o)}{(\sin^2\theta + 2(h_R - h_o)/R_e)^{1/2} + \sin\theta} \quad \text{(km)} \qquad (2)$$

where R_e is the effective radius of the Earth (8,500 km). For $\theta \geq 10°$, equation (2) may be simplified to:

$$L_S = \frac{2(h_R - h_o)}{\sin \theta} \quad \text{(km)} \tag{3}$$

3. The horizontal projection, L_G, of the slant-path length is found from (see Fig. 3-3):

$$L_G = L_S \cos \theta \quad \text{(km)} \tag{4}$$

4. The reduction factor, r_p, for 0.01% of the time is calculated from:

$$r_p = \frac{90}{90 + 4L_G} \tag{5}$$

5. Obtain the rain intensity exceeded for 0.01% of an average year from the maps of rain climates given in Fig. 3-2 and the corresponding rain rate values given by Table 3-2.

6. Obtain the specific attenuation, γ_R (dB/km), from

$$\gamma_R = k(R_p)^{\alpha} \text{ (dB/km)} \tag{6}$$

The attenuation coefficients, k and α, for the broadcasting-satellite service and feeder link frequencies of interest are:

	Horizontal Polarization		Vertical Polarization	
	k_H	α_H	k_V	α_V
12.5 GHz	0.0212	1.21	0.0192	1.19
17.5 GHz	0.0539	1.12	0.0502	1.10

For other polarizations, the coefficients in equation (6) can be calculated from the k_H, k_V, α_H and α_V values by the approximate equations:

$$k = [k_H + k_V + (k_H - k_V) \cos^2\theta \cos 2\tau]/2 \quad (6a)$$

$$\alpha = [k_H \alpha_H + k_V\alpha_V + (k_H\alpha_H - k_V\alpha_V) \cos^2\theta \cos 2\tau]/(2k) \quad (6b)$$

where θ is the path elevation angle and τ is the polarization tilt angle relative to the horizontal (τ = 45° for circular polarization).

(For other frequencies, refer to Table I of Report 721-1 for attenuation coefficient values.)

7. The attenuation exceeded for 0.01% of an average year may then be obtained from:

$$A_{0.01} = \gamma_R L_s r_p (dB) \quad (7)$$

8. The attenuation to be exceeded for other percentages of an average year, p, in the range 0.001% to 1%, may be estimated from the attenuation to be exceeded for 0.01% of an average year by using:

$$A_p = c\, A_{0.01}(p/0.01)^{-a}$$

where

$$c = 1 \text{ and } a = 0.33 \text{ for } 0.001 \leq p \leq 0.01 \quad (8)$$
$$c = 1 \text{ and } a = 0.41 \text{ for } 0.01 \leq p \leq 0.1$$
$$c = 1.3 \text{ and } a = 0.50 \text{ for } 0.1 \leq p \leq 1.0$$

* * * * * * *

System planning often requires the attenuation value, exceeded for the time percentage p_w of the "worst month."

Using the following approximate relation (see § 5 of Report 723), the corresponding annual time percentage, p, may be obtained:

$$p = 0.29\, p_w^{1.15}\ (\%) \quad (9)$$

The attenuation exceeded for this annual time percentage, p, calculated in step (e) or (f) (see § 3.2.3.1 above), may then be taken as the attenuation value exceeded for p_w % of the worst month.

* * * * * * *

Rain attenuation and rain depolarization may be related below 30 GHZ by the equation:

$$XPD = U - V \log (CPA) \quad dB \tag{10}$$

where:

XPD: cross-polarization discrimination

CPA: co-polar attenuation (use circular polarized CPA for both linear and circular polarized XPD calculations)

$$U = \kappa^2 - 10 \log 1/2 \, [1 - \cos(4\tau) \exp(-\kappa_m^2)] + 30 \log (f) - 40 \log (\cos \varepsilon) \tag{11}$$

$$V = 20 \text{ for } 8 \leq f \leq 15 \tag{12}$$
$$= 23 \text{ for } 15 \leq f \leq 35$$

where

f : the frequency in GHz with $8 \leq f \leq 35$

ε : the angle of elevation in degrees with $10 \leq \varepsilon \leq 60$ (for values of $\varepsilon > 60$, the value of 60 should be used in (11))

τ : the polarization tilt angle with respect to horizontal (for circular polarization $\tau = 45°$)

The terms κ and κ_m relate to the effective parameters of the rain-drop canting angle in degrees. Conservative values of $\kappa = 0$

and κ_m = 0.25° are recommended at present, and this gives a maximum improvement of 15 dB in XPD for τ = 0° or τ = 90° for linear as compared with circular polarization. Higher improvements have been observed (see Report 722-1). It should be noted that the second factor in expression (11) above gives a direct prediction of the improvement of linear with respect to circular polarization in terms of XPD.

The Final Acts of the RARC (ITU, 1983) give, as the rain attenuation A_p of circularly polarized signals exceeding for 1% of the worst month at 12.5 GHz,

$$A_p = 0.21\ \gamma Lr.$$

From Equations (7), (8), and (9) of the CPM report given above, we have

$$A_p = 0.2414\ \gamma Lr.$$

Therefore, A_p (expressed in decibels) in the RARC model is 13% less than that in the CPM model. Since no data are given for the percentage values other than p = 0.29 (i.e., p_w = 1.0) in the Final Acts, we use as the c value in (8) the c values that are 13% less than those given right below (8) in the CPM report.

The Final Acts of the RARC (ITU, 1983) give a simplified expression for XPD, which is obtained by equating κ_m to zero and θ to 45° in Equations (10) through (12) in the CPM report. In GSOAP, however, we use the κ_m value recommended in the CPM report (i.e., κ_m = 0.25), since the use of κ_m = 0 would result in an infinite XPD value for τ = 0 or 90° for a linearly polarized signal. For τ = 45°, the XPD value calculated with κ_m = 0.25 differs from the value calculated with κ_m = 0 by less than 0.2 dB.

To implement this model in GSOAP, we have processed the world rain-zone map in the same manner as for the CCIR model. We have read the rain-zone indices at all grid points of 3° intervals both in longitude and latitude from the world rain-zone map. We have converted the alphabetic indices A through P (excluding I and O) into the numerical indices 1 through 14 and stored the numerical index values in a data file. We calculate the rain-zone index for a given earth point by finding the square in the 3° grid that includes the earth point, by interpolating the index value from the index values at the four corners of the square with a bilinear interpolation formula with respect to the longitude and latitude, and by taking the nearest integer to the interpolated result.

Since GSOAP must cover a wide range of frequencies, use of the attenuation coefficients, k and α, given for 12.5 GHz and 17.5 GHz only is not appropriate. Instead, we have included all k_H, k_V, α_H, and α_V, values given in Table I of CCIR Report 721-1 and provided a linear interpolation procedure (on a logarithmic scale of the frequency) for an arbitrary frequency value.

For a circularly polarized radio wave, the polarization tilt angle of the radio wave used for calculating the rain-induced depolarization is set to 45°, as noted in the source document. For a linearly polarized radio wave, it is calculated with the method described by Akima (1984).

3.4. Gaseous Absorption Model

A model for calculating the gaseous absorption by atmospheric water vapor and oxygen is described in CCIR Report 719-1 (CCIR, 1982a). Excerpts from Sections 2 and 3 of the CCIR Report follow.

> 2.1 The calculation of the specific absorption produced by either the oxygen or water vapour components of the gaseous atmosphere is complex, requiring computer evaluation for each value of temperature, pressure and water vapour concentration. Approximate techniques can however be employed for practical application.
>
> One technique is to employ an approximation based on the Van Vleck-Weisskopf line shape profile with coefficients adjusted to fit the computer calculations. This led to the following formulae, valid at a temperature 20°C at ground level:

$$\gamma_o = \left[\frac{6.6}{f^2 + 0.33} + \frac{9}{(f - 57)^2 + 1.96}\right] f^2\, 10^{-3} \quad \text{dB/km} \qquad (2a)$$

for f < 57 GHz

$$\gamma_o = 14.9 \quad \text{dB/km} \qquad \text{for } 57 < f < 63 \text{ GHz} \qquad (2b)$$

$$\gamma_o = \left[\frac{4.13}{(f - 63)^2 + 1.1} + \frac{0.19}{(f - 118.7)^2 + 2}\right] f^2\, 10^{-3} \text{ dB/km} \qquad (2c)$$

for f < 350 GHz

It should be noted that the formula (2b) is very approximate, due to the many oxygen lines in this spectrum region.

$$\gamma_w = \left[0.067 + \frac{2.4}{(f - 22.3)^2 + 6.6} + \frac{7.33}{(f - 183.5)^2 + 5} + \frac{4.4}{(f - 323.8)^2 + 10}\right] f^2 \rho \, 10^{-4} \quad \text{dB/km} \qquad (3)$$

for f < 350 GHz

where f is the frequency expressed in GHz, and ρ is the water vapour density expressed in g/m^3.

The attenuation values obtained by using formulae (2) and (3) have been included in Fig. 2. For water vapour, a value of 7.5 g/m^3 was selected, which represents 1% of water vapour molecules mixed with 99% of dry air molecules. It may be noted that this value corresponds, for example, to ground level, at 50% humidity with a temperature of 16.5° or 75% humidity for a temperature of 10°.

*   *   *   *   *   *   *

3.2.1 For an inclined path or an Earth-space path, the expression must be integrated through the atmosphere to obtain the total path attenuation.

A first order approximation is to use the concept of equivalent heights for oxygen and water vapour components. In Europe these equivalent heights may be approximated by 8 km for oxygen and 2 km for water vapour. Moreover, we can adopt a "cosecant law" for elevation angles θ greater than 10°. Hence the total attenuation A_α is given by the relation:

$$A_\alpha = \frac{8\gamma_o + 2\gamma_w}{\sin \theta} \quad \text{dB} \qquad (6a)$$

For elevation angles less than 10°, the cosecant law must be replaced by a more accurate formula allowing for the real length of the atmospheric path. This leads to the following relation:

$$A_\alpha = \frac{16\gamma_o}{\sqrt{\sin^2\theta + \frac{16}{R}} + \sin\theta} + \frac{4\gamma_w}{\sqrt{\sin^2\theta + \frac{4}{R}} + \sin\theta} \qquad (6b)$$

R being the effective earth radius including refraction, given in Report 718, expressed in km (a value of 8500 km is generally acceptable).

We have implemented the method in GSOAP with two slight modifications: first, the way of implementing Equation (3) given above and, second, the inclusion of the elevation (or altitude) of the earth point.

Because the last three terms in the brackets in Equation (3) are essentially nonoverlapping, we divide the whole frequency range into three narrower ranges in applying the equation. We use the first and second terms for $f \leq 100$ GHz, the first and third terms for $100 \leq f \leq 260$ GHz, and the first and fourth terms for $f \geq 260$ GHz.

Equations (6a) and (6b) give the earth-space path absorption assuming the earth point at sea level. We take a simple approximation to include the elevation of the earth point in these equations by subtracting the elevation from the equivalent heights of 8 km for oxygen and 2 km for water vapor. (When the elevation of the earth point exceeds the equivalent heights, we assume that no absorption will take place.)

4. NORMALIZED RECEIVED POWER

We use the concept of normalized received power in GSOAP. The normalized received power is defined as the power received by the receiving antenna calculated with the EIRP (equivalent isotropically radiated power) of the transmitting station of 1 W or 0 dBW. It is expressed as the combined relative antenna gain (relative to the sum of the copolar on-axis gains of the two antennas) plus the copolar on-axis gain of the receiving antenna less the copolar transmission loss.

To represent the normalized received power in this section, we use a lower-case character for a variable expressed as a power ratio and the corresponding upper-case character for the same variable expressed in decibels. We use the following symbols:

A = copolar rain attenuation (in dB),
g = antenna gain relative to the copolar on-axis gain (as a power ratio),
G = antenna gain relative to the copolar on-axis gain (in dB),
G_0 = copolar on-axis gain of the receiving antenna (in dBi),
L = transmission loss under clear-sky conditions (in dB),
P = normalized received power (in dB),
x = crosspolarization discrimination (as a power ratio),
$\Delta\beta$ = relative alignment angle of the earth-station and satellite antennas.

We use a pair of subscripts, cs and rs, to indicate the clear-sky and rainy-sky conditions, respectively. We use a pair of subscripts, cp and xp, to denote the copolar and crosspolar components of antennas; an antenna gain without cp or xp is an effective antenna gain including both the copolar and crosspolar components. We use a pair of subscripts, e and s, for the earth-station and satellite antennas; an antenna gain without e or s is a combined antenna gain.

Under clear-sky and rainy-sky conditions, the normalized received power is expressed by

$$P_{cs} = G_{cs} + G_0 - L,$$

$$P_{rs} = G_{rs} + G_0 - L - A,$$

respectively. Descriptions of each of the terms in these expressions follow.

Combined Relative Antenna Gain

In general, a transmitting antenna produces both a copolar component and a crosspolar component, and a receiving antenna responds to both components. Under rainy-sky conditions, an additional crosspolar component is produced when the radio wave passes through the rainy atmosphere. Some components add up in voltage (or coherently), while others add up in power (or in random phases).

The combined relative antenna gain under clear-sky and rainy-sky conditions, g_{cs} and g_{rs}, respectively, are expressed by

$$g_{cs} = g_{cs,cp}\cos^2(\Delta\beta) + g_{cs,xp}\sin^2(\Delta\beta),$$

$$g_{rs} = g_{rs,cp}\cos^2(\Delta\beta) + g_{rs,xp}\sin^2(\Delta\beta).$$

If we assume power additions, the four component gains are expressed by

$$g_{cs,cp} = g_{e,cp}g_{s,cp} + g_{e,xp}g_{s,xp},$$

$$g_{cs,xp} = g_{e,cp}g_{s,xp} + g_{e,xp}g_{s,cp},$$

$$g_{rs,cp} = g_{cs,cp} + g_{cs,xp}/X,$$

$$g_{rs,xp} = g_{cs,xp} + g_{cs,cp}/X.$$

GSOAP implements, in addition to these expressions based on power additions, the following five combinations as user options:

(1) a voltage addition in the calculation of $g_{cs,xp}$ used in the expression of g_{cs} and $g_{rs,xp}$, and power additions otherwise (that means recalculation of $g_{cs,xp}$ for use in the calculation of $g_{rs,cp}$), as described in the CPM report (CCIR, 1982b);

(2) voltage additions in the expressions of $g_{cs,cp}$ and $g_{cs,xp}$, and power additions otherwise;

(3) voltage additions in the expressions of $g_{rs,cp}$ and $g_{rs,xp}$, and power additions otherwise;

(4) exclusive use of voltage additions; and

(5) copolar components only (i.e., all crosspolar components are set to zero).

Conversion of any of the above four expressions from power addition to voltage addition is done by taking the square roots of the right-hand-side terms before addition and taking the square of the sum after addition.

Relative Alignment Angle

The relative alignment angle, $\Delta\beta$, in the above expressions for g_{cs} and g_{rs} is the difference in the polarization angle between the projections of the polarization vectors of the transmitting and receiving antennas in a plane normal to the path between the two antennas. When both antennas are circularly polarized, the relative alignment angle is either 0° or 90° depending on whether the polarizations of both antennas are the same or opposite. When one antenna is circularly polarized and the other is linearly polarized, the relative alignment angle is set to 45°. When both antennas are linearly polarized, we calculate the polarization angles of the polarization vectors of the two antennas with the method described by Akima (1984).

Relative Gains of Individual Antennas

The relative copolar and crosspolar gains of earth-station and satellite antennas, $g_{e,cp}$, $g_{e,xp}$, $g_{s,cp}$, and $g_{s,xp}$, are calculated with the gain patterns given in Section 2 of this report. Calculations of the antenna gains with these gain patterns require the off-axis angle as the input data except for the satellite antenna polygon and shaped-beam patterns. The off-axis angle is calculated by

$$\phi = \cos^{-1}[p/(d_1 d_2)],$$

$$p = (x_1-x_0)(x_2-x_0) + (y_1-y_0)(y_2-y_0) + (z_1-z_0)(z_2-z_0),$$

$$d_1 = [(x_1-x_0)^2 + (y_1-y_0)^2 + (z_1-z_0)^2]^{1/2},$$

$$d_2 = [(x_2-x_0)^2 + (y_2-y_0)^2 + (z_2-z_0)^2]^{1/2},$$

where x, y, and z are the coordinates of the earth or satellite point in an arbitrary Cartesian coordinate system. As such a coordinate system, we use the earth-center coordinate system described in Appendix B to this report. For an earth-station antenna, three subscripts, 0, 1, and 2, are for the earth point, the wanted satellite point, and the unwanted (interfering or interfered with) satellite point, respectively. For a satellite antenna, the roles of the earth and satellite points are reversed; three subscripts, 0, 1, and 2, are for the satellite point, the wanted earth point, and the unwanted earth point, respectively.

The 3-dB beamwidth of the elliptical-beam satellite antenna used for calculating the antenna gain in the direction of the earth point, ϕ_0, is calculated by

$$\phi_0 = \{[(\cos \delta)/\phi_a]^2 + [(\sin \delta)/\phi_b]^2\}^{-1/2},$$

where ϕ_a and ϕ_b are the major-axis and minor-axis beamwidths of the elliptical-beam antenna, and δ is the difference in the orientation angle between the earth point and the major axis of the elliptical beam. For a given service area, the three antenna parameters, the major-axis and minor-axis beamwidths and the orientation angle of the major axis relative to a line parallel to the equatorial plane, of the minimum elliptical-beam antenna can be calculated with the method developed by Akima (1981). The orientation angle of an earth point relative to a line parallel to the equatorial plane at the aim point of an ellipticalbeam satellite antenna is calculated with the method described in Appendix B to this report.

Angle Between an Earth Point and a Polygon

Calculation of the gain of a satellite antenna with the polygon or shaped-beam pattern requires calculation of the angle between an earth point and a polygon seen from the satellite, that is the minimum angle seen from the satellite between an earth point and a point on the sides of the polygon. Rigorous calculation of the angle consists of the following four steps: (1) Coordinate transformation of the earth point to the coordinate system having, as a coordinate plane, the plane in which the polygon is represented; (2) selection, on the sides of the polygon, of the point that is closest to the earth point; (3) coordinate transformation of the two points (i.e., the given earth point and the closest point) to a Cartesian coordinate system, unless the coordinate system in which the polygon is represented is Cartesian; and (4) calculation of the angle between the two points seen from the satellite with the formulas for calculating the off-axis angle given above.

In all the polygon and shaped-beam patterns currently included in GSOAP, a polygon is represented in the angle coordinate system in which the first and second coordinates are the "pitch" and "roll" angles, respectively, i.e., the angles in the east and north directions measured from the line connecting the satellite to its subsatellite point. (The subsatellite point of a satellite is an earth point due beneath the satellite.) Coordinate transformation of the earth point from the earth center coordinate system to the angle coordinate system can be done in the following two steps: (1) coordinate transformation to the subsatellite-point coordinate system in which the coordinate plane with the first and second axes is tangent to the earth surface at the subsatellite point, the first axis lies in the equatorial plane of the earth, and the third axis points toward the satellite; and (2) calculation of the arctangent angles of the ratios of the first and second coordinates of the earth point to the third coordinate of the satellite. (The subsatellite-point coordinate system is a special case of the equatorial-plane coordinate system described in Appendix B to this report.) Since the calculation of the arctangent is involved in the second step, the angle coordinate system is not Cartesian. Rigorously speaking, therefore, step (3) in the preceding paragraph cannot be spared.

For simplicity, however, we skip step (3) in our calculation. In other words, we calculate the distance between the two points in the coordinate plane of the angle coordinate system in which the polygon is represented and use this distance as the angle between the earth point and the polygon seen from the satellite. This approximation generally results in an overestimation of the angle, but the error stemming from this approximation is not considered significant. The error is estimated not to exceed 0.08°, which is considered negligible in practice if we consider the coding process of the polygons from the graphically given gain contours.

Rain Attenuation and Crosspolar Discrimination

The copolar rain attenuation, A, and crosspolarization discrimination, X, are calculated with the method described in Section 3 of this report. These calculations require, as the input data, the polarization angle of the radio wave and the elevation angle of the satellite seen from the earth point. When the transmitting antenna is circularly polarized, an angle of 45° is used as the polarization angle of the radio wave. When the transmitting antenna is linearly polarized, the polarization angle of the radio wave is calculated with the method described by Akima (1984). The elevation angle of a satellite seen from an earth point is calculated by

$$\varepsilon = 90° - \cos^{-1}[(p/(rd)],$$

$$p = x_e(x_s-x_e) + y_e(y_s-y_e) + z_e(z_s-z_e),$$

$$r = (x_e{}^2 + y_e{}^2 + z_e{}^2)^{1/2},$$

$$d = [(x_s-x_e)^2 + (y_s-y_e)^2 + (z_s-z_e)^2]^{1/2},$$

where x, y, and z are the coordinates of the earth or satellite point in an arbitrary Cartesian coordinate system having its origin at the center of the Earth. As such a coordinate system, we use the earth-center coordinate system described in Appendix B to this report.

Transmission Loss Under Clear-Sky Conditions

The transmission loss under clear-sky conditions, L, is calculated by

$$L = 20 \log (4\pi d/\lambda)$$
$$= 20 \log (4\pi d/(c_0/f)),$$

where d is the distance between the earth point and satellite, λ is the wavelength of the radio wave, c_0 is the velocity of light in a vacuum, and f is the frequency of the radio wave. The distance, d, is calculated by the same formula as given above for the calculation of the elevation angle.

Universal Constants

As the velocity of light, the radius of the Earth, and the radius of the geostationary satellite orbit, we use the following values

$$c_0 = 2.9979 \times 10^8 \text{ m/s},$$
$$r_e = 6378.2 \text{ km},$$
$$r_s = 42164.0 \text{ km},$$

throughout GSOAP.

5. CARRIER-TO-INTERFERENCE RATIOS (CIR'S)

We describe the method for calculating the CIR (carrier-to-interference ratio) value that is exceeded for all except a small percent of the time. How to treat the NRP's (normalized received powers) of the wanted and interfering radio waves under clear-sky and rainy-sky conditions is a problem. Calculation of the CIR for each transponder is another problem.

We begin with the case where each satellite has a single transponder and the transponders of all satellites are identical in the center frequency and bandwidth. After addressing the first problem with this rather simple case, we consider a more general case where each satellite has a number of transponders. Calculation of CIR's in the single-transponder and multiple-transponder cases are discussed in Subsections 5.1 and 5.2, respectively.

In this section, we use the following upper-case symbols:

E = EIRP (equivalent isotropically radiated power) at a transmitting antenna (in dBW),

P = NRP (normalized received power) at a receiving antenna (in dB),

R = CIR (carrier-to-interference ratio) (in dB),

$W = E + P$ (received power) (in dBW).

We use the lower-case symbols corresponding to these upper-case symbols to denote the same quantities represented as a power in watts or as a power ratio.

We use a pair of subscripts, cs and rs, to denote the clear-sky and rainy-sky conditions, respectively. We also use subscript 0 for the wanted carrier or radio wave, and subscripts i, $i = 1, 2, \ldots, n$, for interferers, where n is the number of interferers. We use another subscript, t, for the total interference.

5.1. Single-Transponder Case

In this case the CIR is calculated by simple additions and subtractions among the EIRP's and NRP's. Since weather affects the radio waves only near the earth point, the CIR calculation for a downlink case where only one earth point is involved is different from that for an uplink case where two earth points are involved.

Downlink Case

We begin with a single-entry CIR, i.e., the ratio of the wanted carrier power to the power of an interferer. As a single-entry CIR between the wanted carrier and the ith interferer, we can, in general, calculate the following four ratios

$$r_{i,cs,cs} = w_{0,cs}/w_{i,cs},$$

$$r_{i,cs,rs} = w_{0,cs}/w_{i,rs},$$

$$r_{i,rs,cs} = w_{0,rs}/w_{i,cs},$$

$$r_{i,rs,rs} = w_{0,rs}/w_{i,rs},$$

where

$$W_{0,cs} = E_0 + P_{0,cs},$$

$$W_{0,rs} = E_0 + P_{0,rs},$$

$$W_{i,cs} = E_i + P_{i,cs},$$

$$W_{i,rs} = E_i + P_{i,rs}.$$

In the downlink case, however, we exclude the second and third ratio (i.e., $r_{i,cs,rs}$ and $r_{i,rs,cs}$), since both the wanted carrier and interferer are received at an earth point under identical weather conditions. Selection of the right value out of the first and the last ratios (i.e., $r_{i,cs,cs}$ and $r_{i,rs,rs}$) requires a close examination of the two ratios, as follows.

When the elevation angle of the ith interfering satellite is greater than that of the wanted satellite, as illustrated in the upper half of Figure 1, the wanted radio wave suffers more from rain attenuation than does the interfering radio wave, and we have

$$r_{i,rs,rs} < r_{i,cs,cs}.$$

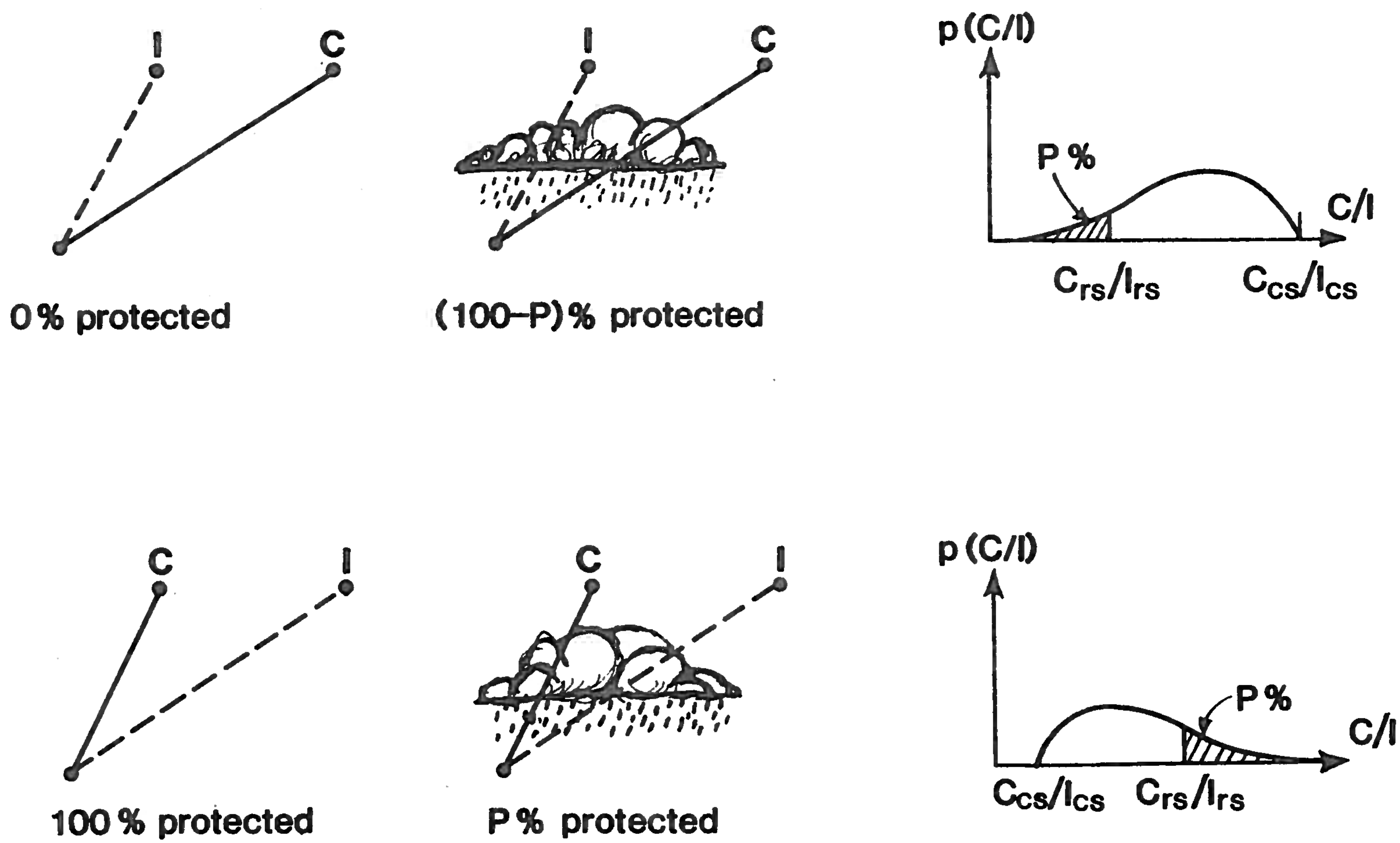

Figure 1. CIR calculation--downlink case.

Ratio $r_{i,rs,rs}$ represents the level below which the CIR does not fall for more than the specified small percent (say, 0.1 %) of the time or the level that is exceeded for most of the time (say, 99.9%); this ratio is the CIR needed for the analysis of use of the geostationary satellite orbit. The other ratio $r_{i,cs,cs}$ represents the level which is never exceeded or the level below which the CIR always falls; this ratio is not meaningful for the analysis. In this case, therefore, we use $r_{i,rs,rs}$, which happens to be the smaller of the two ratios.

When the elevation angle of the ith interfering satellite is smaller than that of the wanted satellite, as illustrated in the lower half of Figure 1, on the other hand, the interfering radio wave suffers more from rain attenuation than does the wanted radio wave, and we have

$$r_{i,cs,cs} < r_{i,rs,rs}.$$

Ratio $r_{i,cs,cs}$ represents the level below which the CIR never falls or the level that is always exceeded; this ratio is useful since it is considered to be very close to the level below which the CIR does not fall for more than the specified small percent (say, 0.1%) of the time. The other ratio $r_{i,rs,rs}$ represents the level that is exceeded for the specified small percent (say 0.1%) of the time or the level below which the CIR falls for most of the time (say 99.9%); this ratio is meaningless for the analysis. In this case, therefore, we use $r_{i,cs,cs}$, which is again the smaller of the two ratios.

Summarizing the preceding three paragraphs, we define the representative value of the single-entry CIR by

$$R_i = \min \{R_{i,cs,cs}, R_{i,rs,rs}\},$$

where symbol min {...} represents "the minimum of" the quantities enclosed in the braces. We consider that the single-entry CIR does not fall below R_i for more than the specified small percent of the time regardless of the relative elevation angles of the two satellites.

Extension of the above result for the single-entry CIR to the expression of the total CIR is straightforward. We define the representative value of the total CIR by

$$R_t = \min \{R_{t,cs,cs}, R_{t,rs,rs}\},$$

where

$$r_{t,cs,cs} = w_{0,cs}/(\sum_i w_{i,cs}),$$

$$r_{t,rs,rs} = w_{0,rs}/(\sum_i w_{i,rs}),$$

and where the summations, Σ's, are over all interferers. We consider that the total CIR does not fall below R_t for more than the specified small percent of the time regardless of the relative elevation angles of the satellites involved.

Unless the elevation angles of all interfering satellites are smaller than the elevation angle of the wanted satellite, we must calculate $R_{t,cs,cs}$ and $R_{t,rs,rs}$ and compare them. In general, therefore, we must calculate the $W_{i,rs}$'s over all interfering downlink paths.

Uplink Case

Each radio wave suffers from rain attenuation at each earth point in an uplink case. The lowest CIR value occurs when the wanted path is rainy and all interfering paths are clear as illustrated in Figure 2. Therefore, if we define the representative values of single-entry and total CIR's by

$$r_i = w_{0,rs}/w_{i,cs},$$

$$r_t = w_{0,rs}/(\sum_i w_{i,cs}),$$

where the summation, Σ, is over all interferers, neither the single-entry CIR nor the total CIR falls below R_i and R_t for more than the specified percent of the time. Calculation of the $W_{i,rs}$'s is not needed here.

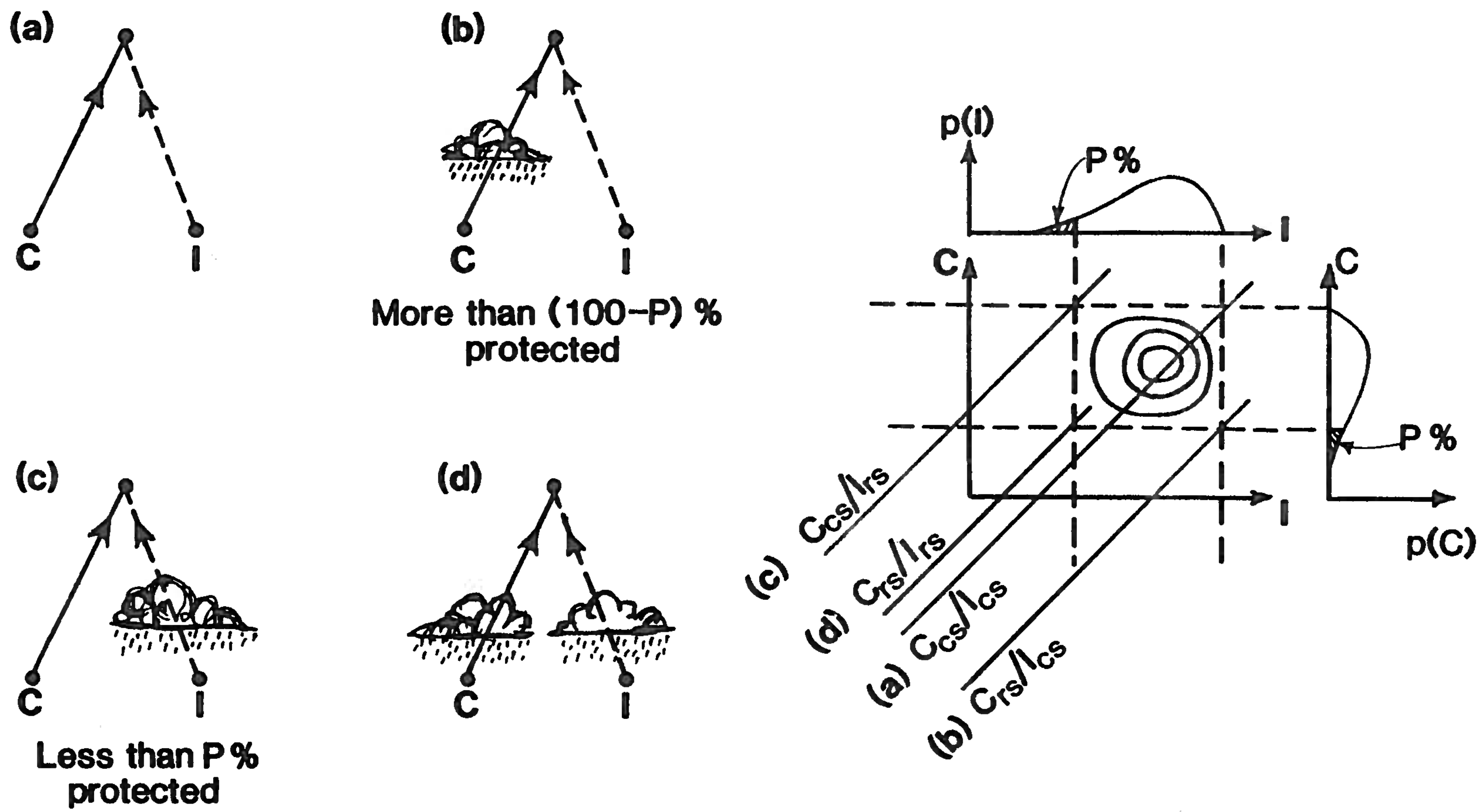

Figure 2. CIR calculation--uplink case.

5.2. Multiple-Transponder Case

When each satellite has a number of transponders, one must calculate the CIR for each transponder signal (i.e., for the signal intended for or from each transponder) of a wanted satellite, unless all satellites have an identical transponder arrangement. To do this calculation, we modify the expressions for R_i and R_t given for the single-transponder case in the preceding subsection to include the ratio of the portion of the interfering transponder signal power intercepted by the receiver of the wanted transponder signal to total interfering transponder signal power. Each interfering signal power, $w_{i,cs}$ or $w_{i,rs}$, in the expressions in the preceding subsection must be multiplied by this ratio in the multiple-transponder case.

Rigorous calculation of this ratio requires a knowledge of power spectrum shape for the interfering transponder signal as well as the pass-band shape of the receiver for the wanted transponder signal. Currently, GSOAP uses an approximation that obviates the necessity for such knowledge. We assume that, for the signal passing through each transponder, the shapes of both the signal spectrum and receiver pass band are rectangular and their bandwidths are identical. Then, when an interfering transponder overlaps with the wanted transponder in frequencies, the ratio in question is calculated simply as

$$[\min \{f_{0u}, f_{iu}\} - \max \{f_{0\ell}, f_{i\ell}\}]/(f_{iu} - f_{i\ell}),$$

where $f_{0\ell}$ and f_{0u} are the lower and upper bound frequencies of the wanted transponder and $f_{i\ell}$ and f_{iu} are the lower and upper bound frequencies of the interfering transponder.

6. CONCLUSIONS

The technical basis for calculating the CIR's (carrier-to-interference ratios) in GSOAP (Geostationary Satellite Orbit Analysis Program) are described in this report. Main areas include antenna radiation patterns, radio wave propagation models, calculation of normalized received powers by combining antenna gains and propagation phenomena, and calculation of CIR's from the normalized received powers.

Antenna radiation patterns are described in Section 2. Some 10 antenna patterns are identified from the CCIR, ITU, and FCC documents (CCIR, 1982a; ITU, 1982; ITU, 1983; FCC, 1984). An FSS (fixed-satellite service) earth-station antenna pattern that could replace the earth-station antenna pattern for the feeder link for a broadcasting satellite adopted by the 1983 RARC-BS-R2 (ITU, 1983) has been developed. Two general earth-station antenna patterns with sidelobe suppression have been added. In addition, two new methods have been developed for modeling a shaped-beam satellite antenna pattern; one uses a polygon that approximates a gain contour, and the other uses several gain contours.

Three propagation models for calculating the rain attenuation and rain-induced depolarization of a radio wave are described in Section 3. They are the 1977 WARC-BS model adopted by the 1977 WARC-BS (ITU, 1977) and included in Appendix 30 to the ITU Radio Regulations (ITU, 1982), the CCIR model described in CCIR Report 564-2 (CCIR, 1982a), and the 1983 RARC-BS-R2 model adopted by the 1983 RARC-BS-R2 (ITU, 1983). The way in which the world maps of rain-zone index data presented in the ITU and CCIR documents are coded numerically is also described. In addition, the CCIR model for calculating the gaseous absorption is described.

The method for calculating the normalized received powers is described in Section 4. The method includes calculation of the earth-station and satellite antenna gains, combining of these two antenna gains, calculation of the basic transmission loss in free space, and calculation of the rain attenuation and crosspolar discrimination. Equations for combining the satellite and earth-station antenna gains for a path are given for clear-sky and rainy-sky conditions separately. Although the equations for clear-sky conditions are obtained from those for rainy-sky conditions as a special case of infinite crosspolarization discrimination, they are presented explicitly in this report to eliminate possible confusion and inadvertent errors in the CIR calculations that use the combined antenna gains.

Calculation of CIR's is discussed in Section 5. Two problems are identified for the CIR calculations. The first problem is concerned with the treatment of weather conditions for the wanted and interfering radio waves. It is addressed for the uplink and downlink cases separately. The second problem is concerned with the treatment of multiple transponders on each satellite. For simplicity, rectangular emission spectrum and pass-band shapes with an identical bandwidth are assumed for each transponder.

7. ACKNOWLEDGMENTS

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APPENDIX A. EARTH-STATION ANTENNA PATTERN FOR THE FEEDER LINK FOR A BROADCASTING SATELLITE

In Subsection 2.1 of this report, we have listed two patterns, EFFL83 and EFFM83, as the FSS earth-station antenna patterns for a feeder link to a broadcasting satellite. The former was adopted by the 1983 RARC-BS-R2 (ITU, 1983), supplemented with the information given in the CPM report (CCIR, 1982). The latter has been developed by modifying the former. This appendix explains why the latter had to be developed despite the existence of the former and describes how the latter has been developed. It deals only with the copolar curves of the patterns.

In this appendix, all antenna gains are in absolute values, i.e., relative to the gain of an isotropic antenna (instead of the copolar on-axis gain), expressed in decibels above isotropic (dBi). We use the following symbols:

- D : diameter of the antenna in meters,
- G_c : copolar gain in dBi,
- G_0 : copolar on-axis gain in dBi,
- R : D/λ,
- λ : wavelength of the radio wave in meters,
- ϕ : off-axis angle in degrees.

Note that these symbol definitions are local to this appendix.

We begin with a close look at the EFFL83 pattern. With the above-introduced notations, the copolar curve of the EFFL83 pattern is expressed in five parts as follows:

$$G_c = 8 + 20 \log (R) - 0.0025R^2\phi^2 \quad \text{for } 0 \le \phi \le 0.1000, \qquad \text{(A-1)}$$

$$G_c = 36 - 20 \log (\phi) \quad \text{for } 0.1000 \le \phi \le 0.3128, \qquad \text{(A-2)}$$

$$G_c = 51.3 - 53.2\, \phi^2 \quad \text{for } 0.3128 \le \phi \le 0.5426, \qquad \text{(A-3)}$$

$$G_c = 29 - 25 \log (\phi) \quad \text{for } 0.5426 \le \phi \le 36.3078, \qquad \text{(A-4)}$$

$$G_c = -10 \quad \text{for } 36.3078 \le \phi \qquad \text{(A-5)}$$

Curves for several values of R are plotted in Figure A-1. This figure indicates that the curves are in general discontinuous at $\phi = 0.1°$. (Only for the range of R between 350 and 490, the amount of discontinuity remains within 0.2 dB.) Neither of the source documents (CCIR, 1982; ITU, 1983) explains why the curve must jump up to 56 dBi at 0.1° and follow the straight line expressed by

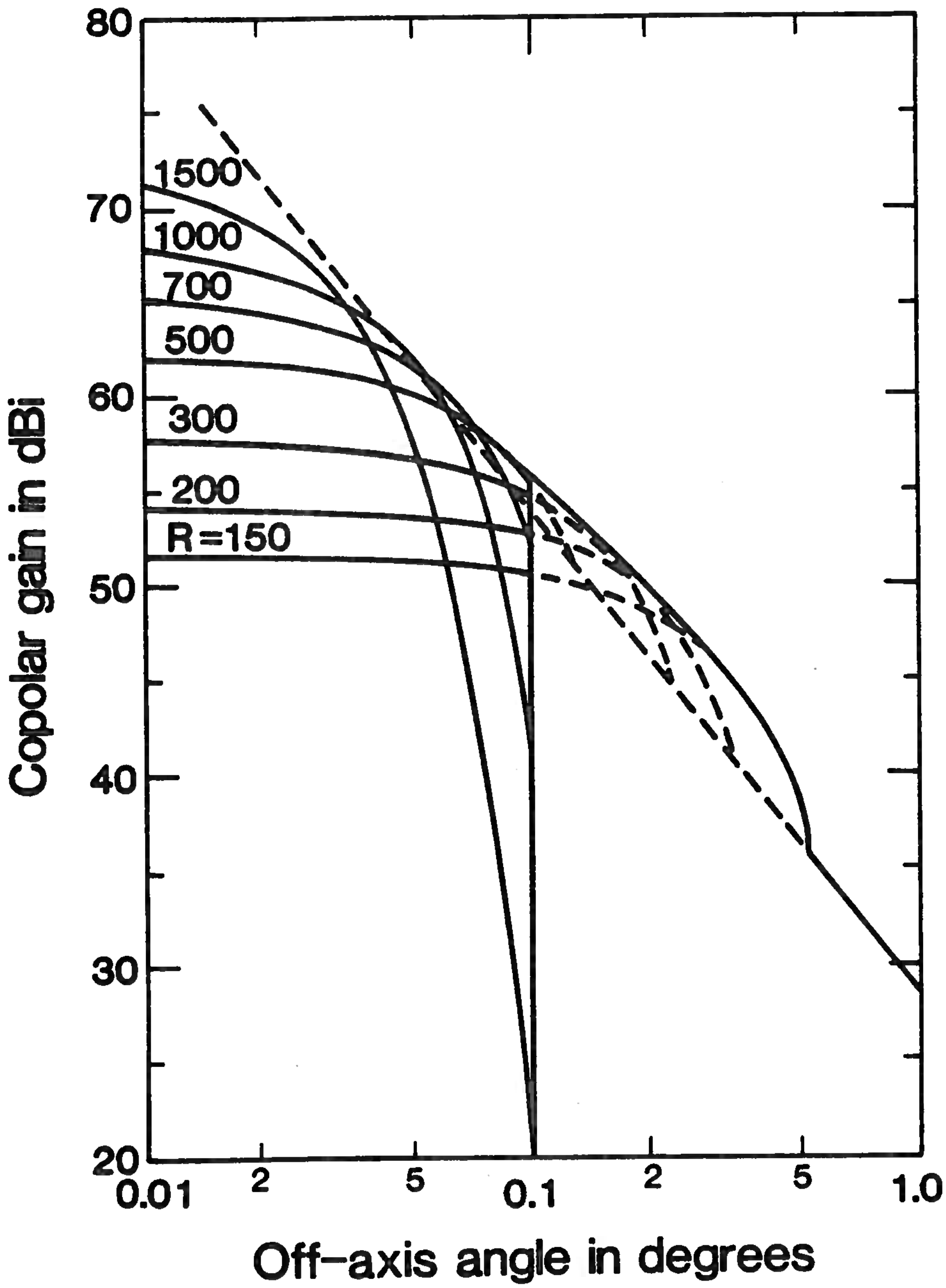

Figure A-1. Copolar gain curves of the FSS earth-station antenna pattern for the feeder link to a broadcasting satellite, adopted by the 1983 RARC-BS-R2.

(A-2), which is a close approximation to the envelope of the main-beam curves expressed by (A-1). The user of the EFFL83 pattern must consider this behavior of the curves.

It seems more natural to extend the main-beam curve expressed by (A-1) beyond $\phi = 0.1°$ until the curve intersects the straight line for the sidelobe expressed by (A-4) for the second time if the curve ever intersects the straight line. This extension is illustrated with the dashed curves in Figure A-1. (When R is greater than a certain value, the curve does not intersect the straight line, as illustrated with the curve for R = 1500 in the figure. We will discuss such a case later.) For the R value not exceeding 1138, the EFFM83 pattern uses equations (A-1), (A-4), and (A-5).

In implementing (A-1) and (A-4) in the EFFM83 pattern, we use a small trick, since it is not very easy to determine the junction point between (A-1) and (A-4). Instead of determining the junction point, we determine a ϕ value, ϕ_s, at which the slope of (A-1) equals the slope of (A-4). We use (A-1) for a ϕ value smaller than ϕ_s and use the maximum of (A-1) and (A-4) for a ϕ value greater than ϕ_s (but smaller than 36.3078). Differentiating (A-1) and (A-4) and equating both derivatives to each other, we obtain

$$-0.005R^2\phi_s = -25M/\phi_s, \qquad \text{(A-6)}$$

where

$$M = \log e = 0.434294482. \qquad \text{(A-7)}$$

From this equation, we can determine the ϕ_s value as

$$\begin{aligned}\phi_s &= (5000M)^{1/2}/R \\ &= 46.5991/R. \qquad \text{(A-8)}\end{aligned}$$

The point on the curve of (A-1) at which the slope of (A-1) equals the slope of (A-4) lies on an equation represented by

$$\begin{aligned}G_c &= 8 + 10 \log (5000M) - 12.5M - 20 \log \phi \\ &= 35.9389 - 20 \log \phi, \qquad \text{(A-9)}\end{aligned}$$

which has been obtained by eliminating R from (A-1) and (A-8).

When R becomes greater than a critical value, R_c, and the corresponding ϕ_s value becomes smaller than a critical value, ϕ_c, the gain represented by (A-9) becomes smaller than (A-4); two curves for (A-1) and (A-4) will not intersect each other in such a case. The critical value for ϕ_s is calculated as

$$\phi_c = 0.04095, \qquad \text{(A-10)}$$

and the critical value for R is calculated as

$$R_c = 1138.0. \qquad \text{(A-11)}$$

When R is greater than R_c, (A-1) and (A-4) do not intersect each other, and we must fill the gap between the two curves.

To fill the gap between (A-1) and (A-4), we determine the envelope for a family of curves represented by (A-1). Differentiating (A-1) with respect to R and equating the derivative to zero, we have

$$\partial G_c/\partial R = 20M/R - 0.005R\phi_e^{\,2} = 0$$

and hence

$$\begin{aligned}\phi_e &= (4000)^{1/2}/R \\ &= 41.6795/R. \end{aligned}\qquad \text{(A-12)}$$

Eliminating R from (A-1) and (A-12), we obtain

$$\begin{aligned}G_c &= 8 + \log\,(4000M) - 10M - 20\log\phi \\ &= 36.0555 - 20\log\phi \end{aligned}\qquad \text{(A-13)}$$

as the equation for the envelope of (A-1).

When R is greater than R_c given in (A-11), we use (A-1) only when ϕ is smaller than ϕ_e given in (A-12). We use (A-4) when ϕ is greater than ϕ_c (but smaller than 36.3078). We fill the gap between ϕ_e and ϕ_c with two segments.

We use the envelope represented by (A-13) when ϕ is greater than ϕ_e but smaller than ϕ_{ec} that is the ϕ_e value corresponding to R_c, i.e.,

$$\begin{aligned}\phi_{ec} &= 41.6795/R_c \\ &= 0.03662. \end{aligned} \quad \text{(A-14)}$$

We use (A-1) with R_c used for R, i.e.,

$$\begin{aligned}G_c &= G_0 - 0.0025R_c^{\,2}\phi^2 \\ &= G_0 - 3237.6\phi^2, \end{aligned} \quad \text{(A-15)}$$

when ϕ is greater than ϕ_{ec} but smaller than ϕ_c.

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APPENDIX B. COORDINATE SYSTEMS FOR THE ANTENNA AND PROPAGATION CALCULATIONS

Three Cartesian coordinate systems are described here. They are the earth-center, equatorial-plane, and local-horizontal coordinate systems. The first one is a reference coordinate system. Angles used in antenna and propagation calculations, such as the off-axis angle orientation angle, polarization angle, etc., are specified or measured in either the second or the third coordinate system. The first one is used for effecting coordinate transformation between a pair of coordinate systems of the second or third type.

Any length can be used as the unit of length as long as it is used consistently in all three coordinate systems. Perhaps the most convenient unit in satellite communications is the radius of the Earth.

Earth-Center Coordinate System

The earth-center coordinate system is a Cartesian coordinate system. The origin is the center of the Earth. The positive x, y, and z axes intersect the surface of the Earth at 0° east and 0° north, at 90° east and 0° north, and at 90° north (i.e., the North Pole), respectively.

In this coordinate system, the three coordinates of a point, x, y, and z, are represented by

$$\begin{aligned} x &= r \cos\theta \cos\phi, \\ y &= r \cos\theta \sin\phi, \\ z &= r \sin\theta, \end{aligned} \qquad \text{(B-1)}$$

where r is the distance between the point in question and the center of the Earth, θ and ϕ are the latitude and longitude of the point. Conversely, r, θ, and ϕ of a point are calculated by

$$\begin{aligned} r &= (x^2 + y^2 + z^2)^{1/2}, \\ \theta &= \tan^{-1}(z/(x^2 + y^2)^{1/2}), \\ \phi &= \tan^{-1}(y/x). \end{aligned} \qquad \text{(B-2)}$$

respectively, when x, y, and z are given for the point.

Equatorial-Plane Coordinate System

The equatorial-plane coordinate system is a Cartesian coordinate system, characterized by two points, a specified earth point (i.e., a point on the surface of the Earth) and a satellite point, and by the equatorial plane of the Earth. The origin is the earth point. The positive z' axis points toward the satellite point. The x' axis is parallel to the equatorial plane of the Earth. As a convention, the sense of the x' axis is taken in such a way that the positive y' axis is on the north side of the z'-x' plane.

In this coordinate system having a specified earth point as the origin, the angle between the vector from the satellite to an arbitrary earth point and the vector from the satellite to the specified earth point is represented by

$$\alpha_e = \tan^{-1}((x_e'^2 + y_e'^2)^{1/2}/(z_s' - z_e')), \qquad \text{(B-3)}$$

where x_e', y_e', and z_e' are the coordinates of the arbitrary earth point, and z_s' is the z' coordinate of the satellite. The orientation angle of an arbitrary earth point relative to the x' axis is represented by

$$\beta_e = \tan^{-1}(y_e'/x_e'). \qquad \text{(B-4)}$$

These angles are useful in calculating the gain pattern of a satellite antenna.

Conversely, when α_e and β_e of an earth point are given, its coordinates, x_e', y_e', and z_e', can also be calculated. If we denote the distance between an earth point (a point on the surface of the earth) and the center of the Earth by r_e, the coordinates must satisfy, in addition to (B-3) and (B-4),

$$(x_e' - x_c')^2 + (y_e' - y_c')^2 + (z_e' - z_c')^2 = r_e^2, \qquad \text{(B-5)}$$

where x_c', y_c', and z_c' are the coordinates of the center of the Earth. Since the origin of the coordinate system is also on the surface of the Earth, we have

$$x_c'^2 + y_c'^2 + z_c'^2 = r_e^2. \qquad \text{(B-6)}$$

With the help of (B-6), we can solve (B-3), (B-4), and (B-5) with respect to x_e', y_e', and z_e'. The results are

$$x'_e = R \sin \alpha_e \cos \beta_e,$$
$$y'_e = R \sin \alpha_e \sin \beta_e, \qquad \text{(B-7)}$$
$$z'_e = z'_s - R \cos \alpha_e,$$

where

$$R = B - (B^2 - C)^{1/2},$$
$$B = (x'_c \cos \beta_e + y'_c \sin \beta_e) \sin \alpha_e + (z'_s - z'_c) \cos \alpha_e, \qquad \text{(B-8)}$$
$$C = (z'_s - z'_c)^2 - z'^2_c.$$

As the expression for R in (B-8) suggests, R has been determined as a root of a quadratic equation. Out of two roots of the quadratic equation, a root that leads to a z'_e value closer to zero has been selected; the other root leads to a more negative z'_e value and corresponds to an earth point that is invisible from the satellite.

The polarization angle of a radio wave is equivalent to the orientation angle mathematically. It is represented by

$$\beta_p = \tan^{-1}(y'_p/x'_p), \qquad \text{(B-9)}$$

where x'_p and y'_p are the x' and y' components of the polarization vector of the radio wave.

This coordinate system is essentially the same as the one called the boresight-point coordinate system and used for calculating the orientation angle of a minimum elliptical beam of a satellite antenna by Akima (1981).

Local-Horizontal Coordinate System

The local-horizontal coordinate system is a Cartesian coordinate system characterized by two points, a specified earth point (i.e., a point on the surface of the earth) and a satellite point, and by the local horizontal plane at the earth point. The origin is the earth point. The positive z' axis points toward the satellite point. The x' axis is parallel to the local horizontal plane at the earth point. As a convention, the sense of the x' axis is taken in such a way that the y' coordinate of the earth center is negative. (When the earth center, the specified earth point, and the satellite point are collinear, the local horizontal plane is normal to the z' axis, and the x' axis is not uniquely determined. In this case, the x' axis is taken, as a convention, in the same way as in the equatorial-plane coordinate system.)

This coordinate system is the same as the equatorial-plane coordinate system except that the x' and y' axis are taken differently. Equations (B-3) through (B-9) hold also for this coordinate system.

Coordinate Transformation

We denote the earth-center coordinates of a point by x, y, and z, and denote the equatorial-plane or local-horizontal coordinates by x', y', and z'. We use subscripts o and s for the specified earth point and the satellite point, respectively. Note that the specified earth point is the origin of the equatorial-plane or local-horizontal coordinate system and that the satellite is on the positive z' axis.

Coordinate transformation from the earth-center coordinates to the equatorial-plane or local-horizontal coordinates is represented by a matrix equation

$$X' = A\,(X - X_o) = AX - AX_o, \tag{B-10}$$

where

$$X = \begin{pmatrix} x \\ y \\ z \end{pmatrix} \tag{B-11}$$

is a three-element column vector containing the earth-center coordinates of a point, where

$$X' = \begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} \tag{B-12}$$

is a three-element column vector containing the new coordinates of the point, and where

$$A = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \qquad \text{(B-13)}$$

is the 3 X 3 matrix of coordinate transformation. Conversely, transformation from the equatorial-plane or local-horizontal coordinates to the earth-center coordinates is represented by

$$X - X_0 = A^{-1}X', \qquad \text{(B-14)}$$

where A^{-1} is the inverse matrix of A.

Since all coordinate systems involved are Cartesian with the same length of unit vectors, the A matrix is orthogonal; the inverse of A is equal to the transpose of A. Therefore, a useful relation

$$A^{-1} = \begin{pmatrix} a_{11} & a_{21} & a_{31} \\ a_{12} & a_{22} & a_{32} \\ a_{13} & a_{23} & a_{33} \end{pmatrix} \qquad \text{(B-15)}$$

is obtained.

Note that each column of A^{-1} or each row of A is the x, y, and z components of the unit vector in the positive direction of the x', y', or x' axis. Also note that each column of A or each row or A^{-1} is the x', y', and z' components of the unit vector in the positive direction of the x, y, or z axis.

Transformation from the Earth-Center Coordinates to the Equatorial-Plane Coordinates

Three elements, a_{31}, a_{32}, and a_{33}, are the x, y, and z components of the unit vector in the positive direction of the z' axis. Since the satellite point is represented by (x_s, y_s, z_s) and by $(0, 0, z_s')$ in the earth-center and the new coordinate systems, respectively, we obtain, from (B-14),

$$\begin{aligned} a_{31} &= (x_s - x_0)/z_s', \\ a_{32} &= (y_s - y_0)/z_s', \\ a_{33} &= (z_s - z_0)/z_s'. \end{aligned} \qquad \text{(B-16)}$$

The z' coordinate of the satellite, z_s', is equal to the distance between the satellite and the origin of the new coordinate system and is represented by

$$z'_s = [(x_s - x_o)^2 + (y_s - y_o)^2 + (z_s - z_o)^2]^{1/2} . \qquad \text{(B-17)}$$

The x' axis of the equatorial-plane coordinate system is parallel to the equatorial plane. This means that

$$z = z_o \text{ when } y' = 0 \text{ and } z' = 0.$$

From (B-14) together with (B-11), (B-12), and (B-15), we have

$$z - z_o = a_{13}x' + a_{23}y' + a_{33}z'.$$

Combining these two relations, we obtain

$$a_{13} = 0. \qquad \text{(B-18)}$$

Three elements, a_{11}, a_{12}, and a_{13}, constitute a unit vector in the positive direction of the x' axis, which is orthogonal to the z' axis. Noting (B-18), therefore, we have

$$a_{31}a_{11} + a_{32}a_{12} = 0,$$

$$a_{11}^2 + a_{12}^2 = 1.$$

Solving this set of equations with respect to a_{11} and a_{12}, we have

$$a_{11} = \mp a_{32}/(a_{31}^2 + a_{32}^2)^{1/2},$$

$$a_{12} = \pm a_{31}/(a_{31}^2 + a_{32}^2)^{1/2}.$$

Since the positive y' axis is taken on the north side of the z'-x' plane, the a_{23} element, which is the z component of the unit vector in the positive direction of the y' axis, must be positive. Since this unit vector is equal to the vector product of the two unit vectors in the positive directions of the z' and x' axes, we have

$$a_{23} = a_{31}a_{12} - a_{32}a_{11} = \pm (a_{31}^2 + a_{32}^2)^{1/2}.$$

Therefore, taking the upper signs in the above expressions for a_{11} and a_{12}, we obtain

$$a_{11} = - a_{32}/(a_{31}^2 + a_{32}^2)^{1/2},$$
$$a_{12} = a_{31}/(a_{31}^2 + a_{32}^2)^{1/2}. \tag{B-19}$$

Finally, since the new coordinate system is a Cartesian system, and since the remaining three elements, a_{21}, a_{22}, and a_{23}, constitute a unit vector in the positive direction of the y' axis, which is the vector product of the two vectors in the positive directions of the z' and x' axis, we have

$$a_{21} = a_{32}a_{13} - a_{33}a_{12},$$
$$a_{22} = a_{33}a_{11} - a_{31}a_{13}, \tag{B-20}$$
$$a_{23} = a_{31}a_{12} - a_{32}a_{11}.$$

Thus, all nine elements of the A matrix have been determined.

Transformation from the Earth-Center Coordinates to the Local-Horizontal Coordinates

The origin and the z' axis in the local-horizontal coordinate system are the same as those in the equatorial-plane coordinates system. Therefore, three elements a_{31}, a_{32}, and a_{33} are determined also by (B-16) and (B-17).

To determine three elements, a_{11}, a_{12}, and a_{13}, we consider three vectors. The first one is the vector from the earth center to the origin of the coordinate system, the second is from the origin of the coordinate system to the satellite, and the third is from the earth center to the satellite. Obviously, the third vector is the sum of the first and the second vectors. Since x' axis is parallel to the local horizontal plane in the local-horizontal coordinate system, it is orthogonal to the first vector. Since it is also orthogonal to the z' axis, which is in the same direction as the second vector, it is also orthogonal to the second vector. It is, therefore, also orthogonal to the third vector. When the earth center, the origin of the coordinate system, and the satellite are not collinear, the vector product of the first and the third vectors is a nonzero vector, and the x' axis is parallel to the vector product. Therefore, three elements, a_{11}, a_{12}, and a_{13}, that constitute a unit vector in the positive direction of the x' axis, are represented by

$$\begin{aligned} a_{11} &= (y_o z_s - z_o y_s)/c, \\ a_{12} &= (z_o x_s - x_o z_s)/c, \\ a_{13} &= (x_o y_s - y_o x_s)/c, \end{aligned} \qquad \text{(B-21)}$$

where c is a constant. Since the three elements constitute a unit vector, c is determined as

$$c = [(y_o z_s - z_o y_s)^2 + (z_o x_s - x_o z_s)^2 + (x_o y_s - y_o x_s)^2]^{1/2} . \qquad \text{(B-22)}$$

Since the positive direction of x' axis is also parallel to the vector product of two unit vectors in the positive directions of the y' and z' axis, both the first vector and the positive y' axis point to the same side of the z'-x' plane. Therefore, the y' coordinate of the earth center is negative. (This reasoning can be verified more directly by calculating the y' coordinate of the earth center after determining the remaining three elements.)

When the earth center, the origin of the coordinate system, and the satellite are collinear, the x' axis cannot be determined by the above procedure. In this case, we take the x' axis in the same way as in the equatorial-plane coordinate system. Therefore, we use (B-18) and (B-19) for the three elements, a_{11}, a_{12}, and a_{13}.

Like the equatorial-plane coordinate system, the local-horizontal coordinate system is also a Cartesian system. Therefore, the remaining three elements, a_{21}, a_{22}, and a_{23}, are determined also by (B-20).

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15. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

The Geostationary Satellite Orbit Analysis Program (GSOAP) is computer software that analyzes system performance and mutual interference of communication satellites using the geostationary satellite orbit. Calculation of the CIR (carrier-to-interference ratio) margins is an essential part of GSOAP. It involves a variety of technical problems, i.e., earth-station and satellite antenna radiation patterns, radio wave propagation models, and related problems such as the polarization angles of linearly polarized emissions, combining of the transmitting and receiving antenna gains, percent of the time for which the CIR is to be protected, and so forth. Various transponder arrangements in the satellites may contribute to the complexity of the calculation. Some of the methods for solving such problems are taken from the ITU (International Telecommunication Union) and CCIR (International Radio Consultative Committee) documents, while others have been developed in the present study. GSOAP is still under development. This report describes the technical basis for GSOAP, Version 2.

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antenna gain pattern; CIR (carrier-to-interference ratio); CIR margin; geostationary satellite orbit; GSOAP (Geostationary Satellite Orbit Analysis Program); radio-wave propagation model

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