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Probability Estimates of Cloud-Obscured Line-of-Sight

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The purpose of this study is to explore the basic relationships between the climatic frequency distribution of sky cover and the frequency and duration of Cloudy-Lines-of-Sight (CLOS) from one or more ground sites to points in space. Through a series of model calculations, estimates are made of the incremental changes in CLOS persistence and recurrence that correspond to changes in the climatic frequency of overcast, broken, scattered and clear sky conditions.

The determination of CLOS recurrence and persistence probability were made using the bivariate normal distribution ~~(see Gringorten, 1972)~~. The analytic stochastic model is based upon the Ornstein-Uhlenbeck class of the simple Markov process. A discussion of the procedures for modeling CLOS behavior is given in a previous report ~~(Hering, 1989)~~.

Model results are presented for CLOS as a function of sky cover and path of sight, CLOS recurrence and persistence probability relative to fixed categories of sky cover, and both single and multiple site CLOS recurrence and persistence probabilities.

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1.0 INTRODUCTION

The purpose of this study is to explore the basic relationships between the climatic frequency distribution of sky cover and the frequency and duration of Cloudy-Lines-of-Sight (CLOS) from one or more ground sites to points in space. The determination of CLOS probability is of particular importance for the assessment of expected downtime of ground-based laser, optical data link and orbital surveillance systems. Through a series of model calculations, estimates are made of the incremental changes in CLOS persistence and recurrence that correspond to changes in the climatic frequency of overcast, broken, scattered and clear sky conditions.

The model calculations of CLOS behavior are of the following type:

a. Given the climatic frequency of sky cover at a selected ground site, what is the likelihood that a path of sight with zenith angle θ

1) will be obscured by clouds?

2) will be obscured by clouds at a particular time and then be obscured by clouds again after time interval t?

3) will be obscured by clouds continuously over time interval t?

b. Given the climatic frequency distribution of sky cover at a group of selected ground sites, what is the joint occurrence frequency and joint persistence probability of CLOS events such as those listed in (1), (2) and (3) above as a function of site separation distance d?

2.0 MODELING PROCEDURES

The determination of CLOS recurrence and persistence probability in this study were made using the bivariate normal distribution (see Gringorten, 1972). The analytic stochastic model is based upon the Ornstein-Uhlenbeck class of the simple Markov process. A discussion of the procedures for modeling CLOS behavior is given in a previous report (Hering, 1989).

Markov model determinations of event probabilities are made through initial conversion of climatic frequency distributions of sky cover into corresponding values of Equivalent Normal Deviate (END). The transformation for any cumulative frequency distribution can be made using standard statistical tables or by computationally fast algorithms.

The fundamental modeling assumption is that the autocorrelation coefficients for sky cover decay exponentially with time or distance. Also, the correlation coefficient for CLOS under fixed sky cover conditions is assumed to decay exponentially with time. The expression for the temporal autocorrelation coefficient is simply

$$\rho_t = \exp(-t/\tau), \tag{1}$$

where t is elapsed time and τ is the preselected relaxation time. The corresponding expression for the spatial autocorrelation coefficient is

$$\rho_d = \exp(-d/D), \tag{2}$$

where d is the site separation distance and D is the input value for the relaxation distance. These correlation functions are used in determining recurrence probabilities.

In this study, nominal input values were used for sky cover relaxation time (16 hours), sky cover relaxation distance (500 mi) and CLOS relaxation time (30 min). The effects of uncertainties in these values will be assessed in association with some of the results as tabulated below.

The modeling procedures (Hering, 1989) are simple and easy to apply. The transformation to the equivalent normal deviate values are exact for any climatic cumulative frequency distribution. Once made, the model estimates of joint event (recurrence) probability are given by a simple regression equation for the bivariate normal distribution as follows:

$$y_t = \rho_t \, y_o + \sqrt{1-\rho_t^2} \; \eta_t \tag{3}$$

where η_t is the END corresponding to the conditional probability $P_r(y \le y_t \mid y_o)$, and y_o and y_t are END equivalents of the cumulative frequency of the initial and final events, respectively. Thus, the expression yields the conditional probability of a weather event following a prescribed initial condition.

The value of y_o in Eq. 3 is defined uniquely for continuous variables by the cumulative frequency distribution at the initial time. For variables expressed only in categories, such as sky cover amount, it is important to subdivide the category probability range into subsets with smaller but equal ranges. The calculations of conditional probability should be carried out in turn using each of the subset midpoints as y_o and the results averaged to yield the composite result for the sky-cover category. Experience shows that division into 6 subsets is sufficient for good results.

A mathematical solution of persistence probability for the bivariate normal distribution is given by Keilson and Ross (1975). Since the computer routine for the formal solution is lengthy, an alternative analytical solution was developed for the CLOS determinations which provides reliable approximation of the formal solution over the desired range of output. The Keilson-Ross solution for the case where the climatic cumulative frequency of the weather event is 50 percent is simply

$$F_o = (1/\pi)\sin^{-1}(\exp -t/\tau) \qquad (4)$$

where F_o is the unconditional probability that $y \leq y_o$ throughout the time interval t.

The solutions for $y_o \neq 0$ in this study were approximated by

$$f_r(y_o) = f(F_o) + y_o\left(1+0.13e^{-0.9\,t/\tau}\right)$$

$$\begin{bmatrix} -2 \leq y_o \leq 2 \\ 0 \leq e^{-0.9\,t/\tau} \leq 3 \end{bmatrix} \qquad (5)$$

where $f_r(y_o)$ is the END corresponding to the probability that $y \leq y_o$ throughout the time interval, $f(F_o)$ is the END of F_o in Eq. 4, and y_o is the unconditional probability of the weather event. In contrast with Eq. 2 for recurrence probability, the persistence expression (Eq. 5) assumes that the climatic frequency of the event remains the same throughout the interval.

The sequence of four steps for the determination of CLOS recurrence and persistence for both single and multiple sites is as follows:

a. calculation of CLOS probability as a function of zenith angle θ and particular category of sky cover amount,

b. calculation of CLOS recurrence and persistence probability as a function of time interval for specific individual categories of sky cover,

c. calculation of sky-cover amount recurrence and persistence probability as a function of time interval, site separation distance, and the climatic frequency distribution of sky cover.

d. given a, b and c, calculation of the recurrence and persistence probability of CLOS at a single site and for simultaneous recurrence and persistence of CLOS at multiple sites as a function of sky-cover frequency distribution, time interval and site separation.

3.0 CLOS AS A FUNCTION OF SKY COVER AND PATH OF SIGHT

The first of many approximations in the modeling process deals with the systematic increase in cloud obscuration as the path of sight shifts from overhead to a direction nearer the horizon in partial sky cover conditions. In this study the Allen and Malick (1983) approximation is used which represents a composite result for all cloud types. The expressions for the probability of a cloud-free line-of-sight $P_r(s, \theta)$ as a function of fractional sky cover, s, and zenith observing angle, θ, are as follows:

$$P_r(s, \theta) = P_s^{(1+b\tan\theta)} \qquad (6)$$

where

$$P_s = 1 - s(1 + 3s)/4, \qquad (7)$$

and

$$b = 0.55 - s/2. \qquad (8)$$

The probability of CLOS is, of course, $1 - P_r(s, \theta)$.

The determinations of CLOS probability in this study were made for a zenith viewing angle of 30 deg. Notice in Fig. 1 that the model approximation for θ = 30 deg represents the overhead portion of the sky dome from zenith down to θ = 50 deg to within a few percentage points over the full range of sky cover.

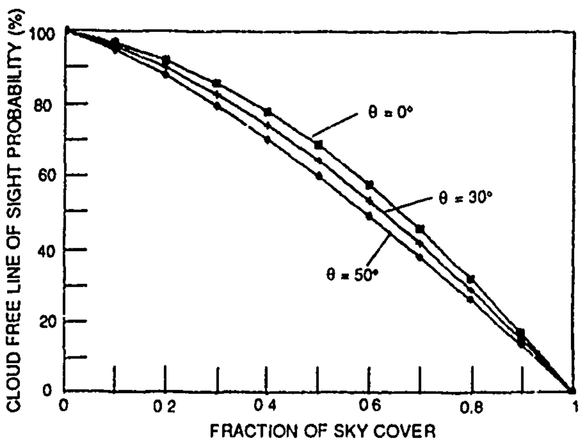

Fig. 1. Probability of a cloud-free line-of-sight as a function of sky-cover calculated using analytic expressions given by Allen and Malick (1983). Values are shown for zenith angles (θ) equal to 0, 30, and 50 deg.

It is important to note that in addition to expected variations with cloud type, Eq. 6 also ignores systematic variations of cloud cover with the azimuth of the path of sight. For example, clouds tend to form and persist over nearby hills during the daytime at particular ground sites, and clouds may be more prevalent over the ocean than land at coastal sites. To the extent that these effects can be defined, they can and should be factored into the modeling process.

4.0 CLOS RECURRENCE AND PERSISTENCE PROBABILITY RELATIVE TO FIXED CATEGORIES OF SKY COVER

Trial calculations of CLOS recurrence and persistence probability were made assuming continuous occurrence of scattered sky cover (1 to 5 tenths), and also for continuous occurrence of broken sky cover (6 to 9 tenths). An even frequency distribution of cloud cover in tenths was assumed within each of the two broad categories, which is commensurate, in general, with detailed climatic summaries of sky cover for individual sites. The determinations based on the broad classes of sky cover were motivated in part by the fact the climatic summaries for many ground sites are limited to overcast, broken, scattered and clear categories. However, the calculations were carried out for the individual subclasses in tenths of sky cover and then summed and averaged to yield the results for the broad sky-cover categories.

Using Eqs. 1, 3 and 6, determinations were made of the frequency that a cloud obscured line of sight at zenith angle 30 deg. (CLOS-30) will occur and then will recur after time interval t for the scattered and for the broken sky cover categories. The results are shown in Fig. 2. A nominal cloud element relaxation time, τ_c, of 30 min was assumed. As discussed in Hering (1989), the value of τ_c is dependent upon the arrangement, size, development and translation speed of the individual clouds visible to the ground observer. The sensitivity of the calculations to variations in assumed relaxation time may be assessed readily by time scale adjustment in Fig. 2. For example from Eq. 1, a change in τ_c from 30 min to 20 min would change 30 min on the abscissa to 20 min, 15 to 10 and so on.

The overall unconditional probability that CLOS-30 will be observed with broken sky cover is 65.2 percent and 18.6 percent with scattered sky-cover. The joint occurrence frequency at time zero and again after a sufficiently long time interval, t, when the autocorrelation coefficient is negligible (about 4 τ_c) is given by the square of the initial unconditional probability or 42.5 percent for broken sky cover and 3.5 percent for scattered sky cover. Application of the Markov model simply determines the rate of decrease from initial to final probability.

Again for the fixed categories of broken and scattered sky cover amount, determinations were made of the probability that episodes of <u>continuous</u> CLOS-30 of duration t would be observed were determined using Eq. 5. The resultant persistence probability estimates for CLOS-30 assuming τ_c = 30 min, are shown in Fig. 3. Notice, for example, with scattered sky cover the occurrence frequency of CLOS-30 with a duration of 10 min is 6.4 percent as compared with 43.9 percent for a similar 10-min episode with broken sky cover. Equal estimates of 1 percent are found for a 45-min, CLOS-30 episode with scattered sky cover and a 4-hr, CLOS-30 episode with broken sky cover.

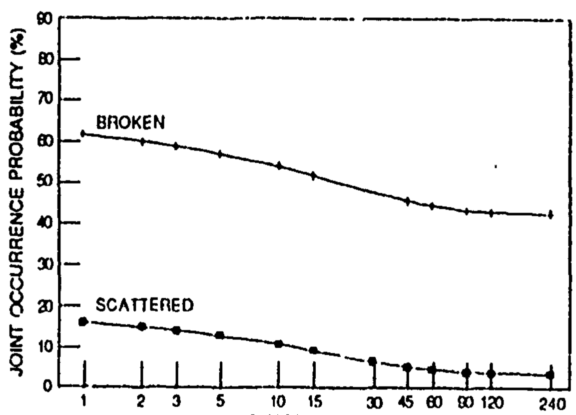

Fig. 2. Model calculations of the joint probability that a cloudy path of sight at zenith angle 30 deg will occur at time zero and recur after time interval t for broken and scattered sky cover.

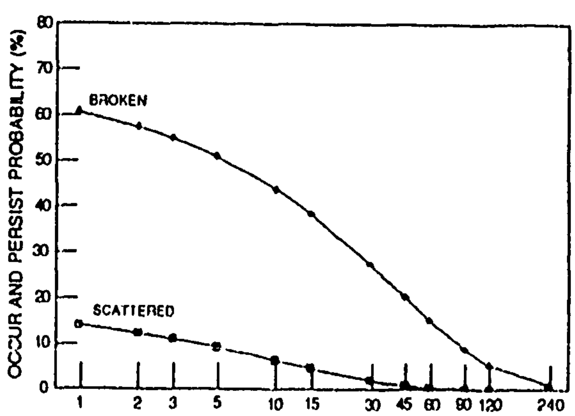

Fig. 3. Model calculations of the probability that a cloudy path of sight at zenith angle 30 deg will persist for time interval t for broken and scattered sky cover.

5.0 SINGLE SITE CLOS RECURRENCE AND PERSISTENCE PROBABILITY

Let us direct attention now to estimates of the temporal variability of CLOS-30 at a particular site. The first step in the determination of the CFLOS-30 recurrence probability is to calculate the climatic frequency distribution of sky cover for that portion of the data base when CLOS-30 is observed at the site and the conditional cumulative probability distribution for selected time intervals following the CLOS-30 occurrence. A sample determination using Eq. 3 is given in Table 1. In this case the climatic frequency distribution of sky cover is 20 percent overcast, 20 percent broken, 30 percent scattered and 30 percent clear. A typical value of sky cover relaxation time, τ_S, for mid-latitudes of 16 hours (Hering, 1989, para. 4.3) was assumed for the trial calculations. Finally, using the calculated conditional frequency distribution of sky cover for each time step and the joint occurrence frequency of CLOS-30 as a function of sky cover category and time interval (Fig. 2), determination is made of the estimated frequency that CLOS-30 will occur and then recur after time interval t. The results for this case are given in the right hand column of Table 1. Shown for comparison in Fig. 4 are determinations of CLOS-30 joint occurrence frequency as a function of time interval for sites

Table 1. Model calculations of the conditional cumulative frequency distribution of sky cover following the occurrence of a cloudy path of sight at zenith angle 30 deg. The joint occurrence frequency that CFLOS-30 will occur and then recur after time interval t is given in the right hand column. The unconditional climatic frequency distribution of sky cover for this case is 20 percent overcast, 20 percent broken, 30 percent scattered and 30 percent clear.

TIME	CUMULATIVE FREQUENCY OVERCAST	OVC+BKN	OVC+ BKN+SCD	Joint Prob. CLOS-30
Min				
0	0.518	0.856	1.000	0.386
5	0.491	0.827	0.981	0.343
15	0.479	0.802	0.966	0.315
30	0.476	0.785	0.953	0.293
Hours				
1	0.470	0.762	0.933	0.274
2	0.452	0.727	0.906	0.257
4	0.416	0.674	0.871	0.240
6	0.387	0.634	0.845	0.227
9	0.351	0.587	0.816	0.211
12	0.322	0.551	0.794	0.200
18	0.282	0.502	0.763	0.183
24	0.256	0.469	0.743	0.172
48	0.212	0.415	0.710	0.154

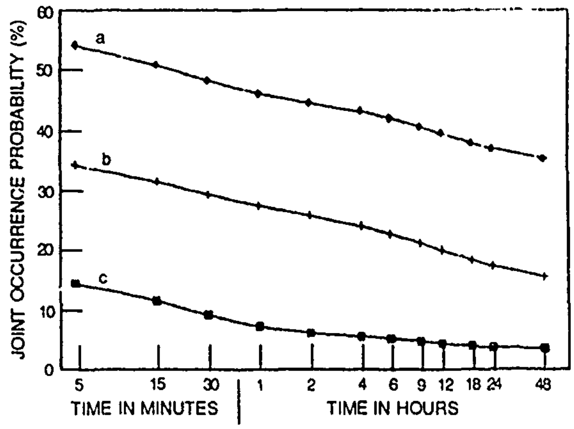

Fig. 4. Probability that a cloudy path of sight will occur and then recur after time interval t. Model calculations are shown for 3 climatic frequency distributions of sky cover: a. 40% overcast, 20% broken, 30% scattered, 10% clear; b. 20% overcast, 20% broken, 30 percent scattered, 30% clear; and c. 0% overcast, 20% broken, 30% scattered and 50% clear.

with different climatic frequency distributions of sky cover. Fig. 4 serves to emphasize the strong dependence of the joint occurrence probability on the climatic sky cover distribution. Notice also the nearly exponential decay of CLOS-30 joint occurrence probability with increasing length of time interval as given by the model estimates.

A similar stepwise process is followed for the determination of the frequency that CLOS-30 will occur and then persist for prescribed intervals of time at a particular site. In this case, however, we must first calculate the persistence probability of the cumulative sky cover distribution, and in turn determine the frequency of continuous episodes of CLOS-30 using the persistence probability of CFLOS-30 as a function of sky cover category given in Fig. 3. A discussion of the modeling procedures as applied to both single and multiple site determinations of CLOS persistence episode probability is given by Hering (1989).

Henceforth for convenience, we shall refer to an episode of continuous occurrence of CLOS-30 over time interval t as "downtime".

Model determination of downtime episode frequency at individual sites with different climatic frequency distributions of sky cover are given in Table 2. Again a value of 16 hours was assumed for the sky cover relaxation time and 30 min for the cloud element relaxation time. The frequency of scattered (30 per-

Table 2. Model calculations of the probability that an episode of continuous cloudy line of sight will occur as a function of duration for selected climatic frequency distributions of sky cover. Note that the unconditional probabilities of broken and scattered sky cover are 20% and 30%, respectively, for all cases. The frequency of overcast ranges from 0 to 40%.

Overcast	0	10	20	30	40
Broken	20	20	20	20	20
Scattered	30	30	30	30	30
Clear	50	40	30	20	10
Time Interval					
Min					
0	0.186	0.286	0.386	0.486	0.586
5	0.117	0.208	0.303	0.400	0.500
15	0.076	0.158	0.248	0.341	0.438
30	0.046	0.120	0.203	0.292	0.386
Hours					
1	0.021	0.082	0.156	0.237	0.326
2	0.006	0.051	0.113	0.184	0.265
4	0.001	0.030	0.076	0.134	0.204
6	0.000	0.020	0.056	0.106	0.167
9	0.000	0.012	0.038	0.076	0.127
12	0.000	0.008	0.026	0.056	0.099
18	0.000	0.003	0.013	0.032	0.061
24	0.000	0.002	0.007	0.018	0.039
48	0.000	0.000	0.001	0.002	0.007

cent) and broken (20 percent) was held constant at all sites. The overcast/clear ratio ranges from 0/50 to 40/10 in the assumed sky cover frequency distributions at the individual sites for the trial calculations of downtime frequency. As expected, Table 2 shows that the climatic frequency of overcast relative to the frequency of clear sky conditions exercises predominant control over the downtime probability, particularly the episodes of long duration. Thus, the accuracy of model estimates of downtime occurrence probability are critically dependent upon good definition of the climatic frequency dist ibution of sky cover for the place, time of year and time of day of interest.

6.0 MULTIPLE SITE OF CLOS RECURRENCE AND PERSISTENCE PROBABILITY

Let us define "downtime" for multisite calculations as the continuous occurrence of CLOS-30 at all sites for specified intervals of time t. The modeling procedures used for the multisite downtime probability determinations are described in Hering (1989). First the joint occurrence frequency of sky cover at the sites is determined using Eqs. 2 and 3. Then the persistence probability of the joint sky cover distribution is calculated using Eq. 5. Finally, the multisite downtime is determined using the calculated occurrence and persistence probability of CFLOS-30 as a function of sky cover category given in Fig. 3. Although the sky cover has significant correlation over rather large separation distances, the arrangement of clouds over 2 sites with partial sky cover may be expected to be independent over separation distances greater than the typical sky-dome diameter of 35 mi. This assumption was made in the modeling procedure. A relaxation distance, d, of 500 mi, (Hering, 1989, para. 5.1) appropriate for middle latitudes was used for the trial calculations.

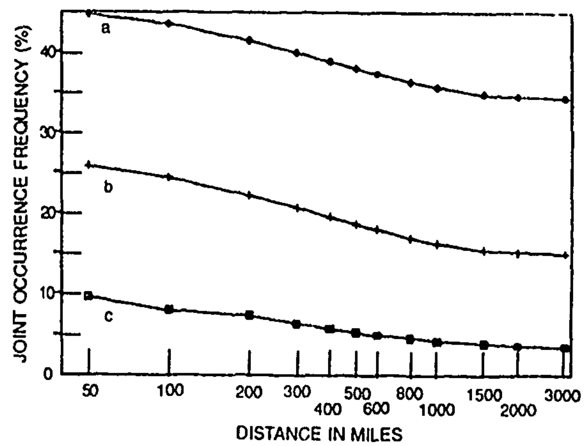

Fig. 5. Model calculations of the probability of joint occurrence of CLOS-30 at 2 sites as a function of site separation distance. The climatic frequency of broken (30%) and scattered (30%) sky cover are the same for curves a, b and c. The overcast/clear ratios are 40/10, 20/30 and 0/50 for a, b and c, respectively.

Shown in Fig. 5 are the model determinations of the probability of the joint occurrence of CLOS-30 at 2 sites as a function of site separation distance for a range of climatic frequency distributions of sky cover. The sky-cover cumulative frequency distributions vary from set to set but were assumed to be the same for the 2 stations in each set.

Notice, for example, in Fig. 5, that for case b where the climatic frequency of overcast is 20 percent the joint occurrence frequency of CLOS-30 is 26 percent at 50 mi and decreases rather slowly to 16 percent for a separation distance of 1000 mi. Again the results show the predominant influence of the sky-cover frequency on the joint CLOS-30 occurrence probability.

The relative sensitivity of the occurrence and duration of downtime for a multisite network to the number of sites in the network, the site separation distance, and the climatic frequency of sky cover is explored in the final comparative series of model determinations. In all cases the input values for cloud-cover and cloud-element relaxation time are 16 hours and 30 min, respectively (see para. 4.0 and 5.0 above). The climatic frequency of broken sky cover is 20 percent and scattered sky cover is 30 percent.

The first of 3 comparative calculations, shown in Fig. 6, depicts the probability of the continuous joint occurrence of CLOS-30 at 2 sites with a separation distance 100 mi as a function of duration interval for 2 sky cover frequency distributions (overcast/clear ratios of 40/10 and 20/30). We see that the large disparity in downtime frequency due to sky cover distribution extends to very long duration episodes.

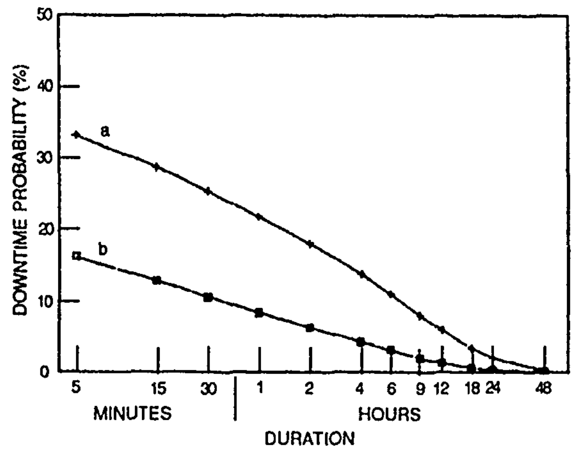

Fig. 6. Comparison of downtime frequency as a function of duration for particular climatic frequency distributions of sky cover. For curve a the overcast/clear ratio is 40/10 and for curve b the overcast/clear ratio is 20/30. The climatic frequency of broken and scattered sky cover is 20% and 30%, respectively, for both a and b. The 2-site separation distance is 100 mi. in both cases.

Fig. 7 compares downtime frequency for a single site and combinations of 2 and 3 sites. The overcast/clear ratio is 20/30 and the site separation distance is 100 mi for this set of model calculations. The results show, for example, that a downtime episode of 30-min duration has an indicated probability of 29 percent for a single site as compared to 10 percent and 6 percent for combinations of 2 and 3-sites, respectively, with the same climatic sky cover distribution.

Finally in Fig. 8, the effect of site separation distance on downtime probability is shown for a pair of sites with an overcast/clear ratio of 20/30. The change in downtime probability is illustrated for a factor of 5 increase in site separation distance from 100 mi to 500 mi.

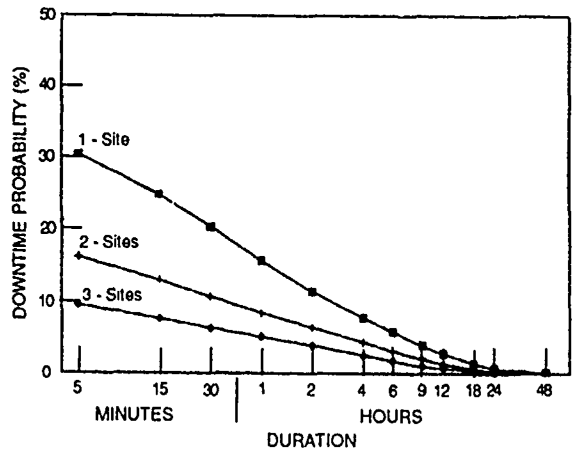

Fig. 7. Comparison of downtime frequency as a function of duration for 1-, 2-, and 3- site networks. The climatic frequency of sky cover is 20% overcast, 20% broken, 30% scattered and 30% clear. The site separation distance is 100 mi.

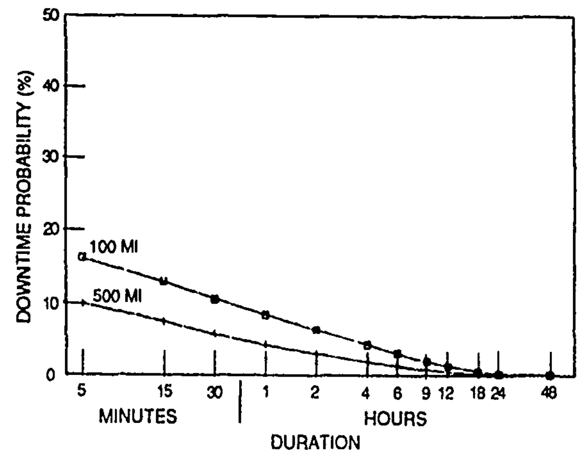

Fig. 8. Comparison of downtime frequency for 2-sites as a function of duration for site separation distances of 100 and 500 mi. The climatic frequency distribution of sky cover is the same as for Fig. 7.

7.0 PRESENT STATUS AND SUMMARY

Modeling procedures for estimating the climatic probability of episodes of cloud obscured lines of sight have not been tested extensively, including some of the procedures used in this study. Verification using actual data is presently underway. A broad experimental field program of minute by minute measurements of sky cover is being carried out by the Marine Physical Laboratory, UCSD. The data base generated by the Whole Sky Imagery (WSI) network will enable validation of the many factors involved in the CLOS modeling process. The trial calculations made in this study provide a first approximation of CLOS behavior relative to the climatic frequency distribution of sky cover. However, certain aspects of the modeling process remained to be analyzed and refined on the basis of more extensive CLOS data.

The relationships between CLOS frequency and the zenith angle of the path of sight will be examined in detail using the new WSI data base. Important refinements include the definition of CLOS dependence on zenith angle as a function of cloud type. In addition, it is important to take a close look at the relative importance of the azimuthal dependence of the climatic frequency of CLOS as revealed by the data from individual sites in the WSI network.

The temporal and spatial variations in sky cover have been analyzed rather extensively using the conventional climatic data base. Thus, the uncertainties in the model input values of sky cover relaxation time and distance and the resultant impact on CLOS probability estimates can be estimated. However, the more detailed WSI network data are necessary for comprehensive analysis of cloud-element relaxation time as defined in paragraph 4.0, and its variations with season and site location. Yet another factor requiring study is the potential variation in cloud-element relaxation time with the zenith angle of the path of sight. As shown by time lapse sequences of ground-based cloud photography, apparent cloud motion overhead is more rapid than near the horizon.

Although all these factors are important, the major determinant of the frequency of downtime caused by continuous occurrences of CLOS is the prevailing sky cover distribution. Accurate estimates of CLOS episode frequency require accurate definition of the climatic frequency distribution of sky cover for the site or for the combination of sites under consideration and, of course, the variations with season and time of day. It follows that the variability in CLOS frequency that can occur in a given month from one year to the next are determined primarily by associated variations in the observed frequency of sky cover. To the extent that the extremes in sky cover distribution for a given month of the year can be determined from existing site records, the expected extremes in CLOS episode frequency can be estimated by model calculations.

8.0 ACKNOWLEDGEMENTS

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